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ARTICLE

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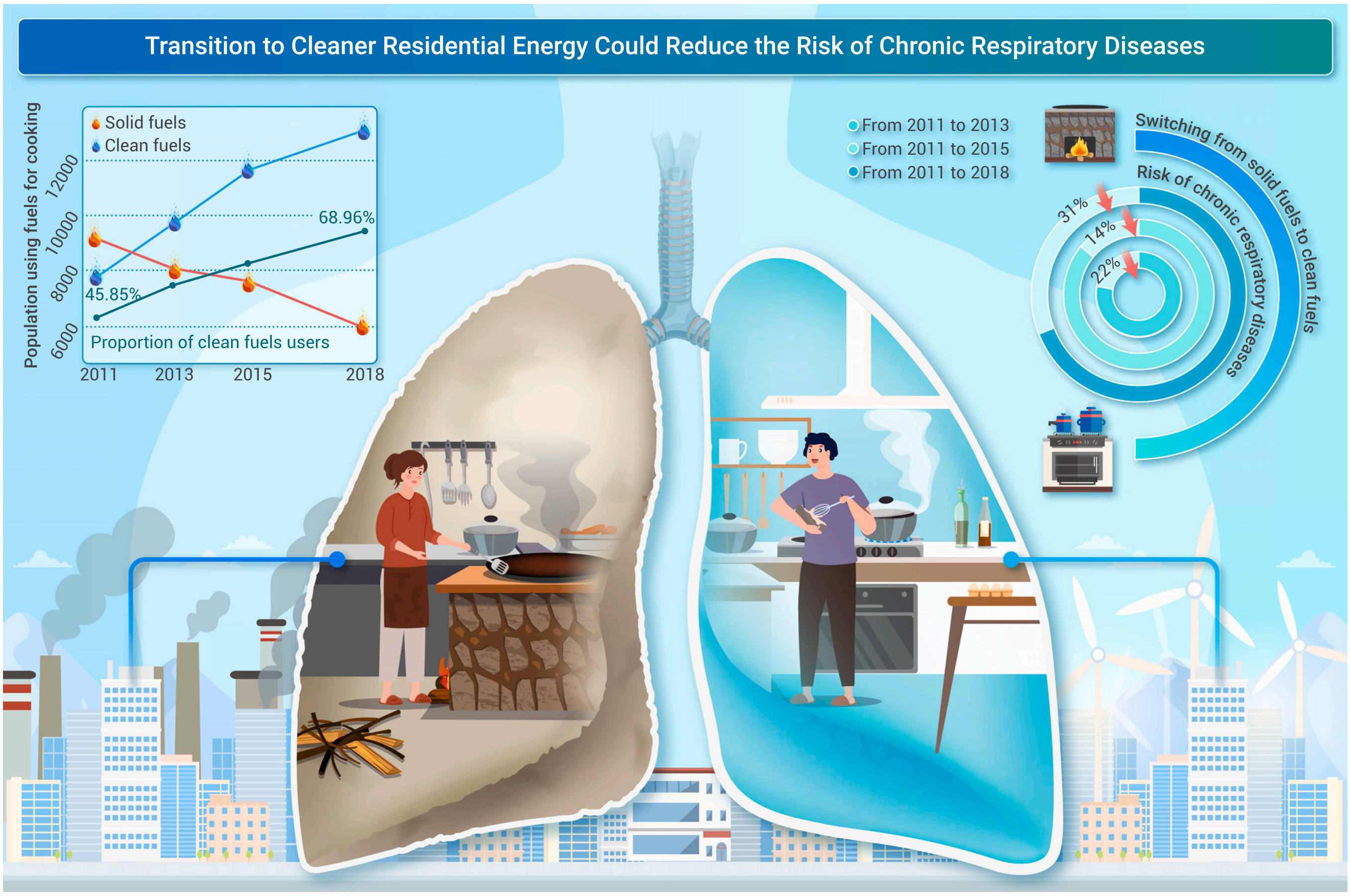
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Obtaining clean energy is of prime importance for planetary health and sustainable development.
- Despite great progress, huge disparities in access to clean energy persist globally.
- Household energy transition from solid to clean fuels could reduce the risk of chronic respiratory diseases.
- Accelerating energy switching could achieve promising gains in public health.

ARTICLE

Residential energy transition and chronic respiratory diseases

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Obtaining clean energy is of prime importance for planetary health and sustainable development. We aimed to assess the association between residential energy transition and the risk of chronic respiratory diseases. Using data from the Global Health Observatory and Global Burden of Diseases, Injuries, and Risk Factors Study, we delineated the spatial distribution and temporal trends of the population using clean fuels for cooking at a global scale. In the China Health and Retirement Longitudinal Study, we performed rigorous and well-structured multistage analyses incorporating both cross-sectional and prospective data analyses to examine the associations between solid fuel use, residential energy transition, duration of solid fuel use, and the risk of chronic respiratory diseases. Despite great progress, huge disparities in access to clean energy persist globally. Residential energy transition was associated with a lower risk of chronic respiratory diseases. In the period of 2011–2013, compared with persistent solid fuel users, both participants who switched from solid to clean fuels (adjusted risk ratio [RR] 0.78, 95% confidence interval [CI] 0.62–0.98) and persistent clean fuel users (adjusted RR 0.71, 95% CI 0.57–0.89) had significantly lower risk of chronic respiratory diseases ($p < 0.001$ for trend). Consistent associations were observed in the period of 2011–2015 and 2011–2018. Household energy transition from solid to clean fuels could reduce the risk of chronic respiratory diseases. This is a valuable lesson for policymakers and the general public to accelerate energy switching to alleviate the burden of chronic respiratory diseases and achieve health benefits, particularly in low- and middle-income countries.

INTRODUCTION

In 2019, approximately 3.8 billion people worldwide, nearly half of the global population, relied on solid fuels, including biomass (e.g., wood, charcoal, dung, and agricultural waste) and coal for domestic purposes.[1] When incompletely combusted indoors, solid fuels generate a hybrid of fine particulate matter ($PM_{2.5}$) and carbon monoxide, as well as other toxic substances, and contribute significantly to both ambient and household air pollution (HAP).[2,3] Exposure to the resulting HAP presents a global health inequity and is a leading risk factor associated with deleterious health effects in low- and middle-income countries (LMICs), accounting for 2.31 million deaths (4.09% of all deaths) and 91.47 million disability-adjusted life-years (DALYs) (3.61% of all DALYs) in 2019.[4]

Chronic respiratory diseases (CRDs) remain the major impediments to the improvement of public health, with chronic obstructive pulmonary disease (COPD) ranking as the third leading cause of death and an estimated 262 million people globally suffering from asthma in 2019.[5–7] Both genetic predisposition and environmental triggers are implicated in the etiology of CRDs, whereas solid fuel use, a proxy for HAP exposure, is a major modifiable risk factor.[8] Findings of several previous observational studies have suggested a higher risk of CRDs from the use of solid fuels.[9–14]

The issue of clean and sustainable household energy is deemed an important part of the sustainable development goals of the United Nations.[15,16] In response to the challenges of achieving carbon neutrality and battling air pollution, the Chinese government implemented the Air Pollution Prevention and Control Action Plan in 2013, a series of regulatory measures including reducing the residential use of unclean fuels.[17] Consequently, residential energy has rapidly transitioned from solid fuels to clean fuels, such as natural gas, liquefied petroleum gas, and electricity.[18–20] These changes provide an unprecedented opportunity to discern the respiratory health benefits of residential energy switching.

It is also noteworthy that China has seen a rapid shift in the distribution of population toward older ages (i.e., population aging), with the population aged 60 and above expected to reach 28% by 2040.[7] Besides, natural aging increases susceptibility and vulnerability to acute respiratory diseases and CRDs.[21] In that context, it is crucial to examine the effects of the transition from solid fuels to cleaner household energy, particularly in middle-aged and older adults.

Although prior studies have reported that switching in household fuels dominated the decline in HAP exposure and the associated premature mortality in China,[19,20,22,23] to the best of our knowledge, epidemiological evidence for the beneficial effects of residential energy transition on CRDs remains limited, with only two cohort studies making the preliminary explorations. One study of about 0.28 million Chinese never-smokers from the China Kadoorie Biobank (CKB) investigated the association between switching to clean fuels and hospitalization or death from major respiratory diseases.[9] However, it has been primarily limited to exposure measurement based on recall information instead of prospective monitoring. Another study from the Prospective Urban and Rural Epidemiology (PURE) cohort examined the association between switching to clean fuels and lung function and respiratory events.[24] Nevertheless, the primary outcome was defined as the composite of all respiratory disease events rather than specific respiratory diseases due to low statistical power, and the study population was limited to individuals living in rural communities. Moreover, for both studies, there is a paucity of information on temporal trends of residential energy use in continuous follow-ups of the study participants, as well as the prevalence of solid fuel use and the attributable disease burden at the global scale.

In light of this, we first characterized the share of the population with primary reliance on clean fuels and technologies for cooking at a global scale. Furthermore, the China Health and Retirement Longitudinal Study (CHARLS), a longitudinal, multi-wave survey of people aged 45 and older nationally, has provided a unique opportunity to quantify residential energy switching and the consequent health impacts in an aging society. Based on the panel data, we performed rigorous and well-structured multistage analyses incorporating both cross-sectional and prospective data analyses to determine the associations between solid fuel use, residential energy transition, duration of solid fuel use, and the risk of CRDs among Chinese middle-aged and older adults.

RESULTS

Exposure to solid fuel use and the attributable burden globally and in China

Figure 1A shows the annualized proportion of the population with primary reliance on clean fuels for cooking in six WHO regions (i.e., Europe, Americas, Eastern Mediterranean, Western Pacific, Southeast Asia, and Africa) from 1990 to 2020. Regional exposure to solid fuel use was notably spatiotemporally heterogeneous. Populations in Europe (94.8%) and Americas (92.5%) regions have almost fully switched from solid fuels to clean fuels for cooking until 2020. The Eastern Mediterranean and Western Pacific regions have seen a modest drop in the use of solid fuels from 1990 to 2020, with the Eastern Mediterranean region elevating the share of its population accessible to clean cooking fuels from 48.2% to 73.2% and the Western Pacific region increasing the percentage of its population accessible to clean cooking fuels from 47.9% to 78.3%. The proportion of the population exposed to solid fuel use in the Southeast Asia region declined

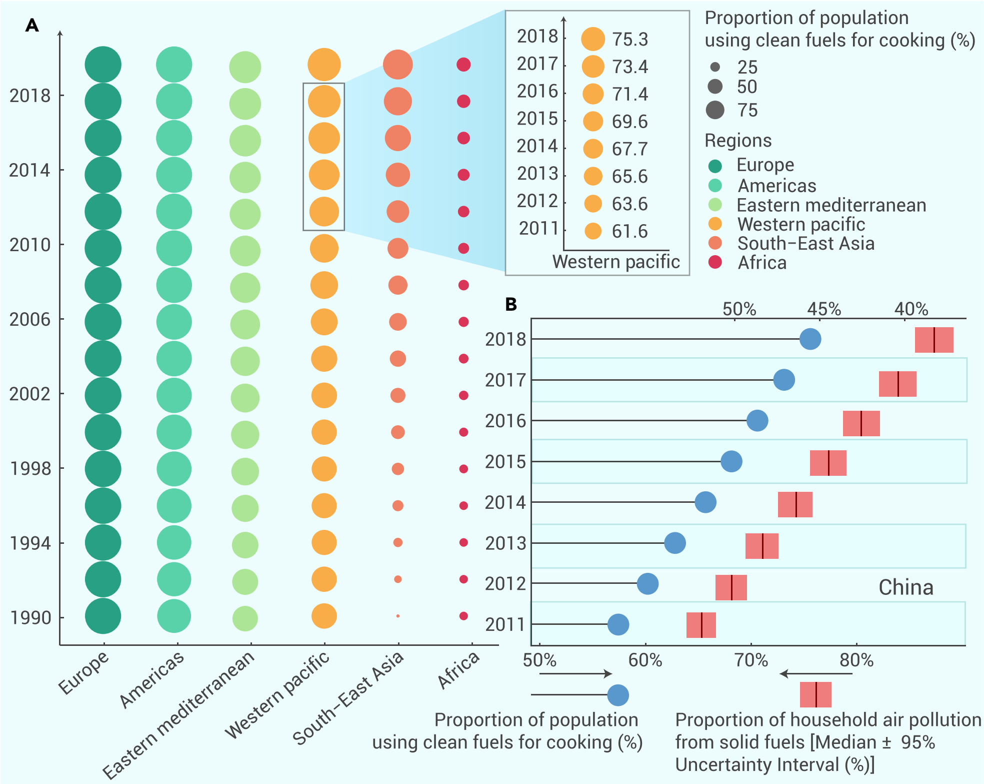

Figure 1. Proportion of the population with primary reliance on clean fuels for cooking globally, particularly in China (A) Percentage of population with primary reliance on clean fuels for cooking globally, 1990–2020. (B) Percentage of population using clean fuels for cooking, and the resulting HAP in China, 1990–2020.

sharply, with a shift from 89.1% to 35.5%. However, people in the African region still suffered the highest exposure to solid fuel use, and the household energy transition was yet too slow, ranging from 13.1% in 1990 to 19.9% in 2020. The detailed information can be found in Table S1.

In China, the proportion of the population using clean fuels for cooking has climbed from 58.0% to 75.6% in the period of 2011–2018, which was likely to primarily drive the corresponding change in the Western Pacific region at the same time (Figures 1A and 1B; Tables S1 and S2). Simultaneously, the resulting HAP reduced from 52% (95% uncertainty interval [UI] 50%–54%) to 38% (95% UI 36%–40%) (Figure 1B; Table S3).

As shown in Figure 2A and Table S4, the highest numbers of deaths attributable to HAP from solid fuels were seen in India, China, and Nigeria (0.60 million, 95% UI 0.39–0.86; 0.36 million, 95% UI 0.18–0.62; 0.13 million, 95% UI 0.09–0.17, respectively). Figure 2C illustrates that the countries or territories with more than 10% of deaths attributable to HAP from solid fuels are mainly distributed in sub-Saharan Africa, South Asia, and Southeast Asia (Table S5). When viewed in terms of DALYs attributable to HAP from solid fuels, similarly, India, Nigeria, and China remained standing in the front ranks across the world (20.90 million, 95% UI 14.12–28.73; 8.75 million, 6.11–11.85; 8.74 million, 4.61–14.59, respectively; Figure 2B; Table S6). HAP from solid fuels was responsible for over 10% of attributable DALYs in a wide range of countries or territories in sub-Saharan Africa, South Asia, and Southeast Asia (Figure 2D; Table S7).

Figures 2E and 2F provide the temporal trends of the health burden attributable to HAP from solid fuels in China from 1990 to 2019. HAP from solid fuels led to an estimated 1.32 million (15.9%) deaths in 1990 and 0.36 million (3.4%) deaths in 2019. The number (percentage) of attributable DALYs has fallen substantially in the past 2 decades, ranging from 44.03 million (10.7%) to 8.74 million (2.3%). The detailed information is shown in Tables S8 and S9.

Characteristics of the CHARLS study participants

Of the 17,284 participants at baseline, the mean (SD) age was 59.4 (9.9) years, and 51.3% were women, with a rural residence predominance (75.9%) (Table 1). Generally, participants using solid fuels for cooking and heating tended to be older, less educated, more physically active, and have worse self-reported socioeconomic status compared with clean fuel users. Solid fuel users were more likely to live in rural residences and living environments with worse building architecture, smaller house areas, and without a kitchen. Smoking was less prevalent for women (10.5%) among all participants, while the proportion of female smokers among solid fuel users (11.9% for cooking; 13.2% for heating) was higher than clean fuel users (8.8% for cooking; 5.2% for heating).

We mapped the prevalence of solid fuel use for both cooking and heating across the four waves in the CHARLS (Figures 3A and 3C). The spatial distribution patterns for solid fuel use for cooking and heating largely overlapped and varied at the province level, with the central and Western regions primarily accounting for the prevalence of solid fuel use. Throughout the four waves, the proportion of participants using clean fuels for cooking switched from 45.9% in 2011 to 69.0% in 2018. Likewise, the proportion of participants using clean fuels for heating revealed a uniform trend, elevating from 26.2% to 36.1% (Figures 3B and 3D). It should be noted that heating fuel use was reported in a very small population in 2015 and 2018 (a total of 2,075 and 1,519 participants, respectively), which led to a sharp decrease in 2015 and 2018 in contrast to the previous waves (see Table S10).

Cross-sectional association of solid fuel use with CRDs

Compared with clean fuel use for cooking, solid fuel use was significantly associated with a higher risk of CRDs in all four cross-sectional waves (adjusted OR 1.31, 95% CI 1.14–1.50 in 2011; 1.24, 1.09–1.41 in 2013; 1.22, 1.03–1.46 in 2015; 1.46, 1.21–1.76 in 2018; Figure 4A). For heating, solid fuel use could be associated with higher risk of CRDs with adjusted ORs of 1.27 (95% CI 1.05–1.52) in 2011, 1.17 (95% CI 1.00–1.38) in 2013, 2.08 (95% CI 1.13–3.83) in 2015, and 2.07 (95% CI 0.97–4.40) in 2018, respectively (Figure 4B).

Prospective association of solid fuel use with CRDs

Consistent associations between exposure to solid fuels and CRDs were observed across the four waves for cooking (adjusted OR 1.24, 95% CI 1.05–1.46; Figure 4A) and heating (adjusted OR 1.23, 95% CI 0.98–1.53; Figure 4B). Prior use of solid fuels for cooking, in contrast to clean fuels, had lag effects on the consequent occurrence of CRDs (adjusted RR 1.26, 95% CI 1.07–1.48 in period 2011–2013; 1.30, 1.11–1.51 in period 2011–2015; 1.19, 1.04–1.36 in period 2011–2018; 1.24, 1.11–1.38 in period 2013–2015; 1.31, 1.09–1.58 in period 2013–2018; 1.39, 1.16–1.66 in period 2015–2018; Figure 4C). Similarly for heating, despite that the lag effects were not statistically significant in all periods, a trend for use of solid fuels being associated with greater risk of CRDs was observed (adjusted RR 1.15, 95% CI 1.00–1.31 in period 2011–2013; 1.28, 1.04–1.58 in period 2011–2015; 1.12, 0.88–1.43 in period 2011–2018; 1.26, 1.03–1.55 in period 2013–2015; 1.18, 0.92–1.51 in period 2013–2018; 0.76, 0.44–1.32 in period 2015–2018; Figure 4D).

Respiratory health benefits of residential energy transition

We next analyzed the respiratory health benefits associated with residential energy transitions. Due to the very low rate of self-reported heating fuel use in 2015 and 2018, the sample size of users experiencing residential energy switching persistent solid/clean fuel users was too small to fit models. The same problem occurred when assessing the long-term effects of solid fuel use on CRDs. Thus, we focused on solid/clean fuels for cooking in the following analyses.

Figure 5A presents the respiratory health benefits of residential energy switching and persistent clean fuel use compared with persistent solid fuel use, from

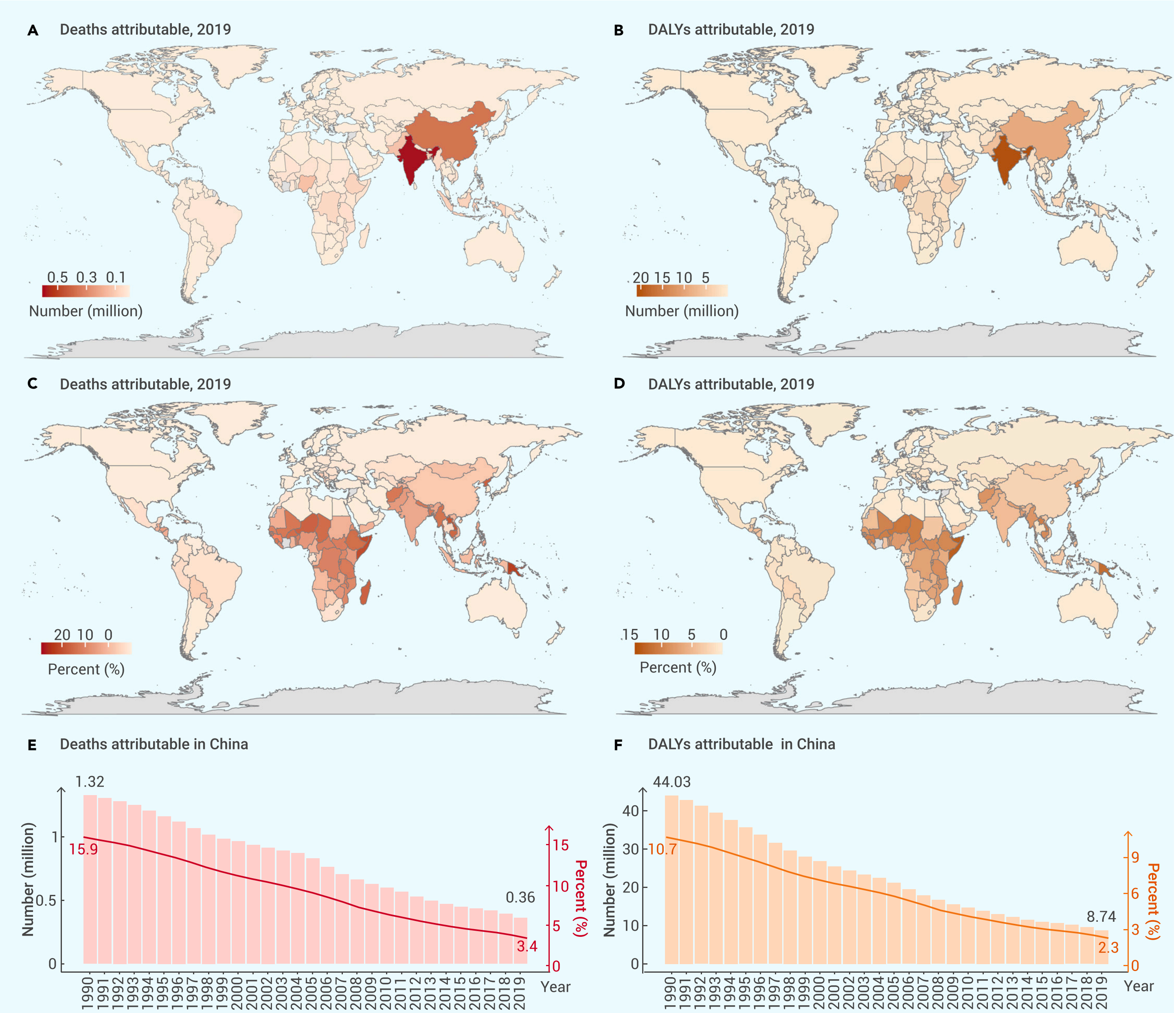

Figure 2. Deaths and DALYs attributable to HAP from solid fuels for all ages and all causes globally, particularly in China (A–D) Deaths and DALYs attributable to HAP from solid fuels by country or territory in 2019. (E and F) The temporal trends of the health burden attributable to HAP from solid fuels in China from 1990 to 2019.

baseline to follow-ups. In the period 2011–2013, compared with persistent solid fuel users, both participants who switched from solid to clean fuels (adjusted RR 0.78, 95% CI 0.62–0.98) and persistent clean fuel users (adjusted RR 0.71, 95% CI 0.57–0.89) had significantly lower risk of CRDs ($p < 0.001$ for trend). In the period 2011–2015, cessation of solid fuel use (adjusted RR 0.86, 95% CI 0.75–0.99) and persistent clean fuel use (adjusted RR 0.68, 95% CI 0.59–0.79), as compared with persistent solid fuel use, could cut the risk of CRDs substantially ($p < 0.001$ for trend). In the period 2011–2018, the adjusted RRs were remarkably weaker in participants who experienced residential energy switching (0.69, 0.55–0.88) and used clean fuels persistently (0.64, 0.50–0.82) than those who used solid fuels persistently ($p < 0.001$ for trend).

Participants with a longer duration of exposure to solid fuel use had a higher risk of CRDs with a significant exposure-response relationship ($p < 0.001$ for trend; Figure 5B). Among participants with 1–7 years' duration of solid fuel use, compared with those with 0-year duration of solid fuel use, the adjusted RR was 1.05 (95% CI 0.80–1.37); however, the risk was not statistically significant. For participants with 7 years of solid fuel use, the corresponding RR was 1.44 (95% CI 1.04–1.99).

When stratified by smoking status, the associations were still significantly restricted to never-smokers (Figure 6). However, no statistically significant differences were noted in ever-smokers, probably attributed to a small sample size. We did not find a significant interaction between either residential energy switching ($p = 0.38$ in the period 2011–2013; $p = 0.73$ in the period 2011–2015; $p = 0.56$ in the period 2011–2018) or persistent clean fuel use ($p = 0.19$ in the period 2011–2013; $p = 0.71$ in the period 2011–2015; $p = 0.33$ in the period 2011–2018) and smoking status in relation to CRDs. Similar patterns were seen in women and men in stratified analyses and interaction analyses according to age, gender, residence, and cooking with/without a kitchen (Figures S1–S4).

To gain insights into the robustness of the main results, we first controlled for regions, and no significant regional heterogeneity was observed (Table S11). We additionally substituted binary variables (i.e., ever-smoked cigarettes or not, ever drank alcoholic beverages or not) with multilevel categorical variables, as well as further adjusted for the current consumption of cigarettes in the main models, respectively. The associations were still consistent with the main findings previously (Tables S12 and S13). Subsequently, we performed the primary analyses in two specific disease subtypes (i.e., asthma and chronic lung diseases), and

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Table 1. Baseline characteristics of study participants according to cooking and heating fuel types

Characteristics	Cooking, %		Heating, %		
	Solid fuels	Clean fuels	Solid fuels	Clean fuels	All participants, %
No.	9,169	7,763	9,235	3,271	17,284
Age, mean (SD), y	60.3 (9.9)	58.4 (9.8)	59.7 (9.8)	58.2 (9.7)	59.4 (9.9)
Female sex	51.1	51.5	51.1	50.9	51.3
BMI, mean (SD), kg/m^2	23.3 (3.6)	24.1 (3.6)	23.8 (3.7)	23.6 (3.6)	23.5 (3.7)
Urban residence	21.6	26.5	24.0	23.6	24.1
Self-reported socioeconomic status					
Bad	42.1	32.6	41.5	31.7	37.1
Fair	45.7	50.9	44.9	51.5	48.9
Good	12.2	16.5	13.6	16.8	14.0
Education level					
Illiterate	30.9	21.6	28.7	22.2	26.7
Primary school or below	42.5	39.8	42.2	41.3	41.2
Middle school	18.1	23.0	19.3	22.6	20.3
High school or above	8.5	15.6	9.8	13.9	11.7
Marital status					
Married/cohabitating	79.4	80.8	79.9	81.1	80.0
Divorced/separated/widows/never married	20.6	19.2	20.1	18.9	20.0
Ever smoke cigarettes					
Men	88.1	91.2	86.8	94.8	89.5
Women	11.9	8.8	13.2	5.2	10.5
Ever drink alcoholic beverages					
Men	81.3	82.6	82.8	81.7	81.8
Women	18.7	17.4	17.2	18.3	18.2
Physical activities					
Do light activities at least 10 min continuously	32.2	36.5	33.1	35.9	34.2
Do moderate activities at least 10 min continuously	32.0	33.9	32.7	33.3	32.8
Do vigorous activities at least 10 min continuously	35.7	29.6	34.1	30.8	33
Take Chinese traditional medicine or Western modern medicine for chronic respiratory diseases	0.08	0.05	0.08	0.05	0.07
Health conditions at baseline					
Chronic respiratory diseases	14.0	9.0	13.7	8.8	11.7
Traffic accident or other major accidental injury	9.7	10.3	9.7	11.3	9.9
Cancer	0.9	1.2	0.9	1.4	1.0
Hypertension	23.9	25.8	24.0	23.7	24.8
Diabetes	4.9	7.0	5.0	6.0	5.8

Table 1. *Continued*

Characteristics	Cooking, %		Heating, %		
	Solid fuels	Clean fuels	Solid fuels	Clean fuels	All participants, %
Heart problems	11.9	12.1	13.2	8.3	12.1
Stroke	2.3	2.5	2.4	2.8	2.4
Type of building structure					
Concrete and steel	30.7	39.5	28.9	42.8	34.7
Bricks and wood	40.8	41.4	42.4	38.8	41.0
Mixed structure	11.0	8.6	10.3	9.8	9.8
Adobe and others	17.5	10.4	18.4	8.6	14.4
Type of building					
Independent-story building	63.2	58.1	66.1	50.6	60.9
Multi-story building	36.8	41.9	33.9	49.4	39.1
Area of house, m^2					
$\geq$120	32.6	39.9	32.6	40.0	36.4
<120	67.4	60.1	67.4	60.0	63.6
Cooking without a kitchen	9.6	8.2	9.5	7.5	9.1

almost the same results were yielded (Figures S5 and S6). Then, significant respiratory health benefits of persistent clean fuel use were observed in 2013–2015, 2013–2018, and 2015–2018, whereas the positive effects of residential energy switching did not show statistical significance (Table S14). What's more, in sensitivity analyses of complete case analysis and excluding participants with cancer, hypertension, diabetes, heart problems, stroke, and accidental injury at baseline separately, associations were consistent (Table S15), indicating that our results were statistically robust.

DISCUSSION

In this study, the spatial distribution and temporal trends of the population using clean fuels for cooking, and the deaths and DALYs attributable to HAP from solid fuels globally, particularly in China, were described. The CHARLS provided a unique opportunity to quantify residential energy switching and the consequent health impacts. We performed rigorous and well-structured multistage analyses incorporating both cross-sectional and prospective data analyses and found that solid fuel use was significantly associated with a higher risk of CRDs among Chinese middle-aged and older adults. Moreover, compared with persistent solid fuel users, both participants who experienced residential energy switching and persistent clean fuel users had significantly lower risk of CRDs. In addition, long-term exposure to solid fuel use was associated with elevated risk of CRDs.

Previous studies have reported a higher risk of CRDs among users of solid fuels, which was congruent with our current findings. A study of 0.28 million Chinese never-smokers from the CKB showed that solid fuel users had adjusted hazard ratios (HRs) of 1.47 (95% CI 1.41–1.52) and 1.10 (95% CI 1.03–1.18) for chronic lower respiratory disease (CLRD) and COPD, respectively.[9] Another study from the CKB reported HAP from solid fuels for both cooking and heating may increase the risk of COPD.[10] Additionally, in the Tasmanian Longitudinal Health Study (TAHS), exposure to HAP from solid fuels over 10 years was related to asthma.[11] A study conducted in India's second National Family Health Survey indicated that the elderly using biomass fuels had a significantly higher prevalence of asthma than those who used clean fuels (adjusted OR 1.59, 95% CI 1.30–1.94).[12] Besides, two studies conducted in LMICs provided evidence that the use of solid fuels for cooking was a risk factor for cardiorespiratory disease and COPD.[13,14] However, there was emerging evidence that clean cooking was not necessarily always beneficial to health, for example in the subclinical tests of volunteers exposed to smoke (STOVES) study,[25] researchers concluded that there were short-term decreases in lung function followed by exposure to cookstove air pollution even for stove exposures with low $PM_{2.5}$ levels, which might be considered as "clean" cooking.

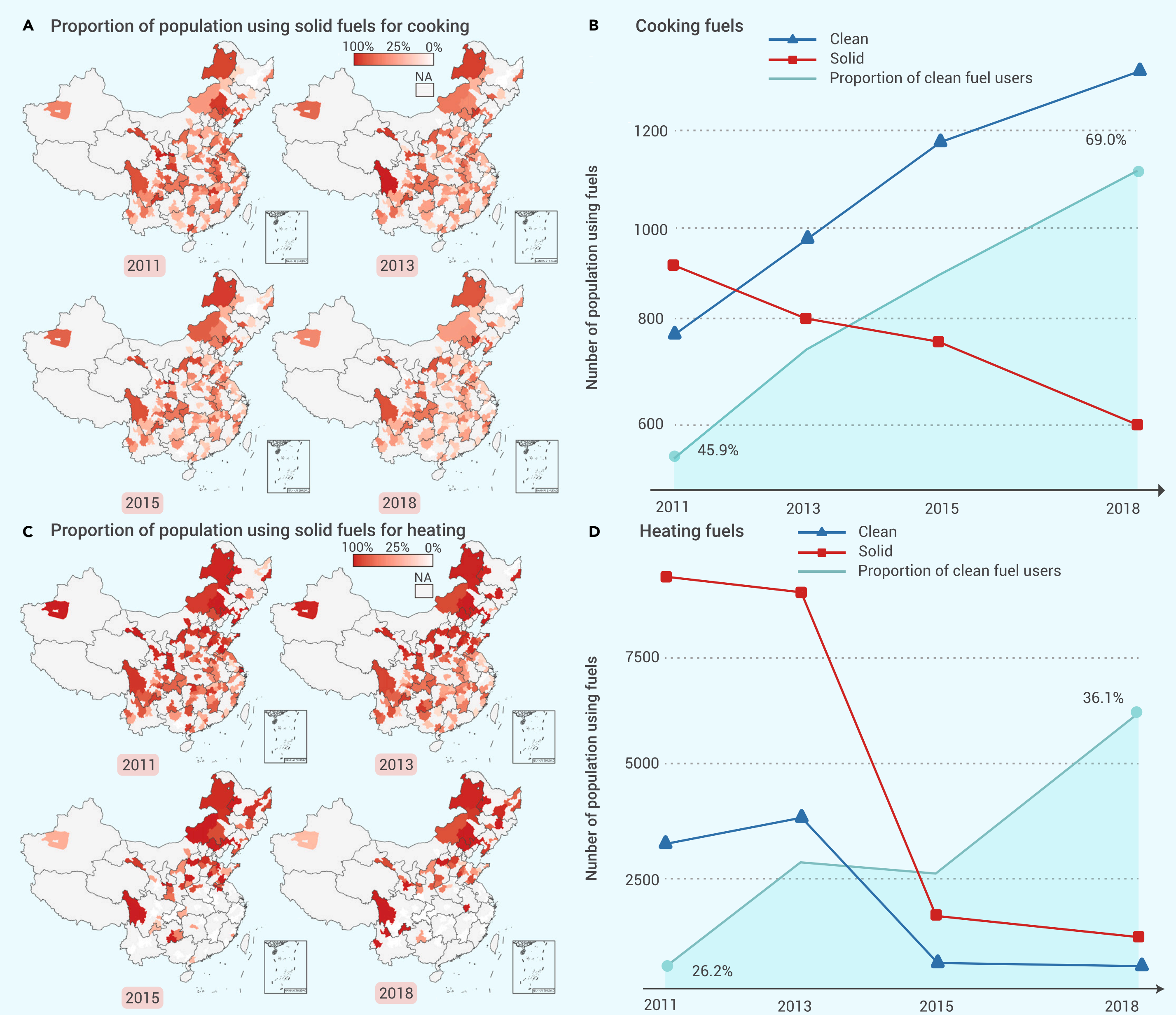

Figure 3. Spatial distribution and temporal trends of the population using solid fuels for residential energy in the CHARLS across four waves (A) Spatial distribution of the population using solid fuels for cooking. (B) Temporal trends of population using solid or clean fuels for cooking. (C) Spatial distribution of the population using solid fuels for heating. (D) Temporal trends of the population using solid or clean fuels for heating.

To date, only the mentioned two studies from the CKB and the PURE cohort investigated the association between switching to clean fuels and hospitalization or death from major respiratory diseases, lung function, or respiratory events. In the CKB study,[9] for CLRD, the adjusted HR was significantly weaker in participants experiencing energy switching than for persistent solid fuel users (1.20, 95% CI 1.15–1.26 vs. 1.47, 95% CI 1.41–1.52). Meanwhile, for COPD, the corresponding HR of energy transition was inverse and not statistically significant (0.96, 0.89–1.03), which was inconsistent with our findings. In that study, solid fuel exposure was assessed using recall information on the three most recent consecutive residences collected at baseline, and participants switching from solid to clean fuel use were involved in primary reliance on clean fuels in the baseline residence but having used solid fuels in earlier residences. Additionally, the study population was restricted to never-smokers aged 50.3 on average, with a female predominance (91%). The unmeasured exposure to cigarettes and tobacco might strongly confound the results. An imbalanced gender structure may also impede the generalizability of conclusions to a wider range of populations.

As for the PURE study,[24] similar to our study, solid fuel exposure as well as household energy transition was monitored at finer timescales prospectively for more accurate measurements with a lower risk of misclassification. Besides, the study population included both never-smokers and ever-smokers. The study showed that individuals who switched from solid to clean fuels had a decreased HR for respiratory events of 0.76 (95% CI 0.57–1.00). However, the researchers focused on the composite of all respiratory disease events instead of specific respiratory diseases due to low statistical power, and the study population was limited to individuals living in rural communities. On the contrary, we performed both primary analyses of CRDs and secondary analyses of asthma and chronic lung diseases, which generated almost the same results and further validated the respiratory health benefits of energy switching.

Apart from observational studies, several intervention studies have evaluated whether actions that prevent HAP and improve indoor air could bring health benefits. Nevertheless, the results were inconsistent. In the randomized controlled trial conducted by the Household Air Pollution Intervention Network (HAPIN) investigators, switching from biomass to liquefied petroleum gas (LPG) for cooking did not result in a higher birth weight.[26] A HAP intervention with LPG did not

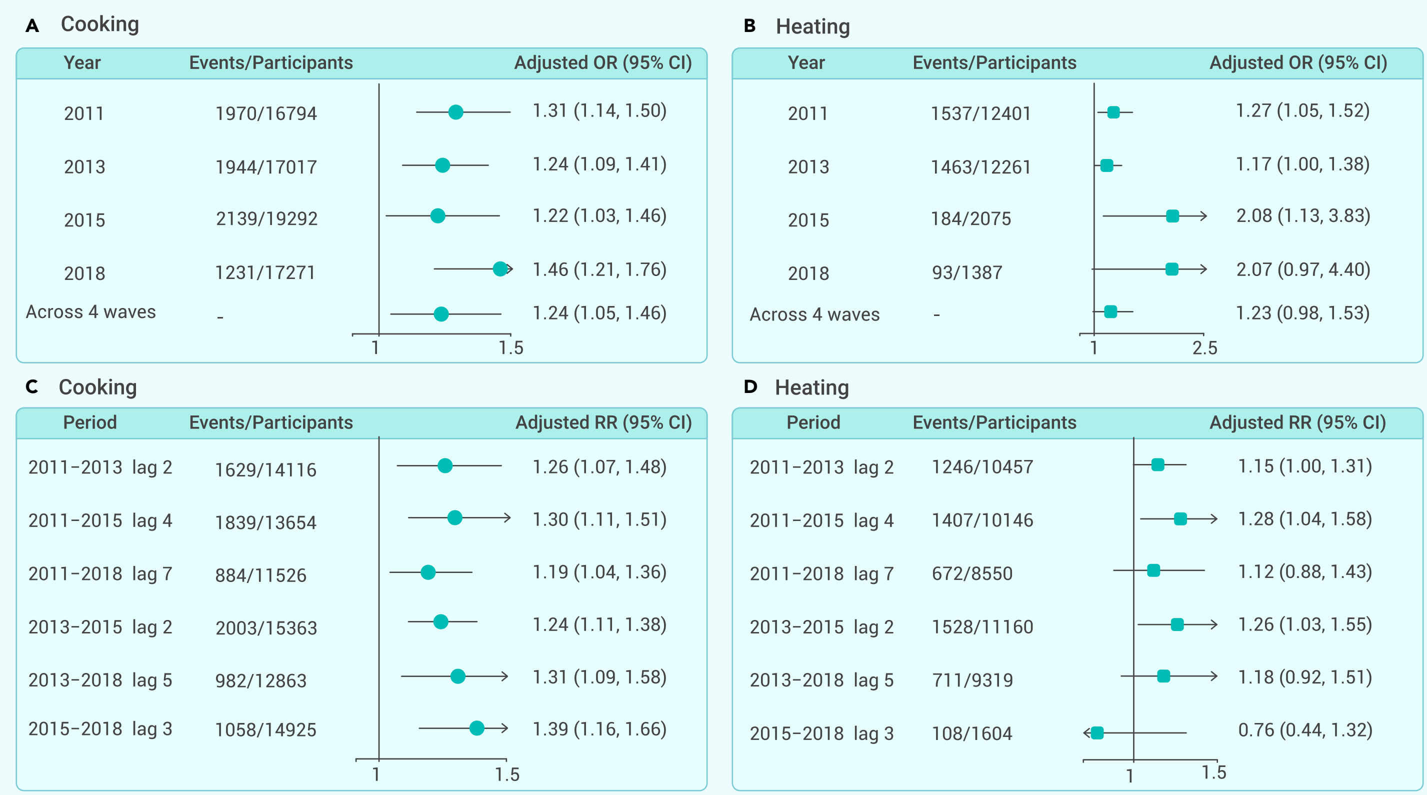

Figure 4. Adjusted odds ratios (ORs) and risk ratios (RRs) for chronic respiratory diseases (CRDs) according to solid fuel use for cooking and heating (A and B) Adjusted ORs for CRDs in four cross-sectional waves separately and across the four waves for cooking/heating. (C and D) The lag effects of prior exposure to solid cooking/heating fuels, as compared with clean fuels, on the consequent occurrence of CRDs with RRs.

improve cardiopulmonary health outcomes in adult women in Peru.[27] There was a report that improved biomass stove intervention significantly benefited the respiratory health of women in rural Mexico.[28] Moreover, a meta-analysis of experimental/quasi-experimental studies concluded that improved cookstoves provided respiratory symptom reduction and may reduce COPD risk among women.[29]

The findings of our study may be of prime importance to obtain promising public health gains. First, although household fuel consumption accounted for a very small fraction of the total energy use in China, it contributed significantly to air pollutant emissions and consequently adverse health effects, as well as environmental costs containing climate change.[22,30] In the present study, we provided solid evidence on the health benefits of residential energy switching, implicating further transition to clean energy to achieve health-climate co-benefits. Second, it is noteworthy that China is experiencing population aging, and the elderly are more vulnerable to environmental stressors. Besides, children suffered a lot in terms of DALYs. In 2019, it was estimated that HAP accounted for 7.7% of all DALYs in the 0–9 years age group, in contrast to 3.1% of all DALYs in the ≥75 years age group.[4] Our findings highlighted that middle-aged and older adults should be closely monitored for CRDs, especially when using solid fuel for residential cooking and heating. Third, high-income countries have almost fully transitioned to clean fuels, but populations in LMICs still suffer the highest exposure to HAP from solid fuels. The remarkable progress in residential energy switching globally might be dominantly driven by the Western Pacific and Southeast Asia regions, and huge disparities in access to clean energy persist. Our study underscored the urgency of accelerating the transition in China, particularly in LMICs.

The main strength of this study was the study design. We delineated the spatial distribution and temporal trends of the population using clean fuels globally and aimed to explore the respiratory health benefits of residential energy switching. However, it is challenging to obtain individual exposure data and the matching health outcomes on a global scale. In this scenario, China has seen a rapid transition from solid fuels to clean fuels, which thereby provides an unprecedented opportunity that allows us to quantify residential energy switching and the consequent health impacts. Consequently, our study started from a global perspective and then focused on China. The interconnection and logical relationship between the global and the regional parts might inspire a research paradigm for the combined use of global data and specific regional data at a smaller scale. Besides, we performed rigorous and well-structured multistage analyses embracing both cross-sectional and prospective data analyses to comprehensively elucidate the impacts of solid fuel use, residential energy transition, and duration of solid fuel use on CRDs among Chinese middle-aged and older adults. In addition, in order for more accurate measurements with lower risk of misclassification, the assessments of exposure were conducted prospectively at finer timescales. Specifically, household energy transition was evaluated based on multiple longitudinal surveys of each participant rather than according to recalling the history of solid fuel use ever before the baseline in the CKB study. Moreover, this study delineated the spatial distribution and temporal trends of the population using clean fuels for cooking, and the deaths and DALYs attributable to HAP from solid fuels globally, particularly in China.

This study has several limitations. First, with regard to exposure assessment, we assumed that the household fuel use had not changed during the intervals between every two visits, which could lead to misclassification. Second, the assessment of exposure and outcome could be inaccurate due to information gathered by self-report. Although self-reported socioeconomic status was used as an alternative, it should be cross-checked with higher-level data to validate the accuracy. Third, considering it was not feasible to directly measure personal exposure to indoor air pollution (eg, $PM_{2.5}$) in our study, fuel types were used as surrogates of HAP exposure. Additionally, given that solid fuels generating low levels of $PM_{2.5}$ might be deemed as "clean" energy, a more refined definition of fuel types used as proxies for HAP exposure, or even direct measurement of indoor air pollution, is needed in further research. Fourth, outdoor and indoor air quality are closely linked, and it is crucial to recognize the interconnectedness of HAP and ambient air pollution against the resulting health effects. However, we did not assess ambient air pollution exposure in our study because in the publicly available CHARLS, individual address information cannot be obtained due to privacy protection. The synergistic effects of indoor-outdoor air pollution should be addressed in future studies. Fifth, although we adjusted for cooking with/without a kitchen, possible effects of cookstoves, air-conditioning, ventilation,

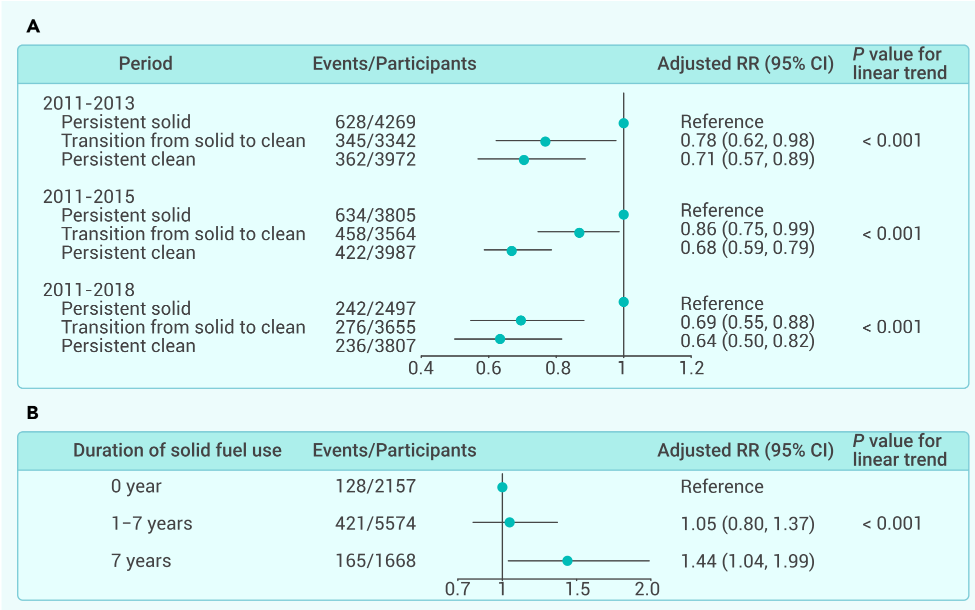

Figure 5. Respiratory health benefits of residential energy transition (A) Adjusted RRs for CRDs in association with residential energy switching and persistent clean fuel use compared with persistent solid fuel use for cooking from baseline to follow-ups. (B) Adjusted RRs for CRDs associated with long-term exposure to solid cooking fuels.

and other important parameters like surface, volume, windows, and extractors, as well as comfort parameters (temperature, humidity) and their interactions with energy switching were unclear. Sixth, other potential unmeasured confounders (eg, survey season, air pollution from neighborhoods or household clusters, individual genetic predisposition, etc.) might bias the results due to the limitations of the database. Therefore, these results should be interpreted with caution.

CONCLUSION

Access to residential clean energy has increased globally from 1990 to 2020, and such change was driven primarily by trends in the Eastern Mediterranean, Western Pacific, and Southeast Asia regions. Despite great progress, huge disparities in access to clean energy persist, with a population in the African region still suffering the highest exposure to HAP from solid fuels. In Chinese middle-aged and older adults, solid fuel use was associated with a higher risk of CRDs, and household energy transition could reduce the risk. Our findings uncovered the respiratory health benefits of residential energy switching and underscored the urgency of accelerating the transition in China, particularly in LMICs, to reduce the burden of respiratory diseases and obtain promising gains in public health.

MATERIALS AND METHODS

Data source and study population

We extracted data on the proportion of the population using solid fuels for cooking globally from the World Health Organization (WHO) Global Health Observatory. Particularly, we further obtained data on the percentage of the population with primary reliance on clean fuels for cooking and the proportion of HAP from solid fuels in China from the Global Health Observatory and Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2019 results using the Global Health Data Exchange (GHDx). Likewise, data on deaths and DALYs attributable to HAP from solid fuels globally and in China were collected with the GHDx.

The CHARLS is a national longitudinal survey of about 17,000 middle-aged and older Chinese adults living in private households.[31] The baseline wave was launched in 2011, covering 28 provinces, 150 countries/districts, and 450 villages/urban communities across the country; the three waves of follow-up assessments were conducted in 2013, 2015, and 2018. Information about socioeconomic and health status of the elderly was collected. The CHARLS sample has an urban/rural representation of people aged 45 and older. The CHARLS study was approved by the Ethical Review Committee of Peking University. All the participants provided signed informed consent.

Our panel data analysis focused on all the four waves from 2011 to 2018. We excluded participants under 45 years old, a cutoff point between young adulthood and middle age, and the final sample sizes for analysis were 17,284 in 2011, 18,214 in 2013, 19,719 in 2015, and 19,581 in 2018, respectively.

Exposure assessment

We gathered information on residential energy sources for cooking and heating in all four waves. Among the primary fuels reported, solid fuels were defined as coal or crop residue/wood, whereas clean fuels were defined as natural gas, marsh gas, liquefied petroleum gas, or electricity. Therefore, a binary indicator of household energy was constructed (use of solid fuels vs. use of clean fuels).

Participants were further categorized as persistent solid fuel users, persistent clean fuel users, or users experiencing the transition from solid to clean fuels. In our study, household energy transition was evaluated based on multiple longitudinal surveys of each participant. Specifically, self-reported fuel switching was deemed to change from primary reliance on solid fuels at baseline to clean fuels in any of the three follow-ups. For example, someone who used solid fuels at baseline in 2011 but then used clean fuels in 2013 was considered to have experienced a household energy transition from 2011 to 2013. Likewise, persistent solid/clean fuel users referred to participants who used solid/clean fuels at baseline and continued to use solid/clean fuels in any of the three follow-ups. For example, someone who used solid/clean fuels at baseline in 2011 and continued to use solid/clean fuels in 2013 was considered a persistent solid/clean fuel user from 2011 to 2013.

Furthermore, among subjects restricted to individuals who participated in all four waves, a semi-quantitative indicator of the duration of long-term exposure to solid fuels was derived. The duration of solid fuel use was calculated by summing the years across the surveys when primary reliance on solid fuels was reported, assuming that the household fuel use had not changed during the intervals between every two visits. Generally, the duration of solid fuel use was classified as 0 years, 1–7 years, and more than 7 years. Specifically, the duration of solid fuel use was 0 years (ie, consistent clean fuel use) if individuals used clean fuels in all four waves, while the duration of solid fuel use was 7 years (ie, consistent solid fuel use) if individuals used solid fuels in all four waves. Besides, the duration of solid fuel use was 1–7 years if individuals used solid fuels in one or more waves (except for all four waves), namely previously used solid fuels.

Covariates

A range of potential confounders associated with solid fuel use and CRDs was identified as follows: age (continuous), gender (male and female), body mass index (BMI) (continuous), household income (continuous), residence (rural and urban), an education level (illiterate, primary school or below, middle school and high school or above), marital status (married/cohabitating and divorced/separated/widows/never married), ever smoke cigarettes (yes and no), ever drink alcoholic beverages (yes and no), physical activities (do light/moderate/vigorous activities at least 10 min continuously), take Chinese traditional medicine or Western modern medicine for CRDs (yes and no), type of building structure (concrete and steel, bricks and wood, mixed structure, and adobe and others), type of building (independent-story building and multi-story building), area of house ($\geq$120 m^2 and <120 m^2), and cooking with an independent kitchen (yes and no). Notably, since there were considerable missing values regarding household income in our study (81.3% in 2011, 80.3% in 2013, 82.6% in 2015, and 82.3% in 2018, respectively), self-reported socioeconomic status was used as an alternative.

Outcome measures

In the CHARLS, a rich set of information on self-rated health status, including measures of general health status, whether the respondent has been diagnosed by doctors for having certain chronic diseases, and whether the respondent has had any accidents or falls, was collected. The primary outcomes of our study are CRDs. The ascertainment of CRDs was based on self-reports of the diagnosis by a doctor at baseline and in follow-up surveys

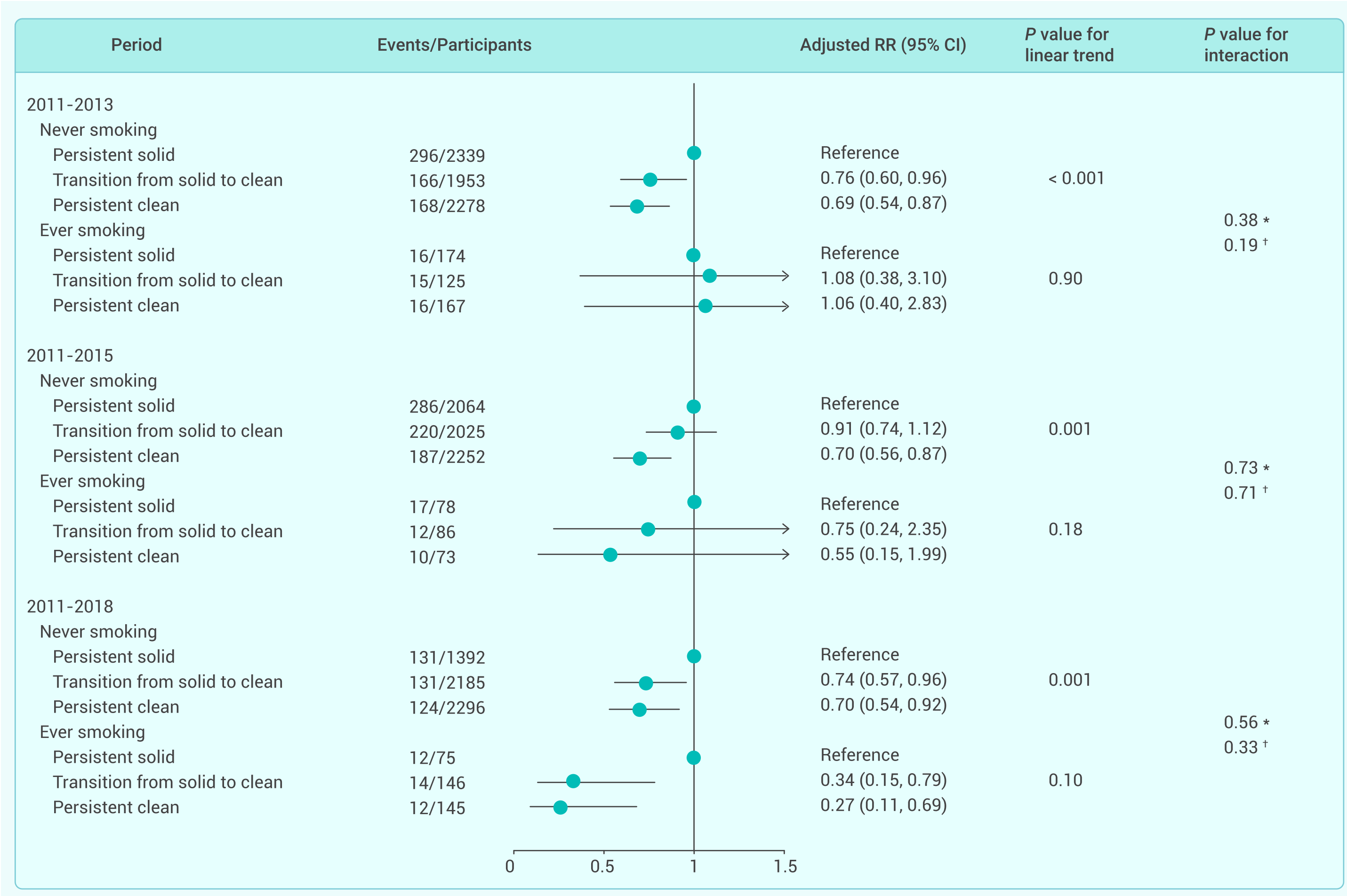

Figure 6. Adjusted RRs for CRDs in association with residential energy switching and persistent clean fuel use compared with persistent solid fuel use for cooking stratified by smoking status from baseline to follow-ups *Represents p value for interaction between residential energy switching and smoking status in relation to CRDs; †represents p value for interaction between persistent clean fuel use and smoking status in relation to CRDs.

("Have you been diagnosed with asthma or chronic lung diseases, such as chronic bronchitis, emphysema except for tumors or cancer by a doctor?").

Statistical analysis

The overall study design is shown in Figure 7. First, in Phase I, the spatial distribution and temporal trends of the population using clean fuels for cooking and the deaths and DALYs attributable to HAP from solid fuels globally, particularly in China, were described in numbers or percentages.

In Phase II, the prevalence of solid fuel use for both cooking and heating across the four waves in the CHARLS was mapped. The baseline characteristics of the CHARLS population were presented as means ± standard deviations (SDs) or percentages according to the household fuel types, where appropriate. All descriptive analyses were weighted to explain the complex, multistage study design.

Next, in Phase III, we performed rigorous and well-structured multistage analyses involving both cross-sectional and prospective data analyses to comprehensively elucidate the impacts of solid fuel use, residential energy transition, and duration of the solid fuel use on CRDs among Chinese middle-aged and older adults.

(1) Generalized linear models were used to estimate odds ratios (ORs) and 95% confidence intervals (CIs) for the risk of CRDs in relation to solid fuel use with the cleaner fuel use group as the reference exposure for cooking and heating separately in every cross-sectional wave.
(2) To handle the variations over time and the dependent repeated measurement data, generalized linear mixed models were fitted to verify the association between solid fuel use and CRDs across the four waves. After that, we constructed log-binomial models to investigate the lag effects of prior exposure to solid fuels, as compared with clean fuels, on the consequent occurrence of CRDs with risk ratios (RRs) and 95% CIs.
(3) We used log-binomial models to quantify the respiratory health benefits of residential energy switching and persistent clean fuel use compared with persistent solid fuel use from baseline to follow-ups. Further, RRs and 95% CIs were calculated to assess the long-term effects of solid fuel use on CRDs, as well as the potential exposure-response relationship. Simultaneously, the chi-square test for trend was performed to test for a linear trend between groups.

In the above analyses, all models were fully adjusted for age, gender, BMI, residence, self-reported socioeconomic status, education level, marital status, ever-smoked cigarettes, ever-drunk alcoholic beverages, physical activities, medication history, and building environment (including the type of building structure, type of building, area of the house, and cooking with an independent kitchen or not). With regard to missing values of covariates, we gave priority to replacing values from adjacent waves, and then multiple imputations with 100 iterations were performed with the MICE package.

To identify the potential modification of the respiratory health benefits associated with the household energy transition, stratified analyses and interaction analyses by baseline characteristics were conducted. To test the robustness of the main results, we further carried out several sensitivity analyses: (1) further controlling the potential effects of regional heterogeneity on the main results using generalized linear mixed models; (2) substituting binary variables (i.e., ever smoke cigarettes or not, ever drink alcoholic beverages or not) with multilevel categorical variables in the fully adjusted models; (3) additionally adjusting for current consumption of cigarettes in the main models; (4) estimating adjusted RRs for asthma and chronic lung diseases in association with transition from solid to clean fuels, respectively; (5) quantifying the respiratory health benefits of residential energy switching in the periods of 2013–2015, 2013–2018, and 2015–2018, besides the periods from baseline to

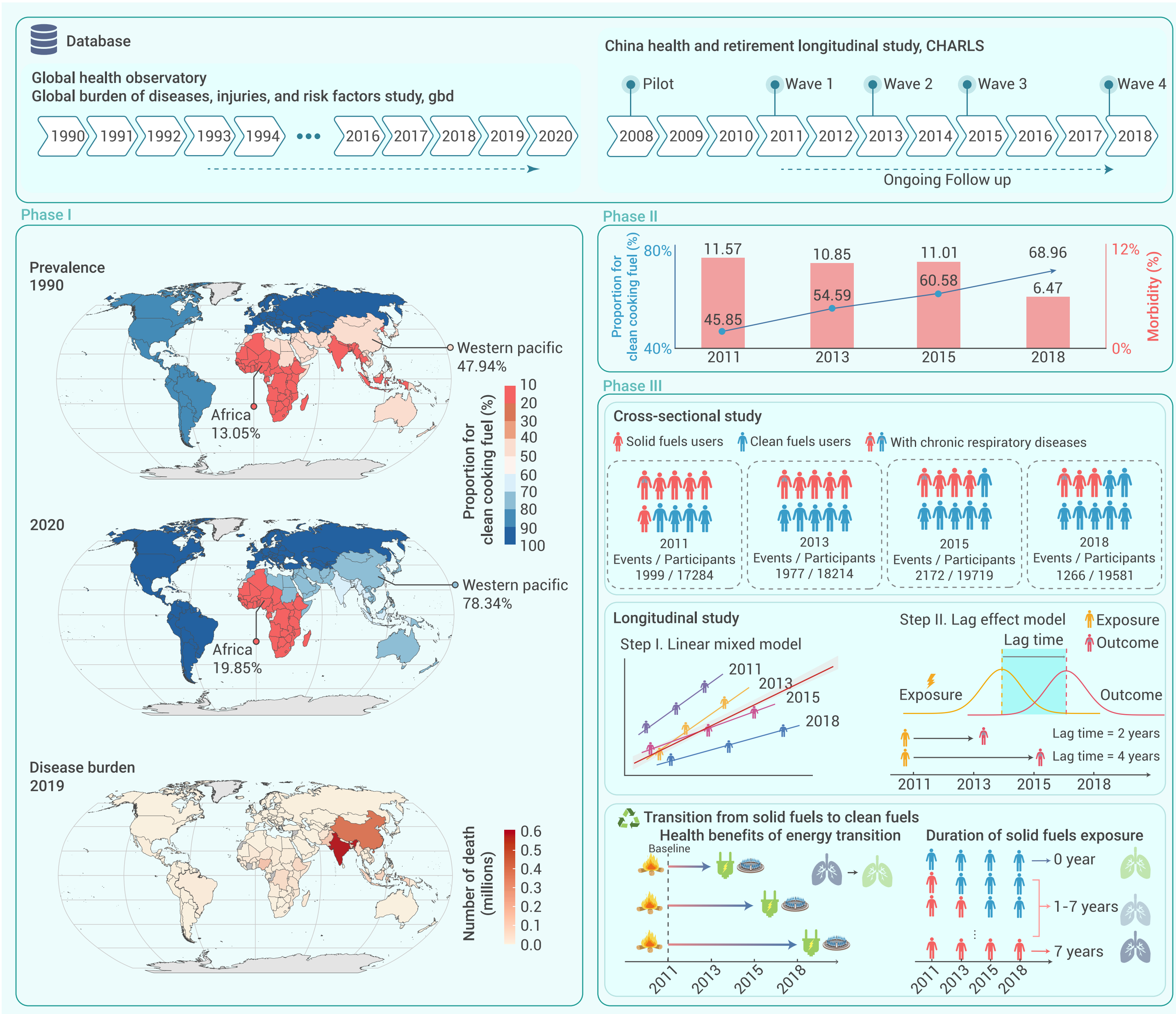

Figure 7. The overall study design Phase I: Describing the spatial distribution and temporal trends of the population using clean fuels for cooking, and the deaths and DALYs attributable to HAP from solid fuels globally, particularly in China. Phase II: Mapping the prevalence of solid fuel use for both cooking and heating across the four waves in the CHARLS. Phase III: The multistage analyses involving both cross-sectional and prospective data analyses.

follow-ups; (6) excluding participants who have missing data on covariates; and (7) separately excluding participants with cancer, hypertension, diabetes, heart problems, stroke, and accidental injury at baseline.

Two-sided p values were used, and $p < 0.05$ was judged statistically significant. All analyses were performed using R software (version 4.2.2).

DATA AND CODE AVAILABILITY

Data on the spatial distribution and temporal trends of residential energy use as well as the corresponding health burden around the world and in China can be obtained from the WHO Global Health Observatory (https://www.who.int/data/gho) and the GHDx (https://vizhub.healthdata.org/gbd-results/). The CHARLS data are publicly available at Peking University Open Research Data Platform (https://charls.pku.edu.cn/en/).

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AUTHOR CONTRIBUTIONS

H.C. and Y.X. designed the study; H.C., Q.Y., and D.C. analyzed the data and prepared the original draft of the manuscript; M.Z., Q.G., B.H., A.M.S., and A.C. contributed significantly to reviewing and editing. All of the authors read and approved the final version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.1016/j.xinn.2024.100597.

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https://gwxy.njmu.edu.cn/2017/0718/c8952a98575/page.htm.