An evaluation of air quality, home heating, and well-being under Beijing's program to eliminate household coal use

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Nature Energy, Volume 4, pages 416-423,
DOI:10.1038/s41560-019-0386-2, May 2019
r2019.05.27

Abstract

To mitigate health and environmental effects from coal-based home heating, the Beijing Municipality has implemented a program in 3,700 villages that subsidizes electric heat pumps and electricity, and bans coal. Here we estimate this program's impacts on household energy use and expenditures, well-being, and indoor environmental quality by comparing treated and untreated villages in three districts that vary in socioeconomic conditions. We find that under this program, households in high- and middle-income districts eliminated coal use with benefits for indoor temperature, indoor air pollution, and life satisfaction. In a low-income district, the policy had partial effectiveness: coal use was contingent on household wealth, and there were fewer benefits to the indoor environment, and negative impacts on well-being. These results suggest that a rapid household energy transition can be effective, but appropriately controlling subsidies and fine-tuning supports to limit transitional hardships for the less affluent are essential.

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1 Introduction

The transition of households from coal-based to electric heating is emblematic of the convergence of three global grand challenges: the mitigation of greenhouse gas emissions, the reduction of regional and household air pollution as major causes of disease and mortality, and access to affordable, reliable, sustainable, and modern energy. At this nexus, China lies possibly most prominent of all, with 30% of global GHG emissions, 70% of which is from coal [1]; an estimated 1.6 million yearly premature deaths due to air pollution [2]; and over a third of Chinese homes using coal heating stoves [3].

In response, China is undertaking an ambitious plan to transition up to 70% of all households in northern China to clean space heating (see Supplementary Note 1 for more context). If the integrated program proves effective, it will lie in sharp contrast to many past household energy intervention programs in China and globally, often for cooking, which have had limited impact on air pollution and health despite large allocations of resources [4, 5, 6, 7].

Residential coal burning emits a mixture of harmful air pollutants, including high concentrations of particulate matter (PM) into homes and surrounding communities and also substantially contributes to ambient air pollution, thus impacting populations over large areas [8]. Residential coal burning can account for nearly half (45%) of monthly averaged outdoor fine particulate matter ($PM_{2.5}$) in winter months in northern China, and up to 57% during winter haze episodes (one to several days), exceeding the combined contribution of the transportation and power sectors [9, 10, 11].

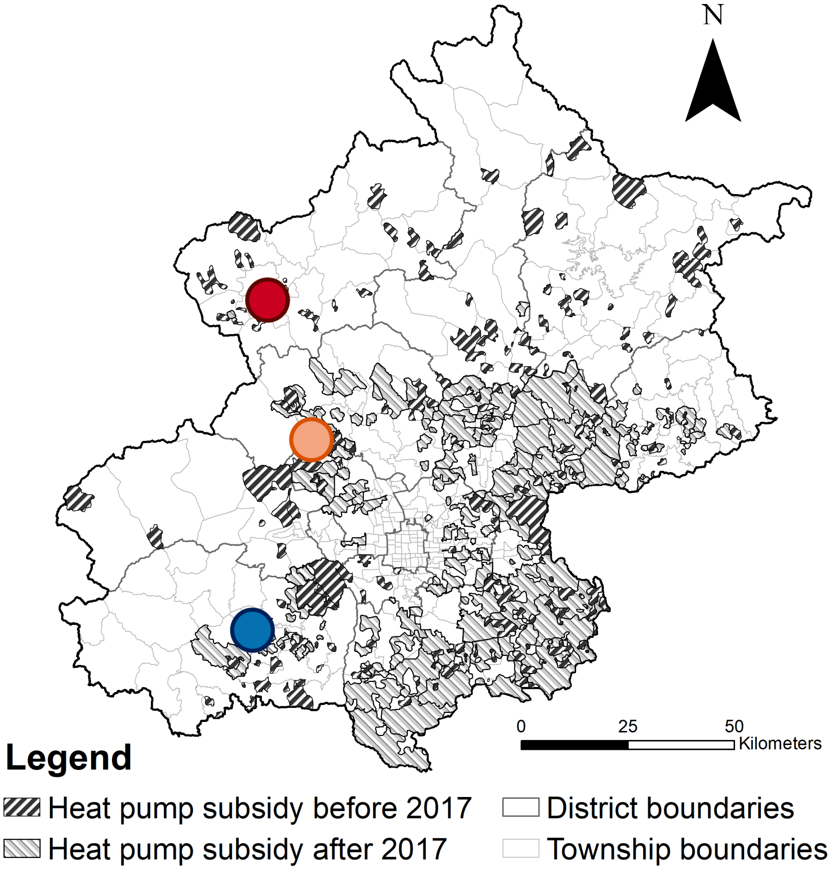
In response to severe and persistent haze episodes in northern China, the Chinese State Council released an "Air Pollution Prevention and Control Action Plan" that set regional coal consumption caps in key regions, including Beijing-Tianjin-Hebei (BTH), and ambitious new air quality targets, such as a 25% reduction in annual mean $PM_{2.5}$ concentrations from the 2012 level by 2017 [12], recently updated to make further reductions by 2020 [13]. In the effort to meet this target the Beijing municipal government announced in 2016 an ambitious two-pronged "coal to electricity" program (and a parallel "coal to natural gas" program) that designates coal restricted areas and, simultaneously, offers subsidies to nighttime electricity rates and for the purchase and installation of electric-powered, air-source heat pumps to replace traditional coal heating stoves (Figure 1).

The policy is being rolled out rapidly, village-by-village, with seeming geographic uniformity. While there is some evidence that the extended mountainous regions within the municipality will systematically receive the policy at later times, there is little that predicts whether villages have these programs in peri-urban Beijing, and village leaders themselves are unsure when they will receive the policy. From anecdotal discussions with policy implementers, the rationale for when the policy is applied in a village may include considerations for the road network, political feasibility, geographic equity, energy infrastructure, among others. These reasons vary considerably and unsystematically, allowing us to treat the roll-out of the program as a quasi-randomized intervention.

Various contextual factors, such as financial constraints, preferences, and social capital can determine how households might be impacted by this type of program. Even just considering simple budget constraints suggests that, when household affluence and subsidies are high enough, households under the coal ban program will embrace the benefits of convenience and improved indoor air quality, and pay the higher cost of electric heating. When affordability is questionable, households should substitute consumption away from other goods, or possibly

A B C

Figure 1: Coal storage and heating equipment. Coal storage for one household's winter needs is typically conspicuous (A). In (B), a cook stove to the left and a coal heating stove in the middle are both vented to the outside. The coal stove heats water for consumption as well as for distribution through radiators. In (C), a typical compressor for air-source water-heating heat-pump systems is also conspicuous outside a home in a treated village.



Sources: Beijing Municipal Office of Rural Affairs, 2017
China Statistical Yearbook, 2010

Figure 2: Study site locations within Beijing. Study site locations Yanqing (red), Haidian (orange), and Fangshan (blue), contained some villages that had already adopted the coal ban and heat pump subsidy as of 2017, and some villages that had not [14].

increase labor market participation to fund the transition and higher heating cost. Finally, when household finances are insufficient to cover the cost of the transition, households may cut back on heating and possibly continue burning coal. When enforcement is imperfect, the second and third cases may also be characterized by lesser compliance.

In our study we compare treated (coal ban in place with installed, subsidized heat pumps and subsidized nighttime electricity) and untreated (no ban nor subsidy) villages to assess three types of outcomes of this policy: fuel use and economic behaviour, subjective well-being, and indoor environmental conditions. Our study design consists of 302 door-to-door surveys in six villages, with one treated and one un-treated village in each of three districts chosen to represent different socioeconomic and geographic conditions present in peri-urban Beijing (Figure 2). Demographic variables were similar between village pairs, but income differences separate the three districts. Haidian is high-income; Fangshan is middle-income; and Yanqing is lower-income. We find evidence that the policy is successful in reducing or eliminating the use of coal for household heating, that these reductions lead to lower exposure to indoor $PM_{2.5}$, and that households generally experience warmer and better regulated temperature under the policy. More affluent households reported higher or similar subjective well-being under the treatment, while in the low income district satisfaction was lower and the elimination of coal was not entirely effective.

2 Impacts on household fuel use, expenditure, and behaviour

The primary goal of the policy is to eliminate coal from rural household heating. This is intended to occur through fuel substitution, but an overall reduction of heating is also a possible consequence of the policy since the cost of operating a heat pump is greater than purchasing coal. Therefore, in addition to surveying households' total expenditures on energy, we also estimated the amount of coal burned in each house as well as how much indoor space heating was being carried out, room-by-room.

We find that coal use is entirely absent in treated villages in Haidian and Fangshan, and significantly lower in the treated as compared with the untreated village in Yanqing (Figure 3). Both types of subsidised technologies, air-to-water heat pumps and air-to-air heat pumps, made significant contributions to the replacement of coal. In addition in all three districts, heat pumps may have substituted for less-efficient resistive electrical heating, as evidenced by the lower (or zero) reported use of resistive heating in treated villages as compared with untreated ones.

Total contributions to heating by six different energy sources or technologies, measured as room-hours per day (Figure 3a), were greater in treated villages compared with their untreated counterparts. In Haidian, total mean heating was significantly higher (Δ=45 room-hours, p=.002, N=87) in the treated than untreated village. So were the fraction of house area that was heated (Δ=12%, $p=2\times10^{-4}$, N=91) and the fraction of rooms that were heated (Δ=7%, p = .03, N=87). Similarly, a higher fraction of rooms was heated in the treated village in Fangshan (Δ=9%, p = .04, N=93) and a higher fraction of house area was heated in the treated village in Yanqing (Δ=14%, p = .005, N=87) as compared with their untreated counterparts (Supplementary Table 1) even though treated villages were generally similar, or less affluent, than their untreated counterparts on a variety of objective measures (see Supplementary Note 2 and Supplementary Table 2 for pooled estimates of treatment effects).

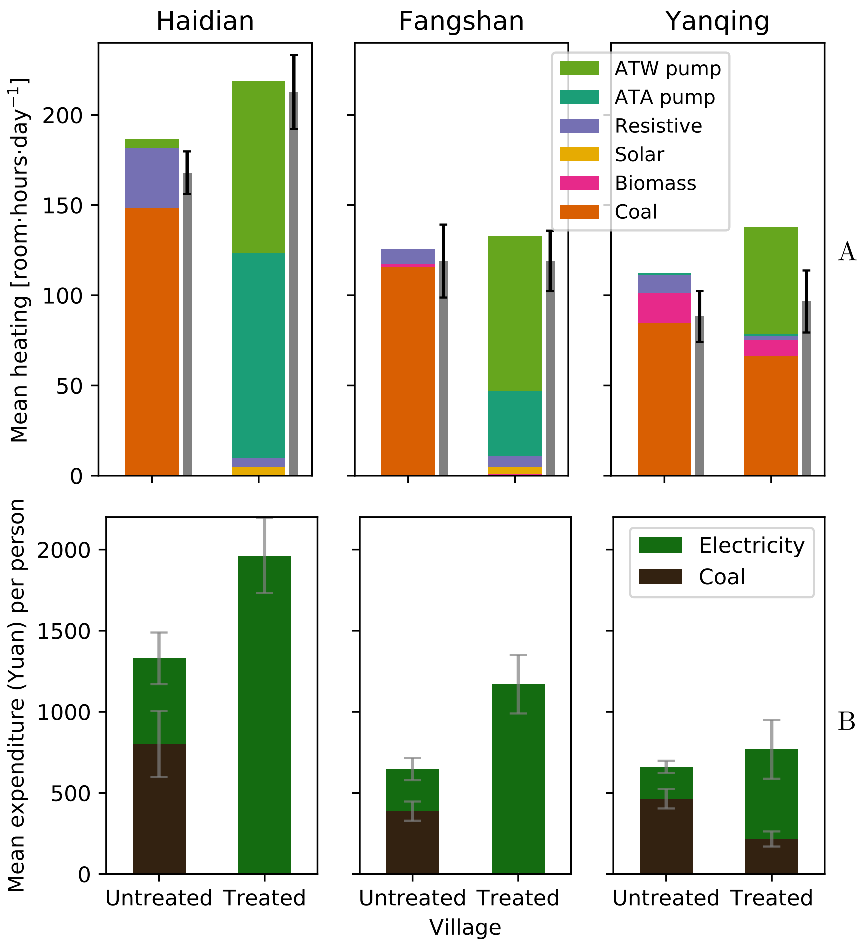


Figure 3: Heating and expenditure for coal and electricity. Stacked coloured bars (A) show total contributions to heating by six different energy sources or technologies, measured as room-hours per day per household in treated and untreated villages in Haidan (treated $N = 42$, untreated $N = 45$) Fangshan (treated $N = 48$, untreated $N = 45$), and Yanqing (treated $N = 39$, untreated $N = 48$) districts. The gray bars quantify total heating, measured as room-hours per day per household. Means are calculated across households, the majority of which use one method for heating (see Methods). The Resistive category includes mobile electric heater, wall-mounted electric heater, electric floor heating, thermal storage (electricity), electric blanket, air conditioners used in ohmic heating mode, and hot water radiators fired by electric heater. The Biomass category refers to wood-fired kang (under-bed heater). The Coal category includes coal-fired kang, coal-fired open stove, and coal-fired hot water radiator, using various grades of coal. (B) Mean per person expenditure (by contrast, the text describes per household expenditure; both sets of values are given in Supplementary Table 1) for coal and electricity for the entire heating season in treated and untreated villages in Haidian, Fangshan, and Yanqing districts. Error bars show 95% confidence intervals.

These differences are independently corroborated by the expenditures that households reported for coal and electricity (Figure 3b). Average combined expenditures on electricity and coal were higher in treated compared with untreated villages (Haidian: Δ=2500 RMB season^{-1}, p=.0001, N=90; Fangshan: Δ=1700 RMB season^{-1}, p=10^{-5}, N=89; Yanqing: Δ=200 RMB season^{-1}, p=.36, N=87). In Fangshan, the difference in electricity expenditures was twice the amount spent on coal in the untreated village. In Yanqing, expenditures on coal persisted after the subsidized installation of heat pumps, but were half as high as in the untreated village (Δ=$-$670 RMB season^{-1}, p=10^{-7}, N=87). Treated households in Yanqing used a mix of heat-pump technologies, coal stoves, and, to a limited extent, biomass for heating.

The incomplete enforcement of the coal ban in one of our treated study villages (Yanqing district) presents an opportunity for a further examination of household behaviour. Because heat pumps were installed in this village, we are able to examine the dependence of fuel substitution on household financial resources in the case of a subsidized but seemingly voluntary transition away from coal use. Figure 4A shows the relationship within the treated village in Yanqing between the fraction of expenditure on coal and an index of household wealth. The index is constructed as the first principal component of a set of measures of household income, expenditures, and assets (see Methods). The relationship between coal use and household wealth is strongly negative (p=.005, N=38), and nearly all incidences of coal-free households are in the upper half of the wealth distribution (Figure 4B). Regardless of how much of the electricity expenditure is actually for non-heating needs, this constitutes evidence of a wealth substitution effect away from coal.

We find no differences between village pairs for the number or fraction of household occupants engaged in the labor market, for the monthly consumption of meat, or for reported household incomes (Supplementary Table 1).

3 Impacts on well-being

Dimensions of human well-being such as comfort, convenience, and financial hardship are often difficult to capture. Households heating with coal are faced with procurement, storage, shovelling, and monitoring tasks, in addition to breathing polluted air. However, this comes at less financial burden than electric heating. To try to better account for households' full experience, we asked respondents to report on their overall life satisfaction, as a way to quantify their quality of life [15, 16].

We find large differences in well-being within two of the districts (Figure 5). In the middle-income district (Fangshan), where the transition to electric heating was complete, satisfaction with life (SWL) and satisfaction with living conditions (SWC) were higher (ΔSWL=+0.7 on a 0–10 scale, p=.049, N=93; ΔSWC=+1.0, p=.005, N=93) in the treated village than the untreated. By contrast, in the less affluent (low-income) district, both satisfaction measures were lower (ΔSWL=$-$1.0, p=.015, N=87; ΔSWC=$-$1.5, p=, N=87) in the treated village as compared with the untreated village.

These differences are large. In a simple regression explaining life satisfaction with income, the effect on life satisfaction of a doubling of household income is only 0.36 (see Supplementary Note 2, Supplementary Table 3, Supplementary Table 4, and Supplementary Table 5). The magnitude of this effect is consistent with a large literature on life satisfaction and income

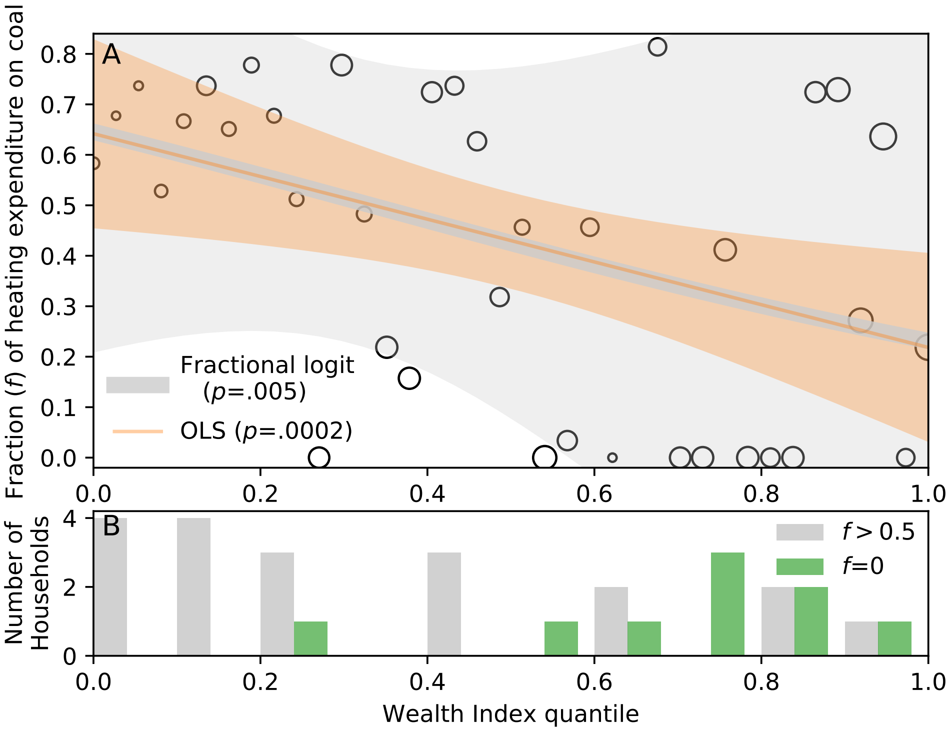


Figure 4: Coal use versus wealth. Households are from a village with subsidized, installed heat pumps but incomplete enforcement of the coal ban. Households with higher wealth index spend less on coal as a fraction of total heating-related expenditures. (A) Linear least squares (OLS) and fractional logit models for this relationship give nearly identical predictions, with high statistical confidence. Shaded regions show 95% confidence intervals. Circle size indicates reported household income. (B) Wealthier households are more likely to eschew coal completely (coal fraction of expenditure $f=0$), and less likely to spend at least half ($f \geq 0.5$) of their heating / electricity budget on coal. See Methods for details of the household wealth index, and details of estimates.

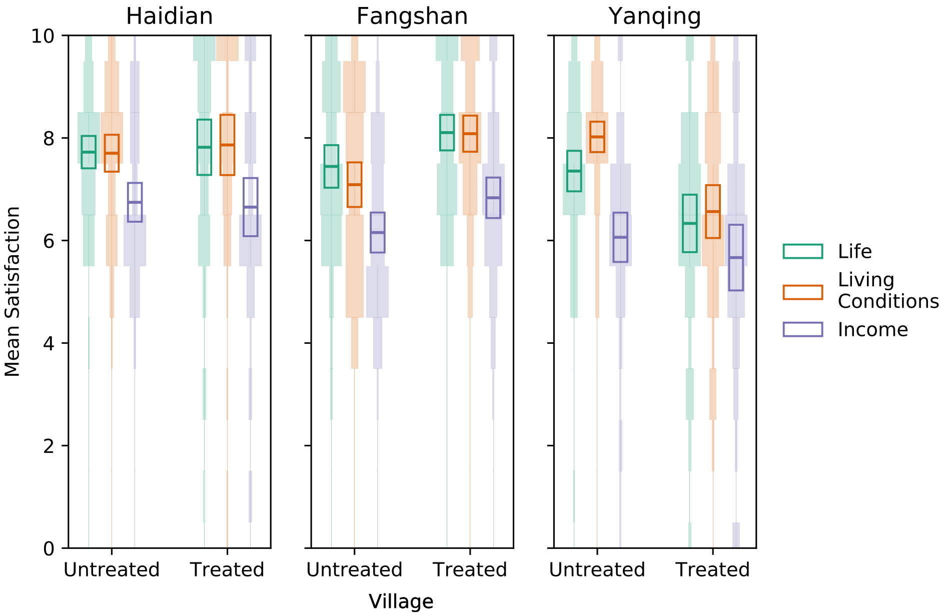


Figure 5: Subjective evaluations of well-being. Ratings of satisfaction with life (green) living conditions (orange), and income (purple) in treated and untreated villages in Haidan (treated $N = 44$, untreated $N = 47$) Fangshan (treated $N = 48$, untreated $N = 45$), and Yanqing (treated $N = 39$, untreated $N = 48$). Means and 95% confidence ranges shown by boxes. Shaded regions show full distributions over discrete response values.

[e.g., 16]. Our observed well-being differences of $+0.7$ and -1.0 are similar to those one would expect from an income increase of 200% and income decrease of 85%, respectively. We found no difference in life satisfaction between villages in Haidian, despite larger expenditures on heating and electricity in the treated village.

4 Impacts on indoor environmental quality

In a randomly selected subsample of 6 to 12 homes (3–6 per day) in each village (total n=55), we measured daytime (6- to 8-h) or daily (24-h) indoor air temperature and indoor concentrations of $PM_{2.5}$ in the room where residents reported spending the largest fraction of their awake time (excluding kitchens). For homes with 24-h measurement (n=26), we also calculated average indoor temperature and $PM_{2.5}$ concentration separately for daytime (8AM to 6PM) and nighttime (6PM to 8AM). In addition to indoor sources of $PM_{2.5}$ (e.g., combustion of solid fuel, tobacco smoking), indoor air quality is also influenced by $PM_{2.5}$ generated from outdoor sources like traffic and local industry that infiltrate across the residential building envelope, and by the rate at which air moves in and out of the home. Indoor $PM_{2.5}$ concentrations were higher in Haidian than in Fangshan and Yanqing, which likely reflects the higher ambient $PM_{2.5}$ levels on measurement days in Haidian (see Methods). To account for the influence of ambient air pollution, which can vary due to factors independent of coal-restriction status, we subtracted time-averaged outdoor $PM_{2.5}$ concentrations from indoor $PM_{2.5}$ concentrations measured and time-averaged over the same time period.

In homes in the two treated villages adhering completely to the coal ban (Haidian and Fang-

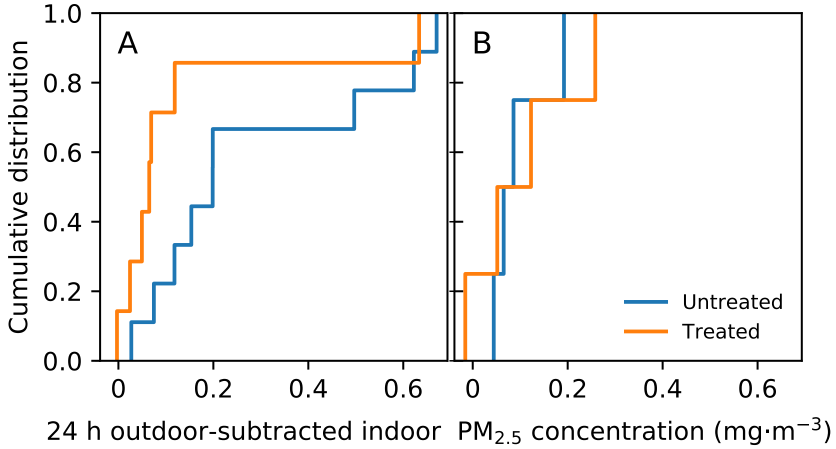


Figure 6: Cumulative distributions of indoor 24-h PM$_{2.5}$ concentrations. Average 24-hour, outdoor subtracted indoor PM$_{2.5}$ concentrations in treated and untreated villages in (A) Fangshan and Haidian (treated N=8, untreated $N = 9$), where participants in the coal-restricted villages did not report coal use, and (B) Yanqing (treated N=4, untreated N=4), where participants in the coal-restricted village reported using coal.

shan), average outdoor-subtracted, indoor 24-h PM$_{2.5}$ concentrations (mean ± standard deviation: 0.145±0.218 mg·m^{-3}; n=7) were lower compared with untreated homes (0.275±0.244 mg·m^{-3}; n=10) (Figure 6A). In Yanqing, where households in both the treated and untreated villages reported using coal, average indoor 24-h PM$_{2.5}$ concentrations were similar (Figure 6B), with slightly higher concentrations in the treated village (0.098±0.117 mg·m^{-3}; n=4) than in the untreated village (0.079±0.066 mg·m^{-3}; n=4). Outdoor-subtracted indoor PM$_{2.5}$ concentrations in Yanqing homes were lower than in homes in Haidian or Fangshan, and may be attributable to higher air change rates in Yanqing homes (1.9±0.9 hr^{-1}) compared with Haidian (0.5±0.2 hr^{-1}) and Fangshan (0.7±0.3 hr^{-1}) homes [17, 18] [See also the SI in 18, for full details of method of estimation]. Warmer ambient temperatures on measurement days in Yanqing (16±2°C) compared with Haidian (9±1°C) and Fangshan (12±1°C) may also have reduced demand for heating, and thus coal-burning, in Yanqing homes.

We observed more pronounced differences in indoor PM$_{2.5}$ between homes in treated versus untreated villages (see Methods) at night (6PM to 8AM), compared to daytime (8AM to 6PM). This may reflect coal burning activity in the evenings for space heating in untreated homes [19, 20]. Overall, regardless of time of day, we observed lower indoor PM$_{2.5}$ in treated versus untreated households, but only in the two districts where treated villages reported adhering to the coal ban. Thus, we interpret these differences to be at least partly attributable to the new household energy transition policy.

In Fangshan and Haidian, the indoor environment was also warmer (Figure 7) in the homes that transitioned to clean space heating (mean ± standard deviation: 18.8±0.7 °C; n=17) compared to homes still using coal (17.4±0.5 °C; n=19). In Yanqing, indoor temperatures were similar, on average, between the two villages (treated: 19.1±0.5 °C; n=10; untreated: 19.6±1.3 °C; n=7). Treated households in Fangshan and Haidian were consistently warmer than counterpart homes in the untreated villages over the full range of observed temperatures (14–25°C) during daytime hours. Across the observed temperature range, households in treated villages maintained a narrower range of indoor temperatures, with fewer households

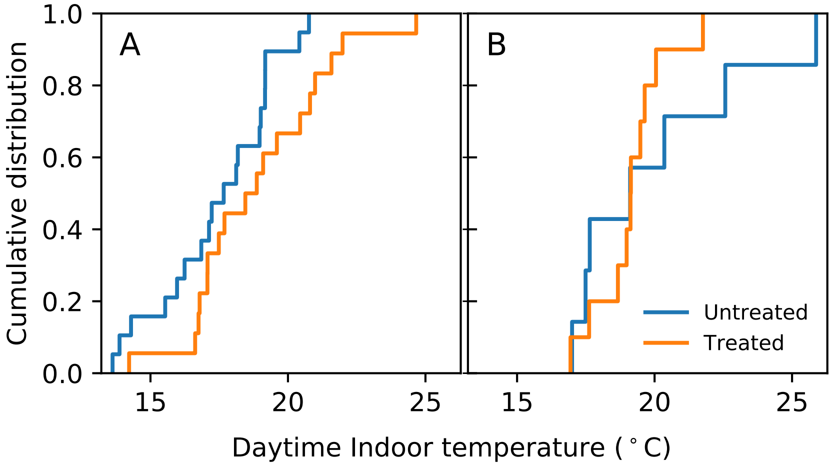


Figure 7: Cumulative distributions of observed daytime temperature. Average daytime temperature in treated and untreated villages in (A) Fangshan and Haidian (treated $N=$18, untreated $N=$19), where participants in the coal-restricted villages did not report coal use, and (B) Yanqing (treated $N=$10, untreated $N=$7).

experiencing temperatures below the degree-day threshold and more households above the degree-day threshold compared with untreated villages in the same district.

One interpretation of these results for Yanqing could be that, at lower temperatures, particularly temperatures below the heating degree day balance point for China (18°C), households in the treated village may have supplemented their clean space heating with coal when their space heating demand could not be met with the new household technology and energy source alone.

5 Discussion

Four aspects of our findings show that lower indoor air pollution and better convenience associated with the use of heat pumps rather than coal may confer household benefits in the short term that outweigh the higher costs. First, their discretionary use in Yanqing shows that some combination of heat pumps' palpable benefits to health, comfort, and convenience are jointly sufficient for households to prefer paying a higher price to heat, at least partially, with electric heat pumps rather than coal. Our most telling finding in the treated village in Yanqing is that wealthier households are the ones who eschew coal entirely. This means that the relationship shown in Figure 4A is more than a reflection of higher consumption of electricity for non-heating purposes by the wealthy; instead, it constitutes behavioural evidence that, at the existing prices, the switch away from coal to new electric technology is desirable. Second, the undiminished or higher satisfaction of residents in the coal ban villages in Haidian and Fangshan suggest that, despite large increases in expenditures, the transition away from coal is a net benefit. A caveat is that we cannot precisely distinguish between electricity expenditure on heating versus other household appliances. Therefore, some of the program benefit for these wealthier households may be the subsidized marginal cost, and consequent higher consumption, of other electrified services in the home. Third, in wealthier districts, indoor temperature was higher, suggesting that the overall benefits of non-coal heating are such that households shifted their expenditures towards it. Fourth, all treated villages heated a higher fraction of rooms or area than their untreated counterparts. This provides further support for our interpretation that non-pecuniary costs (inconvenience and discomfort) of heating by coal can be more important than the lower price.

These findings are remarkable because most of the program benefits are likely to come through long run outcomes such as reduced GHG emissions, improved air quality, and better population health outcomes — benefits that are external to the individual affected households. Indeed, even if the overall benefits to rural households under the program were negligible or slightly negative, the program could provide net benefits to the region.

The importance of our findings and this program are underscored by ambitions within the United Nations' Sustainable Development Goals (SDGs), in particular in SDG 13 (climate action), SDG 3 (health & well-being), and SDG 7 (clean energy), and by the challenges experienced in the past. Previous large-scale rural energy programs in China were enormously successful in deploying cookstoves into hundreds of millions of homes [4, 5] but sustained low levels of stove use [6] and marginal or no improvements in indoor air quality [7]. By contrast, our results are consistent with Beijing's coal-to-electricity program changing behaviour while improving well-being, thus achieving its desired social and environmental aims.

Based on evidence from our treated, lower-income village, this appears to be in part a reflection of heat pumps' technological efficiency. With electricity subsidies and heat pumps in place in the lower-income district, we observed heat pump usage but near-zero use of traditional electric heating ("Resistive" in Figure 3). Thus, the heat pumps' factor of $\sim$3 higher efficiency, possibly along with their better safety and convenience, apparently made their use — but not that of traditional electric heaters — economical in this district with the electricity subsidies in place. Notably, we did not observe higher use of biomass fuel in any of the treated villages, indicating that they did not switch to another inexpensive and polluting solid fuel as a replacement for coal.

As a cross-sectional survey, our study has limitations in its ability to identify causal effects. However, we note that villages in each of our pairs have similar characteristics, including location and economic and demographic characteristics. In addition, our ability to leverage within-village variation in the case of the treated Yanqing village complements and corroborates our comparative approach. While our villages generally reflect conditions in greater Beijing, our small sample also limits our ability to generalize to the region. Our study focuses on the replacement of coal by electricity, despite the existence of a parallel coal-to-natural-gas program that may not have an identical geographical distribution [21]. We assess household concentrations of $PM_{2.5}$ but do not directly measure personal exposures or quantify the program's acute or long-term health impacts, even though these may be the most important benefits of the program. Similarly, while a systematic review of randomized evaluations showed that household temperature and energy interventions can improve both physical and mental health outcomes, as well as socioeconomic indicators [22], our study does not measure these benefits directly. Further qualitative work may also be able to illuminate other non-financial impacts of the program.

Untreated villages in our sample burned on average 3.7, 4.2, and 3.4 tonnes of coal per household per winter in Haidian, Fangshan, and Yanqing, respectively, while treated villages burned on average 0, 0, and 1.8 tonnes per household. If these are representative effects, it can be expected that the program might achieve an annual reduction of 6.6 MT of coal combustion, similar to the total estimated for household heating in Beijing prior to the coal reduction program [21], and corresponding to ∼13 MT CO_2e of greenhouse gas emissions assuming an eventual transition to renewable generation of electricity, and ∼6.6–66 kT of PM emissions. Reducing domestic coal burning in China would decrease emissions of important gaseous pollutants, including SO_2 and NO_x, which also contribute to environmental and health impacts through secondary formation of PM, ecosystem acidification, and regional climate change. Further, household coal emissions are uniquely hazardous to human health compared with other solid fuels [23], and are classified as carcinogenic to humans [24]. Eliminating emissions from domestic coal combustion in China could reduce annual mortality by over 40,000 premature deaths [25], based only on the contribution of household coal use to ambient air pollution, and reduce exposures for the over 200 million Chinese homes using coal stoves [3].

Our positive findings for program outcomes in terms of indoor daytime temperature, night time and 24-h air pollution, overall life satisfaction, and avoidance of coal burning all hold primarily for wealthier homes. With sufficient resources, households under the policy appear to be willing to pay more for non-coal heating, to heat more rooms, to keep higher indoor temperatures, and to have better indicators for their physical and psychological outcomes. However, if many households are economically unable to comply with the coal ban or suffer a reduction in life quality as a result of it, the scalability and political portability of the policy may be questionable, even if the subsidies are sustainable and even if net benefits to the aggregate population are positive overall. Our findings could be taken to suggest that subsidies may not have been equally necessary in each village or for each household, and may, arguably, have been insufficient in Yanqing (and by the same token, lower subsidies might have achieved the same result in Haidian). We have focused on household benefits and costs, but do not evaluate net benefits in light of the substantial subsidies involved.

As a groundbreaking model for rapid transition and technological "leap-frogging" to address simultaneously climate, health, and development, Beijing's ambitious policy deserves global attention and monitoring. Future research should better quantify the health effects and savings of the policy, and to follow households through the transition in order to better identify causal effects of the natural experiment provided by the distributed roll-out of the program.

Methods

Sample

We selected three districts (Figure 2) within Beijing Municipality that cover a range of economic and geographic conditions (see Supplementary Note 1 for more context). Haidian was selected for its close proximity to Beijing city and relatively high living standards, Fangshan represents a "typical" peri-urban suburb of Beijing, and Yanqing is a more mountainous area on the fringes of the Beijing municipality. Within each district, we selected two villages within relatively close proximity of one another: one which was a current participant in the coal-to-electricity program (treated), and another that was not yet enrolled (untreated). In each village we first met with local village leaders to obtain permission to conduct the surveys.

Within villages, selection of households was semi-random. While enumerators were instructed to select households randomly, village leaders were often helpful in identifying homes with household members currently present. In some villages, this approach reached a considerable fraction of the total number of households, further minimizing any possible sample bias.

Prior to data collection, we piloted a preliminary survey instrument with $\sim$25 households in Haidian and Yanqing districts to ensure our instrument accurately reflected the range of situations we might encounter. Our survey instrument and procedures complied with, and were approved by, the research ethics board at McGill University. Informed consent for the study was obtained from all participants.

Sampling was carried out in March and April of 2017. Surveys included a complete roster of heating methods and their contributions in each room. All survey data were collected via handheld electronic tablets using Surveybe data collection software, which facilitated secure data transmission and archiving and minimized input errors, with a field team hired locally. Visual surveys of the home were also conducted to assess household amenities and to verify respondent reports regarding fuel use; signs of coal storage and use are generally clearly discernible (Figure 1).

Our overall sample included 302 households, distributed across six villages in Haidian (treated $N = 50$; untreated $N = 52$), Fangshan (treated, $N = 50$; untreated $N = 50$), and Yanqing (treated $N = 50$; untreated $N = 50$). Supplementary Table 6 shows descriptive statistics for our main survey variables. Due to some non-response, our sample sizes are slightly smaller than 302 for most statistics; exact values are listed in Supplementary Table 6.

Due to our cross-sectional design, we compare villages both to show similarity and to estimate treatment effects, through simple t-tests of village means. Supplementary Table 1 shows comparisons between village pairs for a number of variables, roughly grouped into those we considered to be independent (slow to change) and those we considered to be possible response variables. Supplementary Figure 1 illustrates two independent and four response variables.

Measurements

In households selected (randomly) for instrumentation, sensors for indoor temperature (Thermochron iButtons, Models DS1922L/DS1921G, Berkeley Air, USA) and $PM_{2.5}$ concentrations (DustTrak Model 8520; TSI Inc.; USA) were deployed at a height of approximately 1–1.5 m in a common occupied room (not a kitchen) at a location that would not interfere with household activities. In these locations, temperature sensors were attached to an internal wall of the home. Measurements were averaged over 10-min intervals, recorded on the device, and downloaded at the end of the measurement onto a project computer. Time-weighted means for temperature were computed over the sampling period in each home (n=55). Time-weighted means for indoor $PM_{2.5}$ concentrations were computed in each home (n=55) with and without subtracting hourly outdoor $PM_{2.5}$ concentrations [26], which were obtained from the nearest environmental air quality monitoring stations (Supplementary Table 7) operated by the Beijing Municipal Environmental Monitoring Center in each district in Beijing. The average distance of our study villages to the nearest outdoor monitoring station was 6.3±1.9 km.

Temperature measurements

Supplementary Figure 2 provides comparisons of the cumulative distribution functions of observed indoor temperature for mean daytime temperatures, mean nighttime temperatures, and 24 hour mean temperatures. As described in the main text, we group the middle and high income districts together to maximise sample size.

$PM_{2.5}$ measurements

The air pollution estimates from the light-scattering laser photometers used in this study are subject to measurement error, and were thus calibrated against indoor and outdoor 'gold standard' gravimetric $PM_{2.5}$ measurements conducted in settings where household solid fuel burning contributes to air pollution (see below for more detail on calibration of light-scattering measurement).

We removed one household observation with an indoor $PM_{2.5}$ concentration >1 mg$\cdot$m^{-3} (or 1000 μg$\cdot$m^{-3}) because the continuous measurement was indicative of potential instrument failure. Supplementary Figure 3 shows daytime, nighttime and 24 h distributions of $PM_{2.5}$ with this observation excluded, while Supplementary Figure 4 shows the same distributions without the exclusion.

Indoor $PM_{2.5}$ concentrations may be influenced by particulate matter of outdoor origin that infiltrates across the residential building envelope. In our study, daily average outdoor air pollution levels were higher on days when measurements were conducted in Haidian compared with days when measurements were conducted in Fangshan or Yanqing (Supplementary Table 8). Indoor $PM_{2.5}$ concentrations (Supplementary Figure 5) were also higher in Haidian compared with indoor $PM_{2.5}$ concentrations in Fangshan and Yanqing, which we interpret to be partially attributable to infiltration of $PM_{2.5}$ of outdoor origin. Supplementary Figure 6 shows the indoor and outdoor concentrations on sampling days.

Subjective measures

Our survey includes three questions soliciting subjective evaluations in the form of overall satisfaction with life as a whole, with living conditions, and with household income. The wordings/translations are as follows: 总的来说，您对现在的生活满意程度评价如何？请选择0–10的整数 ("Taking all things into account, how satisfied are you with life as a whole these days? [0–10]"); 总的来说，您对现在的居住环境满意程度评价如何？请选择0–10的整数 ("How satisfied are you with your living conditions as a whole? [0–10]"); 总的来说，您对现在

的家庭收入满意程度评价如何？请选择0–10的整数 (“How satisfied are you with the income of your household? [0–10]”). These questions are answered on an eleven point numerical scale with end-points anchored Completely unsatisfied (0) to Completely satisfied (10).

These questions, in particular the first one, are semi-standardized [27, 28] and are the subject of a large literature. Life satisfaction is typically used to assess the integrated impact, or costs and benefits, of all social and material conditions of life, including environmental and other outcomes not accessible by revealed preference (choice) nor market measures. Studies can simultaneously resolve variation due to income and to small variations in environmental pollutants [16, 29].

Statistical tests and inference

Due to the small sample sizes for temperature and $PM_{2.5}$ concentrations, we do not carry out formal difference tests, but instead report means and standard deviations of comparison groups.

For other statistics where we report standard errors for regression coefficients or means, intervals can be calculated for a desired confidence level by assuming normality of errors.

While we cannot statistically identify causal effects in our sample, interpreting reduced or zero coal use as outcomes of the coal ban policy is reasonable even in principle. Our estimates of resultant particulate and GHG emissions impacts of the program make use of emission factors $\sim$2 t CO_2e per t coal [1, 30] and $\sim$1–10 kg PM per t coal [31, 1, 32, 33]. Our extrapolation assumes 2.1 million rural households (7.9 million residents; average household size 3.8 residents) and, from our sample, a reduction in coal use of 3.17 t/household.

Wealth index

Although we asked for self-reported income, savings, and loans, enumerators reported resistance and unreliability for these questions. To supplement these self-reported measures, we took an inventory of certain appliances in each sampled home, and categorized them heuristically into three groups. Class 1 represents major investments (cars, stoves), Class 2 large convenience appliances and investments (motorbikes, scooters, fridges, washing machines, freezers), and Class 3 smaller appliances and luxury items (computers, televisions, air cleaners, microwaves, air conditioners). Our variables describing each category are the total number of appliances observed.

In order to discriminate between different levels of affluence within and between villages, we construct an index from available information on household assets, expenditures, and income, using a principal components analysis following the asset index literature [34]. We treat this combination of measures as complementary components of wealth. Especially in light of China’s notoriously high savings rates [35, 36], we chose not to rely simply on assets alone as does much of the asset index literature. We further use the heuristic categorization for assets to avoid problems of high-dimensionality with low sample sizes in principle components analysis [37].

Supplementary Figure 7 shows that the first component captures 40% of the overall variance, and we therefore take it as a scalar measure of wealth. The constituent variables and the coefficients comprising the first three components are given in Supplementary Table 9. The first component has positive and uniformly large coefficients on all our proxies for wealth. More-over, as a further check on the meaningfulness of our wealth index, we plot mean values of each constituent measure for households grouped by the wealth index, and find quasi-monotonicity for every measure (Supplementary Figure 8).

Supplementary Figure 9 shows the distributions of household asset inventories for assets comprising our three groups. Our asset counts were capped at 4 (for "4 or more"). Except for motorbikes, there are no rare assets nor outlier counts. When aggregated into our three classes, the asset counts are well distributed.

Characterization of household heating

Our survey recorded for each household a roster of all methods used to heat each room, and how long each method contributed to heating. In addition, when a room's heating methods included a wall-mounted or under-floor hot water radiator, we considered it to be heated by the methods used to power the radiator system in the household. In some cases (Supplementary Table 10) radiator systems were heated by more than one method. In these cases, we obtained no record of which radiator heat source was being used during the time when a given room was heated. In order to minimize double-counting of heat sources, we made the following simplifying assumptions: (1) When electrical resistive heating and an ATW heat pump were both connected to a hot water radiator system, the resistive heater was considered not to be used. (2) When a solar heater was connected to a radiator also heated by either coal or an ATW, the solar was considered not to be used. The resulting simplifed distribution of radiator heat sources still contains some multiple-heating cases, but they constitute a small fraction of the total (Supplementary Table 11).

In the majority of households, one heating method accounted for all the room heating. In some cases, houses used more than one method (Supplementary Table 12) to heat, and in some cases individual rooms were considered to be heated by more than one method. When two methods were recorded as heating the same room, we assumed that the heating times overlapped. Thus we attributed the largest daily heating times among methods used for a given room as the room's heating time when estimating total room-heating for a household (gray bars in Figure 3). This overlap accounts for the fact that the gray bars in Figure 3 are shorter than the stacked coloured ones.

Calibration of light-scattering laser photometers

Our real-time indoor $PM_{2.5}$ measurements were conducted using laser photometers, which are subject to measurement error. However, we applied a correction factor based on co-location of these instruments with 'gold standard' gravimetric measurements in previous studies where household solid fuel burning contributes to air pollution, and the residual error in $PM_{2.5}$ measurement due to monitors should be randomly distributed across our study households. Similarly, while there is likely some measurement error in our estimated village-level outdoor $PM_{2.5}$ concentrations by using the nearest outdoor air monitoring station as a surrogate, the distance to nearest station was similar for treated (4 to 8 km) and untreated (3 to 7.5 km) villages. Thus, while the absolute values of indoor $PM_{2.5}$ and outdoor subtracted-indoor $PM_{2.5}$ concentrations may slightly change with use of different air quality instruments or with local measurement of outdoor PM with the same instruments, our overall findings on the differences in indoor $PM_{2.5}$ between treated and untreated villages should not be impacted or would be underestimated.

The light-scattering laser photometers (DustTrak 8520, TSI Inc.) used in this study were calibrated against 'gold standard' gravimetric monitors in separate studies that observed very similar levels of instrument bias. The first study involved winter and summer measurements of indoor (household) and outdoor $PM_{2.5}$ in Windsor, Ontario (Canada), a moderate pollution setting where industrial coal burning and household wood-burning stoves contribute to outdoor PM (pooled positive bias of a factor of 2.64 for outdoor $PM_{2.5}$, estimated using OLS regression; n=799 measurement days). The level of positive bias in that study was similar for indoor PM (factor of 2.39) [38]. The second study using the same laser photometers also included indoor $PM_{2.5}$ measurements that were conducted in urban and peri-urban Bucaramanga (Colombia) where solid fuel burning and traffic contribute to moderate PM levels (positive bias of a factor of 2.49, estimated using OLS regression; n=23 measurement days; unpublished data). The average bias-corrected precisions in those studies were within 10%, indicating that a proper correction for bias brought the same instruments used in this study into very good agreement with standard reference methods. Notably, the instrument bias factors observed in the Canada and Colombia studies were nearly identical to the factor estimated for the same Model 8520 DustTrak instruments after co-location with gravimetric instruments in our previous study of household solid fuel burning in rural China (positive bias of a factor of 2.67, estimated using OLS regression; n=424 measurement days) [18]. Together, these studies demonstrate that the laser photometers used in this study are consistent in their instrument bias factors across diverse indoor and outdoor study settings and air pollution ranges, and that correction for that bias can lead to estimates of $PM_{2.5}$ concentrations that are similar to 'gold standard' instruments.

To further evaluate the use of a single correction factor in a setting where coal burning is a contributor to PM, we co-located 4 of the DustTrak instruments used in this study with an outdoor reference monitor (Thermo Scientific Model 5030 SHARP) located on the roof of a building on the Peking University (Beijing) campus in the winter season when household coal burning is estimated to be a large contributor (30–50%) to ambient air pollution [25, 9, 11]. The DustTrak instruments and reference monitor were simultaneously run for a period of 5 consecutive days, and we compared the average within-day bias across monitors. The within-day coefficient of variation for the instrument bias factors ranged from 6–13% (median=9%), indicating a very good consistency in the degree of measurement error across monitors.

Data availability statement

Datasets generated and analysed during the current study will be made available on a case-by-case basis by the corresponding author with input from co-authors, subject to compliance with Research Ethics Board restrictions for the survey data.

Acknowledgements

We are grateful to Alex Ballyk and Marina Smailes for research assistance and to Sam Harper and Ravi Ravishankara for comments on a draft of the manuscript, and to Shangwei Liu for suggesting a post-publication clarification to this open version of the manuscript. This work was supported by a McGill University Emerging Scholars Accelerator grant and by Canada's Social Science and Humanities Research Council grants 435-2016-0531 and 430-2017-00998.

Author Contributions

CBL, JB, EC, and BR designed the study, led the field work, and wrote the paper. CBL and EC carried out the analysis. CBL, JB, EC, BR, ST, and YZ discussed the results and commented on the manuscript.

Competing Interests statement

The authors declare no competing interests.

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Supplementary Information:

An evaluation of air quality, home heating, and well-being under Beijing's program to eliminate household coal use

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This supplement accompanies the article
DOI:10.1038/s41560-019-0386-2 in *Nature Energy*, 2019.

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	Overall	Haidian				Fangshan				Yanqing			
	Mean	Untreated	Treated	Δ	p	Untreated	Treated	Δ	p	Untreated	Treated	Δ	p
Income (Yuan/month)	8.0	11.0	9.7	−1.37	.62	8.8	8.6	−.20	.90	5.6	4.0	−1.68	.16
	(.58)	(1.08)	(2.6)	(2.8)		(1.37)	(.95)	(1.66)		(.89)	(.66)	(1.17)	
Log(income)	1.62	2.2	1.61	**−.60***	.005	1.76	1.85	.089	.64	1.25	.94	−.31	.17
	(.064)	(.096)	(.19)	(.21)		(.14)	(.12)	(.19)		(.16)	(.16)	(.23)	
Residents (winter)	3.8	4.3	4.1	−.16	.67	4.7	4.3	−.38	.29	2.9	2.8	−.085	.78
	(.11)	(.23)	(.31)	(.38)		(.27)	(.22)	(.35)		(.20)	(.22)	(.31)	
Land area	2.2	1.72	.18	−1.53	.28	2.8	1.06	−1.79	.15	2.8	4.1	1.33	.15
	(.35)	(1.45)	(.051)	(1.41)		(1.13)	(.20)	(1.24)		(.49)	(.81)	(.92)	
House area	209	236	240	4.2	.80	212	250	37.6	.13	162	145	−17.7	.28
	(6.1)	(9.9)	(13.4)	(16.7)		(15.8)	(18.0)	(24.3)		(11.1)	(11.4)	(16.2)	
Number of rooms	8.5	8.4	9.9	***1.46***	.043	8.8	8.7	−.11	.87	7.5	7.8	.33	.70
	(.21)	(.39)	(.59)	(.71)		(.50)	(.42)	(.66)		(.54)	(.62)	(.83)	
Group 1 appliances	1.99	2.6	1.52	**−1.12†**	$<10^{-8}$	2.6	1.45	**−1.15†**	$<10^{-5}$	1.98	1.67	*−.31*$^+$	.066
	(.064)	(.12)	(.13)	(.17)		(.21)	(.13)	(.25)		(.10)	(.13)	(.17)	
Group 2 appliances	3.6	3.9	3.9	−.007	.98	4.4	3.9	−.53	.11	3.0	2.7	−.24	.38
	(.093)	(.21)	(.22)	(.31)		(.28)	(.16)	(.33)		(.18)	(.19)	(.26)	
Group 3 appliances	5.6	7.1	6.8	−.38	.55	6.2	6.8	.59	.33	2.9	3.3	.39	.31
	(.19)	(.43)	(.45)	(.63)		(.46)	(.39)	(.60)		(.26)	(.28)	(.38)	
House tenure (yrs)	25.3	17.7	38.2	**20.5†**	$<10^{-5}$	32.1	26.8	−5.3	.13	17.2	19.6	2.4	.38
	(1.12)	(2.7)	(3.1)	(4.2)		(2.1)	(2.8)	(3.5)		(1.73)	(2.1)	(2.7)	
House age	1998	2002	1995	**−6.8†**	.0006	1993	2003	**9.8†**	.0003	1999	1996	−2.8	.33
	(.75)	(1.37)	(1.28)	(1.90)		(2.1)	(1.48)	(2.6)		(1.81)	(2.2)	(2.9)	
House rent value	2237	3057	1879	**−1178***	.001	1125	3550	**2425***	.003	1057	2740	1682	.19
	(228)	(217)	(266)	(351)		(134)	(770)	(771)		(380)	(1236)	(1258)	
Wealth Index	−.046	.94	.50	−.44	.22	.38	.57	.18	.63	−1.12	−1.47	−.36	.26
	(.12)	(.20)	(.30)	(.36)		(.30)	(.24)	(.39)		(.23)	(.21)	(.32)	
Satisfaction with life	7.5	7.7	7.8	.095	.80	7.4	8.1	***.66***	.049	7.4	6.3	***−1.02***	.015
	(.11)	(.19)	(.33)	(.38)		(.25)	(.21)	(.33)		(.24)	(.34)	(.41)	
Satisfaction with living conditions	7.6	7.7	7.9	.16	.70	7.1	8.1	**.99***	.005	8.0	6.6	**−1.46†**	$<10^{-4}$
	(.11)	(.22)	(.36)	(.42)		(.26)	(.21)	(.34)		(.18)	(.31)	(.35)	
Satisfaction with income	6.4	6.7	6.7	−.094	.82	6.2	6.8	*.68*$^+$	.050	6.1	5.7	−.40	.42
	(.12)	(.23)	(.34)	(.41)		(.24)	(.24)	(.34)		(.29)	(.39)	(.48)	
meat/month	6.8	8.0	9.5	1.44	.48	5.8	6.8	1.00	.34	6.0	4.6	−1.41	.37
	(.46)	(.86)	(1.84)	(2.0)		(.74)	(.73)	(1.05)		(1.31)	(.61)	(1.57)	
mobile expenses/month	214	256	232	−24.3	.55	254	246	−7.7	.89	181	113	*−68.1*$^+$	.090
	(13.1)	(23.7)	(33.4)	(40.5)		(50.1)	(20.3)	(53.3)		(32.6)	(16.7)	(39.7)	
Workers/household	1.99	2.4	1.98	−.45	.21	2.1	2.4	.26	.29	1.60	1.31	−.30	.29
	(.088)	(.23)	(.27)	(.36)		(.17)	(.18)	(.25)		(.18)	(.21)	(.28)	
Guests	6.1	4.4	6.2	1.86	.28	7.2	9.6	2.3	.62	4.0	4.9	.94	.31
	(.87)	(.77)	(1.53)	(1.71)		(1.40)	(4.4)	(4.7)		(.41)	(.89)	(.92)	
Income earners/household	31.8	2.7	184	182	.24	2.2	2.8	.51	.35	1.69	1.67	−.021	.92
	(26.0)	(.20)	(158)	(155)		(.14)	(.50)	(.54)		(.14)	(.16)	(.22)	
Remittances	737	2149	636	−1513	.30	711	0	−711	.14	583	272	−312	.53
	(268)	(1312)	(461)	(1444)		(487)	(0)	(477)		(425)	(160)	(499)	
Living subsidy received	3.7	0	22.8	22.8	.30	.089	0	−.089	.30	0	0		
	(3.7)	(0)	(22.4)	(22.0)		(.088)	(0)	(.086)		(0)	(0)	(0)	
Savings	16.1	11.5	8.6	−3.0	.53	74.1	6.6	−67.4	.28	1.26	1.90	.64	.52
	(10.0)	(2.8)	(3.8)	(4.7)		(70.1)	(2.3)	(62.0)		(.68)	(.65)	(.98)	
Loans	1.56	7.1	.92	−6.2	.11	.82	.13	−.69	.31	0	0		
	(.65)	(3.4)	(.77)	(3.8)		(.68)	(.13)	(.68)		(0)	(0)	(0)	
Heated area (m^2)	160	192	218	*26.0*$^+$	.059	162	184	21.7	.24	97.2	103	5.9	.64
	(5.1)	(9.5)	(9.5)	(13.6)		(11.4)	(13.8)	(18.2)		(9.2)	(7.8)	(12.6)	
Fraction heated (area)	.77	.82	.94	**.12†**	.0002	.79	.76	−.030	.49	.60	.74	**.14***	.005
	(.013)	(.021)	(.020)	(.030)		(.033)	(.028)	(.043)		(.034)	(.035)	(.050)	
Fraction heated (rooms)	.83	.86	.92	***.067***	.034	.80	.89	***.089***	.043	.75	.78	.035	.45
	(.012)	(.021)	(.022)	(.031)		(.035)	(.026)	(.044)		(.032)	(.032)	(.046)	
Unheated area (m^2)	48.8	44.0	22.2	***−21.8***	.035	50.2	66.0	15.8	.35	65.1	41.4	***−23.6***	.021
	(3.8)	(5.5)	(8.6)	(10.2)		(13.2)	(10.2)	(16.7)		(6.6)	(7.5)	(10.0)	
heated rooms	7.0	7.2	8.9	**1.75***	.008	7.0	7.8	.79	.25	5.4	5.9	.57	.40
	(.20)	(.38)	(.52)	(.64)		(.52)	(.44)	(.68)		(.42)	(.53)	(.68)	
unheated rooms	1.49	1.22	.93	−.29	.40	1.82	.92	***−.91***	.011	2.2	1.92	−.24	.56
	(.11)	(.19)	(.29)	(.35)		(.30)	(.18)	(.35)		(.26)	(.31)	(.41)	
Heating ($\sum_{\text{fuels}}\sum_{\text{rooms}}$hours)	152	187	219	*32.0*$^+$	.098	126	133	7.2	.70	118	139	21.2	.31
	(6.0)	(11.3)	(15.4)	(19.2)		(12.3)	(13.5)	(18.5)		(11.0)	(18.1)	(20.6)	
Heating ($\sum_{\text{rooms}}$hours)	133	168	213	**44.7***	.002	119	119	.085	1.00	88.3	96.6	8.3	.54
	(5.0)	(7.2)	(12.5)	(14.3)		(12.3)	(10.2)	(16.1)		(8.6)	(10.5)	(13.6)	
Coal used (tonnes)	2.2	3.8	0	**−3.8†**	$<10^{-15}$	4.2	0	**−4.2†**	$<10^{-25}$	3.4	1.84	**−1.55†**	$<10^{-5}$
	(.14)	(.37)	(0)	(.38)		(.27)	(0)	(.27)		(.21)	(.20)	(.30)	
No coal used	.40	.089	1.00	**.91†**	$<10^{-33}$	.089	1.00	**.91†**	$<10^{-37}$	.021	.23	**.21***	.002
	(.030)	(.042)	(0)	(.044)		(.042)	(0)	(.042)		(.021)	(.067)	(.066)	
Coal expenditure (Yuan/season)	1033	2757	0	**−2757†**	$<10^{-13}$	1623	0	**−1623†**	$<10^{-20}$	1161	494	**−668†**	$<10^{-7}$
	(84.0)	(295)	(0)	(305)		(128)	(0)	(131)		(90.3)	(57.3)	(114)	
Elecricity Expenditure (Yuan/season)	2785	1960	7241	**5281†**	$<10^{-12}$	1167	4520	**3354†**	$<10^{-13}$	525	1419	**894†**	.0007
	(191)	(371)	(484)	(613)		(211)	(295)	(366)		(61.0)	(268)	(254)	
Coal+Elec. Expenditure (Yuan/season)	3818	4717	7241	**2524†**	.0001	2790	4520	**1731†**	$<10^{-4}$	1687	1913	226	.36
	(175)	(399)	(484)	(632)		(228)	(295)	(376)		(107)	(233)	(245)	
Coal expenditure (Yuan/person/season)	320	802	0	**−802†**	$<10^{-7}$	388	0	**−388†**	$<10^{-16}$	465	216	**−249†**	$<10^{-5}$
	(29.3)	(124)	(0)	(128)		(35.9)	(0)	(36.7)		(36.7)	(28.3)	(48.6)	
Elecricity Expenditure (Yuan/person/season)	769	528	1963	**1436†**	$<10^{-12}$	259	1170	**911†**	$<10^{-10}$	196	552	**356†**	.0009
	(54.0)	(96.9)	(140)	(171)		(41.5)	(109)	(117)		(23.1)	(110)	(103)	
Coal+Elec. Expenditure (Yuan/person/season)	1089	1329	1963	**634***	.007	647	1170	**523†**	$<10^{-4}$	660	768	108	.29
	(54.2)	(175)	(140)	(228)		(48.2)	(109)	(120)		(44.6)	(96.3)	(101)	
Fraction of heating expenditure on coal	.40	.59	0	**−.59†**	$<10^{-18}$	.63	0	**−.63†**	$<10^{-28}$	.70	.42	**−.28†**	$<10^{-5}$
	(.022)	(.050)	(0)	(.051)		(.036)	(0)	(.037)		(.026)	(.050)	(.054)	

Significance: **0.1%†** **1%*** ***5%*** *10%*$^+$

Supplementary Table 1: T**-tests for differences between paired villages**. Characteristics in the upper section are unlikely to have responded to the treatment, while the lower section describes features which could in principle have differed before treatment and/or responded to treatment. Overall, Treated, and Untreated columns show means and, in parentheses, standard error of the mean. The Difference columns (Δ and p) show the raw estimated difference from an OLS regression, along with the standard errors in parentheses and p values for a two-sided t-test. Sample sizes for each group are given in Supplementary Table 6, and for the differences estimates by the sum over the two groups' sizes. The number of degrees of freedom for the difference estimates is two less than the sample size.

	Fraction of heating expenditure on coal							Fraction of heating room-hours on coal								
	Pooled		Haidian	Fangshan	Yanqing			Pooled		Haidian	Fangshan	Yanqing				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
coal ban	**$-.51^{\dagger}$**	**$-2.7^{\dagger}$**						**$-.67^{\dagger}$**	**$-3.8^{\dagger}$**							
	(.030)	(.19)						(.037)	(.33)							
Wealth Index	**$-.025^{\star}$**	**$-.16^{\star}$**	$-.029$	$-.011$	**$-.039^{\dagger}$**	**$-.093^{\dagger}$**	**$-1.80^{\star}$**	**$-.034^{\star}$**	**$-.29^{\star}$**	$-.012$	.008	**$-.085^{\dagger}$**	**$-.14^{\dagger}$**	**$-.18^{\dagger}$**	**$-.72^{\star}$**	**$-.92^{\star}$**
	(.008)	(.057)	(.042)	(.016)	(.010)	(.023)	(.64)	(.012)	(.10)	(.040)	(.012)	(.023)	(.036)	(.046)	(.26)	(.33)
Haidian	**$.57^{\dagger}$**	.28						**$.80^{\dagger}$**	**$1.61^{\dagger}$**							
	(.038)	(.19)						(.035)	(.26)							
Fangshan	**$.58^{\dagger}$**	*.29*$^{+}$						**$.79^{\dagger}$**	**$1.57^{\dagger}$**							
	(.031)	(.15)						(.036)	(.28)							
Yanqing	**$.78^{\dagger}$**	**$1.49^{\dagger}$**						**$.94^{\dagger}$**	**$2.8^{\dagger}$**							
	(.028)	(.18)						(.043)	(.47)							
constant			**$.62^{\dagger}$**	**$.64^{\dagger}$**	**$.67^{\dagger}$**	**$.29^{\dagger}$**	***.60***			**$.88^{\dagger}$**	**$.89^{\dagger}$**	**$.71^{\dagger}$**	**$.34^{\dagger}$**	**$.55^{\dagger}$**	*−.84*$^{+}$	.22
			(.065)	(.041)	(.024)	(.068)	(.26)			(.052)	(.045)	(.047)	(.083)	(.057)	(.46)	(.26)
fracLogit		✓					✓		✓						✓	✓
Treated	pooled	pooled	×	×	×	✓	✓	all	pooled	×	×	×	✓	✓	✓	✓
Quantile index							✓									
Normed index														✓		✓
obs.	242	242	43	38	47	38	38	242	242	44	37	47	38	38	38	38
R^2(adj)	.821		$-.011$	$-.021$	.142	.123		.832		$-.021$	$-.025$	.246	.196	.196		
log likelihood	11.9	-92.8	-13.5	.30	27.0	-6.3	-19.2	-39.5	-85.8	-7.5	-2.7	4.2	-13.3	-13.3	-19.8	-19.8
F	252		.47	.43	15.4	16.5		244		.089	.48	14.4	16.2	16.2		

Significance: **0.1%**† **1%*** ***5%*** *10%*$^{+}$

Supplementary Table 2: Coal use versus wealth. The fraction of expenditure on coal (1–7) and the fraction of heating by coal (8–16) is modeled as dependent on an index of household wealth. Columns (6)–(7) and (13)–(16) are estimates for the coal-restricted village in the lower income district. All models are ordinary least squares regressions except for those marked as fractional logit.

	Satisfaction with life																			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
coal ban											−.065	−.095	.057	*.60*$^{+}$	***−.90***	−.36	−.35	.21	.023	*−.74*$^{+}$
											(.22)	(.23)	(.40)	(.35)	(.41)	(.25)	(.25)	(.50)	(.38)	(.41)
Log(income)	**.52**†	**.41**†					.22	.23								.19	.21	.37	−.33	***.66***
	(.11)	(.12)					(.15)	(.15)								(.15)	(.15)	(.28)	(.20)	(.31)
Income (Yuan/month)			**.050**†	**.041**†																
			(.012)	(.011)																
meat/month							*.020*$^{+}$	***.024***								*.019*$^{+}$	***.022***	.026	.009	.004
							(.011)	(.011)								(.011)	(.011)	(.020)	(.042)	(.020)
mobile expenses/month							.0004	.0004								.0004	.0004	−.0007	**.002**†	−.001
							(.0006)	(.0006)								(.0006)	(.0006)	(.001)	(.0004)	(.001)
Group 1 appliances							−.029	−.006								−.11	−.087	.23	*−.28*$^{+}$	***.43***
							(.11)	(.11)								(.11)	(.11)	(.32)	(.14)	(.22)
Group 2 appliances							−.077	−.083								−.081	−.087	−.12	−.10	.058
							(.092)	(.094)								(.091)	(.093)	(.15)	(.14)	(.20)
Group 3 appliances							***.11***	.088								***.12***	*.10*$^{+}$	−.001	**.21***	.12
							(.051)	(.058)								(.052)	(.059)	(.11)	(.070)	(.15)
House area							**.005**†	**.005**†								**.005**†	**.005**†	**.007***	***.004***	.004
							(.001)	(.001)								(.001)	(.001)	(.003)	(.002)	(.004)
Wealth Index									**.40**†	**.37**†	**.40**†	**.37**†	***.36***	**.36***	**.44***					
									(.083)	(.083)	(.083)	(.083)	(.16)	(.13)	(.16)					
Residents (winter)							−.12	−.15	*−.15*$^{+}$	***−.18***	*−.15*$^{+}$	*−.17*$^{+}$	−.033	−.14	***−.56***	−.11	−.14	−.023	.006	***−.68***
							(.093)	(.097)	(.084)	(.089)	(.084)	(.089)	(.11)	(.13)	(.25)	(.091)	(.095)	(.11)	(.13)	(.31)
Heated area (m^2)					**.008**†	**.007**†														
					(.001)	(.001)														
Unheated area (m^2)					**.005**†	**.005**†														
					(.001)	(.001)														
meat/person/month					.025	.028														
					(.031)	(.031)														
Haidian		**7.0**†		**7.4**†		**6.2**†		**6.2**†		**8.1**†		**8.1**†					**6.4**†			
		(.36)		(.26)		(.33)		(.53)		(.43)		(.44)					(.53)			
Fangshan		**7.0**†		**7.4**†		**6.2**†		**6.4**†		**8.3**†		**8.4**†					**6.6**†			
		(.29)		(.20)		(.30)		(.47)		(.42)		(.45)					(.51)			
Yanqing		**6.3**†		**6.6**†		**5.9**†		**6.0**†		**7.8**†		**7.8**†					**6.2**†			
		(.25)		(.22)		(.29)		(.37)		(.33)		(.34)					(.38)			
constant	**6.6**†		**7.0**†		**6.0**†		**6.0**†		**7.9**†		**8.0**†		**7.5**†	**7.9**†	**9.3**†	**6.2**†		**5.2**†	**6.4**†	**6.5**†
	(.23)		(.17)		(.27)		(.37)		(.34)		(.35)		(.46)	(.63)	(.87)	(.38)		(.98)	(.72)	(.91)
District		f.e.		f.e.		f.e.		f.e.		f.e.		f.e.	Haidian	Fangshan	Yanqing		f.e.	Haidian	Fangshan	Yanqing
obs.	251	251	251	251	267	267	231	231	244	244	244	244	80	79	85	231	231	75	77	79
R^2(adj)	.078	.948	.058	.947	.139	.952	.148	.951	.100	.948	.097	.948	.061	.112	.115	.152	.951	.089	.197	.133
F	23.5	1291	16.7	1275	18.0	1075	6.2	577	13.5	966	9.0	824	2.2	3.8	3.8	5.5	546	2.1	5.6	2.7

Significance: **0.1%**† **1%*** ***5%*** *10%*$^{+}$

Supplementary Table 3: Regression models for life satisfaction. See Supplementary Note 2 for explanation of models. Coefficients are interpreted as follows, for instance in model (column) 1: an increase of 1 in log of income (ie, an increase by a factor of e, or 2.718) predicts an increase of 0.52 in life satisfaction (on a 0–11 scale). Equivalently, a doubling of income predicts an increase of $\log(2) \times 0.52 \approx 0.36$ in life satisfaction.

	Satisfaction with income																			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
coal ban											.16	.16	−.053	***.75***	−.24	−.15	−.15	.12	.068	−.42
											(.24)	(.24)	(.42)	(.34)	(.48)	(.26)	(.27)	(.51)	(.43)	(.49)
Log(income)	**.58†**	**.53†**					***.34***	***.35***								***.33***	***.34***	.30	−.20	*.68*$^+$
	(.12)	(.13)					(.15)	(.16)								(.16)	(.16)	(.25)	(.22)	(.36)
Income (Yuan/month)			**.060†**	**.055†**																
			(.012)	(.012)																
meat/month							**.074†**	**.076†**								**.074†**	**.076†**	**.098†**	**.15†**	.031
							(.016)	(.016)								(.016)	(.017)	(.021)	(.040)	(.022)
mobile expenses/month							−.0005	−.0005								−.0005	−.0005	***−.003***	.0003	−.0006
							(.0006)	(.0006)								(.0006)	(.0006)	(.001)	(.0003)	(.001)
Group 1 appliances							−.031	−.024								−.064	−.059	.30	−.082	.19
							(.11)	(.11)								(.12)	(.11)	(.30)	(.17)	(.27)
Group 2 appliances							.026	.021								.023	.018	−.085	−.056	.18
							(.097)	(.098)								(.097)	(.098)	(.17)	(.14)	(.24)
Group 3 appliances							***.13***	***.14***								***.14***	***.14***	.054	**.24***	.13
							(.059)	(.064)								(.061)	(.067)	(.11)	(.086)	(.18)
House area							.002	.002								.002	.002	.003	.003	.001
							(.002)	(.001)								(.002)	(.002)	(.004)	(.002)	(.003)
Wealth Index									**.46†**	**.45†**	**.46†**	**.45†**	*.32*$^+$	**.44†**	**.60***					
									(.094)	(.094)	(.094)	(.095)	(.17)	(.13)	(.22)					
Residents (winter)							***−.19***	***−.20***	*−.17*$^+$	*−.17*$^+$	*−.17*$^+$	*−.17*$^+$	−.017	−.24	−.35	***−.19***	***−.20***	−.099	−.13	−.39
							(.094)	(.098)	(.093)	(.099)	(.093)	(.099)	(.13)	(.16)	(.26)	(.093)	(.097)	(.13)	(.14)	(.30)
Heated area (m^2)					**.007†**	**.006†**														
					(.001)	(.002)														
Unheated area (m^2)					*.003*$^+$	*.003*$^+$														
					(.002)	(.002)														
meat/person/month					***.16***	***.16***														
					(.064)	(.063)														
Haidian		**5.6†**		**6.1†**		**5.0†**		**4.9†**		**6.9†**		**6.9†**					**5.0†**			
		(.34)		(.26)		(.39)		(.52)		(.45)		(.47)					(.52)			
Fangshan		**5.5†**		**6.0†**		**5.0†**		**5.1†**		**6.9†**		**6.8†**					**5.2†**			
		(.30)		(.21)		(.34)		(.46)		(.48)		(.50)					(.49)			
Yanqing		**5.2†**		**5.6†**		**4.7†**		**4.9†**		**6.8†**		**6.8†**					**5.1†**			
		(.28)		(.23)		(.33)		(.39)		(.38)		(.39)					(.40)			
constant	**5.4†**		**5.8†**		**4.8†**		**5.0†**		**6.9†**		**6.8†**		**6.4†**	**6.8†**	**7.6†**	**5.1†**		**5.0†**	**4.6†**	**4.8†**
	(.25)		(.16)		(.30)		(.39)		(.38)		(.39)		(.59)	(.74)	(.92)	(.40)		(1.08)	(.66)	(.96)
District		f.e.		f.e.		f.e.		f.e.		f.e.		f.e.	Haidian	Fangshan	Yanqing		f.e.	Haidian	Fangshan	Yanqing
obs.	250	250	250	250	266	266	230	230	243	243	243	243	79	79	85	230	230	74	77	79
R^2(adj)	.094	.923	.079	.923	.113	.920	.177	.928	.110	.919	.108	.919	.026	.164	.073	.175	.928	.126	.297	.088
F	23.0	821	23.5	813	11.1	562	8.2	344	13.5	606	9.3	527	1.32	5.4	3.2	7.2	316	5.8	6.0	2.2

Significance: **0.1%†** **1%*** ***5%*** *10%*$^+$

Supplementary Table 4: Regression models for satisfaction with income. See Supplementary Note 2 for explanation of models, and Supplementary Table 3 for interpretation.

	Satisfaction with living conditions																			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
coal ban											−.12	−.10	.11	**1.02***	**−1.36**†	***−.58***	***−.60***	.24	.033	**−1.54**†
											(.23)	(.23)	(.45)	(.37)	(.36)	(.25)	(.25)	(.53)	(.40)	(.39)
Log(income)	**.42**†	**.40**†					.14	.14								.11	.10	.18	−.28	.13
	(.10)	(.12)					(.13)	(.14)								(.14)	(.14)	(.28)	(.26)	(.25)
Income (Yuan/month)			**.043**†	**.039**†																
			(.010)	(.011)																
meat/month							.018	.015								.016	.013	*.043*$^{+}$	.031	−.019
							(.011)	(.013)								(.013)	(.014)	(.025)	(.040)	(.017)
mobile expenses/month							***.0008***	*.0008*$^{+}$								***.0008***	*.0008*$^{+}$	−.0001	**.001***	−.0009
							(.0004)	(.0004)								(.0004)	(.0004)	(.002)	(.0004)	(.0008)
Group 1 appliances							−.18	*−.21*$^{+}$								**−.32***	**−.35***	.36	**−.52***	.091
							(.12)	(.12)								(.12)	(.12)	(.31)	(.17)	(.20)
Group 2 appliances							−.050	−.046								−.057	−.053	−.18	.042	.14
							(.10)	(.10)								(.10)	(.10)	(.18)	(.18)	(.18)
Group 3 appliances							***.094***	***.13***								***.11***	***.15***	.039	***.16***	***.33***
							(.048)	(.057)								(.050)	(.059)	(.12)	(.077)	(.13)
House area							**.005***	**.005***								**.005***	**.005**†	*.006*$^{+}$	***.006***	.003
							(.002)	(.002)								(.002)	(.002)	(.004)	(.002)	(.003)
Wealth Index									**.40**†	**.43**†	**.39**†	**.42**†	***.45***	**.38***	**.34***					
									(.080)	(.091)	(.080)	(.090)	(.19)	(.15)	(.12)					
Residents (winter)							−.11	−.083	***−.15***	*−.13*$^{+}$	*−.15*$^{+}$	−.13	−.11	−.17	−.015	−.094	−.065	−.15	−.009	−.047
							(.080)	(.083)	(.077)	(.079)	(.078)	(.080)	(.13)	(.14)	(.14)	(.082)	(.084)	(.15)	(.13)	(.18)
Heated area (m^2)					**.007**†	**.009**†														
					(.001)	(.001)														
Unheated area (m^2)					**.005***	**.005***														
					(.002)	(.002)														
meat/person/month					.023	.019														
					(.033)	(.034)														
Haidian		**7.1**†		**7.4**†		**5.9**†		**6.0**†		**7.9**†		**8.0**†					**6.4**†			
		(.37)		(.29)		(.35)		(.60)		(.40)		(.38)					(.57)			
Fangshan		**6.9**†		**7.2**†		**5.8**†		**5.9**†		**7.8**†		**7.9**†					**6.3**†			
		(.27)		(.20)		(.30)		(.48)		(.38)		(.39)					(.48)			
Yanqing		**6.8**†		**7.1**†		**6.2**†		**6.5**†		**8.2**†		**8.3**†					**6.9**†			
		(.23)		(.20)		(.27)		(.40)		(.33)		(.32)					(.37)			
constant	**6.9**†		**7.2**†		**6.1**†		**6.4**†		**8.1**†		**8.1**†		**7.8**†	**7.5**†	**8.4**†	**6.8**†		**5.7**†	**6.0**†	**6.2**†
	(.22)		(.16)		(.25)		(.40)		(.32)		(.30)		(.49)	(.63)	(.52)	(.38)		(1.26)	(.65)	(.56)
District		f.e.		f.e.		f.e.		f.e.		f.e.		f.e.	Haidian	Fangshan	Yanqing		f.e.	Haidian	Fangshan	Yanqing
obs.	251	251	251	251	267	267	231	231	244	244	244	244	80	79	85	231	231	75	77	79
R^2(adj)	.051	.947	.042	.946	.123	.952	.116	.949	.092	.948	.090	.948	.061	.163	.221	.132	.950	.024	.269	.270
F	16.3	1189	16.9	1211	14.4	952	5.6	488	12.5	944	8.4	835	2.1	5.5	11.5	5.5	541	1.87	4.8	4.1

Significance: **0.1%**† **1%*** ***5%*** *10%*$^{+}$

Supplementary Table 5: Regression models for satisfaction with living conditions. See Supplementary Note 2 for explanation of models, and Supplementary Table 3 for interpretation.

	Overall					Haidian										Fangshan										Yanqing									
						Untreated					Treated					Untreated					Treated					Untreated					Treated				
	min	max	mean	std	N	min	max	mean	std	N	min	max	mean	std	N	min	max	mean	std	N	min	max	mean	std	N	min	max	mean	std	N	min	max	mean	std	N
Income (Yuan/month)	.24	100	8 (.58)	9.1	251	2	36	11 (1.08)	7	42	.24	100	9.7 (2.6)	16.1	38	.60	50	8.8 (1.37)	9.1	44	.60	26	8.6 (.95)	6.5	47	.24	26	5.6 (.89)	5.9	44	.48	18	4 (.66)	3.9	36
Log(income)	−1.43	4.6	1.62 (.064)	1.02	251	.69	3.6	2.2 (.096)	.62	42	−1.43	4.6	1.61 (.19)	1.16	38	−.51	3.9	1.76 (.14)	.95	44	−.51	3.3	1.85 (.12)	.85	47	−1.43	3.3	1.25 (.16)	1.04	44	−.73	2.9	.94 (.16)	.96	36
Residents (winter)	1	14	3.8 (.11)	1.80	271	1	7	4.3 (.23)	1.55	47	2	14	4.1 (.31)	2.1	44	1	9	4.7 (.27)	1.82	45	1	8	4.3 (.22)	1.54	48	1	8	2.9 (.20)	1.41	48	1	7	2.8 (.22)	1.39	39
Land area	0	50	2.2 (.35)	5.3	238	0	50	1.72 (1.45)	8.4	34	0	1	.18 (.051)	.31	37	0	50	2.8 (1.13)	7.4	43	0	4.8	1.06 (.20)	1.21	38	0	12	2.8 (.49)	3.4	48	0	20	4.1 (.81)	5	38
House area	30	750	209 (6.1)	100	271	70	400	236 (9.9)	67.9	47	80	600	240 (13.4)	88.8	44	80	750	212 (15.8)	106	45	80	600	250 (18)	125	48	30	450	162 (11.1)	76.9	48	50	360	145 (11.4)	71.1	39
Number of rooms	2	22	8.5 (.21)	3.5	267	5	22	8.4 (.39)	2.6	45	5	22	9.9 (.59)	3.8	42	3	19	8.8 (.50)	3.3	45	5	16	8.7 (.42)	2.9	48	2	19	7.5 (.54)	3.8	48	2	21	7.8 (.62)	3.9	39
Group 1 appliances	0	8	1.99 (.064)	1.06	270	1	5	2.6 (.12)	.81	47	0	4	1.52 (.13)	.84	44	0	8	2.6 (.21)	1.40	45	0	3	1.45 (.13)	.87	47	1	4	1.98 (.10)	.72	48	0	4	1.67 (.13)	.83	39
Group 2 appliances	0	11	3.6 (.093)	1.53	270	2	8	3.9 (.21)	1.46	47	1	9	3.9 (.22)	1.48	44	2	11	4.4 (.28)	1.90	45	2	7	3.9 (.16)	1.13	47	0	7	3 (.18)	1.25	48	0	5	2.7 (.19)	1.17	39
Group 3 appliances	0	15	5.6 (.19)	3.1	270	0	15	7.1 (.43)	2.9	47	1	15	6.8 (.45)	3	44	1	14	6.2 (.46)	3.1	45	0	12	6.8 (.39)	2.7	47	1	10	2.9 (.26)	1.78	48	1	9	3.3 (.28)	1.74	39
House tenure (yrs)	1	81	25.3 (1.12)	18.2	266	1	81	17.7 (2.7)	17.6	44	4	80	38.2 (3.1)	20.9	44	3	74	32.1 (2.1)	13.8	45	2	74	26.8 (2.8)	19	47	1	45	17.2 (1.73)	12	48	1	49	19.6 (2.1)	13.1	38
House age	1965	2017	1998 (.75)	12.1	257	1980	2016	2002 (1.37)	8.3	37	1970	2010	1995 (1.28)	8.5	44	1973	2016	1993 (2.1)	14.2	44	1980	2016	2003 (1.48)	10	46	1972	2016	1999 (1.81)	12.6	48	1965	2017	1996 (2.2)	13.9	38
House rent value	0	30000	2237 (228)	3145	190	400	8000	3057 (217)	1320	37	200	6000	1879 (266)	1680	40	0	3500	1125 (134)	759	32	0	20000	3550 (770)	4216	30	0	8000	1057 (380)	1977	27	0	30000	2740 (1236)	6055	24
Wealth Index	−4.4	6.7	−.046 (.12)	1.82	244	−1.94	4.3	.94 (.20)	1.35	44	−3.4	6.7	.50 (.30)	1.83	36	−3.3	5.8	.38 (.30)	1.83	38	−1.58	4.4	.57 (.24)	1.55	41	−4.1	3.3	−1.12 (.23)	1.54	47	−4.4	2.1	−1.47 (.21)	1.27	38
Satisfaction with life	0	10	7.5 (.11)	1.83	271	4	10	7.7 (.19)	1.32	47	1	10	7.8 (.33)	2.2	44	3	10	7.4 (.25)	1.69	45	6	10	8.1 (.21)	1.46	48	1	10	7.4 (.24)	1.66	48	0	10	6.3 (.34)	2.1	39
Satisfaction with living conditions	0	10	7.6 (.11)	1.82	271	4	10	7.7 (.22)	1.50	47	0	10	7.9 (.36)	2.4	44	4	10	7.1 (.26)	1.77	45	5	10	8.1 (.21)	1.48	48	5	10	8 (.18)	1.25	48	2	10	6.6 (.31)	1.96	39
Satisfaction with income	0	10	6.4 (.12)	1.98	270	4	10	6.7 (.23)	1.58	47	1	10	6.7 (.34)	2.3	43	3	10	6.2 (.24)	1.59	45	3	10	6.8 (.24)	1.66	48	0	10	6.1 (.29)	2	48	0	10	5.7 (.39)	2.4	39
meat/month	0	60	6.8 (.46)	7.5	267	1	17	8 (.86)	5.8	45	0	60	9.5 (1.84)	12.1	43	0	25	5.8 (.74)	4.9	45	1	20	6.8 (.73)	5	47	0	60	6 (1.31)	9.1	48	0	16	4.6 (.61)	3.8	39
mobile expenses/month	0	1997	214 (13.1)	206	248	21	750	256 (23.7)	161	46	0	1000	232 (33.4)	206	38	25	1997	254 (50.1)	309	38	30	700	246 (20.3)	130	41	10	1300	181 (32.6)	224	47	5	500	113 (16.7)	103	38
Workers/household	0	10	1.99 (.088)	1.45	271	0	7	2.4 (.23)	1.59	47	0	10	1.98 (.27)	1.76	44	0	5	2.1 (.17)	1.13	45	0	6	2.4 (.18)	1.22	48	0	5	1.60 (.18)	1.25	48	0	5	1.31 (.21)	1.28	39
Guests	0	200	6.1 (.87)	14	260	0	25	4.4 (.77)	5.2	46	0	60	6.2 (1.53)	10.2	44	0	50	7.2 (1.40)	9.3	44	0	200	9.6 (4.4)	29.3	45	0	10	4 (.41)	2.8	46	0	30	4.9 (.89)	5.3	35
Income earners/household	0	7000	31.8 (26)	428	271	0	7	2.7 (.20)	1.34	47	0	7000	184 (158)	1050	44	1	5	2.2 (.14)	.95	45	0	25	2.8 (.50)	3.5	48	0	4	1.69 (.14)	.98	48	0	5	1.67 (.16)	1	39
Remittances	0	50000	737 (268)	4415	271	0	50000	2149 (1312)	8996	47	0	20000	636 (461)	3061	44	0	20000	711 (487)	3270	45	0	0	0 (0)	0	48	0	20000	583 (425)	2943	48	0	5000	272 (160)	1001	39
Living subsidy received	0	999	3.7 (3.7)	60.6	271	0	0	0 (0)	0	47	0	999	22.8 (22.4)	149	44	0	4	.089 (.088)	.59	45	0	0	0 (0)	0	48	0	0	0 (0)	0	48	0	0	0 (0)	0	39
Savings	0	2000	16.1 (10)	141	200	0	100	11.5 (2.8)	19	45	0	130	8.6 (3.8)	22.1	34	0	2000	74.1 (70.1)	371	28	0	80	6.6 (2.3)	13.9	37	0	20	1.26 (.68)	3.8	31	0	13	1.90 (.65)	3.3	25
Loans	0	100	1.56 (.65)	10.5	261	0	100	7.1 (3.4)	23.3	46	0	30	.92 (.77)	4.8	39	0	30	.82 (.68)	4.5	44	0	6	.13 (.13)	.87	47	0	0	0 (0)	0	47	0	0	0 (0)	0	38
Heated area (m^2)	0	420	160 (5.1)	83.8	271	70	400	192 (9.5)	65	47	80	340	218 (9.5)	63	44	60	400	162 (11.4)	76.2	45	70	420	184 (13.8)	95.9	48	0	350	97.2 (9.2)	63.8	48	40	240	103 (7.8)	49	39
Fraction heated (area)	0	1	.77 (.013)	.22	271	.40	1	.82 (.021)	.15	47	.45	1	.94 (.020)	.13	44	.27	1	.79 (.033)	.22	45	.33	1	.76 (.028)	.19	48	0	1	.60 (.034)	.23	48	.29	1	.74 (.035)	.22	39
Fraction heated (rooms)	0	1	.83 (.012)	.20	267	.44	1	.86 (.021)	.14	45	.46	1	.92 (.022)	.14	42	0	1	.80 (.035)	.24	45	0	1	.89 (.026)	.18	48	.33	1	.75 (.032)	.22	48	.40	1	.78 (.032)	.20	39
Unheated area (m^2)	0	550	48.8 (3.8)	62.1	271	0	180	44 (5.5)	37.7	47	0	333	22.2 (8.6)	56.8	44	0	550	50.2 (13.2)	88.3	45	0	300	66 (10.2)	70.7	48	0	180	65.1 (6.6)	45.4	48	0	180	41.4 (7.5)	46.8	39
heated rooms	0	19	7 (.20)	3.3	267	4	19	7.2 (.38)	2.5	45	4	18	8.9 (.52)	3.4	42	0	19	7 (.52)	3.5	45	0	15	7.8 (.44)	3.1	48	2	15	5.4 (.42)	2.9	48	2	17	5.9 (.53)	3.3	39
unheated rooms	0	8	1.49 (.11)	1.79	267	0	5	1.22 (.19)	1.30	45	0	7	.93 (.29)	1.89	42	0	8	1.82 (.30)	1.99	45	0	6	.92 (.18)	1.27	48	0	6	2.2 (.26)	1.83	48	0	7	1.92 (.31)	1.95	39
Heating ($\sum_{\text{fuels}}\sum_{\text{rooms}}$hours)	0	624	152 (6)	97.4	267	77	480	187 (11.3)	76.1	45	96	624	219 (15.4)	99.7	42	0	456	126 (12.3)	82.6	45	0	504	133 (13.5)	93.6	48	41	427	118 (11)	76.2	48	31	590	139 (18.1)	113	39
Heating ($\sum_{\text{rooms}}$hours)	0	456	133 (5)	81	267	77	300	168 (7.2)	48	45	96	432	213 (12.5)	81.1	42	0	456	119 (12.3)	82.5	45	0	264	119 (10.2)	70.7	48	28	336	88.3 (8.6)	59.5	48	20	312	96.6 (10.5)	65.3	39
Coal used (tonnes)	0	10	2.2 (.14)	2.3	266	0	10	3.8 (.37)	2.5	46	0	0	0 (0)	0	44	0	8	4.2 (.27)	1.80	45	0	0	0 (0)	0	44	0	6	3.4 (.21)	1.47	48	0	5	1.84 (.20)	1.26	39
No coal used	0	1	.40 (.030)	.49	267	0	1	.089 (.042)	.28	45	1	1	1 (0)	0	42	0	1	.089 (.042)	.28	45	1	1	1 (0)	0	48	0	1	.021 (.021)	.14	48	0	1	.23 (.067)	.42	39
Coal expenditure (Yuan/season)	0	7850	1033 (84)	1370	266	0	7850	2757 (295)	2000	46	0	0	0 (0)	0	44	0	3600	1623 (128)	859	45	0	0	0 (0)	0	44	0	3080	1161 (90.3)	626	48	0	1400	494 (57.3)	358	39
Elecricity Expenditure (Yuan/season)	0	18000	2785 (191)	3123	266	0	11000	1960 (371)	2515	46	2000	18000	7241 (484)	3209	44	0	8000	1167 (211)	1414	45	1000	10000	4520 (295)	1959	44	50	2000	525 (61)	422	48	0	8000	1419 (268)	1673	39
Coal+Elec. Expenditure (Yuan/season)	358	18000	3818 (175)	2846	266	800	11000	4717 (399)	2708	46	2000	18000	7241 (484)	3209	44	1000	8190	2790 (228)	1528	45	1000	10000	4520 (295)	1959	44	358	3480	1687 (107)	743	48	620	8000	1913 (233)	1458	39
Coal expenditure (Yuan/person/season)	0	3925	320 (29.3)	477	266	0	3925	802 (124)	838	46	0	0	0 (0)	0	44	0	1350	388 (35.9)	241	45	0	0	0 (0)	0	44	0	1330	465 (36.7)	254	48	0	560	216 (28.3)	177	39
Elecricity Expenditure (Yuan/person/season)	0	6000	769 (54)	880	266	0	2600	528 (96.9)	657	46	667	6000	1963 (140)	932	44	0	1333	259 (41.5)	279	45	250	4500	1170 (109)	725	44	50	750	196 (23.1)	160	48	0	3800	552 (110)	685	39
Coal+Elec. Expenditure (Yuan/person/season)	175	6132	1089 (54.2)	884	266	200	6132	1329 (175)	1188	46	667	6000	1963 (140)	932	44	200	1650	647 (48.2)	323	45	250	4500	1170 (109)	725	44	204	1450	660 (44.6)	309	48	175	3800	768 (96.3)	601	39
Fraction of heating expenditure on coal	0	1	.40 (.022)	.37	266	0	1	.59 (.050)	.34	46	0	0	0 (0)	0	44	0	1	.63 (.036)	.24	45	0	0	0 (0)	0	44	0	.95	.70 (.026)	.18	48	0	1	.42 (.050)	.31	39

Supplementary Table 6: Descriptive statistics of main survey variables

District	Station Name and Coordinates (lat/long)	Status	Distance between Village and Station (km)
Haidian	Beibuxinqu (40.09, 116.174)	Treated	4.7±0.2
		Untreated	3.1±0.2
Fangshan	Fangshan (39.742, 116.136)	Treated	8.0±0.1
		Untreated	7.1±0.7
Yanqing	Yanqing (40.453, 115.972)	Treated	7.3±0.3
		Untreated	7.5±0.1

Supplementary Table 7: Average distances (mean ± standard deviation) of our study villages to the nearest outdoor monitoring stations.

District	Status	Dates (2017)	Average $PM_{2.5}$ concentration (μg·m^{-3})	
			outdoor	indoor
Haidian (海淀区)	Treated	March 20-21	118±35	407±281
	Untreated	March 22–23	145±30	547±219
Fangshan (房山区)	Treated	March 27–28	38±12	245±326 (148±112)
	Untreated	March 30–31	62±27	151±204
Yanqing (延庆区)	Treated	April 6–7	83±30	201±116
	Untreated	April 8–9	54±29	100±72

Supplementary Table 8: Average outdoor and indoor $PM_{2.5}$ concentrations. Mean ± standard deviation shown for each village. Outdoor data are publicly available records obtained from the nearest environmental air quality monitoring stations (operated by Beijing Municipal Environmental Monitoring Center) in each study district. Red in "Fangshan Treated" indicates the data excluding one house in which indoor $PM_{2.5}$ concentrations were so high as to suggest instrument malfunction.

	PCA_1	PCA_2	PCA_3
Log(income)	.42	−.037	.23
meat/month	.18	−.55	.64
mobile expenses/month	.32	.22	.37
Group 1 appliances	.25	.68	.12
Group 2 appliances	.39	.055	.007
Group 3 appliances	.45	.054	−.090
House area	.39	−.064	−.46
Log(rooms)	.34	−.42	−.41
Variance explained	42%	15%	12%
Eigenvalue	3.4	1.3	1.0

Supplementary Table 9: Principal component coefficients

Hot water heating	Households	Fraction
Coal	104	37%
ATW	43	15%
ATW;Solar;Resistive	21	7%
Coal;Solar;Resistive	17	6%
(none)	15	5%
Coal;Resistive	14	5%
Coal;ATW	13	4%
ATW;Resistive	11	4%
ATW;Solar	11	4%
Coal;Solar	9	3%
Resistive	8	2%
Solar;Resistive	7	2%
Solar	1	<1%

Supplementary Table 10: Distribution of fuels used for radiator heating (prior to simplification)

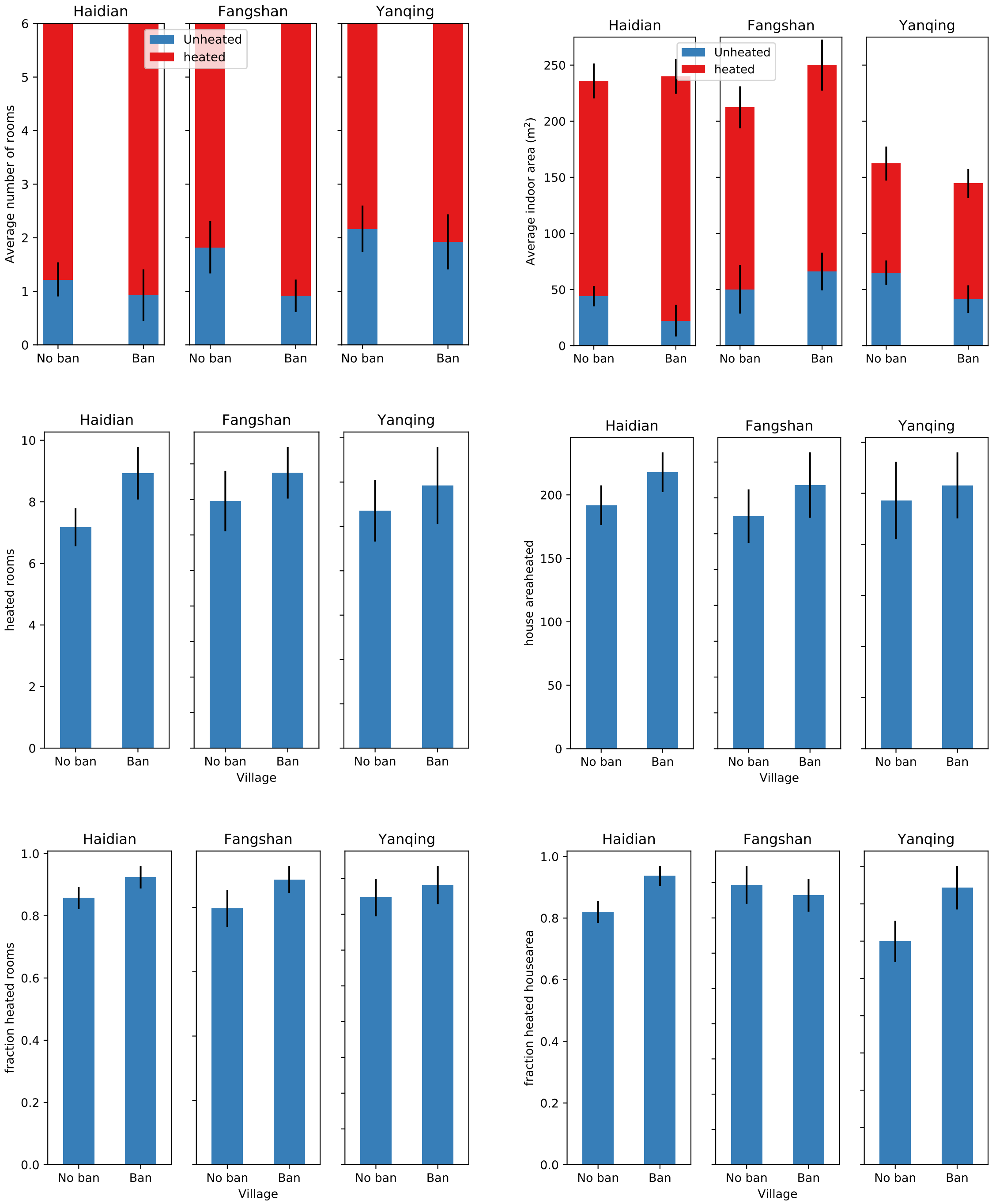
Hot water heating	Households	Fraction
Coal	130	47%
ATW	86	31%
(none)	15	5%
Coal;Resistive	14	5%
Coal;ATW	13	4%
Resistive	8	2%
Solar;Resistive	7	2%
Solar	1	<1%

Supplementary Table 11: Distribution of fuels used for radiator heating (final analysis)

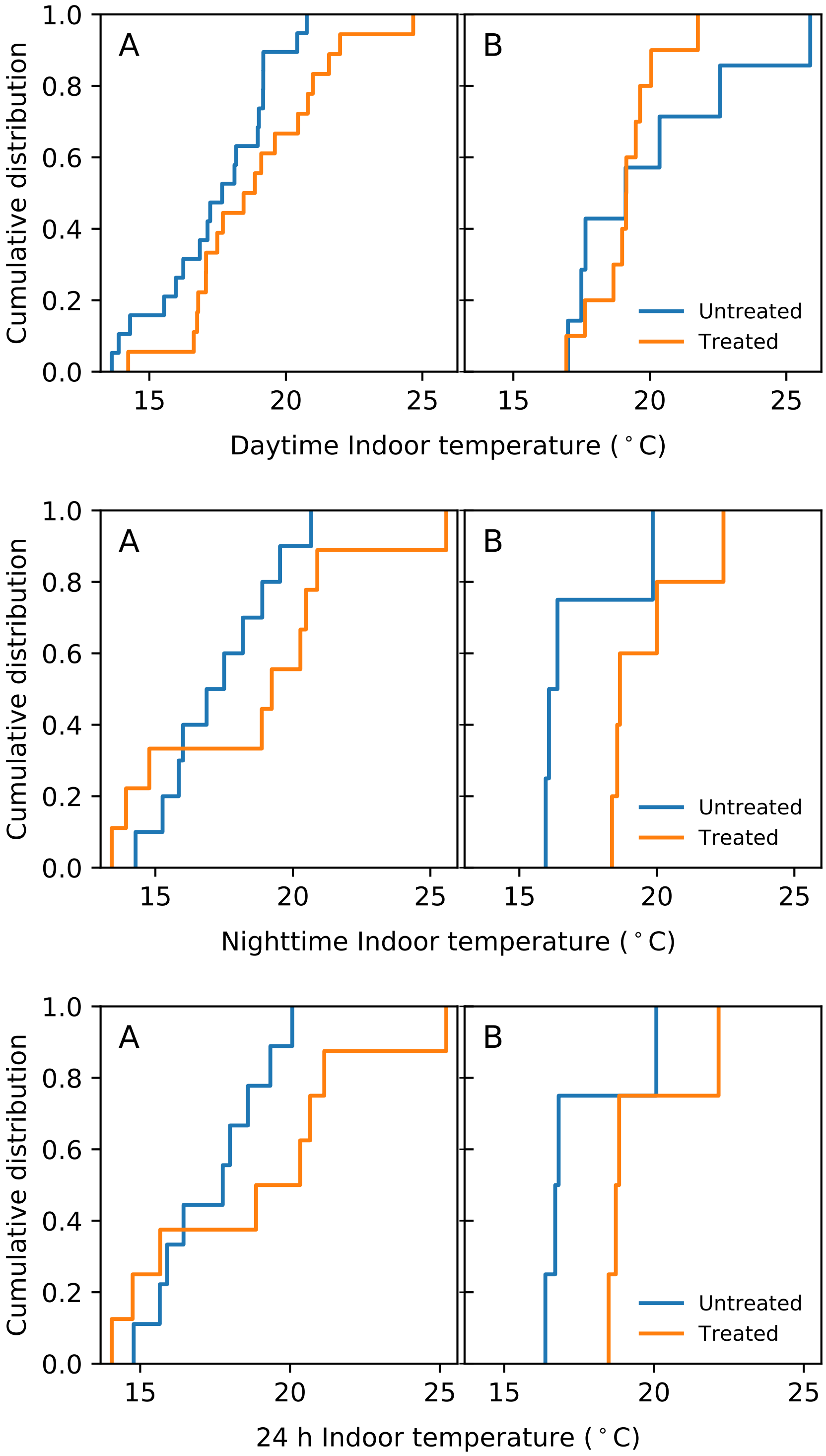
Heating	Households	Fraction
Coal	110	39%
ATW	45	16%
ATA	35	12%
Biomass;Coal	17	6%
Coal;Resistive	11	3%
(none)	10	3%
ATW;Biomass;Coal	9	3%
ATA;ATW	8	2%
Resistive	6	2%
ATW;Biomass	4	1%
Biomass;Coal;Resistive	4	1%
ATW;Coal	4	1%
ATW;Resistive	3	1%
ATA;ATW;Coal	1	<1%
Resistive;Solar	1	<1%
Other;Resistive	1	<1%
ATW;Biomass;Other	1	<1%
ATA;Coal	1	<1%
Biomass;Other;Resistive	1	<1%
Biomass;Coal;Other	1	<1%
ATA;Coal;Resistive	1	<1%
ATA;ATW;Coal;Resistive	1	<1%
Solar	1	<1%
Biomass;Coal;Other;Resistive	1	<1%
ATW;Other	1	<1%

Supplementary Table 12: Distribution of household heating methods

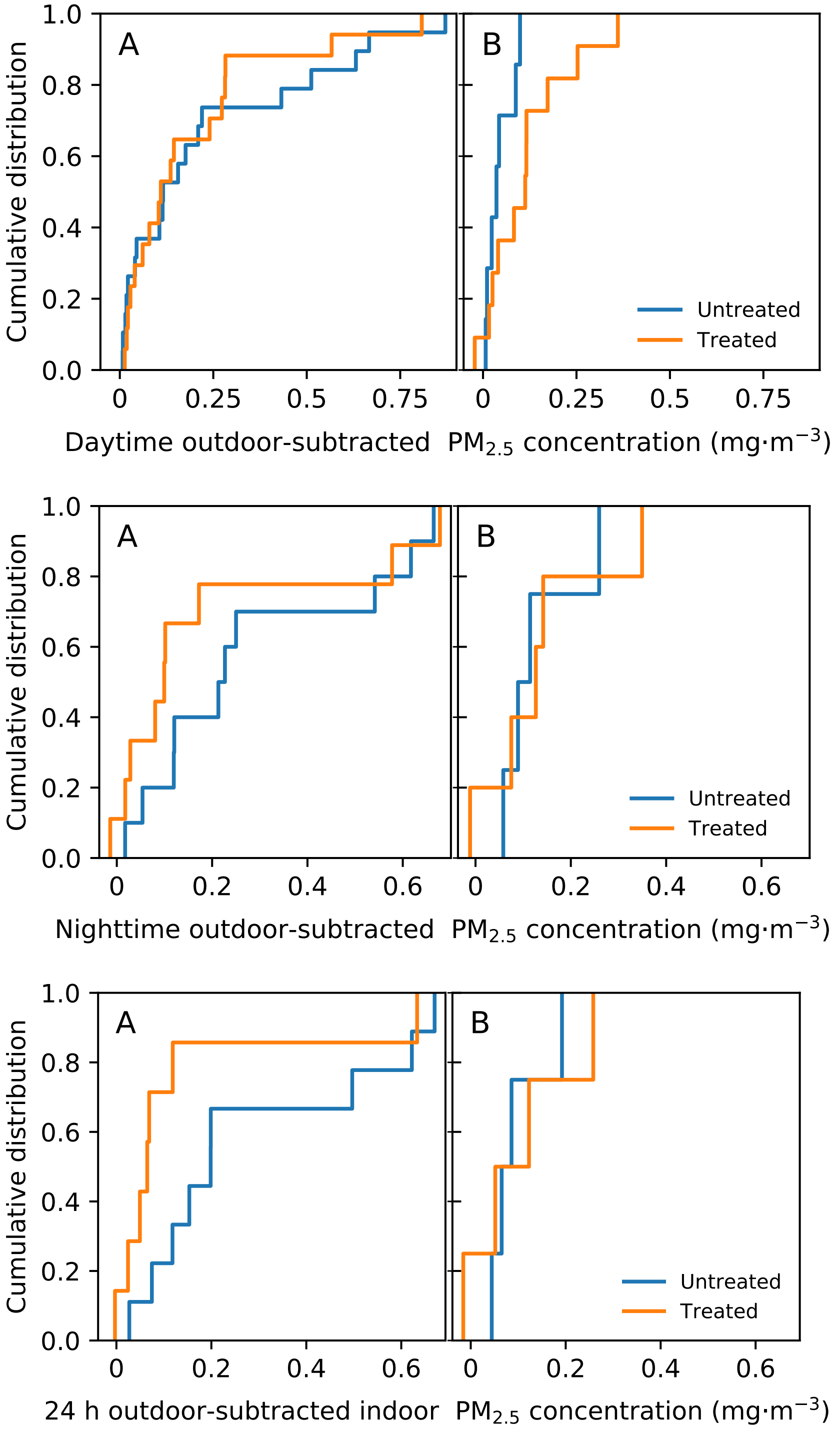
2 Supplementary Figures



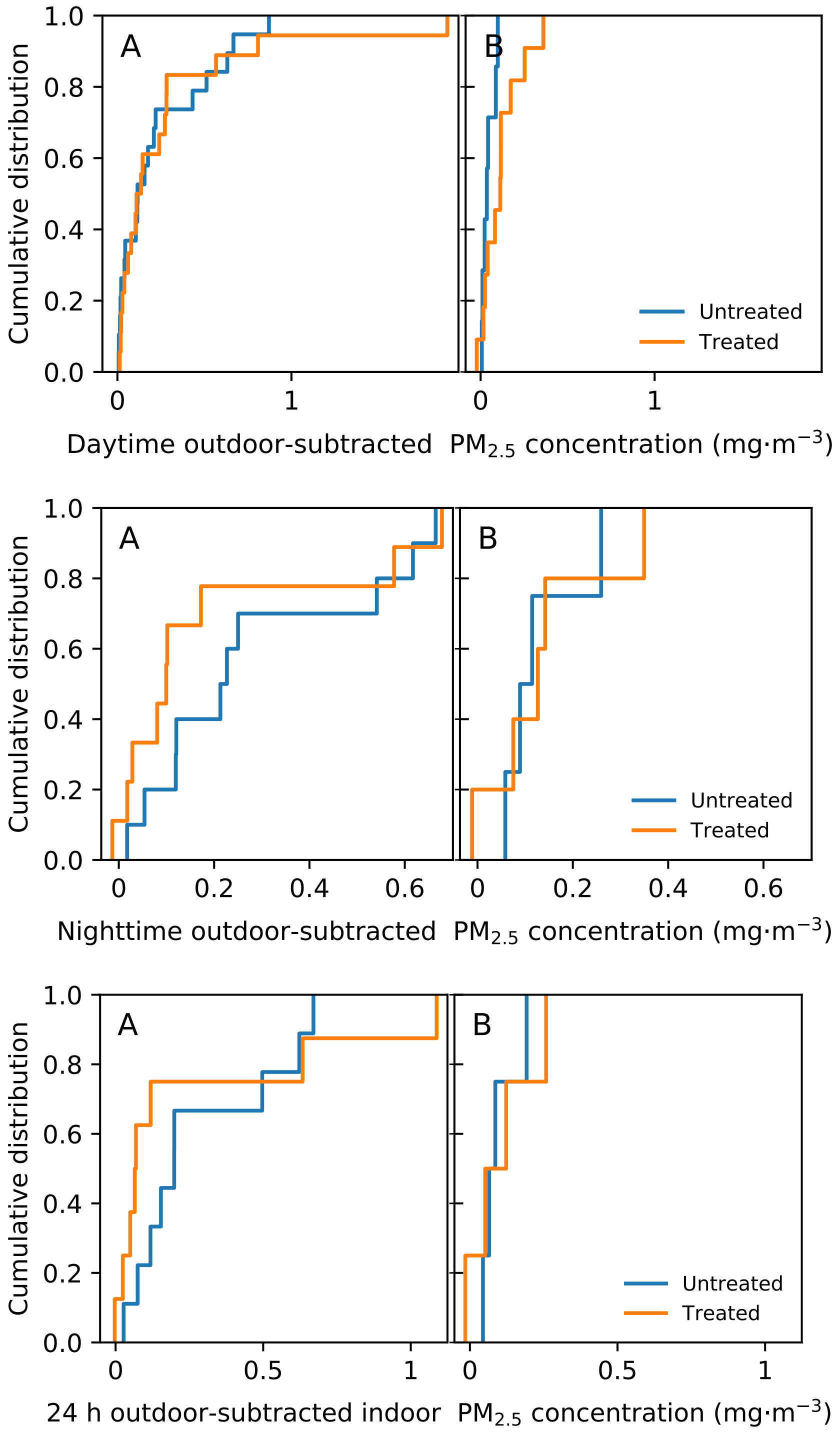
Supplementary Figure 1: Graphical comparisons of villages. See Tables 6 and 1 for tabulated data. Top row: Average number of rooms and indoor area. Middle row: Average number of heated rooms and heated area.Bottom row: Fraction of rooms heated and fraction of area heated.



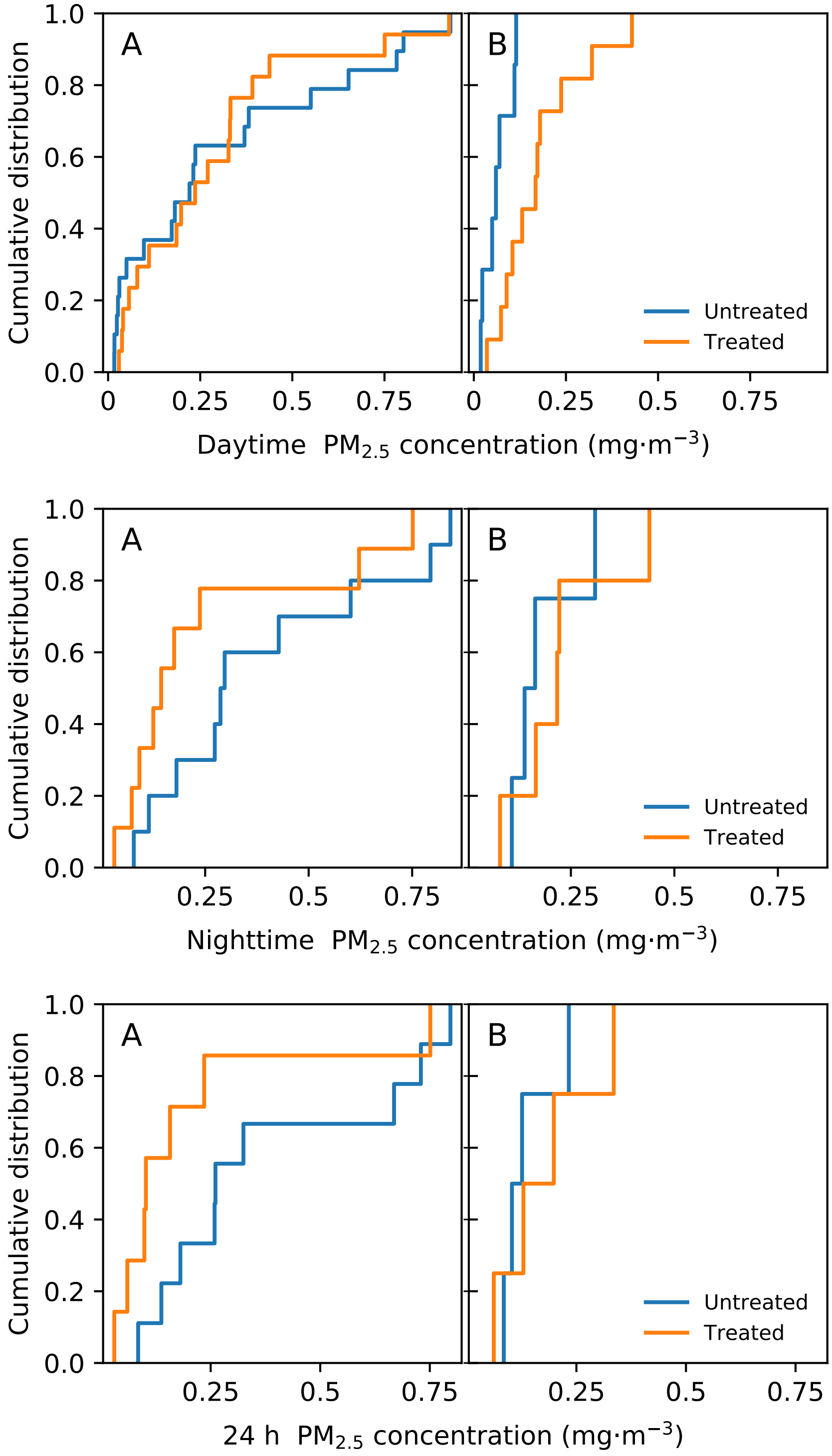
Supplementary Figure 2: Cumulative distributions of observed indoor temperature in (A) Fangshan and Haidian and (B) Yanqing. The top row (daytime) is shown in the main text (Figure 7). The nighttime (middle row) and 24-hour (bottom row) are shown for comparison. Sample sizes (T=Treated, U=Untreated) are: Middle row: N_T^A=9, N_U^A=10, N_T^B=5, N_U^B=4; Bottom row: N_T^A=9, N_U^A=10, N_T^B=5, N_U^B=4.



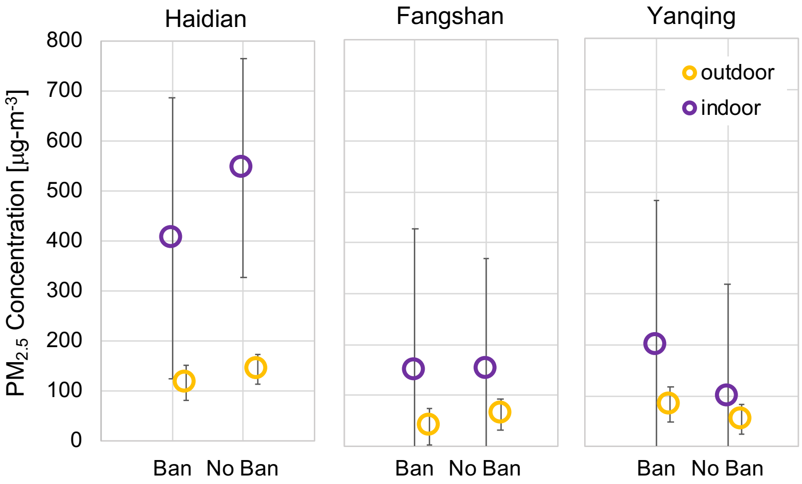
Supplementary Figure 3: Cumulative distributions of outdoor-subtracted indoor PM$_{2.5}$ observed between 8AM and 6PM (daytime, top row), between 6PM and 8AM (nighttime, middle row) and observed over 24 h (bottom row) in (A) Fangshan and Haidian and (B) Yanqing. Each row is arranged like Figure 6, which is identical to the bottom row. Sample sizes (T=Treated, U=Untreated) are: Top row: N_T^A=17, N_U^A=19, N_T^B=11, N_U^B=7; Middle row: N_T^A=9, N_U^A=10, N_T^B=5, N_U^B=4.



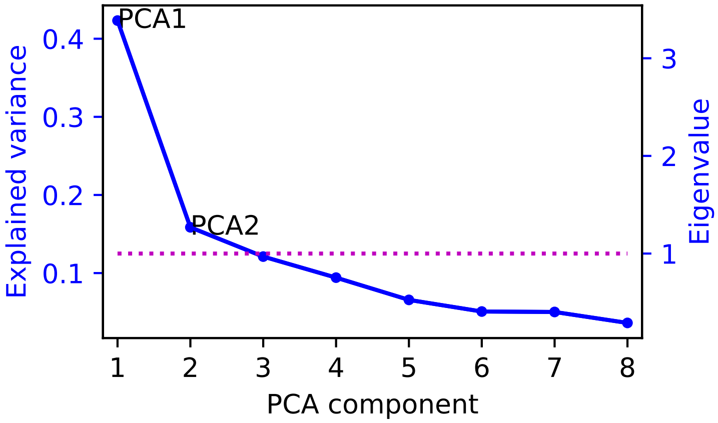
Supplementary Figure 4: Cumulative distributions of outdoor-subtracted indoor PM$_{2.5}$ in (A) Fangshan and Haidian and (B) Yanqing, arranged like Supplementary Figure 3, but including one anomalously high observation. Sample sizes (T=Treated, U=Untreated) are: Top row: N_T^A=18, N_U^A=19, N_T^B=11, N_U^B=7; Middle row: N_T^A=9, N_U^A=10, N_T^B=5, N_U^B=4; Bottom row: N_T^A=8, N_U^A=9, N_T^B=4, N_U^B=4.



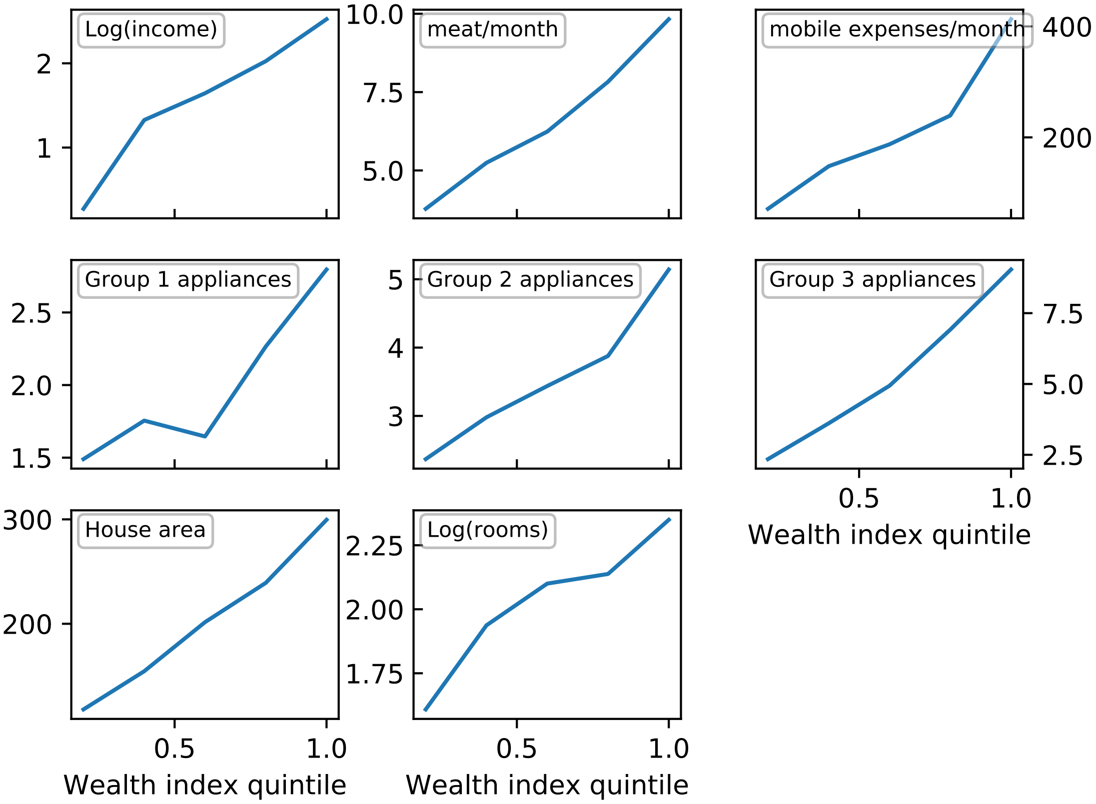
Supplementary Figure 5: Cumulative distributions of indoor PM$_{2.5}$ in (A) Fangshan and Haidian and (B) Yanqing. Layout is as in Supplementary Figure 3 but absolute values are shown, without subtracting outdoor concentrations. Sample sizes (T=Treated, U=Untreated) are: Top row: N_T^A=17, N_U^A=19, N_T^B=11, N_U^B=7; Middle row: N_T^A=9, N_U^A=10, N_T^B=5, N_U^B=4; Bottom row: N_T^A=7, N_U^A=9, N_T^B=4, N_U^B=4.



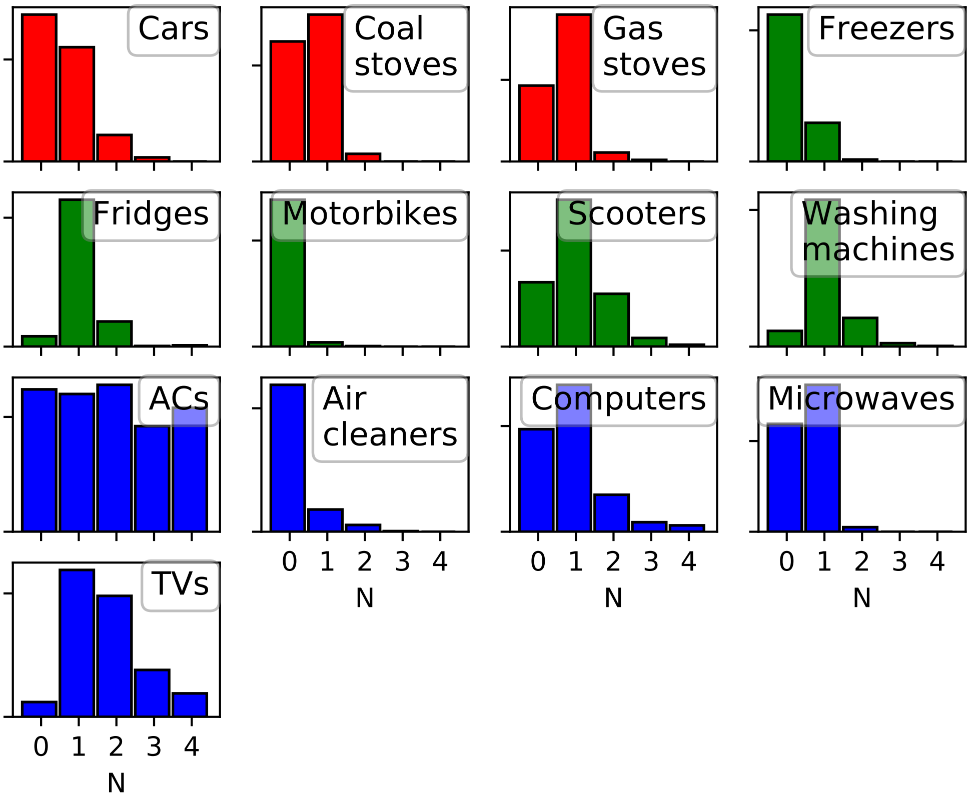
Supplementary Figure 6: Average outdoor and indoor $PM_{2.5}$ concentrations. Arithmetic mean and standard deviation shown for each village. Outdoor data are publicly available records obtained from the nearest environmental air quality monitoring stations (operated by Beijing Municipal Environmental Monitoring Center) in each study district. Tabular data shown in Supplementary Table 8.



Supplementary Figure 7: Principal component analysis diagnostics



Supplementary Figure 8: Monotonicity of wealth index components. Horizontal axes show quantiles of wealth index.



Supplementary Figure 9: Histograms of household asset counts. Assets are grouped by our heuristic asset classes — Class 1 (red), Class 2 (green) and Class 3 (blue).

3 Supplementary Note 1: The coal-to-electricity policy: background and incentives

Air pollution is the fourth leading risk factor for disease burden in China, responsible for an estimated 1.5 million yearly premature deaths [39]. In the greater Beijing-Tianjin-Hebei (BTH) region, ambient air pollution levels are regularly high, especially during the winter heating season, and have annually garnered domestic and global attention. Although ambient $PM_{2.5}$ levels in Beijing have decreased over the past decade [40], they remain consistently higher than both the World Health Organization (WHO) yearly guideline of 10 $\mu g{\cdot}m^{-3}$ and China's National Ambient Air Quality Standard of 35 $\mu g{\cdot}m^{-3}$. For example, in 2016, the average annual and winter season concentrations of $PM_{2.5}$ in the BTH region were 69 $\mu g{\cdot}m^{-3}$ and 135 $\mu g{\cdot}m^{-3}$, respectively [41].

As discussed in the main text, the Beijing coal-to-electricity policy fits into a larger initiative to reduce reliance on coal power as well as coal heating. The policy also involves investments in upgrading electricity distribution infrastructure to accommodate the transition in demand, and complements subsidies in retrofitting rural homes with better insulated windows and walls. In addition to the heat-pump-oriented policy, there is a parallel but smaller coal-to-natural-gas effort. In the summer of 2018, Beijing announced an ongoing commitment, or the next phase, of this "coal-to-electricity" program [42].

As we see it, households face four policy-influenced factors affecting the uptake of new technology such as heat pumps. First, there is the information problem of a substantial investment in a relatively new technology. In China there is choice among providers of heat pumps, and individual households face uncertainty in the quality and durability of different options. Through collective purchasing, governments can mitigate the uncertainty and to some degree help to assure quality. Second, upfront costs are the most commonly reported barrier to household adoption of new energy technologies, even when economic pay-back periods to the owner are near-term [43]. Costs are a deterrent due to both credit constraints and to behavioural biases against long-term investments. The BTH 'coal to electricity" program affords subsidies on this equipment, as high as 100% in our study sites. Third, electricity is still relatively expensive as compared with coal, which reduces the benefit to households from upgrading their infrastructure to electric heat pumps. While villages under the program receive electricity subsidies, those are still competing with existing government subsidies on coal and do not bring total heating costs down to the level to which households were accustomed with coal. Fourth, when coal is banned in a village, the non-pecuniary costs of obtaining it through non-sanctioned means may be high and depend on factors including local geography, availability to nearby villages, and enforcement. Figure 1 depicts a typical coal storage scene, a coal heating stove, and a heat pump installation..

Given the expected increases in monthly electricity costs implied by the program as compared to coal, we expected households to respond to the policy in various ways described under "Approach" in the main text. Household preferences for switching away from coal heating may reflect some immediate health benefits, but are unlikely to fully capture the long-term effects of mitigating the air pollution problems described above.

4 Supplementary Note 2: Predictive models for subjective well-being, coal use, and expenditure

4.1 Predictive models for subjective well-being

All-encompassing life evaluations can in principle be expected to reflect health (influenced by indoor air quality and indoor air temperature), physical living conditions (temperature, adequacy of living space, sufficiency of food and amenities), and binding financial constraints (influenced by capital expenditure on heat pumps, and by ongoing cost of electricity and fuel), among other factors. They are unlikely to reflect fully the external benefits of the program to regional health or global climate.

In order to explore further the multivariate relationships in our cross-sectional design, we provide ordinary least squares estimates of various regression model specifications explaining respondents' self-reports of their satisfaction with life overall (Supplementary Table 3), with their household income (Supplementary Table 4), and with their living conditions (Supplementary Table 5). The *coal ban* variable has value 1 in villages with the policy implemented (regardless of the degree of enforcement) and 0 otherwise. The wealth index and the asset categories are described in the Methods section of the main text.

Models (1)–(4) in each table investigate the relationship between reported income and life satisfaction, optionally controlling for district fixed effects. Models (5)–(6) explain variation in satisfaction using available concrete measures of consumption (heated and unheated area; meat consumption), while models (7)–(8) use the variables we use in our wealth index. The wealth index itself, along with a measure of household size, is used to account for satisfaction in models (9)–(10). The remaining columns are models which estimate, in reduced form, an overall treatment effect of the coal ban on satisfaction. This is done by incorporating an indicator variable (*coal ban*) for the policy, along with our wealth index or its constituents. We estimate these models separately for each district in columns (13)–(15) and (18)–(19) and, generally, find overall large negative coefficients on the *coal ban* variable in the lower-income district (Yanqing), and large positive ones in the middle-income district (Fangshan), in concordance with our descriptive statistics.

We summarize these correlative findings by saying that while our village pairs are similar within districts, the differences in well-being outcomes between some village pairs remain when we control for our available measures of wealth and household size.

4.2 Predictive models for coal use and expenditure

The main text states that the relationship between coal use and household wealth is strongly negative ($p < .01$), based on a Pearson's correlation coefficient ($r = -0.17$) between our wealth index and the fraction of heating (measured in room-hours) done by coal. This result (N=242 in all cases) is maintained when we use a normalized version of our wealth index ($r = -0.43, p = 0.01$) and using non-parametric correlation tests (Spearman's $\rho = -0.39, p = 0.017$; Kendall's $\tau = -0.25, p = 0.025$).

4.3 Coal use when both heat pumps and coal are available

Columns (1)–(7) in Supplementary Table 2 show our estimates of the dependence of coal use on our index of wealth (See Methods section in the Wealth Index for details.) In the high and middle income districts we model the fraction of heating expenditure on coal within the untreated village only, i.e., where coal is still in use. No relationship is found in either district. In the lower income district (columns 5–7) we find strong negative dependence of coal use on wealth, supporting our interpretation that households choose to pay for more expensive alternatives when they have the option. Because the standard deviation of the wealth index within the coal ban village in Yanqing is 1.13 (Supplementary Table 6), the coefficient -0.11 in column (4) and be interpreted as follows: a one standard deviation increase in wealth predicts a 12% decrease in the fractional expenditure on coal.

Because some households in the treated village eschew coal entirely, we estimate in column (7) a fractional logit model, rather than ordinary least squares, to account for the distribution of fractions. The marginal effect estimated this way is very similar (see Figure 4 in the main paper).

Because our measure of expenditure does not discriminate between non-heating electricity and electricity used for heating, we estimate analogous models (columns 8–16) for the fraction of heating (measured by room-hours) carried out using coal, and find similar effects.