


# Household air pollution from solid fuel use and cardiorespiratory disease in the China Kadoorie Biobank Cohort Study

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# ABSTRACT


## Household air pollution from solid fuel use and cardiorespiratory disease in the China Kadoorie Biobank Cohort Study

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**Background:** Worldwide >2.7 billion individuals, including 450 million in China, are regularly exposed to household air pollution (HAP) from solid fuel use. HAP may lead to increased risk of cardiorespiratory disease, but epidemiological evidence is still limited and highly heterogeneous. Moreover, there is little data about the potential mitigation effects of ventilation and clean fuel adoption.

**Methods:** The prospective China Kadoorie Biobank (CKB) enrolled 512,891 adults from five rural and five urban areas of China in 2004-2008. After ~9 years of follow-up, there were 11,464 cardiovascular deaths, including 3,982 from ischaemic heart disease (IHD) and 5,338 from stroke among 463,222 participants without prior history of CVD or cancer at baseline. For respiratory disease, the main analyses were further restricted to never-smokers who had no prior history of respiratory disease to minimise not only reverse causality but also confounding by smoking, one of the strongest risk factors of respiratory disease. Among 289,945 never-smokers, there were 23,078 incident major respiratory diseases, including 12,346 chronic lower respiratory disease (CLRD; with 5,093 chronic obstructive pulmonary disease [COPD]), 8,422 acute lower respiratory infection (ALRI), 3,586 acute upper respiratory infection (AURI) and 793 respiratory deaths. Cox regression was used to estimate adjusted hazard ratios (HRs) and floating absolute risk method was used to calculate group-specific 95% confidence intervals (CIs) of each disease endpoint associated with use of different fuels for cooking and heating separately. This abstract presents the main findings on solid fuel use for cooking.

**Results:** In CKB, the mean age (SD) was 51.6 (10.7) years and 59% were women. Solid fuel use for both cooking and heating had declined over time, particularly in urban areas. At baseline, 85% and 12% of rural and urban participants, respectively, reported using solid fuels for cooking throughout their three most-recent residences (average ~40 years). Compared to long-term clean fuel use, solid fuel use for cooking was associated with increased cardiovascular mortality (HR=1.14, group-specific 95%CI 1.09-1.20), which was mainly driven by stroke (1.27, 1.19-1.35) rather than IHD (0.95, 0.87-1.04). For stroke types, the HRs were somewhat greater for ischaemic stroke (1,200 cases; 1.41, 1.22-1.63) than for intracerebral haemorrhage (3,814 cases; 1.27, 1.18-1.36). Participants who switched from solid to clean fuels had no excess risk of cardiovascular death (0.99, 0.93-1.07), but prolonged use of ventilated cookstoves with solid fuels did not alter the association. The association of solid fuel use for cooking with cardiovascular death was consistent across most population subgroups, but persisted in never- (1.33, 1.15-1.53) but not in ever- (1.00, 0.88-1.14) smokers ($P_{heterogeneity}$=0.0037). Among never-smokers, solid fuel use for cooking was associated with increased risk of different types of respiratory diseases, with adjusted HRs of 1.47 (1.42-1.53) for CLRD, 1.10 (1.03-1.17) for COPD, 1.18 (1.11-1.25) for ALRI, 1.59 (1.48-1.71) for AURI and 1.53 (1.26-1.85) for respiratory death. Participants who switched from solid to clean fuels had smaller HRs for all respiratory outcomes examined, compared with long-term solid fuels users (e.g. CLRD: 1.20, 1.15-1.26; ALRI: 1.08, 1.02-1.13). Compared with those without using ventilated cookstoves, prolonged use of ventilated cookstoves with solid fuels had smaller HRs for CLRD (1.35, 1.32-1.39 versus 1.45, 1.40-1.51) and AURI (1.52, 1.42-1.63 versus 1.81, 1.66-1.96).

**Conclusions:** In this Chinese population, long-term solid fuel use for cooking was associated with significantly elevated risks of a range of cardiorespiratory disease outcomes, some of which may be mitigated by adopting clean fuels or, to a lesser extent, use of ventilated cookstoves.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| AAP | Ambient air pollution |
| ALRI | Acute lower respiratory infection |
| AURI | Acute upper respiratory infection |
| BMI | Body mass index |
| BP | Blood pressure |
| CAS-A1 | Community Air Station-A1 |
| CDC | Center for Disease Control and Prevention |
| CI | Confidence interval |
| CKB | China Kadoorie Biobank |
| CLRD | Chronic lower respiratory disease |
| CO | Carbon monoxide |
| COex | Exhaled carbon monoxide |
| COPD | Chronic obstructive pulmonary disease |
| CVD | Cardiovascular disease |
| DALYs | Disability adjusted life years |
| DBP | Diastolic blood pressure |
| DSP | Disease Surveillance Point |
| ETS | Environmental tobacco smoke |
| $FEV_1$ | Forced expiratory volume in 1 second |
| FVC | Forced vital capacity |
| GBD | Global Burden of Disease Study |
| HAP | Household air pollution |
| HICs | High-income countries |
| HR | Hazard ratio |
| ICD-10 | International Statistical Classification of Diseases and Related Health Problems, 10th Revision |
| ICH | Intracerebral haemorrhage |
| IERF | Integrated exposure-response function |

| | |
|---|---|
| IHD | Ischaemic heart disease |
| IQR | Inter-quartile range |
| IS | Ischaemic stroke |
| LLN | Lower limit of normal |
| LMICs | Low- and middle-income countries |
| MET | Metabolic equivalent of task |
| NDPH | Nuffield Department of Population Health |
| $NO_2$ | Nitrogen dioxide |
| $O_3$ | Ozone |
| OR | Odds ratio |
| OxTREC | Oxford Tropical Research Ethics Committee |
| PATS+CO | Particle and Temperature Sensor plus Carbon Monoxide Sensor |
| PICA | Platform for Integrated Cookstove Assessment |
| PM | Particulate matter |
| $PM_{2.5}$ | Fine particulate matter |
| RCT | Randomised controlled trial |
| RH | Relative humidity |
| RR | Relative risk |
| SBP | Systolic blood pressure |
| SD | Standard deviation |
| SES | Socioeconomic status |
| $SO_2$ | Sulphur dioxide |
| SOP | Standard operation procedure |
| $SpO_2$ | Blood oxygen saturation |
| SR | Systematic review |
| SUMS | Stove Use Monitoring System |
| VOCs | Volatile organic compounds |
| WHO | World Health Organization |
| $YSL_{median}$ | Median of year started living in each residence |

## THE ROLE OF THE AUTHOR IN THIS THESIS

The work described in this thesis is my own, conducted under the supervision of Professor Zhengming Chen, Associate Professor Kin Bong Hubert Lam and Doctors Om Prakash Kurmi and Derrick Anthony Bennett, unless otherwise specified. The CKB was established under the leadership of Professor Chen in 2004-2008, and I was not involved in any of the initial design or data collection work. The concept of studying the health effects of household air pollution from solid fuels in the China Kadoorie Biobank (CKB) was initially developed during discussions with Doctor Kurmi and Professor Chen. The project had been substantially refined and developed with the helpful advice and guidance from my four supervisors. I conducted all the analyses and prepared the first drafts of the publications related to this thesis and they were revised with the input from my supervisors and other co-authors.

The idea of establishing the feasibility study to obtain directly measured data on air pollution exposure originated from Associate Professor Lam and Doctor Kurmi and I engaged in the early discussions to conceptualise the study. My supervisors led the study design and the two grant applications and Associate Professor Lam have been coordinating the implementation of the study. I prepared the first drafts of the study protocol, questionnaire, fieldwork plan and most of the standard operating procedures. I assisted Doctor Kurmi in purchasing of the air quality monitors, and I was responsible for the testing, calibration, management and shipping for most of these devices. With the help of Mr Alex Hacker and Doctor Xiaoming Yang, I selected the study samples for recruitment. Mr John McDonald and Mr Dan Schmidt developed an in-house software for device and data management, and Mr McDonald and Mr Hacker provided programming advice on the initial data cleaning and processing work. Associate Professor Lam led the training of the fieldworkers of all three study sites, one of which I was also involved. Doctor Huaidong Du provided continuous support in facilitating the communication between us and colleagues in China. Doctor Zheng Bian coordinated

the fieldwork in China. Professor Haidong Kan and Associate Professor Kin Fai Ho and their teams provided help with data collection fieldwork and gravimetric sampling and analysis. Finally, Doctor Yang and his team had provided support on IT issues throughout the study.

# CHAPTER 1. INTRODUCTION

## 1.1 RESEARCH CONTEXT

Despite rapid global economic development, >2.7 billion individuals worldwide primarily use solid fuels (e.g. coal, wood) for domestic cooking and heating, and this number has remained relatively stagnant in the past three decades.[1-3] Burning of solid fuels, especially in poorly-ventilated environments, generates high levels of household air pollution (HAP), with documented 24-hour average particulate matter (PM) exposure up to 40 times the World Health Organization (WHO) air quality guidelines value.[4-6]

It is believed that HAP may harm human health through its epithelial effects to the respiratory tract and systemic effects to the circulatory system.[4,7] The Global Burden of Disease Study (GBD) estimated that HAP from solid fuel use for cooking accounted for 2.6 million (7.9% of all) premature deaths and 77 million disability-adjusted life years (DALYs, 7.1%) globally in 2016, predominantly through chronic obstructive pulmonary disease (COPD) and cardiovascular disease (CVD), including ischaemic heart disease (IHD) and stroke.[8] Although these figures were estimated using the best available evidence at the time, substantial uncertainties remain.[8,9]

Regarding solid fuel use, COPD, including emphysema and chronic bronchitis, is the most extensively studied disease outcome, and it was considered as a well-established cause of COPD, especially in non-smokers.[4] However, this notion was based on predominantly cross-sectional and case-control studies, many of which had relatively small sample sizes, used varying exposure classification methods and did not adequately account for key confounders.[9-12] Furthermore, several recent systematic reviews (SRs) and meta-analyses found evidence of publication bias and significant heterogeneity across studies.[9,11,12] More recent studies also suggested that the magnitude of association might have been largely overestimated.[13-17] Apart from COPD,

little is known about whether and how solid fuel use is associated with other important respiratory diseases in adults, such as acute lower respiratory infection (ALRI).[4,18] Prior to this thesis, only two small prospective studies had investigated the associations between solid fuel use and respiratory diseases in adults, with one on respiratory mortality[19] and another on acute respiratory infection,[20] but both had limited statistical power and reported inconclusive results.

Unlike respiratory disease, the linkage between HAP and CVD has not been recognised until recently,[21] with some of the earliest epidemiological studies published in the mid-2000's.[22,23] Both animal and human experimental studies found that small-sized fractions of PM could penetrate through the respiratory epithelial barrier and enter the circulatory system.[24,25] Consistently, growing epidemiological evidence suggests that HAP exposure is associated with systemic inflammation, elevated oxidative stress, higher blood pressure (BP), development of atherosclerosis and self-reported history of CVD in adults.[26-28] However, direct epidemiological evidence linking solid fuel use with long-term CVD outcomes is scarce. Therefore, the GBD developed an integrated exposure-response function (IERF) using the relative risk (RR) estimates corresponding to the average fine particulate matter (i.e. particulate matter with aerodynamic diameter ≤2.5 μm, $PM_{2.5}$) exposure levels associated with ambient air pollution (AAP) and passive and active smoking, from which the RRs for HAP were interpolated based on an approximated $PM_{2.5}$ level associated with solid fuel use for cooking (**Figure 1.1**).[29,30] Although the evidence base continues to grow, only two relevant prospective studies had been published before this thesis.[19,31] Both of these studies were based on a relatively small number of cardiovascular deaths (1,500 and 850), and they reported somewhat conflicting findings, with one showing significant elevated risk of CVD death associated with coal use[31] while another observed a null association with wood use.[19]

Reliable estimation of disease burden associated with a risk factor is fundamental to appropriate resource allocation and global health action, and these in turn rely on high

quality epidemiological evidence on the exposure-outcome relationships. It is also worth-noting that the previous studies on both the exposure pattern and health impact of HAP focused predominantly on cooking fuel use, and the roles of solid fuel use for heating and use of ventilation were often overlooked.[3,32] Overall, there is a pressing need to obtain direct epidemiological evidence to address the knowledge gap on exposure patterns of solid fuel use for heating and use of ventilation, and to enhance the understanding on the cardiorespiratory health impact of HAP from solid fuel use and the potential benefits of improved ventilation or clean fuel adoption in alleviating such impact. The China Kadoorie Biobank (CKB), an ongoing prospective observational study of 0.5 million adult Chinese, provides a valuable data source to address the above knowledge gaps.

## 1.2 RESEARCH AIMS

Based on the data available from the CKB, this thesis aims to:

1. Examine the long-term secular trends and regional variation in solid fuel use for cooking and heating and cookstove ventilation ownership in the study population;
2. Assess the prospective associations between solid fuel use for cooking and hospitalisation and death of major cardiorespiratory disease and to explore the corresponding associations with solid fuel use for heating, and;
3. Explore the potential implications of switching from solid to clean fuels and using ventilated cookstoves alongside solid fuels on these relationships.

## 1.3 OUTLINE OF THE THESIS

**Chapter 1** presents an overview of the thesis. It describes the research context for the thesis – the global health significance of HAP from solid fuel use and the lack of reliable prospective evidence on its relationships with cardiorespiratory disease – which lead to

the aims of this thesis. It also outlines the thesis content by chapter and lists the publications related to this thesis.

**Chapter 2** summarises the current knowledge about HAP from solid fuel use in regard to the nature and patterns of exposure and current assessment methods. It also reviews the existing evidence on the associations between solid fuel use and cardiorespiratory disease and highlights the key limitations of the existing literature and knowledge gaps. Part of this chapter contributed to the introduction and discussion sections of the three published manuscripts based on work done for this thesis (see **Section 1.4**).

**Chapter 3** summarises the study design and methods of the CKB, the primary data source of the analyses presented in this thesis, as well as the baseline characteristics of the study population and the resurvey subsamples.

**Chapter 4** describes the methods of exposure assessment, classification and statistical analysis used in **Chapters 5 to 7**. Details of the specific methods used are also presented in individual chapters.

**Chapter 5** describes the patterns of solid fuel use and cookstove ventilation ownership across study areas, by education and income levels and birth cohorts, and over time in the study population. Most of the work presented in this chapter was published in the *International Journal of Hygiene and Environmental Health* (22 September 2017, Vol. 220, Pages 1370-1381).[33]

**Chapter 6** investigates the associations between solid fuel use for cooking and heating and incident hospitalisation and death of a range of respiratory diseases, including COPD, ALRI and acute upper respiratory infection (AURI). Part of the work presented in this chapter constituted a manuscript in press in the *American Journal of Respiratory and Critical Care Medicine* (5 October 2018).[34]

**Chapter 7** examines the associations of solid fuel use for cooking and heating with the risk of overall and cause-specific cardiovascular death. Sections of the work reported in this chapter were published in the *Journal of American Medical Association* (3 April 2018, Vol. 319, Pages 1351-1361).[35]

**Chapter 8** describes the development and implementation of a feasibility study to collect multi-dimensional data on air pollution exposure in a small subset of the CKB population, in which I was closely involved under the leadership of my supervisors. Some preliminary findings of the pilot investigation are presented to enrich the discussion on the main findings based on original CKB data.

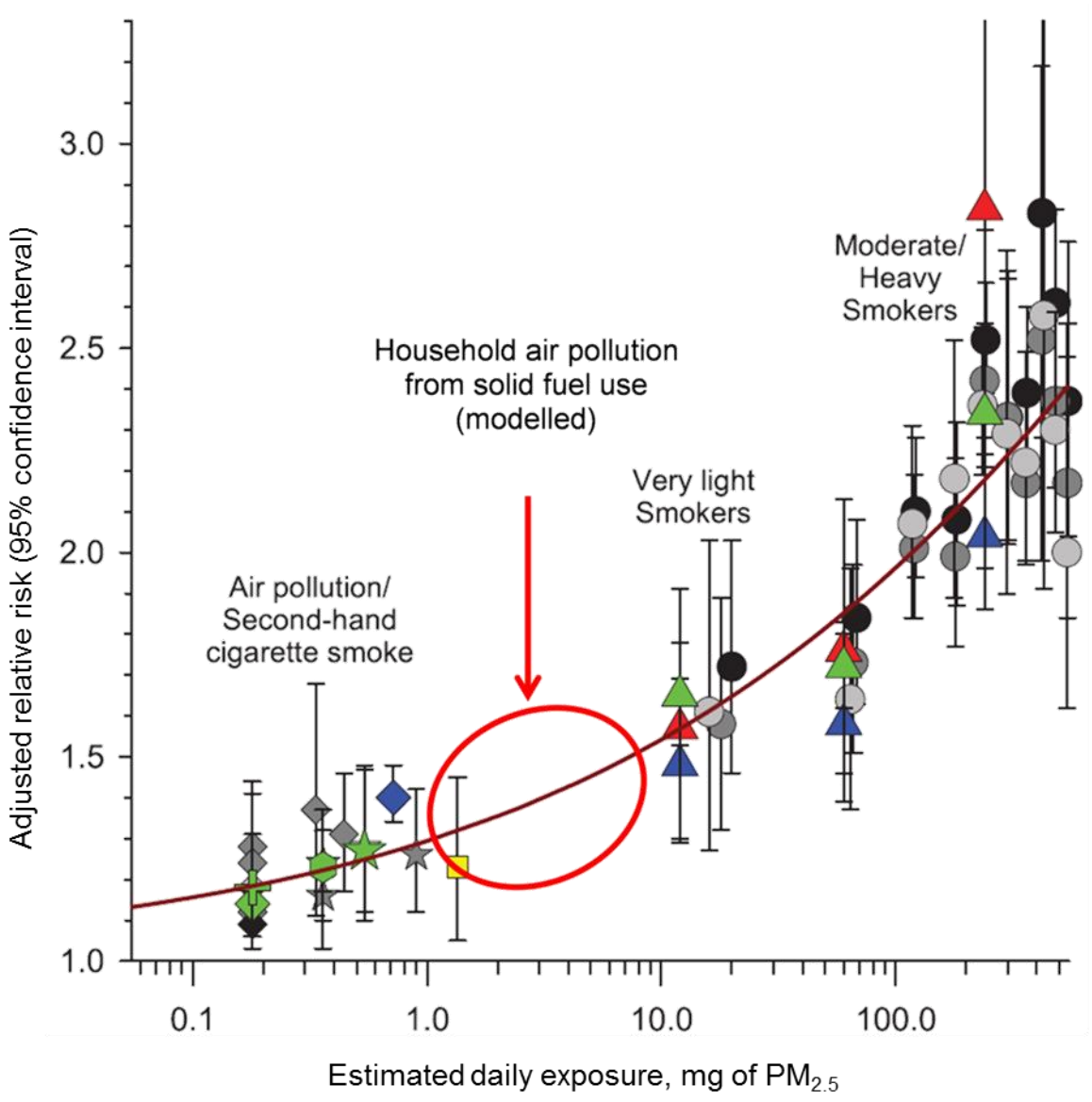
**Chapter 9** summarises the findings of this thesis and discusses their implications in the context of the literature reviews reported in **Chapter 2**. It also highlights the strengths and limitations of the methods used and presents key implications for future research in the wider context.

## 1.4 PUBLICATIONS RELATED TO THIS THESIS

At the time of writing, three first-authored manuscripts have been published based on the work conducted for this thesis (**Appendix A**). These are "Trans-generational changes and rural-urban inequality in household fuel use and cookstove ventilation in China: A multi-region study of 0.5 million adults"[33], "Solid fuel use and risk of cardiovascular and all-cause mortality in rural China"[35] and "Solid fuel use and risks of respiratory diseases: a cohort study of 280,000 Chinese never-smokers".[34] Note that some of the analyses reported in these publications are slightly different from those presented in this thesis, because the methodology had evolved over time and more updated data were used in this thesis.

**Figure 1.1 Illustration of the integrated exposure response function for the $PM_{2.5}$ cardiovascular disease exposure-response relationship**

Adapted from Pope et al. 2018[30] with slight modification. Red circle indicates the range of $PM_{2.5}$ levels associated with household air pollution from solid fuel use for cooking and the corresponding section of the integrated exposure-response function used for global disease burden estimation.



# CHAPTER 2. LITERATURE REVIEW

## 2.1 INTRODUCTION

This chapter first provides greater details on the definitions and patterns of exposure to HAP from solid fuel use and the conventional exposure assessment methods, based on a (non-systematic) review of relevant literature; then, reviews the existing literature regarding the associations of solid fuel use with respiratory and cardiovascular diseases, respectively.

## 2.2 HOUSEHOLD AIR POLLUTION FROM SOLID FUEL USE

### 2.2.1 Definitions and nature of exposure

In this thesis, “solid fuels” refers to coal or biomass (i.e. plant-based products including wood, charcoal, crop residues, and dung); and “clean fuels” refers to energy sources associated with no or relatively low levels of HAP when in use, either because they burn more completely (e.g. gas), generate air pollution in a location that is distant from users’ residence (e.g. electricity) or generate no air pollution (e.g. solar energy). Domestic use of solid fuels for cooking and heating mostly happens in low- and middle-income countries (LMICs) where clean fuels are not sustainably available or affordable,[2] although firewood and coal remain accepted options for heating in some high-income countries (HICs).[36] Wood is the commonest type of solid fuel used worldwide, and most domestic coal users are in China (~70 million).[2,3] Compared to clean fuels, solid fuels tend to combust incompletely because of their complex, carbon-rich organic chemical content, especially in a poorly ventilated setting, thus releasing a large amount of air pollutants. There are three main classes of air pollutants, namely particulate matter (PM; e.g. black carbon), gaseous pollutants (e.g. carbon monoxide [CO], ozone [$O_3$], nitrogen dioxide [$NO_2$], sulphur dioxide [$SO_2$]) and volatile organic compounds (VOCs). Among these, PM is the most extensively studied for its health effects.

In contrast to PM from ambient sources which include not only combustion products but also aerosols from both natural (e.g. sand) and anthropogenic sources (e.g. road surface abrasion),[37,38] that from solid fuel combustion is a mixture of mostly carbon-based particles containing thousands of noxious chemicals, including but not limited to reactive oxygen species, endotoxin and heavy metals.[39] The size of the particulates is believed to be a key determinant of their toxicity, with smaller sizes associated with higher toxicity because of the greater total surface area to volume ratio for harmful chemicals to be adsorbed, higher penetrance into the respiratory tract and ability to translocate to the circulatory system.[24] Particulate matter is conventionally classified by aerodynamic diameter, defined as the diameter of an ideal sphere with standard density (1,000 g/m$^3$) that settles at the same terminal velocity as the particle of interest.[40] The small-sized fractions of PM, $PM_{2.5}$ in particular, are believed to be more harmful and are widely considered as the most representative candidate for the potential harm of air pollution.[24] Generally, burning of biomass produces higher levels of $PM_{2.5}$ than that of coal, and thus, the former is believed to have greater adverse effects on cardiorespiratory health.[5,39] Populations tend to gradually move from the cheaper but more polluting fuels (e.g. wood) to transition fuels (e.g. coal), and to cleaner, modern fuels (e.g. electricity) across a socioeconomic gradient, but there is growing evidence showing a "fuel-stove stacking" phenomenon that individuals tend to use polluting fuels or traditional stoves in parallel with cleaner fuels or advanced stoves during the transition (**Figure 2.1**).[41-43]

### 2.2.2 Determinants and sources of exposure

Personal exposure to HAP is highly variable. It depends on a complex array of determinants, including but not limited to types and condition of fuels and stoves being used, ventilation condition, season, climate, culture and other factors that could influence people's cooking and heating habits, resulting in short- and long-term variability within and between individuals (**Figure 2.2**). Among these determinants, the

rate of emission from fuel combustion and rate of ventilation which disperses the air pollutants emitted (**Figure 2.2 – red circles**) are two pivotal factors determining the intensity of HAP exposure.

In terms of emission, cooking fuel use typically contributes to the largest proportion of household energy need in solid fuel-reliant populations, and it is thus the predominant source of HAP and the primary focus of the existing research and policies on HAP.[2] In most populations that use primarily solid fuels, women are chiefly responsible for domestic cooking, and they are therefore the most exposed population subgroup.[4] Unlike cooking that is usually practiced on a daily basis in most households in LMIC settings, heating is season-, climate- and culture-dependent, and the number of people exposed is believed to be significantly smaller on a global scale.[3] However, data on heating fuel use have rarely been collected until recently, precluding a comprehensive understanding of the global exposure patterns and associated disease burden.[3]

Emerging evidence suggests that solid fuel use for heating, compared to that for cooking, is associated with exposure to HAP of greater intensity and for a longer duration each day, often in a deliberately less-ventilated environment.[32,39,44-46] In countries with high heating needs such as China, heating has been estimated to account for up to 50% of total annual residential energy consumption.[47] A recent national modelling study in China estimated that solid fuel use for heating is associated with 50-200% higher household levels of $PM_{2.5}$ in heating season compared to non-heating seasons.[32] The negligence of heating-related HAP was estimated to have resulted in an average 23% underestimation of annual $PM_{2.5}$ exposure in the population, compared to the conventional approximation based on cooking-related HAP exposure alone.[32] Despite the increasing interest in heating-related HAP, investigations on its independent relationships with risks of cardiorespiratory disease remain scarce (to be discussed further in **Sections 2.3.1 and 2.4.1**).

One key challenge to studying the health effects related to heating is the complex interplay between low temperature, socioeconomic status (SES) and individual's health condition in relation to the choice and behaviour of heating fuel use and risk of cardiorespiratory disease. In particular, low temperature has been consistently associated with higher risks of hospitalisation and death of both cardiovascular and respiratory diseases,[48-54] potentially through inducing bronchoconstriction, mucus hypersecretion and inflammation, supressing respiratory immunological reactions and increasing risk of respiratory infection,[51,54-56] as well as vasoconstriction and elevated BP.[50,57] Previous studies in CKB suggested that the well-established city-wide central heating systems may have cardiovascular benefits against low temperature (e.g. smaller elevation of BP),[50,57] but it is not clear how heating from burning of solid fuels, which brings not only warmth but also high levels of HAP,[44,58] may be associated with cardiorespiratory risk.

While it is evident that a complete switch from solid to clean fuels would be the most efficacious strategy to reduce HAP exposure as the primary source of emission will be removed, it is unlikely to become a feasible option among most of the current solid fuel users in lower-income populations for many years to come.[3] A more extensively investigated option is advanced stove interventions based on better-ventilated stoves with either enhanced capacity to disperse air pollutants from household microenvironments (e.g. chimney cookstove) or higher burning efficiency that reduces incomplete combustion and emissions (e.g. stove with fan-assisted combustion chamber), or both.[59,60] These interventions have been shown to be effective in reducing HAP exposure across experimental (laboratory-based), observational and intervention studies, although with a diminished efficacy in real-life compared to laboratory situation.[59-61] However, most existing evidence on the health effects focused on disease precursor, such as respiratory symptoms, lung function or BP, but not chronic disease outcomes (to be discussed further in **Sections 2.3.2 and 2.4.2**).[59]

### 2.2.3 Methods of assessment

Due to the complexity of personal exposure to HAP, reliable assessment of HAP has been challenging. There are three main approaches to assess HAP exposure, namely through direct measurement, exposure biomarker measurement and self-reported exposure characteristics. The advantages and disadvantages of each approach are summarised in **Table 2.1** and discussed below.

#### *2.2.3.1 Direct measurement*

While data from fixed-site ambient air monitors are increasingly available for urban AAP exposure modelling, measurement of HAP from solid fuel use has to be actively conducted in fixed microenvironments (e.g. kitchen, bedroom) or personal-environment (using wearable monitors). Personal exposure measurement is considered as the gold standard as well as the most challenging option for HAP assessment.[5] Given the complexity of exposure patterns, measurement of HAP has to cover a sufficiently long period of time and be conducted repeatedly (ideally in different seasons) in order to reasonably estimate an individual's usual exposure to HAP, but this is often infeasible in large-scale epidemiological studies. It is especially difficult for personal exposure measurement that requires study participants to carry a monitor continuously.

Most of the previous HAP monitors, especially those for PM, are relatively large, heavy and noisy, which tend to reduce participant compliance in carrying the monitors.[4,5] Limitations on battery life (mostly <48 hours for high temporal-resolution monitoring), air pollutant measurement capacity (e.g. maximum filter load, amount of sensing chemicals) and types of pollutants that can be measured further restrict the length of continuous monitoring and the amount of data that can be collected.[4,5] The cost of high performance real-time HAP monitors (typically >£3,000) has also been a major barrier for large-scale measurement campaigns. As a result, direct measurement of HAP is often only conducted in fixed micro-environments in small study samples (<500 individuals) for a

short period of time (8 to 48 hours), usually with a fraction of the sample having their personal exposure measured, resulting in data of limited generalisability both within and across individuals.[5,39,62]

Nevertheless, wearable monitors have been advancing rapidly in recent years, with increasingly reliable low-cost sensors coupled with low energy demand circuit technologies, light-weight rechargeable batteries and wireless network monitoring methods.[63-68] Together with an increasing number of large-scale prospective studies on chronic diseases in LMICs,[69-72] there are emerging opportunities to quantify the dose-response relationships between HAP and a range of long-term disease conditions more accurately. If measurements could be taken in a sufficiently large and representative subset of a cohort, the measured data can be modelled on personal and environmental factors such that quantitative exposure values could be assigned to conventional exposure proxies (e.g. cooking fuel type) to enhance exposure classification. This has been attempted in a few small-scale studies (400 to 1280 individuals) involving relatively short term (24 to 48 hours) measurement of $PM_{2.5}$ or CO,[73-76] but not in the previous prospective studies on cardiorespiratory health effects of HAP.[19,31] Future studies that harness the advantages of the continuously advancing technology for wearable sensors and established prospective studies may help to address the longstanding knowledge gaps in estimating the global health impact of HAP.

#### *2.2.3.2 Exposure biomarkers*

As compared to direct measurement, assessment of an appropriate exposure biomarker may better reflect the actual absorbed dose of air pollutants, because it inherently takes into account the relevant inter-personal heterogeneity of behavioural (e.g. cooking practices) and physiological factors (e.g. ventilation rate and volume, metabolism of air pollutants). To date, there are several potential candidates under investigation (e.g. exhaled CO [COex], urine hydroxylated polycyclic aromatic

hydrocarbons, airway macrophage carbon), but none of them have been reliably validated so far.[5,77] One major limitation of these existing biomarkers is the lack of specificity that solid fuel smoke is not the only source of the parent chemicals of the biomarkers, with tobacco smoke being one of the major confounders.[4,5] Furthermore, the assessment methods of most of these biomarkers are often time-consuming and laborious such that application in large epidemiological studies is impractical. Some biomarkers such as COex and carboxyhaemoglobin can be measured relatively easily and at a low-cost, but they are also limited by confounding from non-solid fuel sources, relatively short half-lives and high variability, and they, at best, reflect the level of exposure to CO but not necessarily $PM_{2.5}$ or other important pollutants.[77-79]

#### *2.2.3.3 Questionnaire*

Questionnaire-based assessment on fuel use behaviour has long been the conventional HAP assessment method in epidemiological studies.[4,5] In particular, cooking-related behaviours (e.g. fuel and stove types, frequency, duration) have been widely used as the primary proxies of exposure, given its predominant role in producing HAP.[5] In order to approximate long-term exposure, individuals are often asked to retrospectively recall their past experience on cooking and, in more recent studies, on heating as well. Efforts have been made to improve the efficiency and reliability of this method, such as creating an exposure matrix across multiple residences of an individual (similar to the job exposure matrix conventionally used in occupational epidemiology).[31] Compared to the more objective approaches described above, a questionnaire-based method is qualitative and more prone to reporting bias (e.g. recall bias), although it should be less likely to suffer from purposive misreporting (e.g. social desirability bias) as other lifestyle risk factors (e.g. alcohol consumption).[80-82] Furthermore, it could be too crude to capture intra-person variability, especially over a short time period (e.g. between season). However, it can be easily tailored for population-specific assessment and be implemented at a much lower cost and with minimal training for fieldworkers. It is also

a more feasible option to assess long-term exposure, given the limitations of biomarker or direct measurement discussed above. These features make questionnaire assessment a more viable option for HAP exposure assessment in large scale epidemiological studies.

## 2.3 HOUSEHOLD AIR POLLUTION AND RESPIRATORY DISEASE

A literature search was conducted to identify published articles reporting observational (cross-sectional, case-control or cohort design) or intervention studies on the association between HAP from solid fuel use and respiratory diseases in adults (≥18 year-old) up to July 2018 in the PubMed and Embase databases. The main research questions guiding the review were 1) "*whether HAP from domestic solid fuel use for cooking and heating is associated with increased risks of acute and chronic respiratory diseases?*" and 2) "*whether use of ventilation or switching from solid to clean fuels could effectively reduce HAP exposure and mitigate the potentially relevant respiratory risk?*". Search terms used are listed in **Table 2.2**, and they were combined using Boolean operators "OR" and "AND" and searched as MeSH terms and free text in title and abstract. This section summarises the findings of the literature search.

### 2.3.1 Solid fuel use

To date, there have been six SRs of observational studies on the association between solid fuel use and respiratory disease in adults, with five focused on COPD (each with slightly different aims and methods),[9-12,14] one of which also included respiratory infection,[12] and another one focussing on ALRI.[18] Apart from one study[20] included in the SR on ALRI,[18] all others were non-prospective by design, and most did not directly measure HAP levels. Very few studies have examined the respiratory risk associated with heating fuel exposure independently of cooking fuel, and they reported inconsistent findings.[83-90] One prospective cohort study on respiratory death was also found prior to this thesis.[19]

#### *2.3.1.1 COPD*

The earlier SRs on COPD, which included studies published between 1985 and 2010, reported summary odds ratios (ORs) for COPD that ranged from 1.9 to 2.8, with significant heterogeneity and evidence of publication bias observed.[9-12] In contrast, an updated SR, which included studies published between 1991 and 2016,[14] and a recent multi-country cross-sectional study of 12,400 individuals[13] consistently reported a substantially weaker association (~40% excess risk of COPD). This is further complicated by three recent large-scale population-based cross-sectional studies, including two in China, all of which reported a null association.[15-17]

There are several possible reasons behind the discrepancies of the earlier and more recent studies. Many studies included in the earlier SRs did not control for the confounding effects of age, gender or smoking[84,85,91-100] and had a relatively small case number (<100 cases of COPD),[92,93,101-107] both of which tend to bias the pooled ORs away from the null. This is especially problematic since these SRs used random-effects meta-analysis that tends to give disproportionately more weight to smaller studies.[108,109] Conversely, despite some methodological advantages in the four recent large-scale studies, they employed relatively crude exposure classification methods based on either household fuel use[13,16] or short exposure period (6 months).[15,17] Although it is true that individuals not cooking or heating would have been exposed to less solid fuel smoke compared to solid fuel users, they are likely to be distinctively different from those who practice cooking or heating in terms of both known and unknown confounders. Binary classification based on relatively short-term exposure would also tend to dilute the association examined, because COPD is a condition that develops over decades.[110,111] It is also worth-noting that the vast majority of the existing studies examined airflow obstruction defined by spirometry or chronic bronchitis defined by self-reported symptoms,[9-12,14] but it has been consistently reported in China that a large proportion

(35-60%) of these cases are asymptomatic and possibly constitute a relatively small fraction of the burden in the healthcare system.[15,16,112]

Altogether, emerging evidence appears to suggest that the association between solid fuel use and COPD has been overestimated, potentially attributed to inadequate control for confounders and small studies bias where more extreme ORs were reported in the earlier studies. However, the recent large scale studies also suffer from various methodological limitations. More robust evidence is needed urgently to clarify the relationship between solid fuel use and COPD, especially from prospective cohort studies which could examine more severe forms of clinical manifestation of COPD (hospitalisation and death).

#### *2.3.1.2 Other respiratory outcomes*

Apart from COPD, the two relevant prospective studies before this thesis were on respiratory death[19] and respiratory infection (ALRI and AURI),[20] respectively. Mitter et al. examined the association between recalled duration of wood use for cooking or heating and incidence of respiratory death in 50,000 individuals and found no association, but only 155 deaths were analysed and wood was not heavily used in the study population.[19] Ezzati and colleagues monitored the $PM_{10}$ level and duration of nurse-diagnosed respiratory infection in 229 individuals in 200 consecutive days, and reported significantly higher risks of ALRI and AURI associated with higher levels of $PM_{10}$.[20] However, this study included individuals aged 5-49 years, but provided no data to tease out the association in adults.[20] As solid fuel smoke has been largely consistently associated with risk of ALRI in children in observational studies,[4,9] it is possible that the significant associations observed were driven by the child participants.[20] Other non-prospective studies on respiratory infection suffer from a range of methodological limitations, including crude adjustment for confounding effects,[113-115] suboptimal exposure classification (e.g. comparing two types of solid fuels)[113,116-119] and unclear

outcome definition (with ALRI and AURI mixed together).[113,116,118] Overall, the current evidence on the relationship between solid fuel use and non-COPD respiratory outcomes in adults is suggestive but inconclusive.

### 2.3.2 Ventilation and other household air pollution reduction interventions

There were three recent SRs on observational and intervention studies comparing the patterns of cardiorespiratory health indicators or risks of disease outcomes between individuals using traditional stoves with solid fuels and those using advanced stoves (with improved ventilation or better burning efficiency) with solid fuels or switched to clean fuels (either as an active intervention or natural experiment), the latter of which was relatively rare.[59,60,120] The majority of the studies that examined respiratory outcomes in adults were on respiratory symptoms[121-131] or lung function,[122,125,126,128,129,132] and one was on pneumonia mortality[119] and two were on COPD.[103,133] It has been largely consistently reported that the use of advanced cookstoves is associated with significantly less respiratory symptoms in adults (pooled ORs [95% confidence interval (CI)]: 0.72 [0.60-0.87] for cough, 0.65 [0.52-0.80] for phlegm, 0.41 [0.29-0.59] for wheezing or breathing difficulties), but no consistent benefit was observed in lung function.[59,120]

Several randomised controlled trials (RCTs) have examined the effects of HAP reduction interventions on respiratory health in adults to date, but little convincing evidence has been generated (**Table 2.2**).[121,124,126,128,132] Experience from these RCTs has shown that most of the known limitations of RCTs are especially problematic in HAP reduction studies, especially poor compliance (generally <50% in the intervention group), the lack of blinding, spill-over effects and poor sustainability of the intervention (e.g. no local maintenance service).[134] Unlike conventional drug trials that recruit high risk individuals (e.g. elderly with multiple risk exposures) to improve their efficiency (allowing shorter follow-up or smaller sample size with the same statistical power), most

of the HAP trials can only include relatively healthy, young household cooks (typically mean age <30 years) due to the nature of the intervention.[121,124,126,128,132] Furthermore, trials conducted in less developed settings require a resource-intensive active follow-up approach with a relatively short follow-up period (all except one study <15 months), often assessing only self-reported, acute respiratory symptoms or lung function but not longer-term respiratory outcomes such as COPD or ALRI.[121,124,126,128,132]

Not-surprisingly, the observational evidence on major respiratory disease, such as pneumonia and COPD, is far from conclusive. A retrospective cohort study in 42,000 Chinese adults observed significantly lower risks of incident COPD and pneumonia mortality in lifelong coal users who had adopted ventilated cookstove compared to those who did not.[119,133] However, the study on COPD was based on age of self-reported physician-diagnosis,[133] and that on pneumonia mortality examined only 225 events.[119] In the same study, no significant risk difference in pneumonia mortality was observed between smoky and smokeless coal users,[119] which is counter-intuitive given the remarkable risk difference in lung cancer between the two groups found in the same area.[135] Furthermore, disproportionately more individuals using ventilated cookstove in this study were smoky coal users who benefited from a government campaign aiming to alleviate the harm of smoky coal in the area at that time, thus leaving considerable risk of residual confounding to the results.[119] The prospective study on COPD incidence found a markedly lower odds of COPD (OR [95% CI]: 0.28 [0.11-0.73]) associated with adoption of both improved ventilation and clean fuels compared to those who remained using traditional open-fire biomass stoves for cooking.[103] However, no significant improvement was observed in those who adopted either clean fuels or improved ventilation alone, and the study included only 72 COPD cases.[103]

In summary, improved ventilation or clean fuel adoption are associated with less respiratory symptoms but their effect on lung function or clinical disease outcomes is unclear. No RCT has examined the potential benefit of improved ventilation on long-

term respiratory health outcomes (nor would it be an ideal study design). The existing observational studies tend to support that there are significant benefits, but they suffer from a range of methodological limitations.

## 2.4 HOUSEHOLD AIR POLLUTION AND CARDIOVASCULAR DISEASE

Similar to **Section 2.3**, a literature search for articles reporting observational and intervention studies examining the relationship of HAP from solid fuel use with CVD or intermediate cardiovascular conditions was conducted in the PubMed and Embase databases. Intermediate cardiovascular traits such as BP and heart rate variability were also searched for because there has been few epidemiological studies on major CVD (e.g. IHD or stroke). The key research questions were 1) "*whether HAP from solid fuel use for cooking and heating is associated with excess risks of adverse intermediate cardiovascular conditions (e.g. elevated BP) or major CVD outcomes (death and disease development)?*" and 2) "whether *use of ventilation or switching from solid to clean fuels could mitigate the potential adverse cardiovascular risks?*". **Table 2.4** shows the search terms and search strategy employed. The findings are summarised below.

### 2.4.1 Solid fuel use

There was one SR on the association of HAP-related exposure with CVD and intermediate vascular conditions.[26] This review included 17 observational studies on solid fuel use published between 2005-2015.[26] Several studies have been published after this SR, including two prospective cohort studies[19,31] and several cross-sectional studies.[27,28,136-140]

The two prospective cohort studies examined cardiovascular mortality, with one in ~50,000 Iranians with ~1,600 cases[19] and another in ~75,000 Chinese women with ~850 cases.[31] The Iranian study found a null association with duration of wood use for cooking or heating, and the Chinese study observed significant excess risk (18% [95%

CI 2-37%]) associated with ever coal use for cooking. Both studies assessed only household fuel use without considering personal practices.[19,31] This may be especially problematic (e.g. bias towards the null) in the Iranian study that included a large proportion of men, who are less likely to cook in LMIC settings.[19] Conversely, most of the participants in the Chinese study had stopped using coal in their household at the baseline survey, and exposure classification based on ever-household coal use may be too crude.[31] Interestingly, the association observed in the Chinese study appeared to be primarily driven by a small number of IHD death (n = 133; hazard ratio [HR] [95% CI]: 1.61 [1.14-2.27]) whereas stroke death (349 cases) was not associated with ever coal use (1.01 [0.84-1.22]).[31]

Only a few non-prospective studies have investigated prevalent CVD, and they reported suggestive evidence on significant associations between solid fuel use and self-reported doctor-diagnosis of coronary heart disease[137,141], stroke[137] and acute coronary syndromes.[142] Most other studies have investigated BP and largely consistently reported significantly elevated SBP or higher prevalence of hypertension in solid fuel users or individuals from solid fuel-reliant households.[27,28,138,140,141,143-145] Studies also suggested that solid fuel use was associated with higher carotid intima-media thickness, lower heart rate variability and elevated oxidative stress and inflammatory markers, but evidence are limited.[23,144-146]

### 2.4.2 Ventilation and other household air pollution reduction interventions

Only a few studies have examined the potential cardiovascular benefits of HAP reduction interventions through ventilation or clean fuels adoption.[22,147-150] A sub-study of 120 women in the landmark RESPIRE study, a RCT on ventilated cookstove, reported significantly lower mean diastolic blood pressure (DBP; absolute difference [95% CI]: 3.0 [0.4-5.7] mmHg) in the intervention group during the two-year trial period, but no significant difference in systolic blood pressure (SBP) was observed.[22] The control

arm of that study received the intervention stove after the end of the RCT and both SBP (3.1 [0.8-5.3] mmHg) and DBP (1.9 [0.4-3.5] mmHg) were found to be significantly lower after the adoption of the stove when all participants who continued to own the ventilated stove (n = 110) were analysed.[22] Using the same analytic approach, the above study also reported significantly lower odds of ST-segment depression associated with use of ventilated cookstoves, but no significant improvements in heart rate variability.[149] Another RCT comparing an ethanol stove intervention versus traditional kerosene or firewood-burning stove in 324 pregnant women (162 controls) found significantly lower DBP (2.8 [0.6-5.0] mmHg), but not SBP, in the intervention group.[147] In contrast, a before-and-after study in 74 non-smoking women and a RCT in 222 non-smoking women found no significant changes in BP after a subsidised switch from traditional open-fire cookstove to ventilated cookstove.[148,150] To conclude, the current evidence tends to suggest that there might be potential cardiovascular benefits associated with ventilated cookstove or clean fuel adoption, but these were based on mostly non-randomised studies that examined intermediate vascular condition (e.g. BP) with relatively short term follow-up within small study samples.

### 2.5 Summary

This chapter has described the nature of HAP from solid fuel use for cooking and heating, highlighted the complexity of personal exposure to HAP in relation to a wide range of societal, environmental and personal factors, and, against this backdrop, discussed the advantages and disadvantages of three main approaches of HAP exposure assessment. The existing literature on the relationship between HAP and respiratory and cardiovascular disease were reviewed, separately for solid fuel use and HAP reduction intervention. Overall, there has been very limited prospective evidence for both respiratory and cardiovascular disease. For respiratory disease, there has been emerging evidence suggesting that the strength of association between solid fuel use and COPD may be largely overestimated, and there are important knowledge gaps

about the relationship of solid fuel use with other respiratory disease in adults (e.g. ALRI). Observational and intervention studies have largely consistently shown that HAP reduction through improved ventilation or clean fuel adoption is associated with less respiratory symptoms, but its benefit on lung function or longer-term disease outcomes (e.g. COPD or ALRI) remains unclear. The relationship between solid fuel use and CVD is even less well understood. Non-prospective evidence suggested that solid fuel use is associated with elevated BP and risk of hypertension, but the two only relevant prospective cohort studies reported somewhat conflicting findings on cardiovascular death, and both studies were based on relatively small case numbers. Very few studies have assessed the cardiovascular implication of HAP reduction intervention, but there is suggestive evidence linking it to lower BP. Solid fuel use for heating is rarely studied independently of that for cooking, both in terms of exposure patterns and in relation to cardio-respiratory disease risk.

**Table 2.1 Main approaches of household air pollution (HAP) exposure assessment and their advantages and disadvantages**

| Approach | Advantage | Disadvantage | Feasibility in large scale epidemiological studies* |
|---|---|---|---|
| (i) Direct measurement<br>(a) personal<br>(b) fixed-site micro-environment | (a) Objective; accounts for variability of personal behaviour over space and time; recognised as the gold standard if participant compliance is high and measurement is taken over a sufficiently long time period and repeated multiple times; | (a) Wearable real-time monitors are relatively heavy, expensive, has insufficient battery life; difficult to achieve high compliance; reliability and validity heavily dependent on participant compliance; require repeated measurement for sufficiently long time period; | Very low; feasible in a small subset |
| | (b) Objectively measure the air pollution level in designated environment (e.g. kitchen) and capture the area-level variability over time; less dependent on participant compliance as compared to personal measurement; | (b) Cannot capture personal exposure variability; may not reliably reflect personal exposure, depending on the participant's time-activity pattern; relatively high cost compared to questionnaire interview | |
| (ii) Exposure biomarker measurement | If measuring appropriate biomarker: best-reflect actual absorbed dose of air pollutants and accounts for inter-personal heterogeneity of both behavioural and physiological factors (e.g. breathing rate); | No HAP-specific and sensitive biomarker exist (most are prone to confounding from tobacco smoke or ambient air pollution); measurement of more reliable candidates (e.g. airway macrophage carbon) is laborious and expensive; most candidates could only reflect short term exposure and some have high intra-person variability (e.g. exhaled carbon monoxide); | Moderate to low if based on the currently available biomarkers;<br>High if a low cost, easy-to-measure candidate that is specific to HAP is available; |
| (iii) Questionnaire interview | Conventional; relatively easy and low cost to implement; could be readily tailored for population-specific characteristics (e.g. different cultural practice); the most efficient method to approximate long-term exposure | No actual quantitative measurement; subjective; prone to recall bias and misclassification; | High |

* Large scale epidemiological studies: consider a study of >5,000 participants

**Table 2.2 Keywords, MeSH terms and search strategy for respiratory outcomes**

| Exposure (combined with "OR") | Outcome (combined with "OR") |
|---|---|
| 1. "Indoor air pollution"<br>2. "Household air pollution"<br>3. "Indoor smoke"<br>4. "Wood smoke"<br>5. "Solid fuel*"<br>6. Biomass<br>7. Coal<br>8. Wood<br>9. Charcoal<br>10. Straw<br>11. Dung<br>12. "Crop residue"<br>13. "Crop waste"<br>14. Cookstove*<br>15. "Cook stove"<br>16. "Open fire"<br>17. Cooking<br>18. Heating | 1. "Respiratory disease"<br>2. "Chronic obstructive pulmonary disease"<br>3. COPD<br>4. "Chronic bronchitis"<br>5. Emphysema<br>6. "Obstructive lung disease"<br>7. "Chronic airway disease"<br>8. "Airflow obstruction"<br>9. Pneumonia<br>10. "Respiratory infection"<br>11. Cold<br>12. Influenza |

**Final search: (exposure keywords) AND (outcome keywords)**

**Table 2.3 Characteristics of randomised controlled trials on the respiratory health effects of improved cookstoves in adults.**

| Author (year) | Population | Intervention | Comparator | Respiratory outcomes | Length of follow-up | Intervention compliance | Methodological challenge faced |
|---|---|---|---|---|---|---|---|
| Burwen et al. (2012)[124] | 768 women in Ghana (unclear age distribution) | Ventilated cookstove | Traditional cookstove | Bad cough, sore throat, difficulty breathing, chest pain, excessive mucus | 2 months (before the control group received the intervention); 8 months (before outcome assessment) | 49% | Active spill-over of intervention; concurrent use of traditional stove; incomplete and imbalanced outcome assessment (53% in treatment group and 73% in control group); poor reporting; |
| Beltramo et al. (2013)[121] | 790 women in Senegal (mean age ~23 years) | Panel solar cooker | Traditional cookstove | Respiratory symptoms (sore throat, runny or stuffy nose, cough, wheezing, woke up with chest heaviness, coughed up mucus) mixed with other symptoms e.g. fever as composite outcome. | 6 months | 7% | Not intention-to-treat analysis; imbalanced baseline characteristics; active spill-over of intervention; concurrent use of traditional stove; mixed residency of participants (n = 240); |
| Hanna et al. (2012)[132] | 2,695 individuals in India (age not reported) | Ventilated cookstove | Traditional cookstove | Cough, chronic cough, phlegm cough, phlegm, wheeze, tightness of chest; lung function | 4 years | 10% | Poor reporting; unclear analysis approach; |
| Smith-Sivertsen et al. (2008)[126] | 504 women in Guatemala (mean age ~27 years) | Ventilated cookstove | Open fire | Cough, phlegm, wheeze, tightness in the chest; lung function | 14 months (average of two phases) | Not reported | |
| Romieu et al. (2009)[128] | 668 women in Mexico (mean age ~26 years) | Ventilated cookstove | Open fire | Cough, phlegm, breathing difficulty, wheezing, chest tightness; lung function | 10 months | 50% | Major attrition after randomisation and before the start of follow-up (17%); not intention-to-treat analysis; concurrent use of traditional stove; |

**Table 2.4 Keywords, MeSH terms and search strategy for cardiovascular outcomes**

| Exposure (combined with "OR") | Outcome (combined with "OR") |
|---|---|
| 1. "Indoor air pollution"<br>2. "Household air pollution"<br>3. "Indoor smoke"<br>4. "Wood smoke"<br>5. "Solid fuel*"<br>6. Biomass<br>7. Coal<br>8. Wood<br>9. Charcoal<br>10. Straw<br>11. Dung<br>12. "Crop residue"<br>13. "Crop waste"<br>14. Cookstove*<br>15. "Cook stove"<br>16. "Open fire"<br>17. Cooking<br>18. Heating | 1. "Cardiovascular disease"<br>2. Stroke<br>3. Blood pressure<br>4. Hypertension<br>5. Heart<br>6. Coronary<br>7. Atherosclerosis<br>8. Cholesterol<br>9. "Carotid intima media thickness"<br>10. Plague |

**Final search: (exposure keywords) AND (outcome keywords)**

**Figure 2.1 Fuel transition model**

Graphical illustration of the concept of fuel transition such that more socio-economically deprived populations tend to be more reliant on more polluting fuels, and as the socioeconomic position improve, people move to transitional fuels and, eventually, clean fuels
(Adapted and modified from WHO 2014[6]).

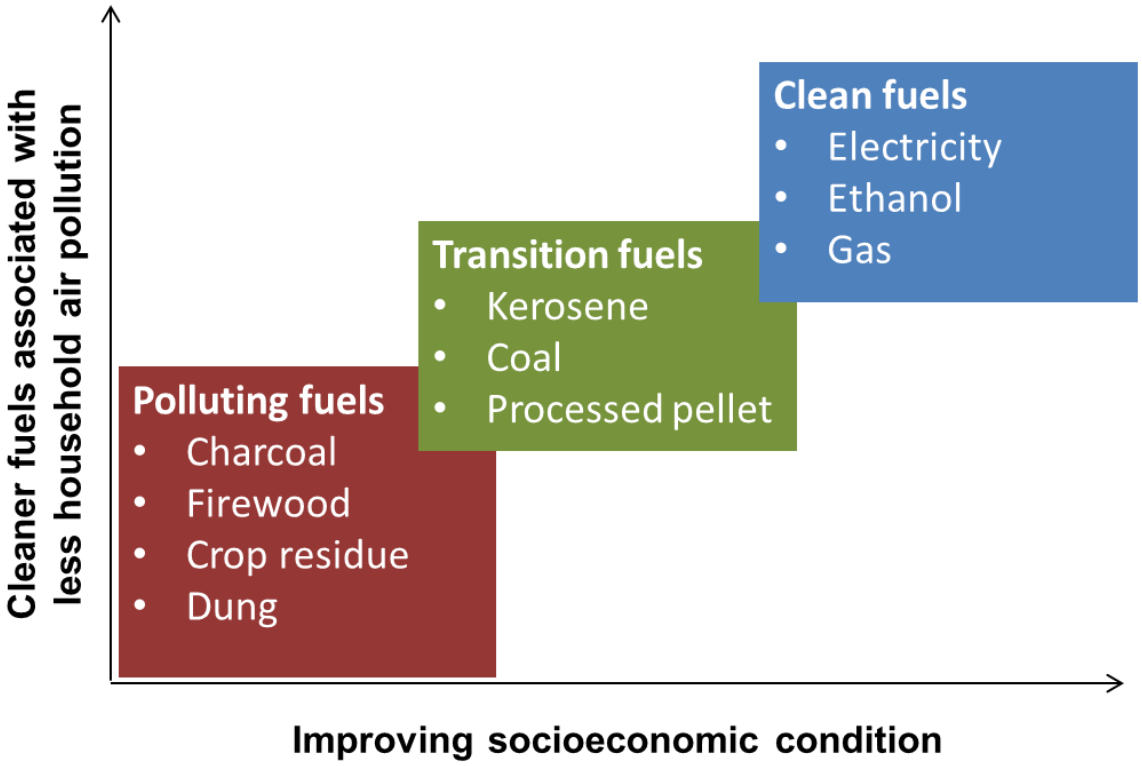
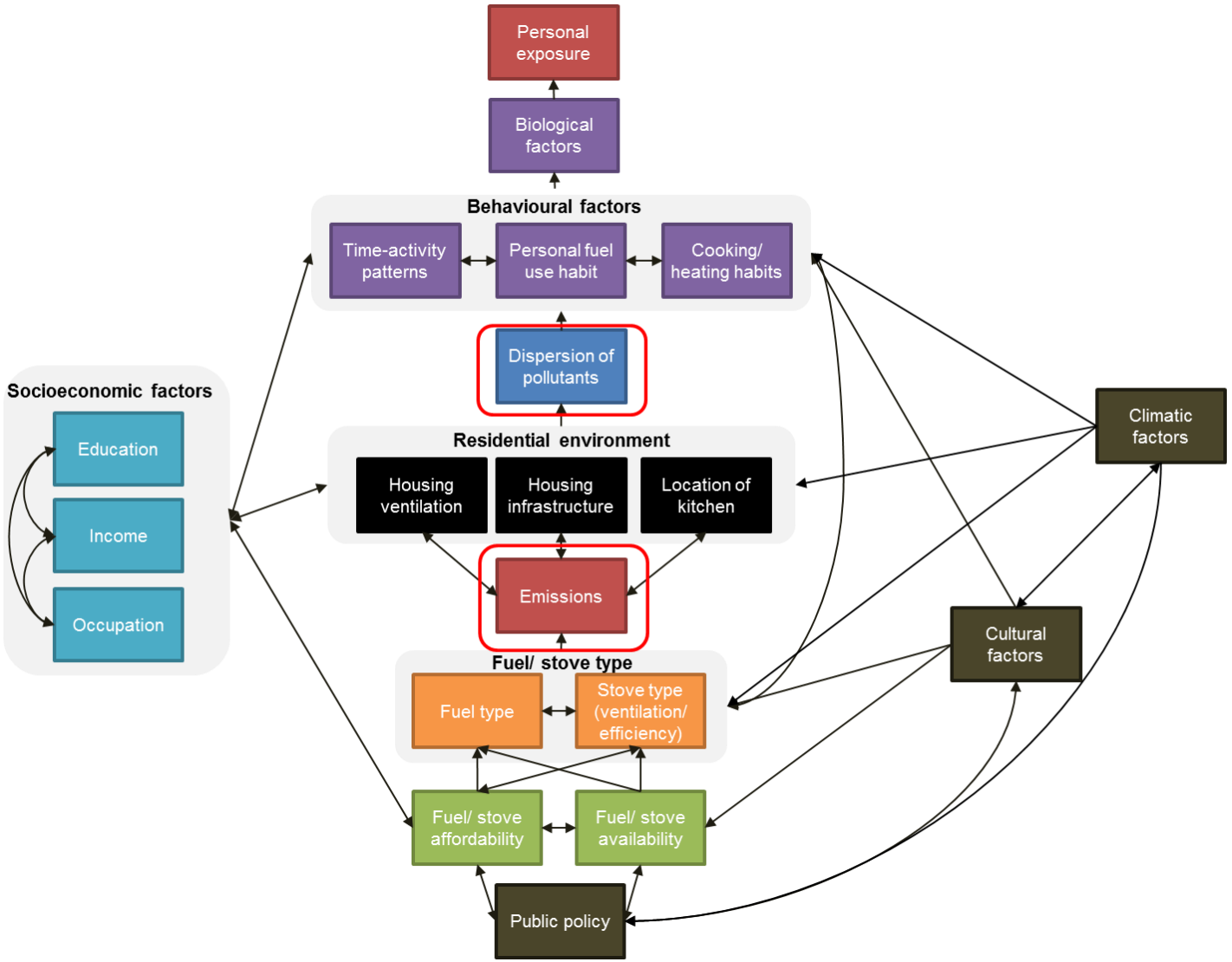


**Figure 2.2 Schematic diagram of key determinants of personal exposure to household air pollution from solid fuels**

(Adapted and modified from Ezzati et al. 2002[151] and IARC 2010[152])



# CHAPTER 3. THE CHINA KADOORIE BIOBANK COHORT STUDY

## 3.1 INTROUCTION

The China Kadoorie Biobank (CKB) is an open-ended, multi-area, prospective observational study involving about 0.5 million Chinese adults. It was established jointly by the Clinical Trial Service Unit and Epidemiological Studies Unit, University of Oxford, UK and the Chinese Academy of Medical Sciences, China in 2004, with a broad aim to build a comprehensive database to enable the assessment of the associations of both established and emerging lifestyle, environmental and genetic risk factors with a diverse range of diseases. It is the primary source of data used in this thesis. The methods and participant characteristics of the CKB has been described in detail in two published cohort profiles[69,153] and are summarised in this chapter. All information presented in this chapter was based on the 12th release of CKB data which became available in April 2017.

## 3.2 STUDY DESIGN AND RECRUITMENT

During 2004-2008, 512,891 adults aged 30-79 years were recruited from ten provinces of China, including five rural counties and five urban cities, based on governmental administrative definitions (**Figure 3.1**). **Table 3.1** shows the names of the rural counties and urban cities, and their corresponding provinces. For the ease of expression, the urban study sites are addressed by the city and rural sites by the province throughout this thesis. The ten areas were purposively selected from China's nationally representative Disease Surveillance Point (DSP) system[154] to encapsulate a diverse range of socio-demographic characteristics, risk factor exposure and disease patterns while considering population stability, quality of death and disease registries and local capacity and commitment. Of note, Suzhou was relatively rural in the early 2000's but it has since urbanised rapidly. Nevertheless, many people still maintained a traditional

way of life, with some baseline characteristics (e.g. education level, smoking patterns) similar to those in other rural study sites.[153] Therefore, although Suzhou is classified as one of the urban sites in CKB, it can be considered as semi-urban in a wider context. The CKB was not designed to be representative of Chinese middle-aged adults and cautious interpretation is required for statistical inference about the exposure and disease patterns in the target population. Nonetheless, the large sample size and the diversity of the cohort could provide adequate heterogeneity to evaluate the biological associations of interest (as presented in **Chapters 6 and 7**). Given adequate understanding about the potential biological mechanisms of these associations, the evidence from this thesis could be reasonably generalised to similar populations, although the actual effect estimates may vary depending on the distribution of potential effect modifiers (e.g. age, gender and genetic susceptibility). .[155]

A multi-stage random cluster sampling scheme was employed. At each study site, a random sample of 100-150 administrative units (rural villages or urban street committees) was selected for participant recruitment. At each administrative unit, all permanent residents aged 35-74 years without known physical or mental disability were identified via official residential records and invited to survey clinics by local community leaders or health workers. There could be more than one participant from a household, thus resulting in a multi-level clustering structure (study areas, administrative units and households), but there was no sufficiently detailed relatedness and residential information necessary to quantify the extent of household-level clustering. Among the 1,801,167 individuals contacted, 500,223 participated (response rate ~30%, with 26-38% in rural sites and 16-50% in urban sites), and another 12,668 who were slightly outside the targeted age range but turned up at the survey clinics were included so as to encourage community commitment, resulting in the final baseline age range of 30-79 years. No personal data were collected from the non-responders.

### 3.3 BASELINE SURVEY

At the survey clinics, invited individuals were screened for identity and eligibility using their unique national identity cards. Eligible individuals were then asked to give a written, informed consent to participate in the study. Then, trained health workers administered a laptop-based, electronic questionnaire to collect information on socio-demographic characteristics (e.g. age, gender and education level), lifestyle factors (e.g. smoking, alcohol consumption, diet and physical activity), exposure to environmental tobacco smoke (ETS) and HAP-related exposure, medical history and current medication, sleeping habits, mental health status and reproductive history. In addition, they undertook physical measurements such as height, weight, lung function and BP, using instruments that were regularly calibrated following standardised protocols.[156,157] A 10 mL non-fasting venous blood sample (with time since last meal documented) was collected for each participant for long-term storage, with a small proportion used for blood spot tests on random blood glucose using the SureStep Plus system (LifeScan Inc., CA, USA).

The electronic data collection system employed stringent logic and error checks to minimise data errors and missing values, and the quality of data collection was closely monitored, with regular feedback and further training provided to health workers. The full baseline questionnaire is available in **Appendix B1**.

### 3.4 RESURVEY

After the baseline survey, two resurveys were undertaken in 2008 and 2013-2014 in 4-5% randomly selected (using cluster random sampling on administrative units) subset of surviving participants from all ten study areas. The first resurvey invited 24,760 participants and 19,760 participated (response rate = 79.8%). The second resurvey invited 33,073 participants and 24,996 participated (response rate = 75.6%). Of all CKB participants, 14,857 participated in all three surveys. The resurveys were conducted to

repeat the assessments (both questionnaire interview and physical measurements) made at baseline, collect additional data to enhance and calibrate baseline data and enable investigation into the temporal trends of risk factor exposure. The full resurvey questionnaires are available online at http://www.ckbiobank.org/, and excerpts of the relevant sections are available in **Appendices B2 and B3**.

### 3.5 ETHICS APPROVAL

Ethics approval was obtained from the Oxford Tropical Research Ethics Committee (OxTREC), Oxford University, UK (reference: 025-04) and the China National Center for Disease Control and Prevention (CDC; reference: 005/2004) before the start of the project.

### 3.6 FOLLOW-UP AND OUTCOME ASCERTAINMENT

The vital status of all participants was monitored through the DSP system,[154] and verified through official residential records and death certificates annually. Information on all hospitalisation events was collected through electronic linkage, using unique personal identification numbers, to local disease registries (for IHD, stroke, cancers and diabetes) available in eight of the ten study areas (Harbin, Suzhou, Liuzhou, Sichuan, Gansu, Henan, Zhejiang and Hunan) and national health insurance claim databases, which had almost complete coverage (>99%) in all study areas. For the small proportion (~5%) of deaths that occurred outside the healthcare system, standardised verbal autopsies were undertaken to review prior hospital records and interview family member or caregivers in determining the probable causes.[154] All deaths and hospitalisation episodes were classified according to the International Statistical Classification of Diseases and Related Health Problems, 10$^{th}$ Revision (ICD-10) by trained staff of the DSP system and medical professionals in hospitals, respectively, all of whom were blinded to baseline information.

### 3.7 BASELINE CHARACTERISTICS OF THE CKB PARTICIPANTS

Of the 512,891 participants (mean [standard deviation (SD)] age 51.5 [10.7] years) included in the baseline survey, there were slightly more women (59.0%) and rural residents (55.9%) (**Table 3.2**). The number of participants recruited from each study area varied from 29,689 (5.8%) in urban Haikou to 63,357 (12.4%) in rural Henan (**Table 3.3**). Over half of the population had no formal education or only completed primary school (50.8%) or had an annual household income of <20,000 Yuan (~£2,300; 57.3%), with women reported lower level of education or household income. The commonest active occupation was agricultural worker (41.7%), followed by factory worker (14.1%). Home makers and retirees constituted about a quarter of the population, with the majority of them being women. Regular smoking and alcohol consumption were common in men (61.3% and 33.4%) but rare in women (2.4% and 2.1%). In terms of regular intake (≥ 1 day/ week) of food groups, virtually all participants consumed fresh vegetables regularly, slightly less consumed red meat (beef, lamb or pork; 82.7%), about 60% consumed fresh fruit, less than half consumed fish or seafood, and about one-fifth had dairy product regularly. More men reported regular intake of meat and fish or seafood, whereas more women reported regular intake of fresh fruit (**Table 3.2**).

For self-reported health conditions, about one-tenth of the population reported poor general health, 6% had prior diagnosis of diabetes, 5% had CVD (chronic heart disease, stroke or transient ischaemic attack), 12% had hypertension, 4% had chronic respiratory disease (emphysema, chronic bronchitis, asthma or tuberculosis), and 0.5% had any cancer (**Table 3.2**). The CKB population was relatively lean, with about two-thirds having a measured body mass index (BMI) <25.0 kg/m$^2$, but about 40% had a waist to hip ratio ≥0.90. Women had slightly lower mean BMI and waist to hip ratio than men. About 30% of the participants had a measured SBP ≥140 mmHg, with men having slightly higher levels than women (mean [SD] 132.3 [20.0] versus 130.5 [22.0]). Similarly, women had slightly lower DBP than men. The CKB population has considerably better

lung function as compared to middle aged Chinese adults,[16] with a mean (SD) forced expiratory volume in 1 second ($FEV_1$) to forced vital capacity (FVC) ratio of 0.85 (0.09). About 5% of the population had a $FEV_1$:FVC <0.7 and 7% had $FEV_1$:FVC <lower limit of normal (LLN), both of which can be considered as a sign of having airflow obstruction (**Table 3.4**).

## 3.8 BASELINE CHARACTERISTICS OF THE RESURVEY SUBSAMPLE

Compared to the whole CKB population, the first and second resurvey subsamples were of similar age, education level, BMI, waist to hip ratio, SBP and DBP levels, and lung function measures at baseline. However, the resurvey subsamples included slightly more rural residents and individuals reporting lower annual household income or had never smoked or drank at baseline. The second resurvey subsample, in particular, reported slightly less health problems at baseline, such as prior doctor-diagnosis of diabetes, CVD, hypertension or chronic respiratory disease (**Table 3.5**). Although these differences between the resurvey subsamples and the study population were statistically significant ($p<0.05$), the absolute differences do not appeared to be clinically significant and thus the subsamples could be considered as reasonably representative of the CKB population. For example, the adjusted baseline prevalence of self-reported poor health (9.8% versus 10.4%), CVD (3.7% versus 4.5%) and chronic respiratory disease (3.8% versus 4.4%) were all slightly lower in second resurvey participants compared to the whole cohort.

## 3.9 SUMMARY

This chapter has first presented the procedures of the establishment, study design, participant recruitment, baseline survey, resurveys and follow-up used in the CKB. Then, the overall and gender-specific distribution of socio-demographic, socioeconomic, lifestyle and health-related characteristics in the CKB population was described,

followed by the comparison of these characteristics between the whole cohort and those who participated in the two resurveys.

**Table 3.1 Names of study areas and corresponding provinces included in the China Kadoorie Biobank Cohort Study**

| Study area | Province |
|---|---|
| **Urban areas (city)** | |
| Qingdao | Shandong Province |
| Harbin | Heilongjiang Province |
| Haikou | Hainan Province |
| Suzhou | Jiangsu Province |
| Liuzhou | Guangxi Zhuang Autonomous Region |
| **Rural areas (county)** | |
| Pengzhou | Sichuan Province |
| Tianshui | Gansu Province |
| Huixian | Henan Province |
| Tongxiang | Zhejiang Province |
| Liuyang | Hunan Province |

**Table 3.2 Adjusted percentages of baseline socio-demographic and lifestyle characteristics in all CKB participants by gender***

| Characteristic | Men | Women | Total |
|---|---|---|---|
| **N** | 210,259 | 302,632 | 512,891 |
| **Age (years), %** | | | |
| <40 | 14.1 | 15.9 | 15.2 |
| 40-49 | 28.0 | 31.0 | 29.8 |
| 50-59 | 30.3 | 31.0 | 30.7 |
| 60-69 | 19.7 | 16.6 | 17.9 |
| ≥70 | 7.8 | 5.5 | 6.4 |
| Mean (SD) | 52.4 (10.9) | 51.0 (10.5) | 51.5 (10.7) |
| **Rural residency, %** | 56.7 | 55.2 | 55.9 |
| **Education level, %** | | | 50.8 |
| No formal | 8.3 | 26.2 | 18.6 |
| Primary school | 32.3 | 31.6 | 32.2 |
| Middle school | 33.2 | 24.7 | 28.3 |
| High-school or above | 26.1 | 17.5 | 21.0 |
| **Annual household income (Yuan), %** | | | 57.3 |
| <10,000 | 26.0 | 29.8 | 28.2 |
| 10,000-19,999 | 28.4 | 29.5 | 29.1 |
| 20,000-34,999 | 25.2 | 24.3 | 24.7 |
| ≥35,000 | 20.3 | 16.4 | 18.0 |
| **Occupation, %** | | | |
| Agricultural worker | 43.1 | 40.1 | 41.7 |
| Factory worker | 19.2 | 10.6 | 14.1 |
| Non-manual labour | 12.6 | 8.7 | 10.2 |
| Retired | 14.2 | 17.8 | 16.6 |
| Home maker | 2.5 | 16.7 | 10.4 |
| Self-employed | 3.6 | 2.1 | 2.7 |
| Unemployed or others | 4.7 | 4.0 | 4.3 |
| **Smoking, %** | | | |
| Never | 14.4 | 94.8 | 61.9 |
| Occasional | 11.4 | 1.8 | 5.7 |
| Ex-regular | 12.9 | 0.9 | 6.0 |
| Current-regular | 61.3 | 2.4 | 26.4 |
| **Alcohol consumption, %** | | | |
| Never | 19.9 | 63.7 | 45.9 |
| Occasional | 38.2 | 33.4 | 35.2 |
| Ex-regular or reduced intake | 8.5 | 0.9 | 4.1 |
| Current-regular | 33.4 | 2.1 | 14.8 |
| **Dietary intake (≥1 day/ week), %** | | | |
| Fresh fruit | 56.8 | 61.5 | 59.6 |
| Fresh vegetables | 99.7 | 99.7 | 99.7 |
| Red meat | 85.9 | 80.3 | 82.7 |
| Poultry | 32.5 | 25.2 | 28.2 |
| Fish/ seafood | 49.3 | 45.1 | 46.8 |
| Dairy product | 19.2 | 21.3 | 20.5 |
| **Total physical activity (MET-hr/d), mean (SD)§** | 22.4 (15.3) | 20.1 (12.8) | 21.1 (13.9) |
| **Self-reported health conditions, %** | | | |
| Self-reported poor health | 8.8 | 11.5 | 10.4 |
| Diabetes | 5.5 | 6.3 | 5.9 |
| Cardiovascular disease† | 4.5 | 4.5 | 4.5 |
| Hypertension | 10.8 | 12.3 | 11.6 |
| Chronic respiratory disease‡ | 5.1 | 3.7 | 4.4 |
| Cancer | 0.4 | 0.5 | 0.5 |

* Means and percentages were standardised to the age and study area structure of the CKB population, where appropriate.
† Cardiovascular disease: chronic heart disease, stroke or transient ischaemic attack.
‡ Chronic respiratory disease: emphysema, chronic bronchitis, asthma or tuberculosis.
§ MET: Metabolic equivalent of tasks.

**Table 3.3 Age-standardised population structure of the CKB population by study area and gender***

| | Men | Women | Total | |
|---|---|---|---|---|
| **Characteristic** | **%** | **%** | **%** | **N** |
| **Study area** | | | | |
| Haikou (urban) | 5.1 | 6.3 | 5.8 | 29,689 |
| Qingdao (urban) | 7.6 | 6.6 | 6.9 | 35,509 |
| Gansu (rural) | 9.3 | 10.0 | 9.8 | 50,041 |
| Liuzhou (urban) | 9.1 | 10.3 | 9.8 | 50,173 |
| Suzhou (urban) | 10.7 | 10.2 | 10.4 | 53,260 |
| Sichuan (rural) | 10.1 | 11.3 | 10.9 | 55,687 |
| Harbin (urban) | 11.0 | 11.5 | 11.2 | 57,555 |
| Zhejiang (rural) | 11.4 | 11.1 | 11.3 | 57,704 |
| Hunan (rural) | 12.5 | 11.1 | 11.7 | 59,916 |
| Henan (rural) | 13.3 | 11.7 | 12.4 | 63,357 |

*Percentages were standardised to the age structure of the CKB population. Study areas are arranged in ascending order of number of participants recruited.

**Table 3.4 Adjusted means and percentages of physical measurements in all CKB participants by gender***

| Characteristic | Men | Women | Total |
|---|---|---|---|
| **N** | 210,259 | 302,632 | 512,891 |
| **Body mass index (kg/m$^2$), %** | | | |
| <21.0 | 23.7 | 20.7 | 22.0 |
| 21.0-24.9 | 45.1 | 45.0 | 45.1 |
| ≥25.0 | 31.2 | 34.3 | 32.9 |
| Mean (SD) | 22.4 (3.2) | 20.1 (3.5) | 23.7 (3.4) |
| **Waist to hip ratio, %** | | | |
| <0.85 | 18.3 | 38.8 | 30.7 |
| 0.85-0.89 | 26.6 | 27.5 | 27.2 |
| ≥0.90 | 55.1 | 33.7 | 42.1 |
| Mean (SD) | 0.90 (0.06) | 0.87 (0.07) | 0.88 (0.07) |
| **Systolic blood pressure (mmHg), %** | | | |
| <120 | 26.9 | 34.8 | 31.8 |
| 120-139 | 43.6 | 36.5 | 39.3 |
| ≥140 | 29.5 | 28.6 | 28.9 |
| Mean (SD) | 132.3 (20.0) | 130.5 (22.0) | 131.1 (21.3) |
| **Diastolic blood pressure (mmHg), %** | | | |
| <80 | 54.2 | 62.7 | 59.3 |
| 80-89 | 29.5 | 25.5 | 27.1 |
| ≥90 | 16.3 | 11.8 | 13.6 |
| Mean (SD) | 79.2 (11.4) | 76.8 (10.9) | 77.8 (11.2) |
| **Lung function measures, mean (SD)** | | | |
| Pre-bronchodilator $FEV_1$, Litre† | 2.69 (0.69) | 1.98 (0.49) | 2.26 (0.67) |
| Pre-bronchodilator FVC, Litre‡ | 3.18 (0.77) | 2.33 (0.55) | 2.68 (0.76) |
| Pre-bronchodilator $FEV_1$:FVC | 0.84 (0.09) | 0.85 (0.08) | 0.85 (0.09) |
| **Possible airflow obstruction, %** | | | |
| $FEV_1$:FVC <0.7 | 6.2 | 4.6 | 5.4 |
| $FEV_1$:FVC <lower limit of normal | 7.2 | 6.5 | 6.9 |

*Means and percentages were standardised to the age and study area structure of the CKB population.

† $FEV_1$: forced expiratory volume in 1 second.

‡ FVC: forced vital capacity.

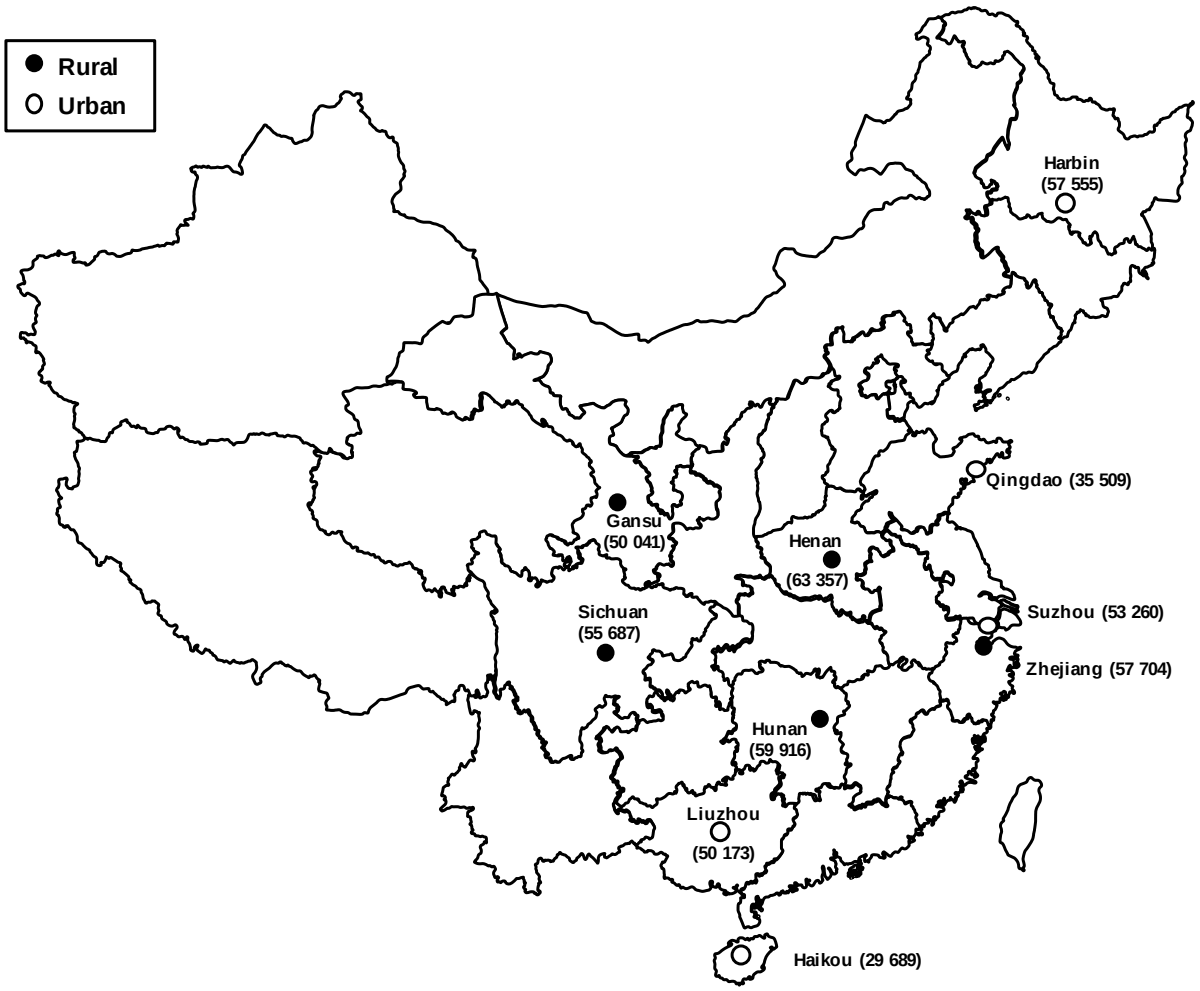
**Table 3.5 Baseline characteristics of all CKB participants compared to the resurvey subsamples**

| Baseline characteristic | Whole cohort | First resurvey | Second resurvey |
|---|---|---|---|
| **N** | 512,891 | 19,760 | 24,996 |
| **Age (years), %** | | | |
| <40 | 15.2 | 15.1 | 15.2 |
| 40-49 | 29.8 | 29.1 | 30.2 |
| 50-59 | 30.7 | 31.4 | 33.0 |
| 60-69 | 17.9 | 18.7 | 17.6 |
| ≥70 | 6.4 | 5.7 | 4.1 |
| Mean (SD) | 51.5 (10.7) | 51.5 (10.6) | 51.0 (10.1) |
| **Women, %** | 59.0 | 60.7 | 61.7 |
| **Rural residency, %** | 55.9 | 58.8 | 57.0 |
| **Education level, %** | | | |
| No formal | 18.6 | 19.9 | 18.7 |
| Primary school | 32.2 | 32.8 | 34.0 |
| Middle school | 28.3 | 27.8 | 28.5 |
| High-school or above | 21.0 | 19.5 | 18.8 |
| **Annual household income (Yuan), %** | | | |
| <10,000 | 28.2 | 32.5 | 31.6 |
| 10,000-19,999 | 29.1 | 30.5 | 30.9 |
| 20,000-34,999 | 24.7 | 22.1 | 22.3 |
| ≥35,000 | 18.0 | 14.9 | 15.2 |
| **Smoking, %** | | | |
| Never | 61.9 | 63.4 | 64.4 |
| Occasional | 5.7 | 5.7 | 5.5 |
| Ex-regular | 6.0 | 5.7 | 5.3 |
| Current-regular | 26.4 | 25.2 | 24.8 |
| **Alcohol consumption, %** | | | |
| Never | 45.9 | 46.3 | 47.3 |
| Occasional | 35.2 | 35.4 | 34.5 |
| Ex-regular or reduced intake | 4.1 | 3.9 | 3.7 |
| Current-regular | 14.9 | 14.5 | 14.6 |
| **Self-reported health conditions, %** | | | |
| Self-reported poor health | 10.4 | 10.5 | 9.8 |
| Diabetes | 5.9 | 5.5 | 4.7 |
| Cardiovascular disease* | 4.5 | 4.7 | 3.7 |
| Hypertension | 11.6 | 11.3 | 10.4 |
| Chronic respiratory disease† | 4.4 | 4.4 | 3.8 |
| Cancer | 0.5 | 0.6 | 0.4 |
| **Physical measurements, mean (SD)** | | | |
| BMI, kg/m$^2$‡ | 23.7 (3.4) | 23.7 (3.4) | 23.7 (3.4) |
| Waist circumference, cm | 80.3 (9.8) | 79.8 (9.7) | 79.5 (9.5) |
| Waist to hip ratio | 0.88 (0.07) | 0.88 (0.07) | 0.88 (0.07) |
| Body fat percentage | 27.9 (8.4) | 28.4 (8.5) | 28.3 (8.3) |
| Systolic blood pressure, mmHg | 131.1 (21.3) | 132.2 (21.7) | 131.0 (20.7) |
| Diastolic blood pressure, mmHg | 77.8 (11.2) | 77.9 (11.3) | 77.6 (11.0) |
| $FEV_1$, Litre§ | 2.26 (0.67) | 2.25 (0.67) | 2.26 (0.65) |
| FVC, Litre¶ | 2.68 (0.76) | 2.66 (0.77) | 2.65 (0.75) |
| $FEV_1$:FVC | 0.85 (0.09) | 0.85 (0.09) | 0.85 (0.09) |

* Cardiovascular disease: chronic heart disease, stroke or transient ischaemic attack.
† Chronic respiratory disease: emphysema, chronic bronchitis, asthma or tuberculosis.
‡ BMI: body mass index
§ $FEV_1$: forced expiratory volume in 1 second
¶ FVC: forced vital capacity

**Figure 3.1 Locations of the 10 study areas of the China Kadoorie Biobank Study**

Solid circles (●) are rural areas and open circles (○) are urban areas included in the China Kadoorie Biobank Study. Number of participant at baseline in each study area is shown in brackets. (Adapted from Chen et al. 2010.)[153]



# CHAPTER 4. METHODS

Following the descriptions about the general study design and methods of the CKB in **Chapter 3**, this chapter highlights the methods used for the main analyses in this thesis, including HAP exposure assessment, participant follow-up and outcome ascertainment and statistical methods used in **Chapters 5 to 7**. Methods specific to each individual chapter will be described in the corresponding chapters in detail. Contents of this chapter constituted the methods sections of the publications related to this thesis.[33-35] The methods of the feasibility study related to this thesis will be described in **Chapter 8** separately.

## 4.1 ASSESSMENT OF SOLID FUEL USE

At the scale of CKB, direct measurement of HAP exposure was infeasible. Therefore, conventional proxies of self-reported exposures related to cooking and heating were assessed via the baseline and resurvey questionnaires (**Appendices B1 - Section 6, B2 and B3**). **Figure 4.1** shows the schematic logic flow of data collection and exposure classification, which is described in detail below.

### 4.1.1 Exposure recall

At baseline, each participant was asked to recall, for up to their three most-recent residences, how many years they had lived there, cooking frequency (no cooking facility, never/rarely, monthly, weekly, daily), ownership of ventilated cookstove (all stoves, some stoves, none), and winter heating behaviour (yes, no). The period that the three residences covered was regarded as the “residential recall period”. Participants who cooked at least monthly or used heating in winter in each respective residence were asked about the corresponding primary fuel type used (central heating [for heating only], electricity, gas, coal, wood, other) for cooking and heating, respectively. These

questions were repeated in the two resurveys regarding their exposure in the current residence.

### 4.1.2 Fuel type classification

The response option “wood” encapsulates both wood and charcoal in the Chinese questionnaire, because they share a common plant-based origin and have similar HAP emission characteristics and that charcoal use is relatively rare in China.[4,158-160] For this thesis, the term wood will be used to address both wood and charcoal. Central heating, a common source of heating in northern China, refers to a municipal heating system that generates heat in a remote, centralised location distant from residential areas and distributes the heat to individual households through underground hot water or steam pipes.[161] If two or more fuel types were used at any residence, the one used the most frequently and for the longest duration was documented as the primary fuel as an approximation of usual exposure in that residence. Electricity and gas were grouped as clean fuels along with central heating for heating fuel, because these are associated with low levels of HAP. Coal and wood were grouped as solid fuels.

### 4.1.3 Long-term exposure classification

To approximate long-term exposure for the prospective analyses in **Chapters 6 and 7**, participants who had always used solid fuels throughout the recall period (long-term solid fuel users) and those who had switched from solid to clean fuels prior to the baseline survey were grouped separately, and they were compared to those who had used clean fuels throughout the recall period (long-term clean fuel users). As noted in **Section 2.3.1.1**, individuals who do not practice cooking or use heating tend to be significantly different from those who do, and, therefore, they were not included as part of the reference category even though they could be considered as being less exposed to HAP from solid fuel use. Instead, they constituted a separate category (never-regular cook; never had heating). The exposure profiles of participants who had cooked or used

heating previously but stopped were considered to be less clear, and they were therefore excluded from the corresponding prospective analyses in **Chapters 6 and 7** (see **Sections 6.3.4 and 7.3.5** for the details of exclusion).

Long-term solid fuel users were further separated into three groups (always coal, always wood, switched between coal and wood) to investigate the potential risks associated with different types of solid fuels. Furthermore, to evaluate the potential exposure-response relationship, a semi-quantitative metric of duration of continuous exposure to solid fuel use was derived from the sum of the duration of residence (years) across consecutive residences where solid fuels were primarily used for cooking or heating (greater details of the calculation are available in **Appendix C**). Long-term solid fuel users were then categorised according to their approximate duration of continuous exposure (<20, 20-39, ≥40 years) and their disease risks were compared against long-term clean fuel users.

For sensitivity analysis, the duration of exposure to solid fuel use for cooking was weighted by cooking frequency, with a weighting of 1.0 for those who cooked daily and 0.5 (median number of days between one to six days [3.5] divided by seven) for those who cooked weekly. The baseline survey collected no data on heating frequency or intensity, so the weighting for duration of solid fuel use for heating was approximated by the proportion of months with average ambient temperature <10°C from February 2005 to December 2017 (total 155 months) in each study area, based on data obtained from local meteorological offices through the China Meteorological Data Service Center.[162] Local meteorological data before February 2005 are less complete and, thus, not included in the calculation. The resulting weighting coefficients for duration of solid fuel use for heating were 0.39 for Qingdao, 0.57 for Harbin, 0.27 for Suzhou, 0.05 for Liuzhou, 0.24 for Sichuan, 0.42 for Gansu, 0.31 for Henan, and 0.23 for Hunan. The resulting weighted duration of exposure were categorised in the same way for cooking (<20, 20-39, ≥40 years) but modified for heating (<10, 10-20, ≥20 years) because of the

downward shift of the distribution after applying the fractional weighting to all participants.

To explore the potential role of the use of ventilated cookstoves alongside solid fuels, participants who had always used solid fuels for cooking were separated into those who had used ventilated cookstoves during ≥50% and <50% of the recall period. In order to assess the specificity of the role of ventilated cookstoves to cooking exposure, the same categorisation was applied to participants who had used solid fuels for heating persistently.

## 4.2 DEFINITIONS OF OTHER KEY BASELINE CHARACTERISTICS

In this thesis, never-smokers refers to participants who either reported to have never smoked or had smoked <100 cigarettes or equivalent in their lifetime. Participants who had any self-reported history of physician-diagnosed 1) chronic heart disease, stroke or transient ischaemic attack were considered as having previous CVD; 2) chronic bronchitis, emphysema, tuberculosis or asthma were considered as having previous chronic respiratory disease. Hypertension refers to self-reported doctor-diagnosis of hypertension plus use of anti-hypertensive medications (angiotensin converting enzyme inhibitors, beta-blockers, diuretics, calcium channel antagonists) or having a measured SBP of 140 mmHg or above or a DBP of 90 mmHg or above at the baseline survey.[156] Diabetes refers to either self-reported doctor-diagnosis of diabetes or, among participants without prior diagnosis of diabetes, 1) having a random plasma glucose level of ≥7.0 mmol/L with time since last meal of ≥8 hours or ≥11.1 mmol/L with time since last meal of less than 8 hours; or 2) a fasting plasma glucose level of ≥7.0 mmol/L on subsequent testing.[157]

## 4.3 FOLLOW-UP AND OUTCOME DEFINITIONS

As described in detail in **Section 3.6**, participants were followed-up for cause-specific hospitalisation and death events through record linkage to the DSP system, local disease registries and national health insurance databases. A small proportion of deaths occurred without prior medical attention, and standardised verbal autopsy was carried out to determine the probable causes for each case.[154] All hospitalisation and death events were ICD-10 coded, by trained staff who were blinded to participant baseline information.

This thesis is based on the 12th release of the CKB data, with follow-up from baseline until 1st January 2016, by which 37,289 (7.3%) participants died and 4,875 (1.0%) were lost to follow-up. For the prospective analyses presented in **Chapters 6 and 7**, participants without the event of interest were censored upon death, loss to follow-up or 1st January 2016, whichever is earlier.

For respiratory disease, this thesis investigated the first event of major respiratory diseases (including chronic lower respiratory disease [CLRD; ICD-10 J40-J47, where J41-J44 were considered as COPD], ALRI [J12-J18, J20-J22], AURI [J00-J06] and other upper respiratory disease [J30-J39]), both combined and separately, and death from any respiratory diseases excluding those due to external agents or intraoperative and post-procedural complications (J00-J47, J80-J94, J96-J99).

For CVD, this thesis examined the overall and cause-specific death from CVD (ICD-10 I00-I88 and I95-I99), including IHD (I20-I25), stroke (I60-I61 and I63; including intracerebral haemorrhage [I61; ICH] and ischaemic stroke [I63; IS]) and other CVD (I00-I16, I27-I52, I62, I65-I88, I95-I99).

## 4.4 GENERAL EXCLUSIONS

A small proportion of the participants (n = 2,302) had reported a greater number of years lived in their three most-recent residences than their age. Their self-reported HAP-related exposures were considered as more prone to error and they were therefore excluded from all analyses in this thesis. For cooking-related analyses, participants who reported using “other” fuel or having no cooking facility in each respective residence were excluded. For ventilation-related analyses, participants with no cooking facility in their respective residence were excluded. For heating-related analyses, participants who used “other” fuel and those from Haikou and Zhejiang, two study areas where <1% of participants reported using heating at baseline, were excluded. Details of exclusions specific to the analyses described in **Chapters 5 to 7** are presented in the methods sections of the corresponding chapter.

## 4.5 STATISTICAL ANALYSIS

This section outlines the statistical methods used across **Chapters 5 to 7**, but each of these chapters also describes the analyses conducted in detail.

### 4.5.1 Descriptive analyses

For continuous metrics such as age and length of recall period that are normally distributed, means and SD will be presented; otherwise, median and inter-quartile range (IQR) will be presented. Means and percentages of selected characteristics were directly standardised to the population structure (age, gender and study area) of the CKB when comparing across population subgroups. In particular, these were used to compare various socio-demographic and lifestyle characteristics across participants of different exposure groups (**Chapters 5 to 7**) as well as those with and without the outcome of interest (**Chapters 6 and 7**). The same method was used to estimate the adjusted percentages of HAP-related exposures across the recall and prospective

period to investigate the temporal trend of HAP-related exposures (**Chapter 5**) and incidence rates of disease outcomes of interest by subgroups of age, gender and area of residence (**Chapters 6 and 7**).

### 4.5.2 Prospective analyses

#### *4.5.2.1 Model construction*

All prospective analyses of CKB studies use age-at-risk-, gender- and study area-stratified multivariable Cox proportional hazard regression models to estimate adjusted hazard ratios (HRs). Stratification by age-at-risk is an established method to more thoroughly control for the confounding effects from both age and birth cohort, and the possibility that age violates the proportional hazard assumption.[163] The concept of age-at-risk is explained in greater details in **Appendix D**. Stratification by study area and gender were necessary to account for the inter-region and between-gender variability of both measured and unmeasured potential confounders related to these two characteristics, as well as to account for the clustering at study area level and the potential non-proportionality of disease hazard across these groups. The clustering effect at administrative unit or household was not taken into account because such data were not available in the existing CKB databases.

Other potential confounders were identified based on the existing literature and they were assessed for their contribution to the model fit, using the likelihood ratio test comparing the model with and without each covariate. Covariates that are considered as crucial to be adjusted for based on prior knowledge of the literature, such as smoking, alcohol consumption and length of recall period, were forced into the models. To enable valid comparison of findings across different outcomes studied within each chapter, the largest set of key covariates was included in the final models for all endpoints.

As per previous CKB studies,[157,164] the proportional hazard assumption related to solid fuel use exposure of interest was assessed by comparing the HRs for the first five years and the subsequent four years of follow-up and formal test based on Schoenfeld residuals.[165]

*4.5.2.2 Subgroup analyses*

To evaluate the potential effect modification by participant characteristics, pre-specified subgroup analyses were conducted by a range of baseline characteristics, including age, gender, rural-urban residency, education level, annual household income, alcohol consumption, smoking, leg length, BMI, measured SBP, baseline diabetes status, chronic respiratory disease history and self-reported health status, where appropriate. The HRs and corresponding standard errors across subgroups were compared using $\chi^2$ tests for heterogeneity or trend (where subgroups can be arranged in a meaningful order) based on the inverse variance-weighted sum of log(HRs) across strata.[166]

*4.5.2.3 Sensitivity analyses*

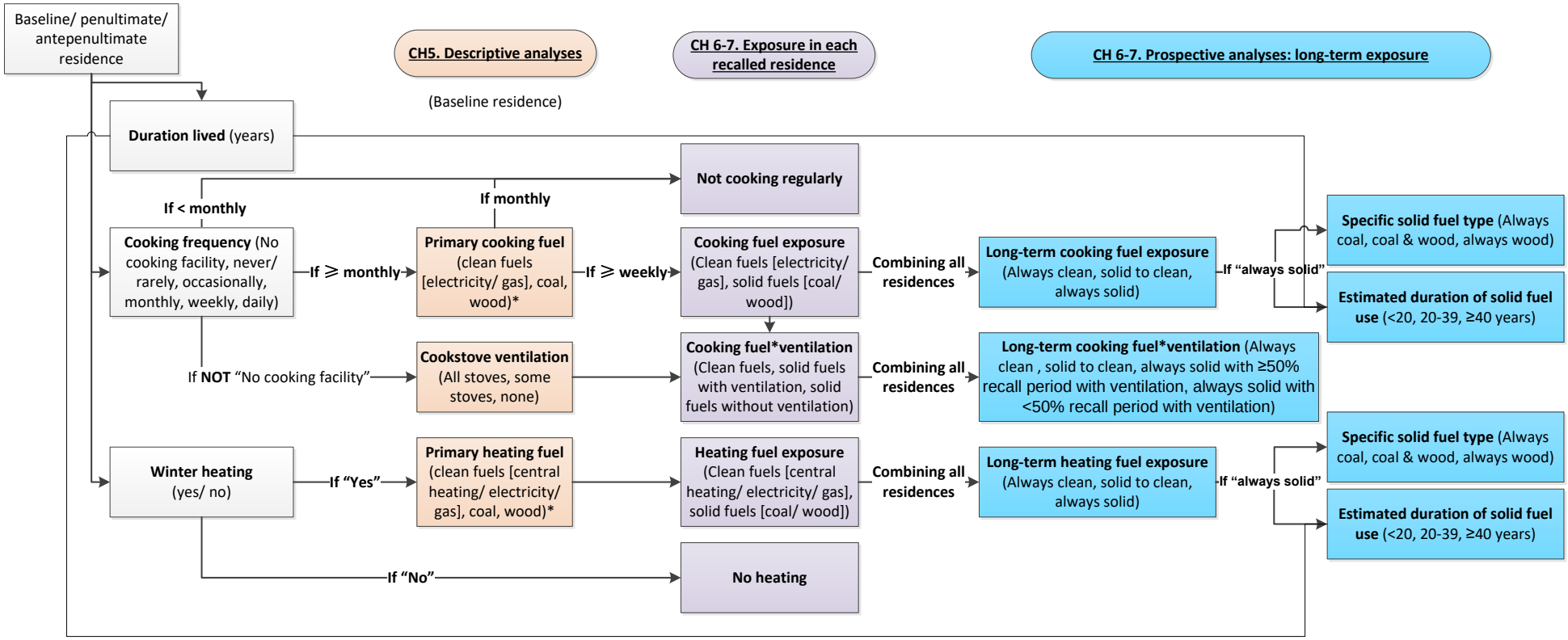
A range of sensitivity analyses were undertaken to assess the robustness of the main findings, mainly by repeating the main analyses comparing long-term solid fuel users and those who switched from solid to clean fuels against long-term clean fuel users, either with adjustment for additional potential confounders (that were considered but not selected for the main analyses) or after further exclusion of participants who are more prone to exposure misclassification or reverse causation bias. As an alternative approach to account for clustering at study area level, robust standard error estimates (and 95% CIs) were calculated using marginal Cox regression using a robust sandwich covariance matrix. Details of the specific sensitivity analyses are described in the corresponding chapters.

### 4.5.3 Other statistical methods

For all main prospective analyses with three or more exposure categories, group-specific 95% CIs of HRs were calculated from the variance of the log hazard in each category (including the reference category), also known as "floating absolute risk".[167] While the point estimate of HR remains unchanged, the group-specific CIs enables valid comparison across any two groups without the influence of the variance from a fixed reference category. This is especially important for the factorial comparisons made across long-term clean fuel users, participants who had switched from solid to clean fuels and long-term solid fuel users (i.e. the main exposure categories) in **Chapters 6 and 7**. Unless otherwise specified (e.g. subgroup analyses), group-specific 95% CIs were presented throughout the thesis, both in-text and in tables and figures for consistency. Most results of prospective analyses were presented graphically to facilitate the interpretation of the group-specific 95% CIs, with a general rule of thumb that the absence of overlapping between two CIs indicates statistically significant difference. Considering the reference group and comparison group having a HR (group-specific 95% CI) of 1.00 (a to b) and k (x to y), respectively, the conventional CI for the comparison group would be ($\sqrt{[xy/k]}$ to $\sqrt{[xyk]}$), where $\log(k) = \sqrt{(\log^2[y/x] + \log^2[b/a])}$. For the HRs from the subgroup analyses, conventional CIs were presented to allow comparison of HRs and 95% CIs across different population subgroups with different reference population.

All statistical analyses described in this thesis were performed using SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA) or R version 3.4.2 (R Foundation for Statistical Computing, Vienna, Austria). All analysis codes were written by myself, with utilisation and enhancements of several in-house SAS macros (for direct standardisation, Cox regression analysis and calculation of group-specific CIs) and a R package (for making forest plots and linear plots) developed by colleagues in the Nuffield Department of Population Health (NDPH).

**Figure 4.1 Schematic logic flow of data collection and exposure classification**




*Participants reported using "other" fuel were excluded.

# CHAPTER 5. PATTERNS OF HOUSEHOLD AIR POLLUTION RELATED EXPOSURE IN THE STUDY POPULATION

## 5.1 INTRODUCTION

In China, it is estimated that 450 million individuals rely on solid fuels for cooking or heating in 2015[2] and it is linked to 0.6 million premature deaths.[168] These estimates were, however, largely based on national modelling data with little empirical evidence to capture the regional variation in HAP exposure and changes over time.[1] Several recent multi-region studies had reported the fuel use patterns in China,[158,169-173] but most of them covered a short timeframe after 2010 and focused only on cooking fuel use, with limited data on heating fuel use and ventilated cookstove ownership – both of which play a significant role in HAP exposure.[6] Although findings from these studies consistently indicated a recent decline of solid fuel use for cooking in China, there is inadequate detailed inter-region evidence regarding the longer-term secular trends and pattern of fuel use across socio-demographics subgroups. In-depth understanding about the long-term exposure patterns in the study population is also crucial to inform the interpretation of the analytical findings of this thesis.

## 5.2 AIM

The aim of this chapter is to examine the regional, temporal and generational patterns of self-reported HAP-related exposure in the CKB population.

## 5.3 METHODS

The methods of the CKB and exposure assessment have been described in detail in **Chapters 3 and 4** and elsewhere,[69,153] and are summarised below.

### 5.3.1 Study design

The CKB is a prospective cohort study of 0.5 million Chinese adults aged 30-79, recruited from five rural and five urban (one semi-urban) areas of China in 2004-2008. At recruitment, trained health workers administered an electronic questionnaire to collect data on socio-demographic, lifestyle, and HAP-related factors. Two resurveys repeating similar questions have been undertaken in 2008 and 2013-2014 in a random subset of 4-5% of the cohort.

### 5.3.2 Assessment of household fuel use and cookstove ventilation

At baseline, participants were asked to recall for up to three most-recent residences ("baseline residence" — the residence at baseline, "penultimate residence" — the previous residence, "antepenultimate residence" — the residence before the penultimate), the duration of residence (year), cooking frequency (daily, weekly, monthly, never/rarely cook, no cooking facility), availability of cookstove ventilation ("complete" — all stoves ventilated, "partial" — some stoves ventilated, "None" — no stove ventilated, no cooking facility), and winter heating (yes/ no). The total duration that the three residences covered constitutes the "residential recall period". For each residence, participants who reported cooking monthly, weekly or daily and those who had used heating in winter were asked for the corresponding primary fuel used. Types of fuel assessed include electricity, gas, coal, wood, and unspecified others, and central heating for heating. The same questions were repeated in the two resurveys assessing the participants' current residence. Electricity and gas were grouped as clean fuels, along with central heating as a clean heating fuel. If more than one type of fuel were used in any residence, the one used most frequently and for the longest duration would be recorded. Long-term exposure to solid fuel use for cooking and heating and persistent lack of any cookstove ventilation were derived by combining the exposure across the recalled residences.

The purpose of this chapter is to understand the regional variations and long-term secular trends of HAP-related exposure in the study population and to make comparison with national data. Although participants who reported cooking monthly should not be regularly and personally exposed to the levels of HAP as those who cooked weekly or daily, their data should enable a valid approximation of the primary fuel types used by the household cooks, providing greater statistical power to understand the exposure patterns in the study population. Therefore, self-reported cooking and heating fuels were used as proxies of the corresponding household fuel types.

### 5.3.3 Participant exclusions

Individuals with a recall period greater than their baseline age (n = 2,302) were excluded from all analyses, resulting in 510,589 participants in the overall study sample. The following exclusions apply to the analyses corresponding to each residence recalled, and the numbers excluded for each residence are presented in detail in **Figure 5.1**. For cooking-related analyses, participants who used “other” fuels were excluded because of the lack of specific information and small sample size and those who cooked less than monthly were excluded, because this chapter aimed to depict the fuel use patterns instead of cooking behaviour in the study population. For the same reasons, participants who used “other” unspecified fuels and those who had no heating were excluded from heating-related analyses. Participants from urban Haikou (n = 29,632), a tropical region where heating is not necessary, and rural Zhejiang (n = 57,685), where <1% reported having heating at baseline, were also excluded from all heating-related analyses. For ventilation-related analyses, participants who had no cooking facility were excluded. For baseline residence, the final sample comprised 377,280 participants for cooking-related analyses, 290,280 participants for heating-related analyses and 509,839 participants for ventilation-related analyses.

### 5.3.4 Statistical analyses

Direct standardisation was used to estimate age, gender and study area adjusted means or percentages of selected baseline characteristics (age, gender, education level and household income) in rural and urban participants according to categories of primary cooking and heating fuel type and availability of cookstove ventilation in the baseline residence. The same method was used to examine the relationships between cooking fuels, heating fuels and cookstove ventilation at baseline. Similarly, percentages of primary cooking and heating fuel type and availability of cookstove ventilation at each residence were adjusted for age, gender and study area based on the structure of the whole CKB population and compared across five periods of residence (antepenultimate, penultimate, baseline and first and second resurvey) using stacked area graphs. On the x-axis were the median of *year started living in each residence* ($YSL_{median}$) or *year of participation* in resurvey (supplemented by the corresponding IQRs reported in text) to indicate the period during which information on fuel use and ventilation availability in the study population was captured.

Using the recall information (which could date back as far as birth), the population-level life-course history of fuel use and ventilation condition across five birth cohorts (before 1940, 1940-1949, 1950-1959, 1960-1969, after 1969) was constructed. First, total duration of exposure to each category of HAP exposure indicator was calculated as the sum of the reported number of years in each residence associated with the specific exposure. Second, the age period that the duration of exposure covered was stratified into sixteen 5-year age bands from 0 to 79 years, in which the age bands with exposure information for each participants was considered as “informative age bands”. The percentages of duration in each informative age band of exposure to each category of each HAP indicator were then standardised for the gender and study area structure of the CKB population, and these percentages were plotted against the median of each

age band across the five birth cohorts. An example illustration of the method is available in **Appendix E1**.

As a sensitivity analysis, the temporal trends of HAP-related exposures in individuals who had provided exposure recall information covering their entire adulthood (i.e. ≥18 year-old; n = 326,619, 64%), whose exposure information provided is presumably more comprehensive, were examined.

## 5.4 RESULTS

### 5.4.1 Baseline characteristics

Of the 510,589 participants (59% women) with their baseline data analysed, the mean (SD) age was 51.6 (10.7) years, and the total recall period was 39.7 (14.5) years, which covered ≥20 years in 90% participants and 64% of the participants' adulthood (≥18 years). The length of recall period was shorter in urban residents than in rural residents (mean difference [95% CI]: 7.3 [7.2-7.3] years). Combining the data from the baseline survey and subsequent two resurveys (mean [SD] prospective period: 8.0 [0.8] years), this study captured on average 50 years of fuel use and cookstove ventilation data between 1960's and 2014 (**Figure 5.2 and Appendix E2**).

There were profound differences in the HAP exposures between urban and rural residents. At baseline, over 85% of rural residents reported using solid fuels (coal and wood) for cooking or heating and only about 21% had ventilation for all cookstoves. In contrast, only about 10% of urban residents used solid fuels for cooking and 75% had ventilation for all cookstoves. Although most urban residents used clean fuels (gas or electricity) for cooking, almost a quarter still relied on solid fuels for heating at baseline, mostly in Qingdao (where 60% used coal) and in Suzhou (where 25% used wood).

Users of solid fuels or unventilated cookstoves were older, more likely to be female and had lower level of education and income (**Table 5.1**). Compared to the participants who

used solid fuels for cooking, those who used clean fuels were more likely to have also used clean fuels for heating or have complete cookstove ventilation, both in rural and urban areas, but almost two-thirds of the rural residents who used clean fuels for cooking still used coal or wood for heating in rural areas. Similarly, participants who used clean fuels for heating tend to have complete cookstove ventilation compared to those who used solid fuels (**Table 5.2**).

### 5.4.2 Temporal trends and regional variation of solid fuels use and ventilation condition

Coal and wood were the main cooking fuels in the antepenultimate residence of both rural ($YSL_{median\ [IQR])}$: 1969 [1960-1979], 98%) and urban ($YSL_{median\ [IQR]}$: 1978 [1967-1986], 75%) participants, but the urban residents adopted clean fuels more rapidly, with only 12% reporting always using solid fuels throughout the recall period (circa 1978-2008), as opposed to 85% among rural residents (circa 1969-2008). However, the changing pattern of clean fuel use as a primary fuel source during 2004-2014 appeared to be more rapid in rural areas **(Figures 5.4(a) and 5.5(a))**.

The pace of heating fuel modernisation was much slower than that of cooking fuel. In rural areas, nearly all used solid fuels for heating in the 1960's (antepenultimate residence $YSL_{median\ [IQR]}$: 1964 [1954-1971]), and over 91% throughout the recall period, and still as high as 72% in 2013-2014 (second resurvey). Likewise, the majority (75%) of urban residents used solid fuels for heating in the 1970's (antepenultimate residence $YSL_{median\ [IQR]}$: 1972 [1961-1984]), but most (96%) had switched to clean fuels by the time of the second resurvey (**Figures 5.4(b) and 5.5(b)**).

The long-term trends in ventilation broadly coincided with changes in cooking fuel, but the adoption of complete ventilation was slower than that of clean cooking fuels, especially in rural areas, where there was an accelerated rate of adoption after 2008. In urban areas, however, the proportion of complete ventilation increased rapidly from 20%

in the antepenultimate residence ($YSL_{median\ [IQR]}$: 1974 [1963-1984]) to about 87% at the second resurvey (2013-2014) (**Figures 5.4(c) and 5.5(c)**). The temporal patterns of types of cooking fuel and cookstove ventilation combined was consistent with that of cooking fuel. However, alongside the increase of clean fuel use, the proportion without ventilated cookstoves among clean fuel users has decreased from 37% to 11% in urban areas but has gone up from 22% to 38% in rural areas (**Figure 5.6**).

Fuel transition was observed across participants with different socioeconomic background, but the change from solid to clean fuels during 1960's to 2010's was more rapid among those with high school or above education, or having the highest category of annual household income (≥35,000 Yuan, i.e. ~£4,025), and was more accentuated in urban areas. For illiterate rural residents and those with low annual household income (<10,000 Yuan, i.e. ~£1,150), there was a modest decrease in the proportion (-2.0 and -4.5 percentage points, respectively) with complete ventilation from 1970's to 1990's, but have since recovered thereafter (**Figures 5.7-5.10**).

Considerable variation existed in temporal trends of HAP exposures across the ten study areas, such that the site-specific rates of fuel transition or ventilation uptake differed not only in magnitude, but at times qualitatively from the overall picture. For example, in urban Qingdao a relatively large proportion of participants reported to use coal for heating (53% in 2008 and 11% in 2013-2014) despite the fact that gas or electricity was almost exclusively used as primary fuel for cooking during the same period. In contrast, in semi-urban Suzhou (**Figures 5.11(h) and 5.12(g)**) and rural Sichuan (**Figures 5.11(d) and 5.12(c)**), heating fuel had modernised more quickly than cooking fuel. In Gansu, a downward trend was observed in the proportion of complete cookstove ventilation, which was contrary to the other four rural areas (**Figure 5.13(e)**). The temporal trend of cooking fuel and cookstove ventilation in semi-urban Suzhou is more similar to other rural areas such as Zhejiang, which is a relatively affluent rural province, especially during the 1970's to 1980's (**Figures 5.11(a) and 5.11(h)** for

cooking fuel; **5.13(a) and 5.13(h)** for ventilation). Finally, the proportion reporting the use of heating increased from 62% to 65% over the past five decades, primarily driven by the uptake in Suzhou, Liuzhou and Sichuan via electricity (**Table 5.3**). Of note, by the time of the second resurvey (2013-2014), 13% of the participants in Zhejiang reported to have heating (92% by electricity), but prior to that <1% had used heating in the three most-recent residences at baseline or at the first resurvey.

### 5.4.3 Estimated population life-course exposure by birth cohorts

Overall, there were substantial differences across birth cohorts in both the rate of fuel transition and the average age at which they switched fuel. The younger generation moved away from solid fuels more rapidly than their older counterparts, and also at a younger age. Such intergenerational disparities widened over time in rural areas but were generally attenuated in urban areas as the older generation eventually switched fuels (**Figures 5.14 and 5.15**). As for cookstove ventilation, birth cohort differences were observed only in urban areas (**Figure 5.16**).

### 5.4.4 Sensitivity analysis

Compared to the overall study sample, participants whose residential recall period covered their entire adulthood were slightly younger (mean [SD]: 49.4 [10.4] years) but, on average, had a longer recall period (46.7 [11.2] years) and the difference between rural and urban residents was markedly smaller (mean difference [95% CI]: 1.8 [1.7-1.9] years). The overall temporal trend of HAP-related exposures were largely consistent in the sensitivity analysis, with rural residents showing a considerably higher percentage of solid fuel use or no complete cookstove ventilation across the five residential periods, especially in the antepenultimate residence, where the $YSL_{median}$ was about 10 years earlier than the overall study sample (**Figure 5.17**).

## 5.5 DISCUSSION

In a Chinese cohort of 0.5 million adults, there was a clear rural-urban difference in the regional variation and temporal trends in household cooking and heating fuel use and availability of cookstove ventilation, with an overall transition from solid to clean fuels and improved ventilation but rural areas were substantially lagging behind during the past five decades. The transition in cooking fuel started much earlier than that for heating fuel. The pace of fuel transition was strongly related to socioeconomic factors, with more rapid changes in individuals who were more educated or had higher household income, regardless of their area of residence. There were also significant birth cohort differences in the pattern of fuel use. Although the majority of the urban residents used clean fuels at baseline, a large proportion of them had used solid fuels previously.

### 5.5.1 Cooking fuel use

Several nationwide surveys have previously examined the patterns of solid fuel use for cooking in China.[169-173] Overall, they showed a general shift from solid to clean fuels, with the recent nationwide surveys showing almost 50% of individuals in China continue to use solid fuel for cooking in 2010 and about 40% in 2012,[169,170] similar to the estimates obtained in our study (48% in 2008), which was not designed to be nationally representative. A recent report based on data from periodic China Health and Nutrition Surveys (CHNS) has also examined the trends in cooking fuel in about 2,000 rural households from nine provinces between 1989 and 2011.[171] During these two decades, they reported a rapid reduction of primary use of solid fuels for cooking among rural residents (from 75% to 35%),[171] broadly similar to the magnitude of change observed (from 85% to 47% during the similar time period) among our rural participants, more of whom were recruited from less-developed rural localities compared with CHNS. In CKB, there was a recent rapid increase of clean fuels for cooking between 2008 and 2013-

2014 (from 48% to 73%), which was primarily driven by the transition consistently observed across rural areas (from 22% to 52%). Of note, there were important differences in cooking fuel use in the five urban areas too. In the more developed urban areas (e.g. Harbin and Qingdao) almost all participants used gas or electricity as their primary cooking fuel, but in Haikou and Suzhou wood remained an important fuel source as many participants (especially those who were older or had lower levels of education or income) were living in semi-urban communities where there was an abundant local supply of firewood.

### 5.5.2 Heating fuel use

Both globally and in China, data on heating fuel use have been scarce.[3,174] The cross-sectional CEERHAPS study reported a smaller proportion of rural residents using solid fuels for heating (62% in 2012 versus 72% in CKB in 2013-2014), and a much higher proportion among urban residents (23% versus 4%).[169] The discrepancy regarding urban areas may be due to the inclusion of several traditionally coal-reliant provinces (e.g. Shandong) in CEERHAPS where coal-fired heating is particularly common in cities. In CKB we also found that participants from Qingdao (the largest city in Shandong) had the highest proportion of coal users among all urban areas (**Figure 5.16**).

To the best of our knowledge, this study is the first to investigate the long-term trends in heating fuel use in China. The overall modernisation trend of heating fuel has been substantially slower than that of cooking fuel, both in rural and urban areas. Most (91%) of the rural residents used solid fuels for heating throughout the recall period prior to the baseline survey, and this was also observed in over a quarter of the urban residents. This may be related in part to the longstanding policy and research agenda that focused on modernising cooking fuel and technology but overlooked heating fuel use.[3,159] As highlighted in **Section 2.2.2**, solid fuel use for heating is an important source of HAP in addition to that of cooking.[32] The significantly slower trends of modernisation of heating

fuel observed in CKB warrant further studies to better understand the barriers and promoters for individuals to adopt clean fuels for heating and to inform policy interventions to promote clean heating energy (e.g. subsidised heating scheme).

In China, subsidised city-wide central heating systems are traditionally available only in regions to the north of Huai River and Qinling Mountains, an arbitrary geographical cut-off set by the Chinese government in the 1950's.[161] Although the central and southern parts of China have shorter and milder winter, there has been growing public demand of subsidised heating in recent years. During 2004-2014, there were increased coverage of home heating, mainly powered by electricity (but not solid fuels or central heating), in the central and coastal study areas to the south of the Huai River-Qinling Mountains cut-off (Suzhou, Liuzhou, Sichuan and Zhejiang). They may be related to the increasingly affordable and accessible electricity supply especially in rural areas,[175] which was also reflected by the increasing expenditure on electricity.[176] Despite this, about 72% rural residents in CKB still used solid fuels for heating in 2013-2014, lagging behind urban residents by approximately 40 years. Meanwhile in Qingdao, amidst the recent rapid expansion of district heating coverage in the city (up to 89% in CKB in 2013-2014; 82% in 2015 according to the city government),[177] the share of coal use for heating fell substantially from 53% in 2008 to 11% in 2013-2014.

### 5.5.3 Cookstove ventilation

During 1982-92 China distributed 130 million improved cookstoves under the National Improved Stove Program.[178] While these cookstoves reportedly burn fuels more efficiently compared to traditional stoves, chimneys were not always installed.[4,179] In our study, there was a relatively modest rate of ventilated cookstove uptake in rural areas during 1955-2008, but apparently a more rapid rise post-2008. Little published evidence on the distribution of ventilated cookstoves is available, but the recent rising trend may be related to the expansion of the commercial market and recent public-private

initiatives promoting improved cookstoves in China.[159,177,180] The trend was generally consistent with the switch to clean cooking fuels in our urban participants. In our rural participants, however, the proportion of clean fuel use without ventilation increased considerably as less people used solid fuels, possibly related to cost implications.[174] For example, in Gansu (one of the least developed region in China) the proportion of participants with complete ventilation decreased alongside increased use of clean cooking fuel, whereas participants in Zhejiang, a more affluent rural area, we observed a trend for adoption in parallel. It is also possible that rural residents could switch to different types of clean fuels without a perceived need for ventilation (e.g. unvented gas stove).

### 5.5.4 Relationship between cooking fuel, heating fuel and cookstove ventilation

Not-surprisingly, collinearity exists between solid fuel use for cooking and heating and the lack of cookstove ventilation, with those having exposed to one factor being more likely to be exposed to the other two. It is, however, worth noting that while incomplete cookstove ventilation (compared to complete ventilation) and wood use (compared to coal and clean fuels) are both associated with lower SES, individuals who used coal for cooking were more likely to have incomplete cookstove ventilation than wood users. The complex interrelation (beyond simple collinearity) is also reflected in the differential exposure patterns of cooking and heating fuel use, with the prior disproportionately affecting individuals who cooked regularly (mostly females) and the latter being highly region-specific (e.g. >99% participants from two areas did not use heating). This support the *a priori* design to examine the prospective association of solid fuel use for cooking and heating in relation to the disease outcomes of interest separately (as described in **Section 4.5**).

### 5.5.5 Population-level life-course exposure patterns across birth cohorts

In CKB, the disparities of HAP exposures persisted trans-generationally both within and across rural and urban areas, highlighting important birth cohort differences in adoption of clean fuels and ventilation. In particular, not only were the rates of switching from more polluting fuels to cleaner fuels slower in older birth cohorts, their life-course trajectories were more consistent with the traditional pathway of transition from wood to coal and to clean fuels (as illustrated in **Figure 2.1**),[6] whereas the younger cohorts were more likely to have switched to clean fuels directly. In the context of the theory of diffusion, cleaner or more energy efficient fuels and ventilated cookstoves could be considered as innovations in a traditional, solid fuel-reliant society.[181] As such, younger and more affluent individuals tend to be the early adopters, subsequently followed by most others and leaving behind a small number who are reluctant to change.[181,182] Urban residents in CKB were younger and they moved house more frequently than rural residents (shorter mean recall period, with mean difference [95% CI]: 7.3 [7.2-7.3] years), so they might also have more opportunity to switch to clean fuels, as it often requires structural changes in the corresponding facilities and dwelling environment. Other societal factors such as faster rate of electric grid expansion, increasing availability and affordability of modern fuels and decreasing availability of solid fuels may also explain the quicker fuel or ventilation modernisation trend in urban areas.[174] The sequentially lower prevalence of early-life exposure in younger generations underlies the epidemiological transition of decreasing HAP-related disease burden in children, but the burden in rural elderly, many of whom continued to use solid fuels, might have proportionately increased as other traditional risk factors such as infectious diseases diminish and the population ages.

### 5.5.6 Strengths and limitations

The main strengths of this study lie in the scale and diversity of the participants, covering 0.5 million adults across 10 urban and rural areas of China. Moreover, I simultaneously examined three key determinants of HAP exposure (cooking, heating and ventilation), and for the first time, explored the life-course trajectories of HAP exposure across birth cohorts, which may be relevant for informing the changing disease patterns and future assessment of health risks associated with long-term HAP exposure.

There are also several limitations that merit discussion. First, the present analyses utilised self-reported residence-based data in constructing the historical evolution of HAP exposures and the exposure information is limited to each residence such that we were not able to capture changes in exposure within the period of residence. As the self-reported residential period could vary substantially across individuals (e.g. younger participants tended to move more frequently), the temporal trends described are not necessarily applicable to individual participants. Nonetheless, the residential recall period in the study population follows a Gaussian distribution and, with the large sample size and diversity of the CKB, the time of changing residence between individuals is reasonably arbitrary after adjustment for age, gender and study area and the within-person reporting errors could be compensated across individuals to give a fair approximation of trends across distinct time periods (represented by median and IQR of calendar year) at the population level. Furthermore, to minimise bias, I excluded all participants with potentially unreliable recall information and also undertook sensitivity analyses in participants whose recall period covered their entire adulthood, which showed highly consistent overall downward trends of solid fuel use for cooking and heating.

Similar to the previous multi-region studies, there was no data on mixed use of fuels, which is common in rural areas where complete transition to clean fuels is difficult.[171,183]

Therefore, the trend of “switching” to clean fuels in China, as found in this chapter, has to be interpreted with caution as it may be that solid fuels are used as auxiliary fuels in homes reported using primarily clean fuels. As parallel use of clean and solid fuels could result in HAP exposure similar to using solid fuels alone,[5] so the use of primary fuel type data may result in underestimation of the total HAP exposure in the population.

Limited by the questionnaire design, the duration of exposure to different fuel types can only be approximated through residential duration in a semi-quantitative manner, as the exact timing of fuel switching may not necessarily coincide with the time of residence change. Together with the potential misclassification due to secondary fuel use, attempts to quantify the extent (e.g. duration) or lag structure of exposure may be subject to greater risk of bias compared to qualitative classification of long-term exposure status. Therefore, the prospective analyses in **Chapters 6 and 7** were based primarily on categorical long-term exposure status and the analyses on approximated exposure duration should be interpreted with caution, although it may still provide indirect evidence on the dose-response relationships of the outcomes of interest.

## 5.6 CONCLUSIONS

In the study population, many rural communities remained users of solid fuel despite the rapid economic development in China over the past 50 years. I have identified the trans- and inter-generational difference across rural and urban areas, and highlighted the under-recognised slower trends of modernisation of heating fuel and availability of ventilated cookstove, as well as the regional variation of such time trends. Household air pollution is a major challenge not only to global health but also poverty, gender equality and climate change.[184] These findings underscore the urgency of region-specific strategies to address the prolonged inequalities across rural and urban areas and socioeconomic subgroups and to promote access to clean household energy in China. Beyond China, fuel modernisation in many LMICs has been comparatively slow.[1]

Further investigation to understand the potential drivers of the recent rapid transition in rural China and to evaluate the recent effort in promoting cheap and sustainable energy and large scale distribution of new-generation ventilated low-emission stoves[159,185] could provide useful insights and strategies for other LMICs. For future epidemiological investigations on the public health impact of HAP from solid fuel use, the distinctive exposure patterns and time trends for cooking and heating fuel use in the study population warrant separate analysis for the two exposures. Additionally, the historical HAP exposure amongst individuals who had switched from solid to clean fuels must be taken into account.

**Table 5.1 Baseline characteristics by household air pollution exposures in rural and urban areas***

| Characteristics | Cooking fuel† | | | Heating fuel‡ | | | Cookstove ventilation§ | | | Overall¶ |
|---|---|---|---|---|---|---|---|---|---|---|
| | Clean fuels | Coal | Wood | Clean fuels | Coal | Wood | Complete | Partial | None | N |
| **RURAL AREAS** | | | | | | | | | | |
| **N** | 29,175 | 99,272 | 68,035 | 15,455 | 90,050 | 65,968 | 58,765 | 129,910 | 95,536 | 284,573 |
| **Age (SD), year** | 48.2 (9.8) | 51.9 (10.1) | 55.5 (10.6) | 48.6 (10.4) | 50.9 (10.4) | 52.3 (10.8) | 50.4 (10.6) | 51.4 (10.4) | 51.7 (10.7) | 51.5 (10.5) |
| **Gender, %** | | | | | | | | | | |
| Female | 69.7 | 78.2 | 78.5 | 55.6 | 58.7 | 60.2 | 56.9 | 58.3 | 59.5 | 58.5 |
| Male | 30.3 | 21.8 | 21.5 | 44.4 | 41.3 | 39.8 | 43.1 | 41.7 | 40.5 | 41.5 |
| **Highest attained education, %** | | | | | | | | | | |
| No formal | 15.6 | 21.5 | 27.4 | 9.7 | 18.7 | 21.1 | 20.7 | 23.8 | 25.4 | 23.9 |
| Primary | 34.3 | 42.6 | 45.6 | 32.3 | 41.5 | 44.9 | 35.8 | 42.5 | 41.9 | 41.8 |
| Middle school or above | 50.1 | 35.9 | 26.9 | 58.0 | 39.8 | 34.0 | 43.5 | 33.7 | 32.7 | 34.3 |
| **Annual household income, %** | | | | | | | | | | |
| <10,000 Yuan | 25.8 | 40.3 | 53.8 | 26.6 | 47.0 | 44.9 | 30.2 | 36.1 | 42.8 | 39.7 |
| 10,000-19,999 Yuan | 28.8 | 28.2 | 23.1 | 32.0 | 31.5 | 31.8 | 27.3 | 29.4 | 27.5 | 28.8 |
| ≥20,000 Yuan | 45.5 | 31.5 | 23.1 | 41.4 | 21.6 | 23.3 | 42.6 | 34.5 | 29.7 | 31.5 |
| **URBAN AREAS** | | | | | | | | | | |
| **N** | 164,249 | 2,915 | 13,634 | 88,767 | 24,480 | 4,561 | 168,303 | 32,035 | 25,290 | 226,016 |
| **Age (SD), year** | 52.4 (10.5) | 56.8 (11.0) | 57.3 (10.6) | 51.2 (11.0) | 55.5 (10.5) | 54.6 (10.8) | 52.4 (10.6) | 55.2 (10.8) | 53.6 (11.1) | 52.8 (10.9) |
| **Gender, %** | | | | | | | | | | |
| Female | 68.9 | 67.8 | 69.7 | 58.4 | 64.2 | 57.9 | 59.3 | 61.2 | 58.5 | 59.6 |
| Male | 31.1 | 32.2 | 30.3 | 41.6 | 35.8 | 42.1 | 40.7 | 38.8 | 41.5 | 40.4 |
| **Highest attained education, %** | | | | | | | | | | |
| No formal | 10.7 | 13.9 | 24.2 | 8.1 | 6.8 | 10.6 | 9.4 | 15.0 | 17.6 | 11.9 |
| Primary | 19.4 | 28.1 | 32.2 | 15.8 | 20.3 | 18.1 | 18.3 | 24.1 | 27.4 | 20.1 |
| Middle school or above | 69.9 | 58.1 | 43.6 | 76.2 | 72.8 | 71.3 | 72.3 | 60.9 | 55.0 | 68.1 |
| **Annual household income, %** | | | | | | | | | | |
| <10,000 Yuan | 12.2 | 27.7 | 39.8 | 7.8 | 22.2 | 23.2 | 9.4 | 19.5 | 30.1 | 13.6 |
| 10,000-19,999 Yuan | 29.0 | 36.0 | 33.2 | 24.4 | 34.8 | 42.2 | 26.7 | 35.5 | 37.5 | 29.2 |
| ≥20,000 Yuan | 58.8 | 36.3 | 27.0 | 67.9 | 43.0 | 34.7 | 64.0 | 45.0 | 32.4 | 57.2 |

* Percentages and means were adjusted for age, gender and study area where appropriate, $\chi^2$ p-value of all association <0.001 in logistic regression. Clean fuels includes gas, electricity and central heating (for heating only).

† Participants who never/ rarely cooked or reported using 'other' fuel were excluded ($n_{rural}$ = 88,091; $n_{urban}$ = 45,218).

‡ Participants from Haikou (n=29,632) and Zhejiang (n=57,685) where >99% participants reported no heating, and participants from other areas who reported no heating ($n_{rural}$ =52,518; $n_{urban}$ =78,474) or used 'other' heating fuel were further excluded ($n_{rural}$ = 1,897; $n_{urban}$ =102).

§ Participants who had no cooking facility at baseline were excluded ($n_{rural}$ = 362; $n_{urban}$ = 388).

¶ Overall number of participants at baseline, after excluding 2,302 participants whose recall period was greater than their age, total N = 510,589.

**Table 5.2. Cooking fuel, heating fuel and cookstove ventilation at baseline***

| Characteristics | Cooking fuel† | | | Heating fuel‡ | | | Cookstove ventilation§ | | |
|---|---|---|---|---|---|---|---|---|---|
| | Clean fuels | Coal | Wood | Clean fuels | Coal | Wood | Complete | Partial | None |
| **RURAL AREAS** | | | | | | | | | |
| **Cooking fuel** | | | | | | | | | |
| Clean fuels | - | - | - | 34.5 | 6.4 | 4.6 | 28.3 | 12.1 | 11.4 |
| Coal | - | - | - | 56.8 | 65.9 | 55.5 | 45.2 | 50.0 | 52.7 |
| Wood | - | - | - | 8.8 | 27.7 | 40.0 | 26.4 | 37.9 | 35.9 |
| **Heating fuel** | | | | | | | | | |
| Clean fuels | 35.7 | 9.0 | 4.9 | - | - | - | 17.2 | 8.0 | 7.9 |
| Coal | 48.5 | 57.2 | 44.3 | - | - | - | 52.4 | 50.3 | 46.0 |
| Wood | 15.8 | 33.9 | 50.9 | - | - | - | 30.4 | 41.7 | 46.1 |
| **Cookstove ventilation** | | | | | | | | | |
| Complete | 37.9 | 19.6 | 16.5 | 44.3 | 20.8 | 18.5 | - | - | - |
| Partial | 34.4 | 43.9 | 52.1 | 28.2 | 40.0 | 43.2 | - | - | - |
| None | 27.7 | 36.5 | 31.4 | 27.5 | 39.1 | 38.3 | - | - | - |
| **URBAN AREAS** | | | | | | | | | |
| **Cooking fuel** | | | | | | | | | |
| Clean fuels | - | - | - | 97.4 | 74.8 | 76.8 | 98.4 | 75.1 | 82.5 |
| Coal | - | - | - | 0.3 | 23.9 | 6.6 | 0.6 | 5.8 | 8.4 |
| Wood | - | - | - | 2.3 | 0.5 | 12.8 | 1.0 | 19.1 | 9.0 |
| **Heating fuel** | | | | | | | | | |
| Clean fuels | 76.7 | 14.0 | 22.4 | - | - | - | 78.3 | 56.6 | 43.7 |
| Coal | 19.8 | 73.2 | 43.0 | - | - | - | 18.2 | 35.4 | 46.1 |
| Wood | 3.5 | 10.1 | 34.4 | - | - | - | 3.4 | 8.0 | 10.3 |
| **Cookstove ventilation** | | | | | | | | | |
| Complete | 79.4 | 32.2 | 23.0 | 88.1 | 54.8 | 51.8 | - | - | - |
| Partial | 10.1 | 32.6 | 46.8 | 8.8 | 25.4 | 25.7 | - | - | - |
| None | 10.5 | 35.2 | 30.2 | 3.2 | 19.8 | 22.5 | - | - | - |

* Percentages and means are adjusted for age, gender and region where appropriate, Clean fuels includes gas, electricity and district heating (for heating only); column percentage is displayed.

† Participants who never/rarely cook or reported using 'other' fuel were excluded (nrural = 88,091; nurban = 45,218).

‡ Participants from Haikou (n=29,632) and Zhejiang (n=57,685) where >99% participants reported no heating, and participants from other regions who reported no heating (nrural =52,518; nurban =78,474) or using 'other' heating fuel were further excluded (nrural = 1,897; nurban =102).

§ Participants who had no kitchen at baseline were excluded (nrural = 362; nurban = 388).

**Table 5.3 Percentages of winter heating and electricity use across five residential periods in Suzhou, Sichuan and Liuzhou***

| | Suzhou | | Sichuan | | Liuzhou | |
|---|---|---|---|---|---|---|
| **Residence** | **Winter heating** | **Electricity use†** | **Winter heating** | **Electricity use†** | **Winter heating** | **Electricity use†** |
| **Antepenultimate** | 2.3 | 31.5 | 9.6 | 11.0 | 19.4 | 11.8 |
| **Penultimate** | 4.3 | 71.0 | 9.9 | 18.3 | 21.2 | 30.9 |
| **Baseline** | 19.7 | 97.9 | 25.7 | 73.0 | 30.7 | 67.7 |
| **1st resurvey** | 16.9 | 96.9 | 16.3 | 89.1 | 27.2 | 78.5 |
| **2nd resurvey** | 24.1 | 99.3 | 16.1 | 99.1 | 45.2 | 96.0 |

*Percentages were adjusted for age and sex.
†Percentage of primary use of electricity for heating among those who reported having winter heating.

**Figure 5.1 (a) Flow chart of number of participants at each stage of analysis—recall period of baseline survey**

Recall period covered up to three most-recent residences counted from the time of baseline survey. Participants whose recall period was greater than their age at baseline were first excluded from all analyses; for cooking fuel, participants reported using “other” fuel or had never/ rarely cook or no kitchen were excluded; for heating fuel, participants from Haikou and Zhejiang, those reported using “other” fuel or had no heating (in the rest of the regions) were excluded; for cookstove ventilation, participants reported having no kitchen were excluded.

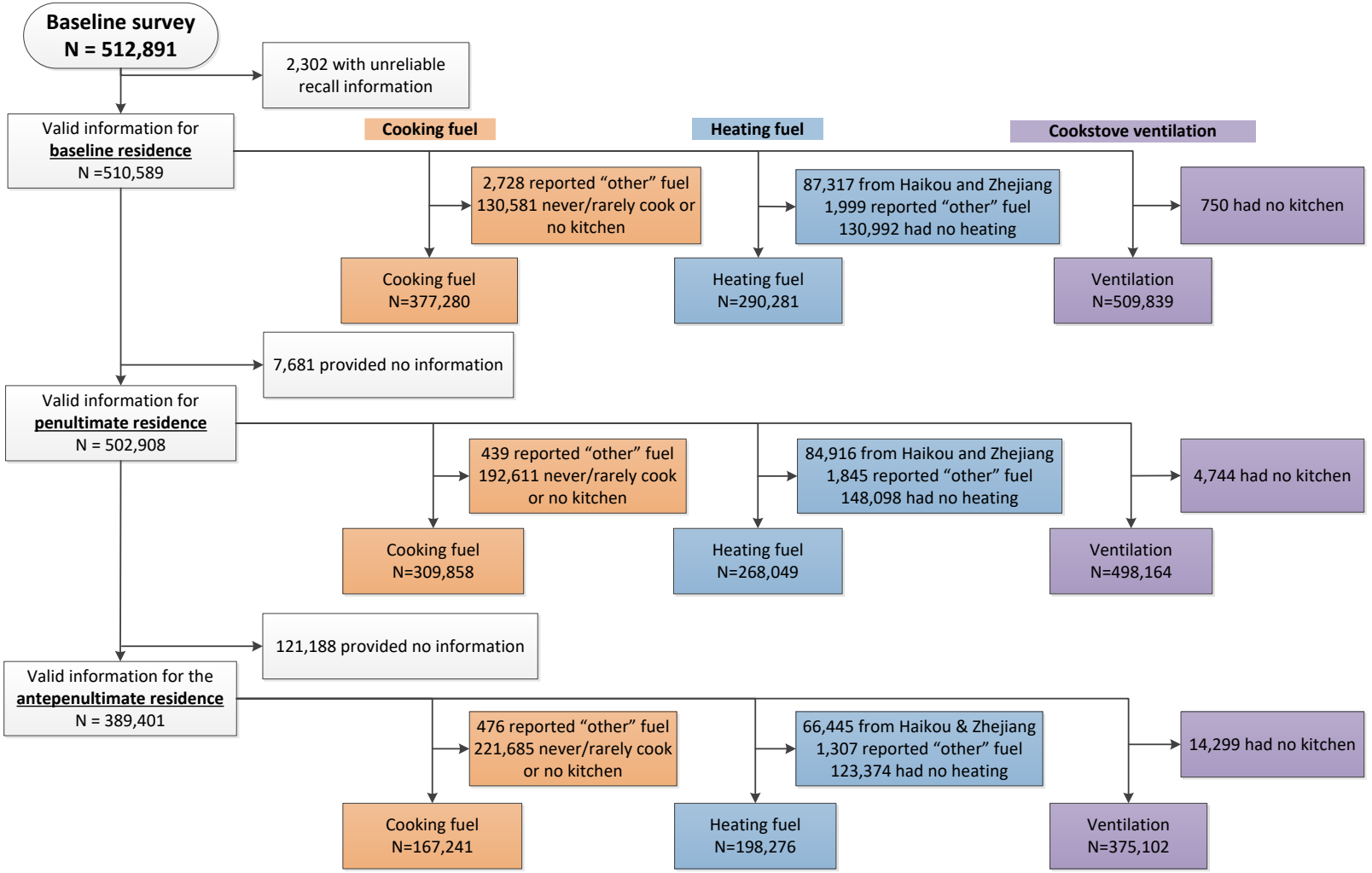


**Figure 5.1 (b) Flow chart of number of participants at each stage of analysis—first and second resurveys**

The first and second resurvey were conducted in 4 to 5% randomly sampled participants of baseline survey. Participants whose recall period was greater than their age at baseline survey were first excluded from all analyses; for cooking fuel, participants reported using “other” fuel or had never/ rarely cook or no facility were excluded; for heating fuel, participants from Haikou and Zhejiang those reported using “other” fuel or had no heating (in the rest of the regions) were excluded; for cookstove ventilation, participants reported having no kitchen were excluded.

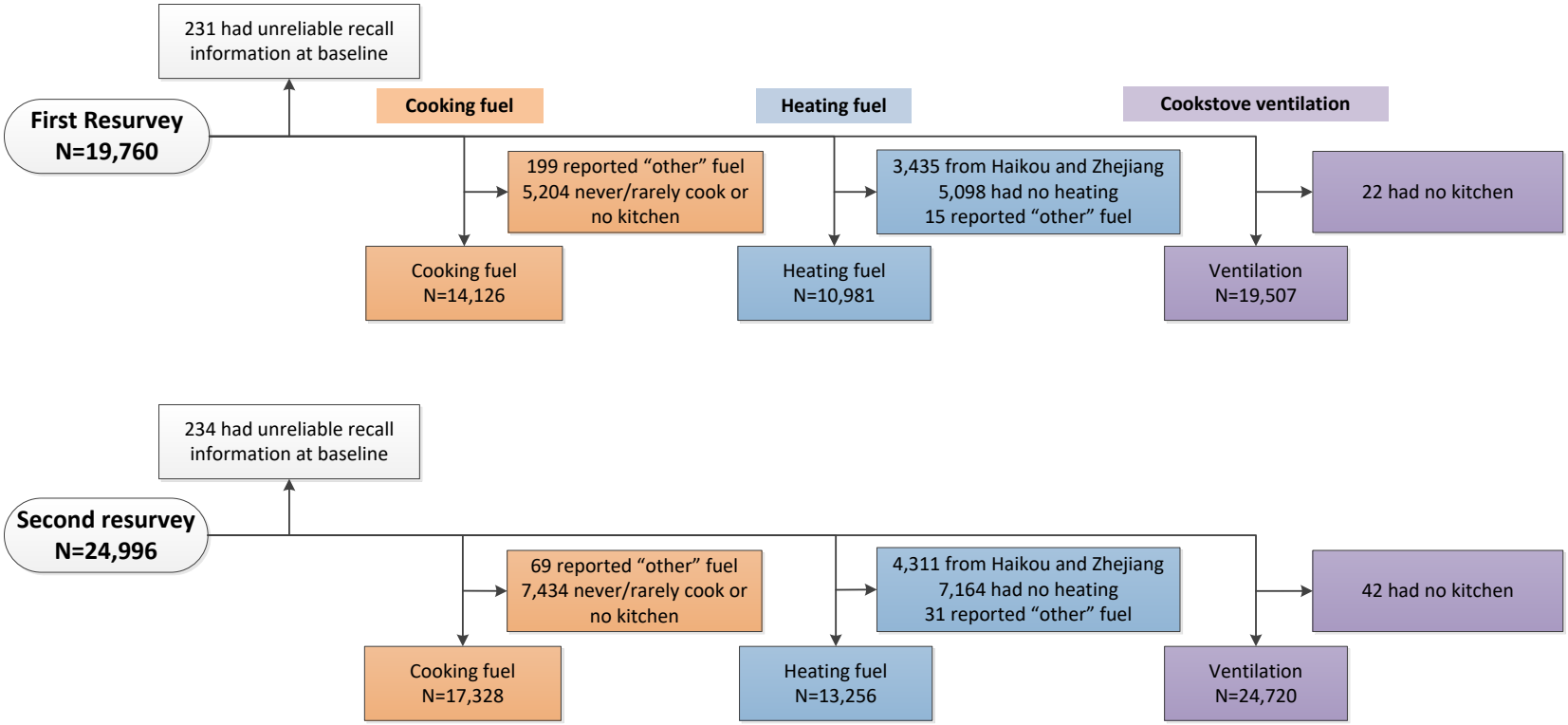


**Figure 5.2 Distribution of time started living in each house (blue) and time of resurvey interview (red)**

Box plots displaying hinges at 75th and 25th percentiles and vertical bold-line at median; four-digit numbers above median lines are equivalent calendar years of median (interquartile range); numbers on two-headed arrows are overall mean (standard deviation) of total recall and prospective periods in years counted from the date of the baseline survey (conducted in 2004-08). See **Appendix D2** for separated information for rural and urban participants.

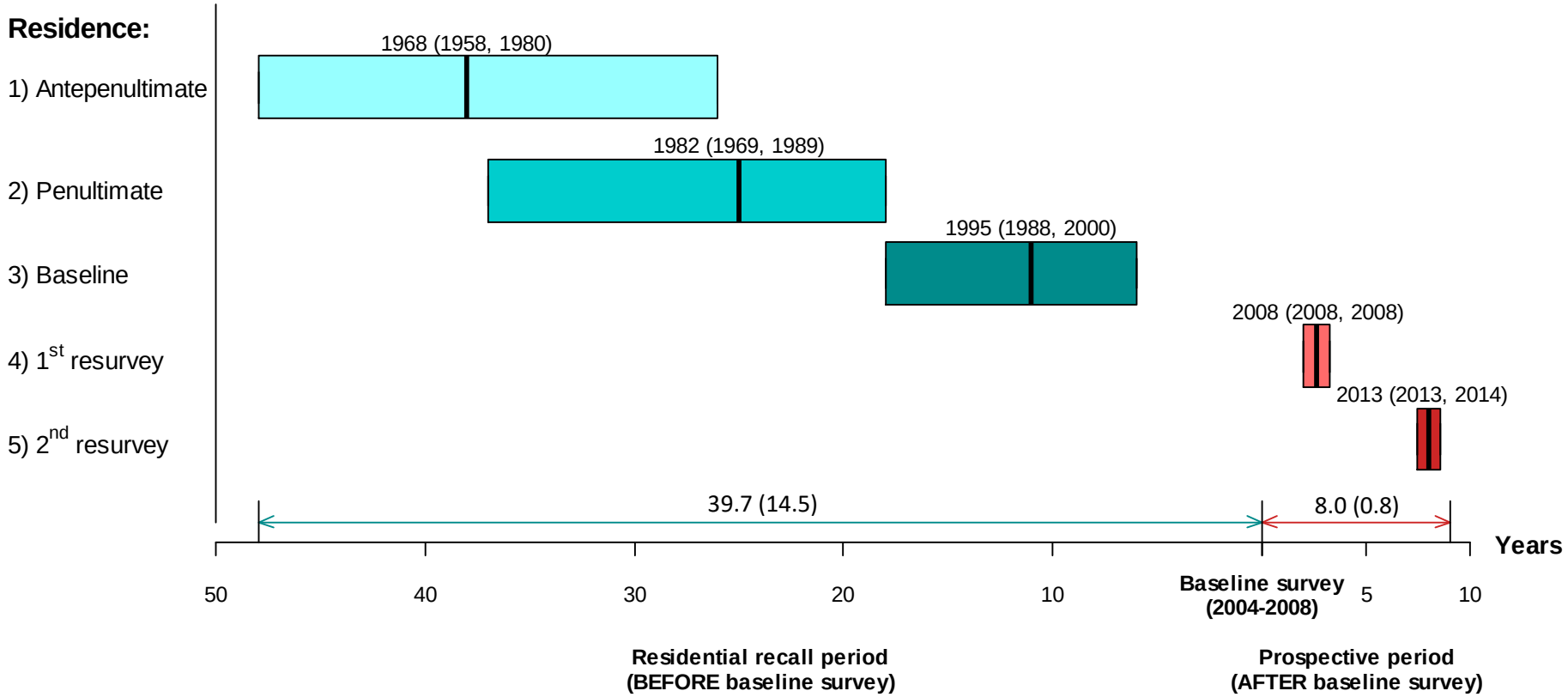


**Figure 5.3 Regional variation of types of (a) cooking fuel and (b) heating fuel; and (c) availability of cookstove ventilation**

Percentage estimates were adjusted for age and gender. Each chart is divided into two sections, with rural areas on the left and urban areas on the right. Areas are ordered by the percentages of solid fuel used for cooking in descending order from left to right. Participants from Haikou and Zhejiang were excluded from the analysis on heating fuel.

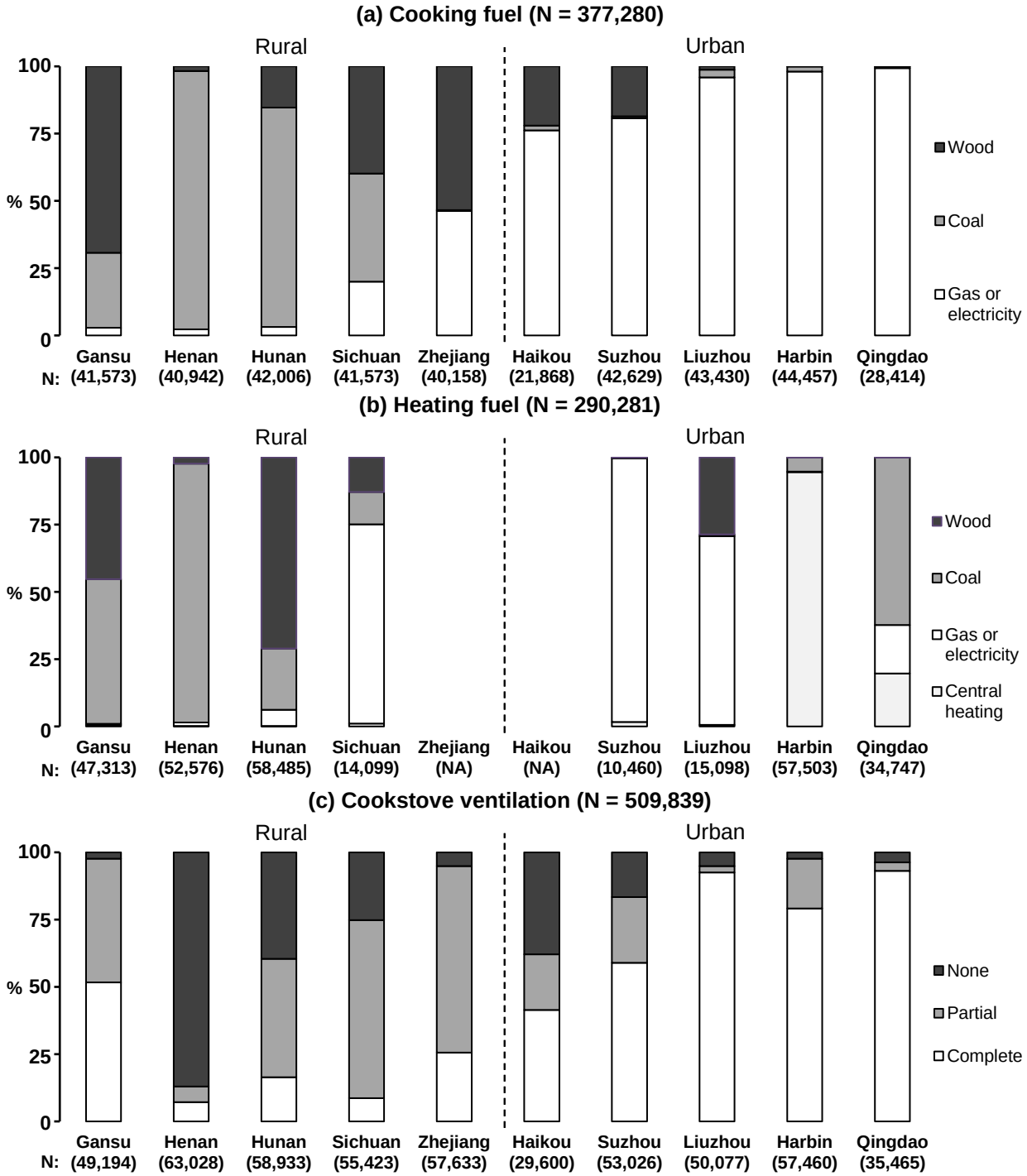


**Figure 5.4 Temporal pattern of self-reported primary fuel type for a) cooking and b) heating; and c) availability of cookstove ventilation, in urban and rural areas**

Percentage estimates were adjusted for age, gender and areas. X-axis labels are 1) the median calendar year when each of the three most-recent residences started and when 1st or 2nd resurvey was conducted; and 2) number of participants that provided information at respective time period/point. Clean fuels include gas, electricity and central heating (for heating only). Participants who never/rarely cooked, reported using 'other' fuel type or had no cooking facility were excluded from (a); participants who had no heating or from Zhejiang and Haikou and those reported using 'other' fuel type were excluded from (b); participants who had no kitchen were excluded from (c).

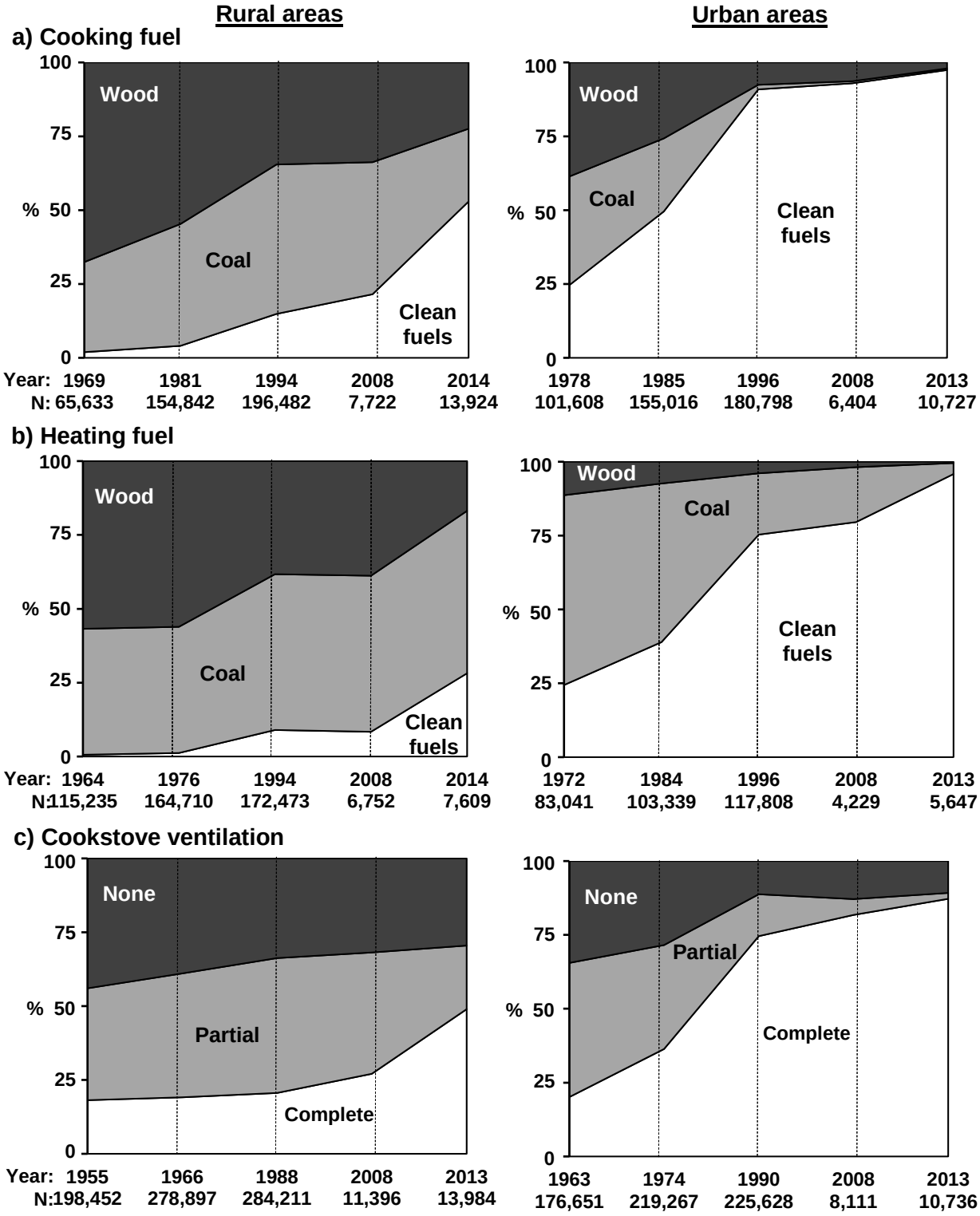
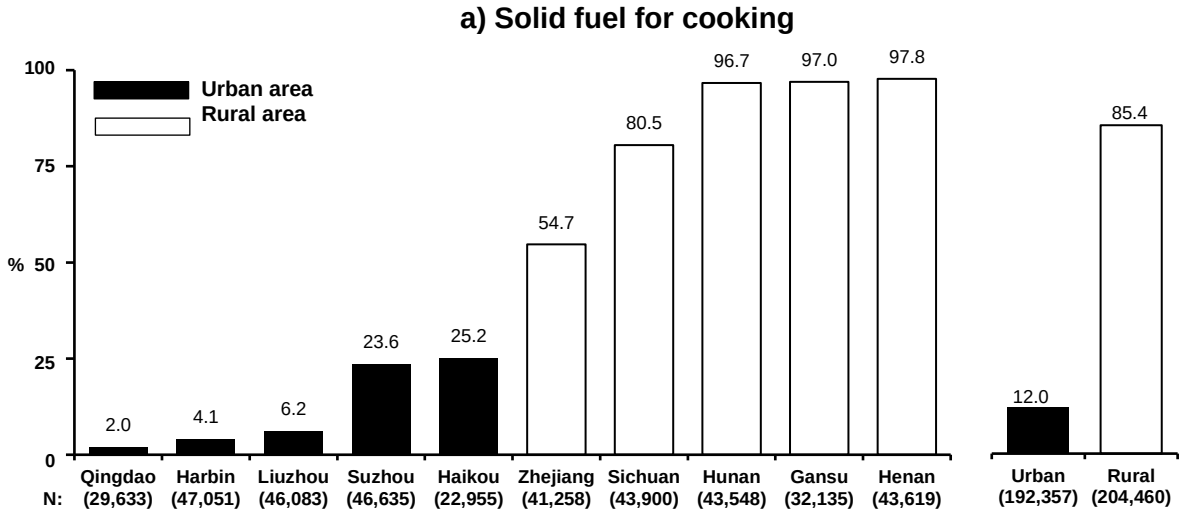
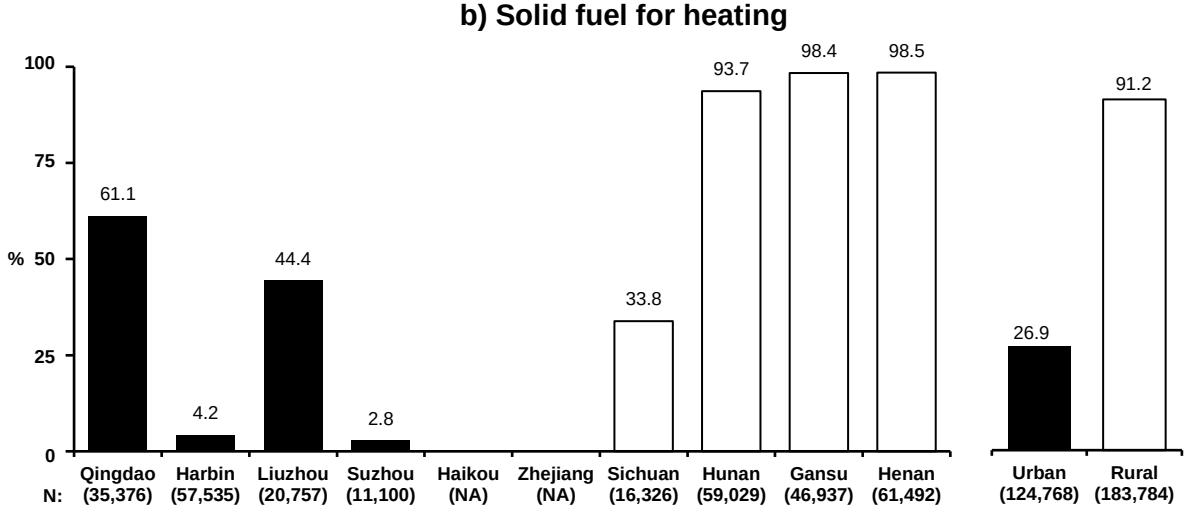


**Figure 5.5 Regional variation of self-reported primary fuel type for a) cooking and b) heating; and c) lack of cookstove ventilation throughout the three most-recent residences at baseline**

Long-term exposure was defined as the use of solid fuels or the absence of ventilated cookstoves in the three most-recent residences. Percentage estimates were adjusted for age and gender. Areas are listed in ascending order (from left to right) by the percentages of solid fuel use for cooking. Participants from Haikou and Zhejiang were excluded in (b).



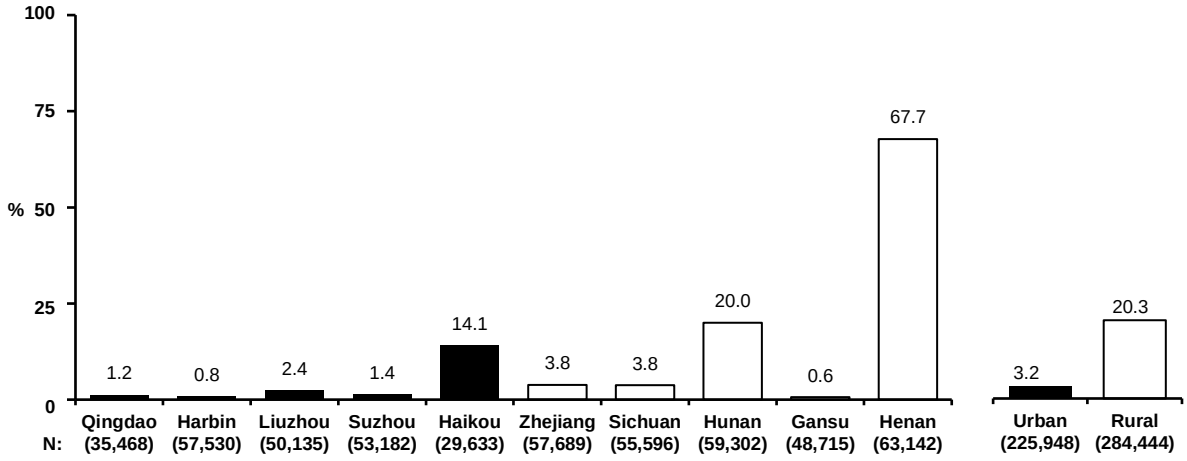



**Figure 5.6 Temporal pattern of self-reported primary fuel type for cooking and availability of cookstove ventilation (combined) by study time in rural and urban areas**

Percentage estimates were adjusted for age, gender and areas. X-axis labels are 1) the median calendar year when each of the three most-recent residences started and when 1st or 2nd resurvey was conducted; and 2) number of participants that provided information at respective time period/point. Clean fuels include gas and electricity. Participants who never/rarely cooked, reported using 'other' fuel type or had no cooking facility were excluded.

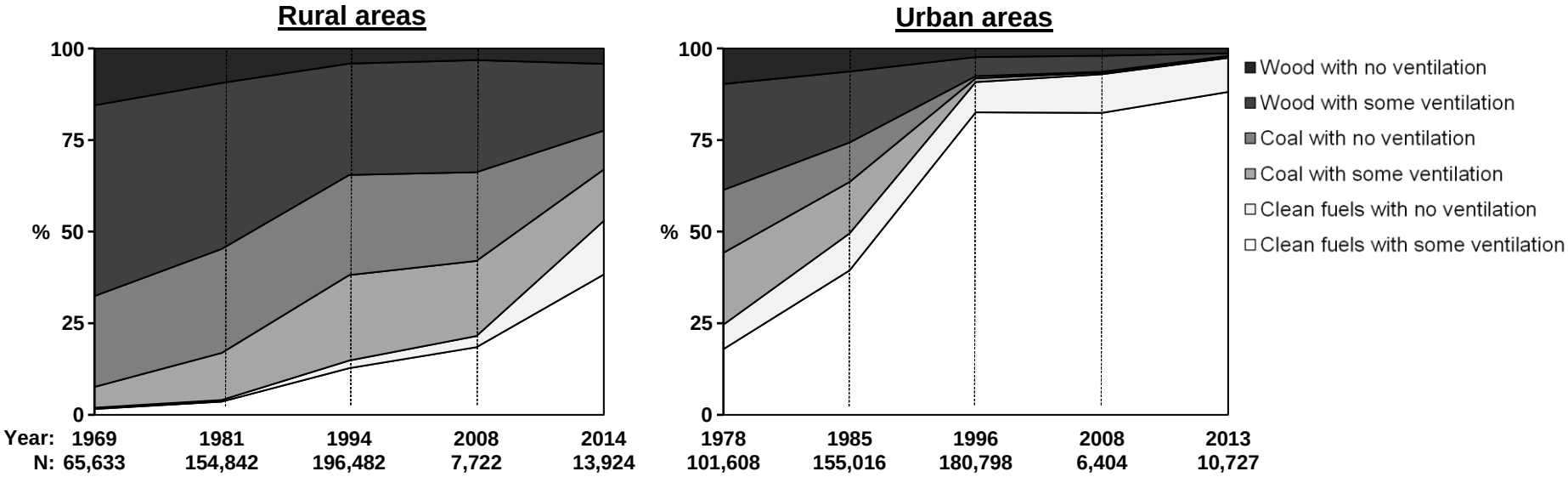


**Figure 5.7 Temporal pattern of self-reported primary fuel type for a) cooking and b) heating; and c) availability of cookstove ventilation by study time by education level in rural areas**

Conventions as Figure 5.4.

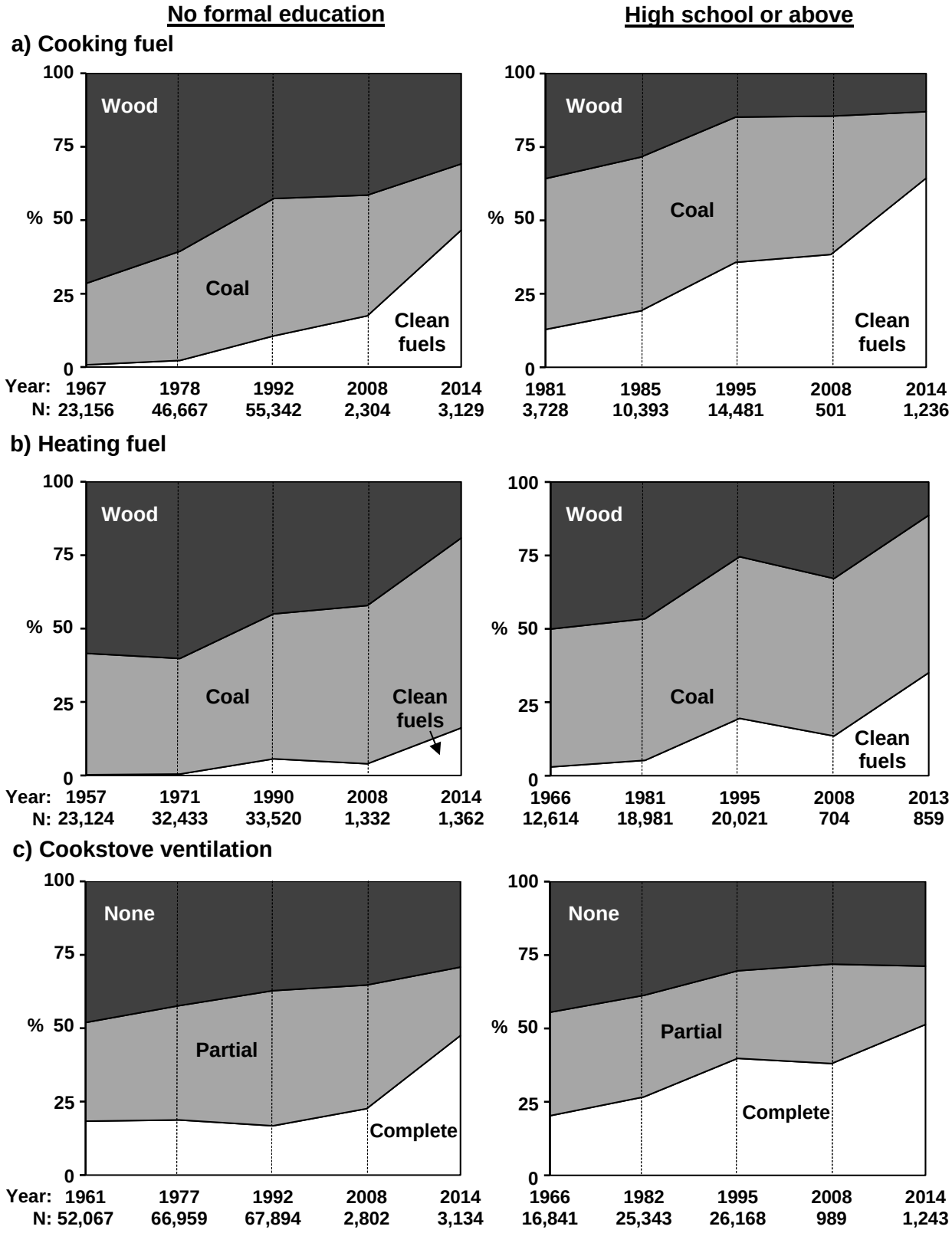


**Figure 5.8 Temporal pattern of self-reported primary fuel type for a) cooking and b) heating; and c) availability of cookstove ventilation by study time by education level in urban areas**

Conventions as Figure 5.4.

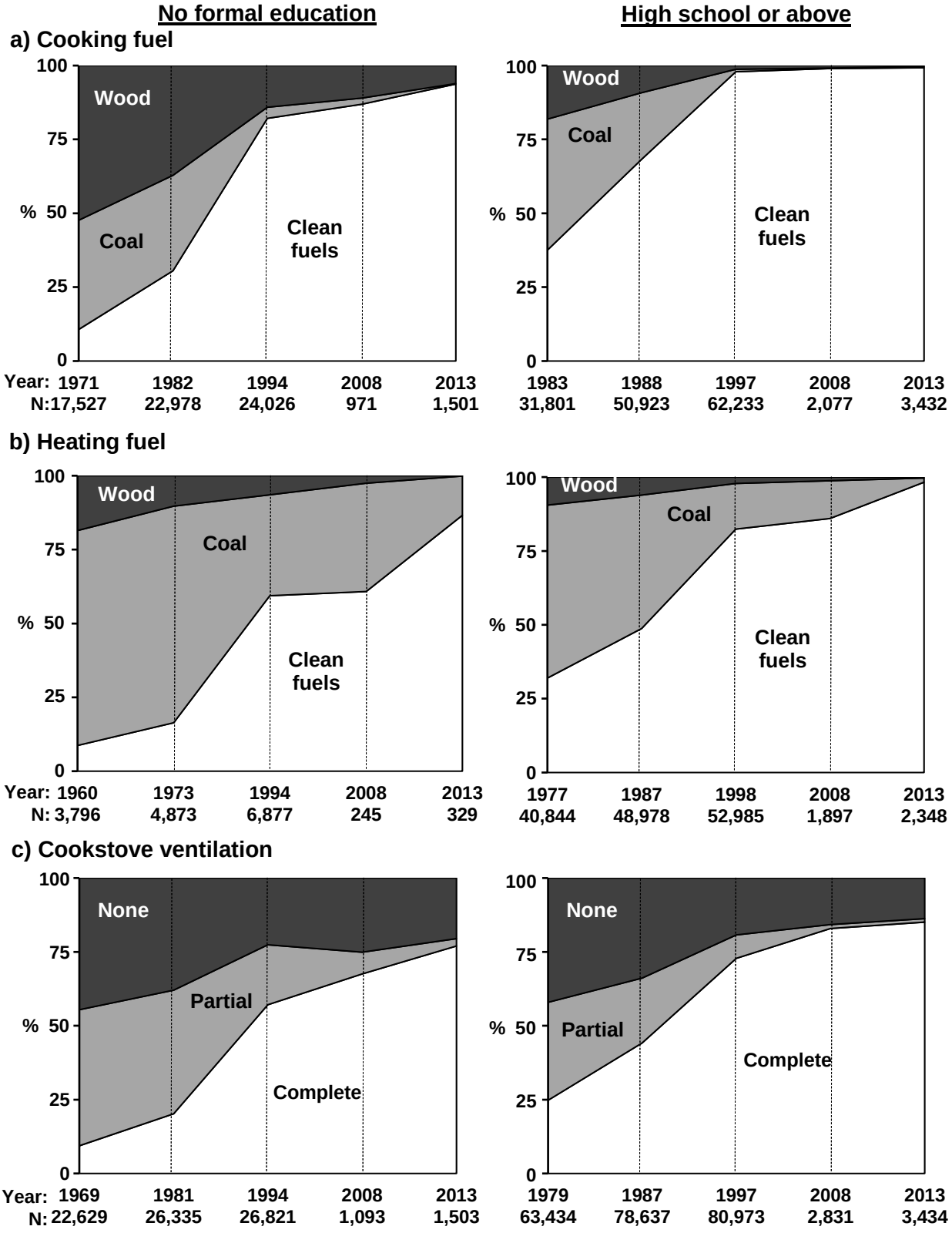


**Figure 5.9 Temporal pattern of self-reported primary fuel type for a) cooking and b) heating; and c) availability of cookstove ventilation by study time by household income level in rural areas**

Conventions as Figure 5.4.

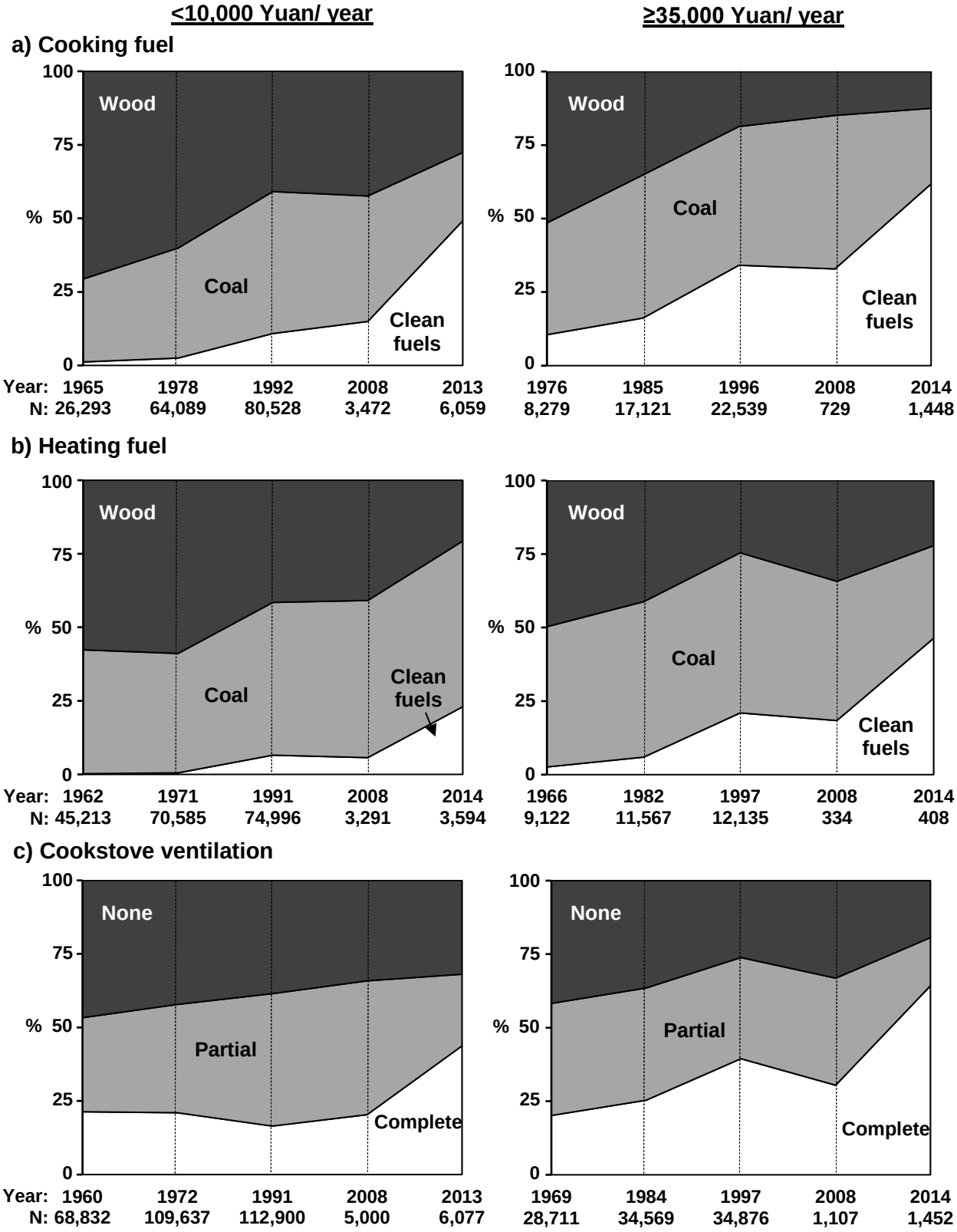


**Figure 5.10 Temporal pattern of self-reported primary fuel type for a) cooking and b) heating; and c) availability of cookstove ventilation by study time by household income level in urban areas**

Conventions as Figure 5.4.

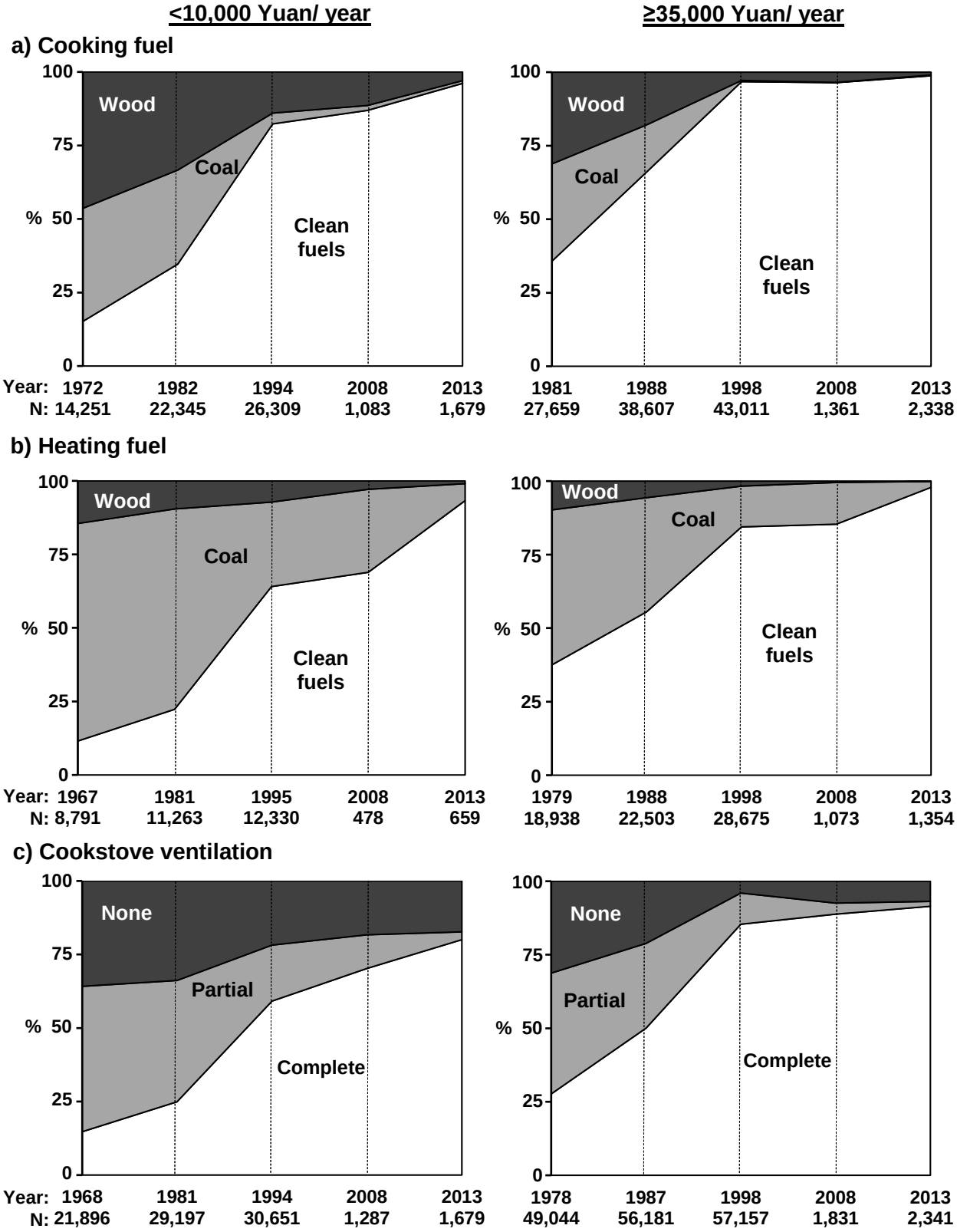


**Figure 5.11 Temporal pattern of self-reported primary cooking fuel type in 10 study areas by time**

Conventions as Figure 5.4. Rural areas are ordered from east to west; urban areas are from north to south.

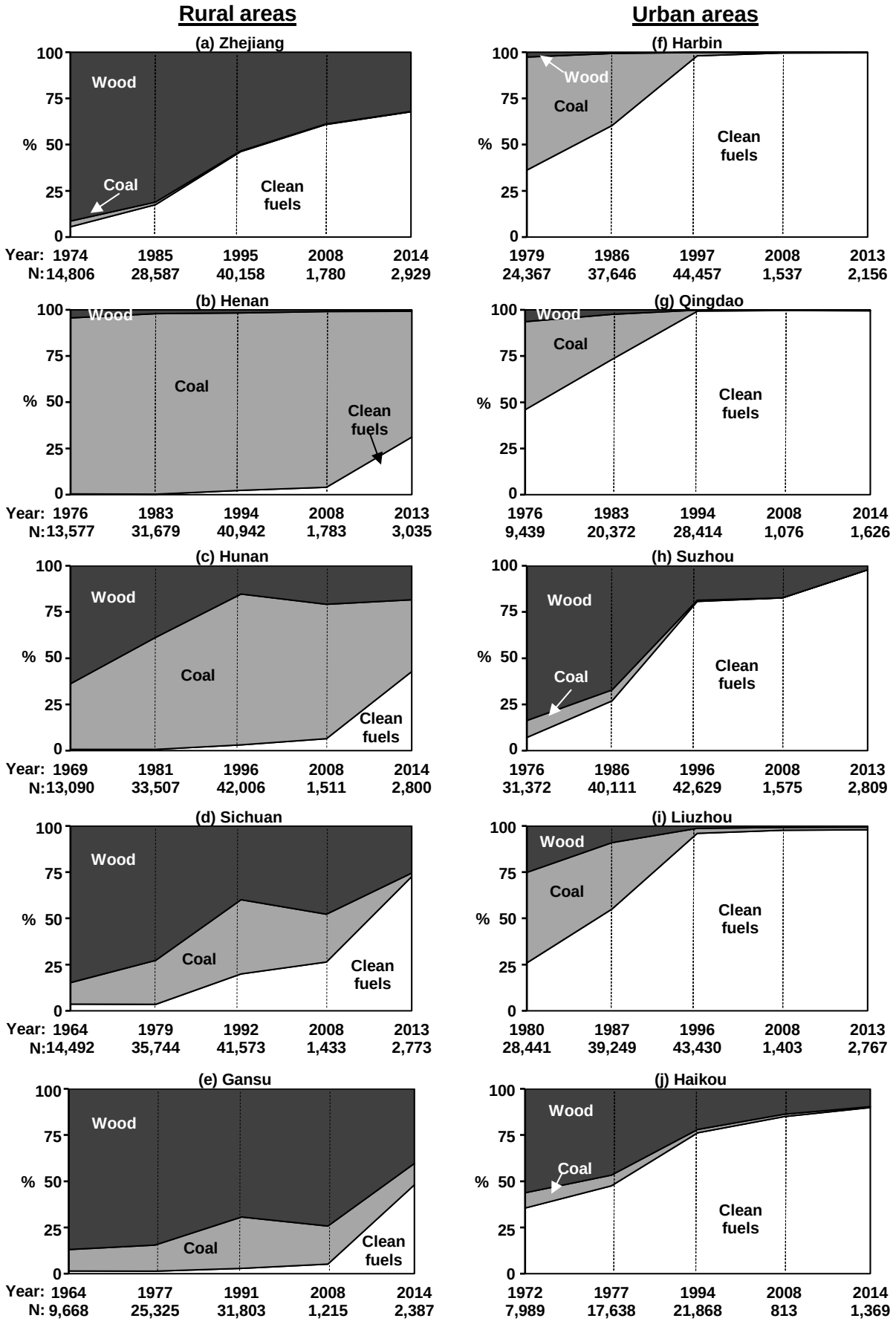


**Figure 5.12 Temporal pattern of self-reported primary heating fuel type in 10 study areas by time**

Conventions as Figure 5.11.

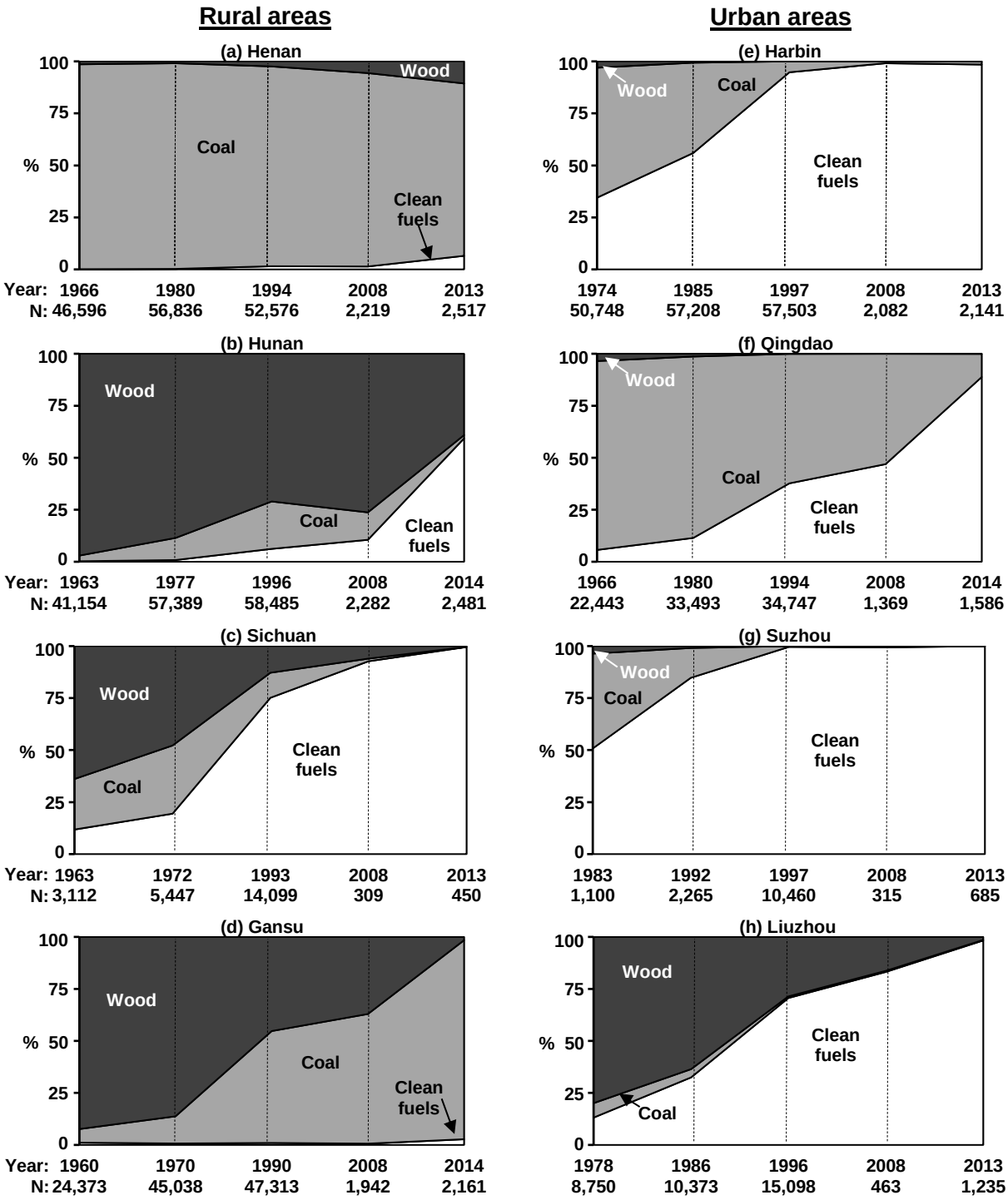


**Figure 5.13 Temporal pattern of availability of cookstove ventilation in 10 study areas by time**

Conventions as Figure 5.12.

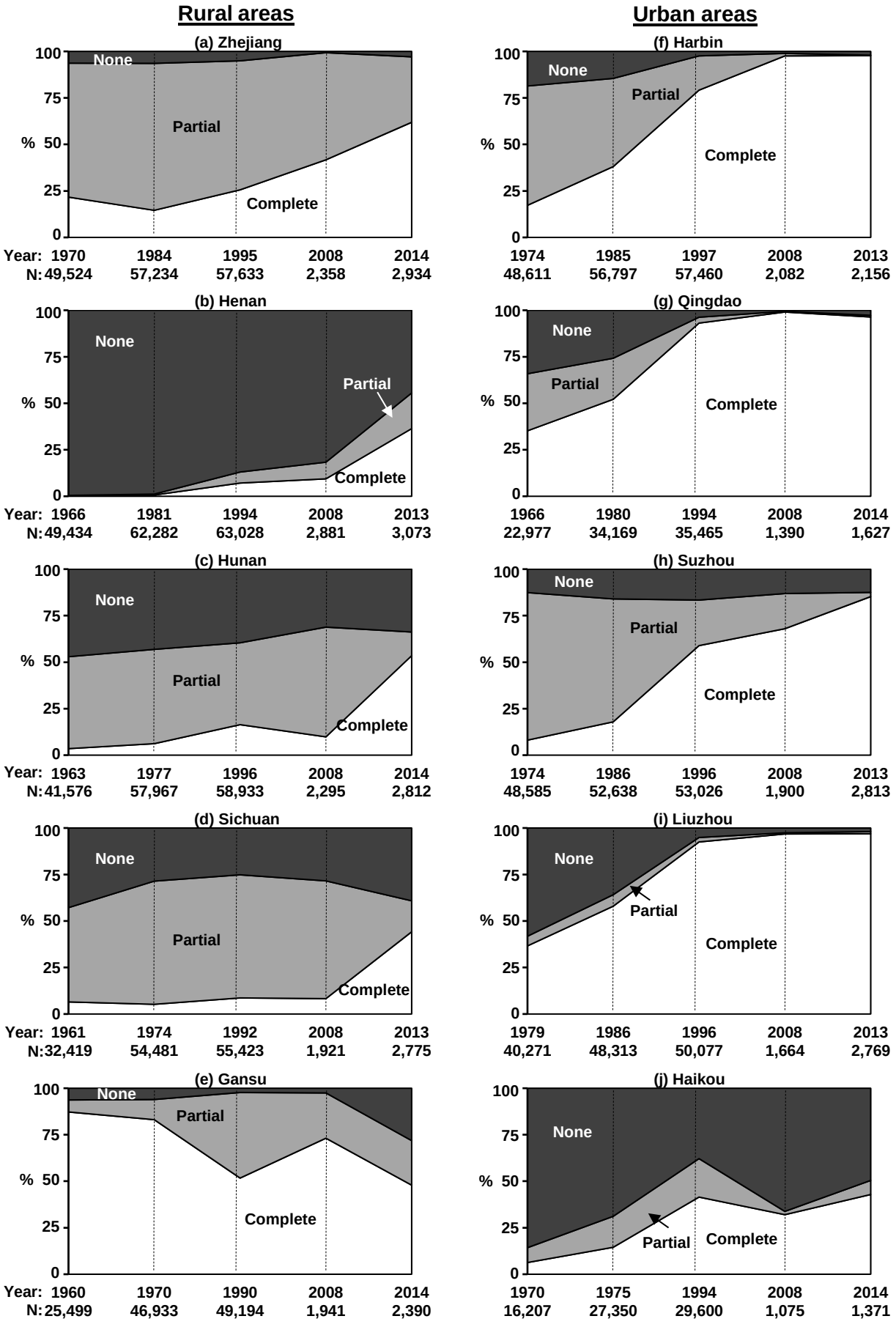


**Figure 5.14 Adjusted percentage of length of age band exposed to specific cooking fuel by five birth cohorts in rural and urban areas**

Left panels: rural areas; right panels: urban areas. Percentage estimates were adjusted for gender and areas. Size of boxes is inversely proportional to the standard error of the respective age band; 95% CI are too narrow to be seen in most graphs. Clean fuels include gas and electricity. Note that the last box of each line (except for the one in the 'Before 1939' group, which was excluded due to the small sample size in this 75-79 age band) is the time point when the baseline survey was conducted (2004-08).

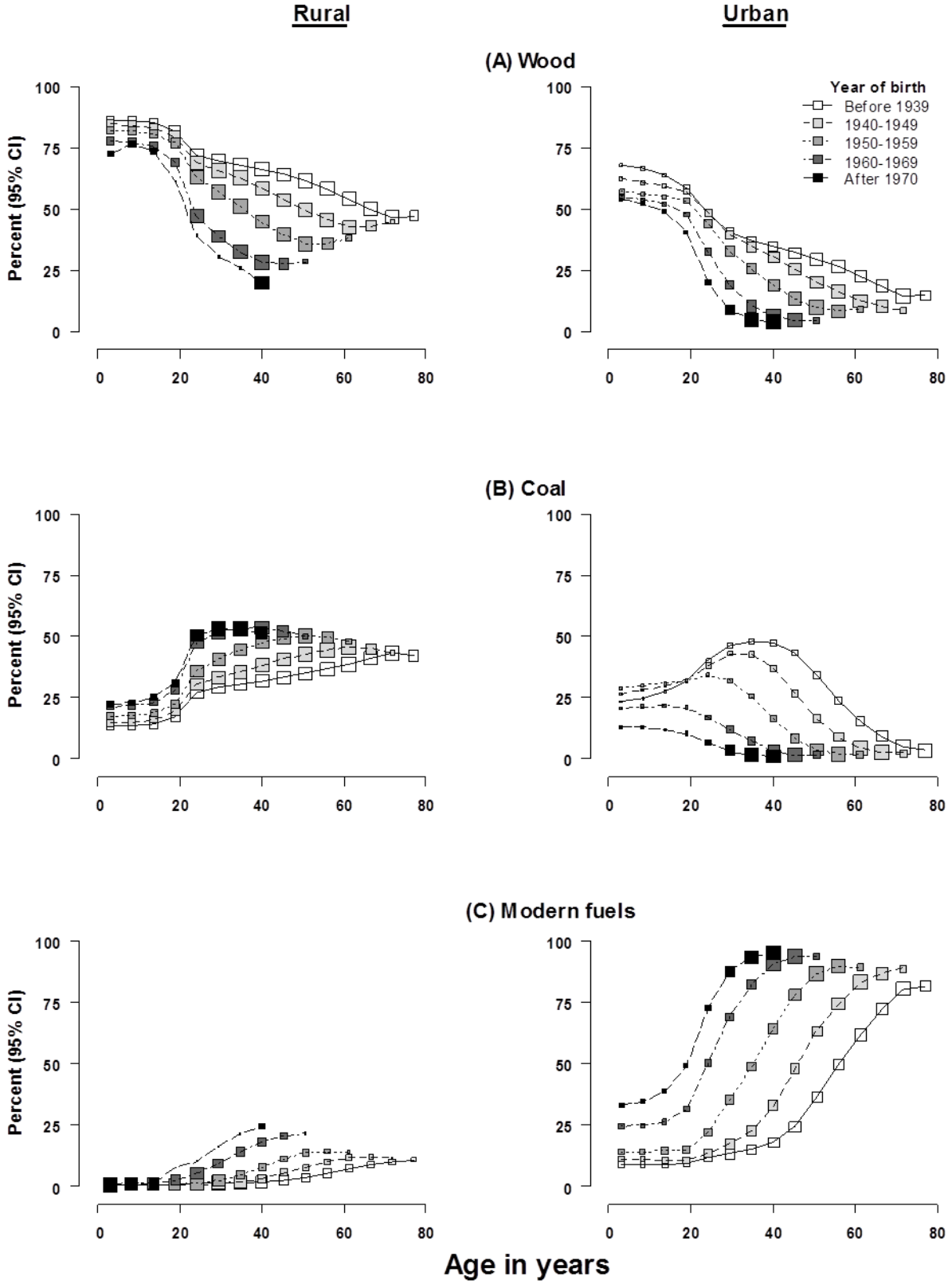


**Figure 5.15 Adjusted percentage of length of age band exposed to specific heating fuel by five birth cohorts in rural and urban areas**

Conventions as Figure 5.14.

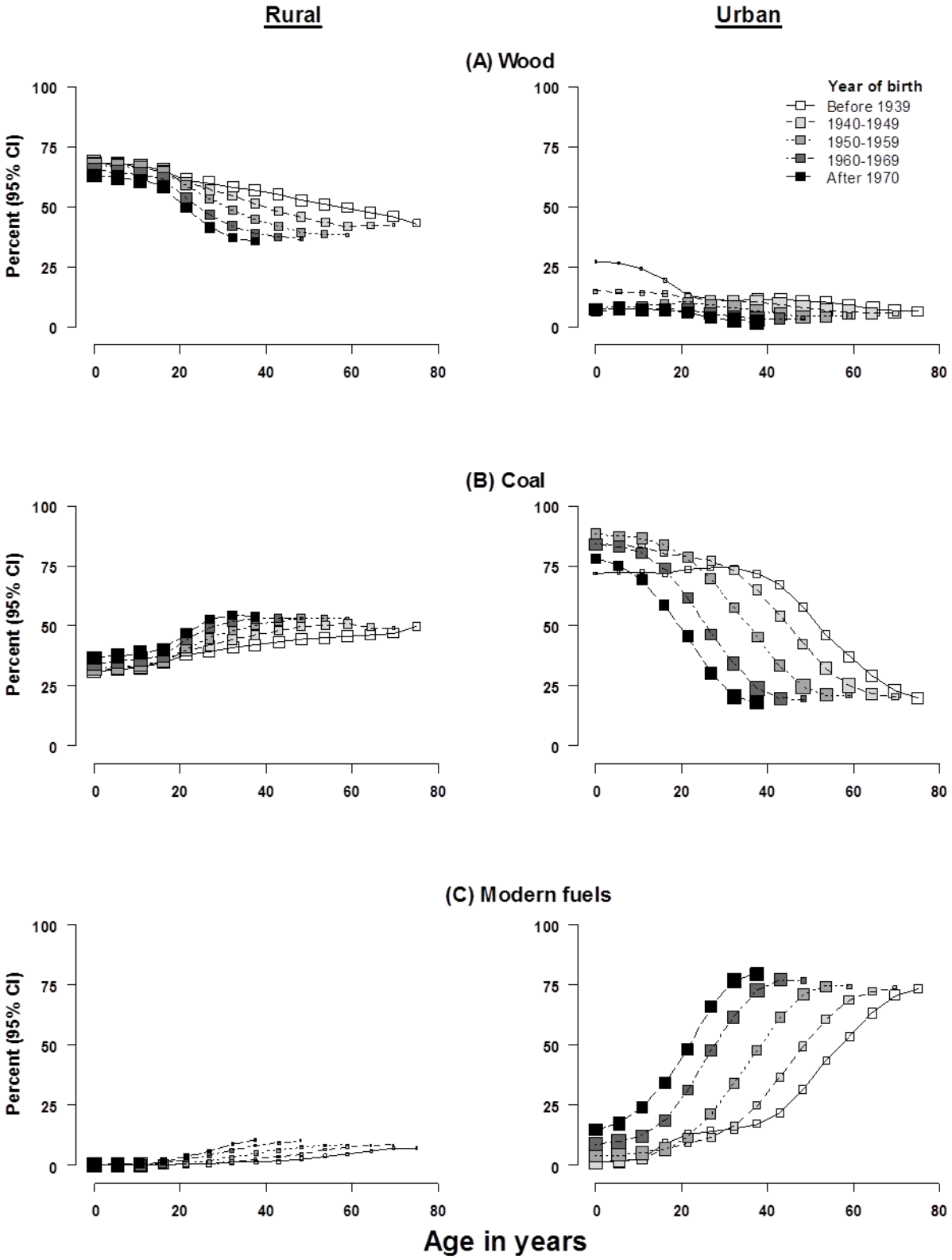


**Figure 5.16 Adjusted percentage of length of age band with different availability of cookstove ventilation by five birth cohorts in rural and urban areas**

Conventions as Figure 5.14.

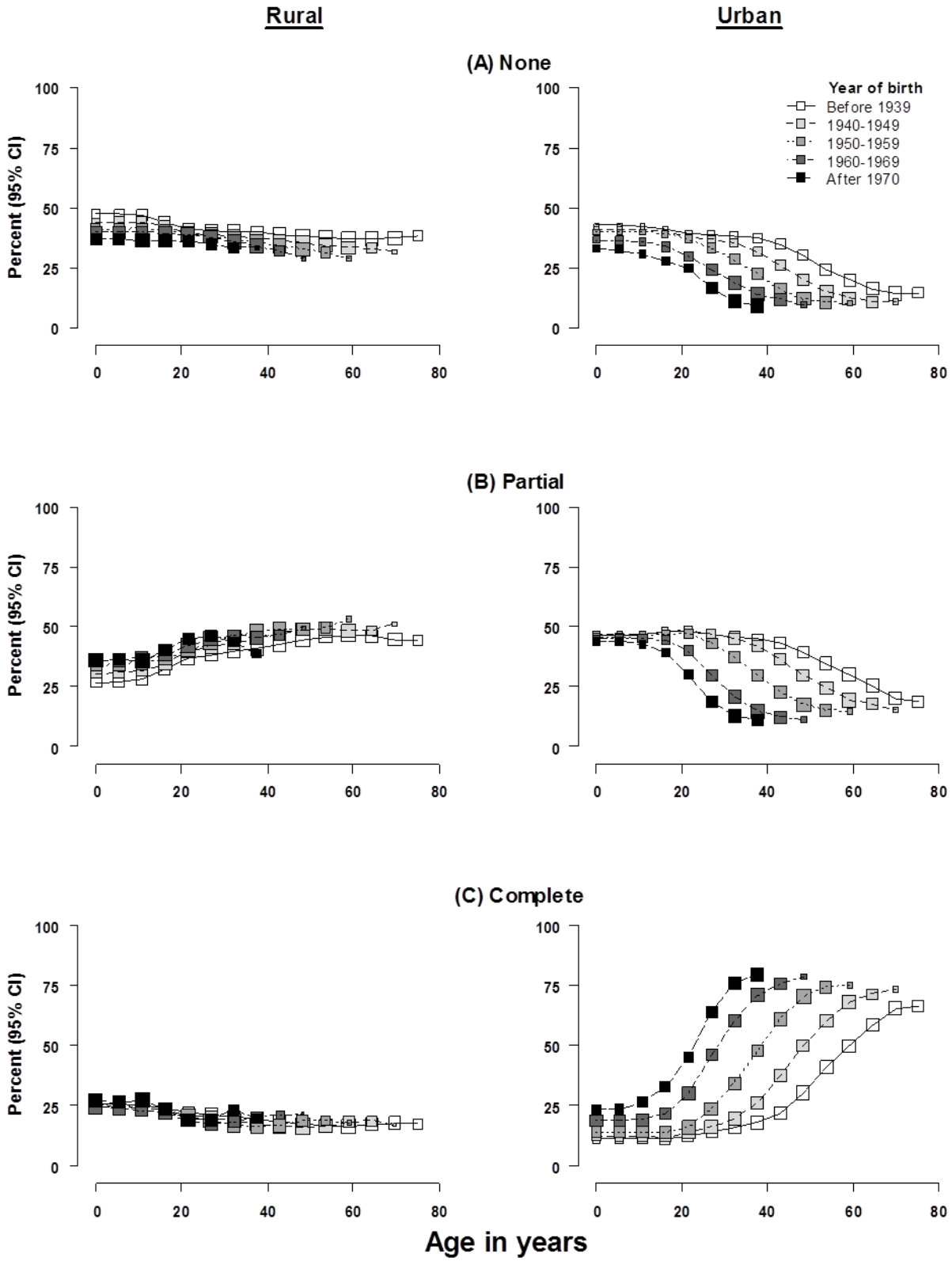
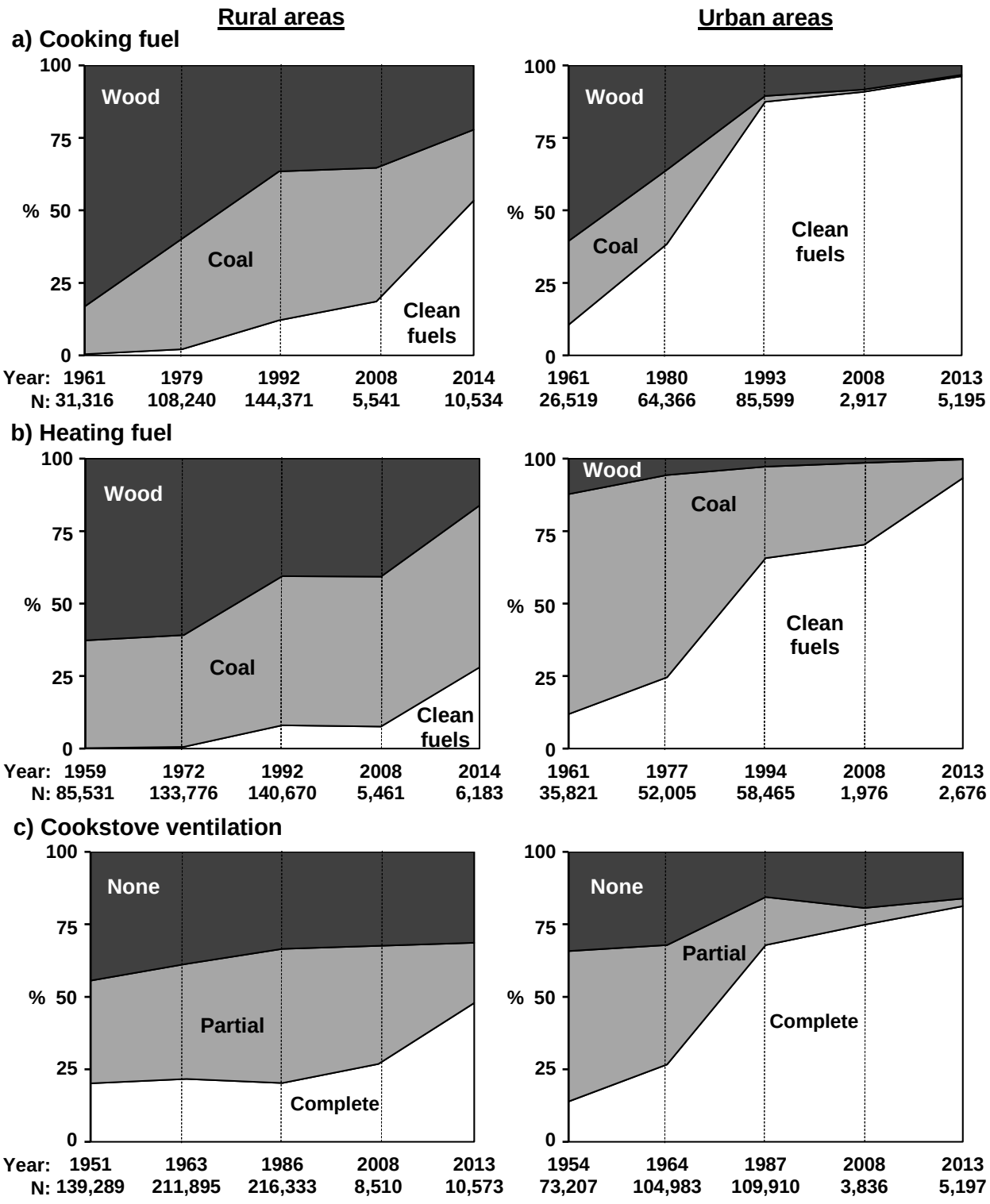


**Figure 5.17 Temporal pattern of self-reported primary fuel type for a) cooking and b) heating; and c) availability of cookstove ventilation, in urban and rural areas in participants whose recall period covered their entire adulthood (≥18 year-old)**

Conventions as Figure 5.4.



# CHAPTER 6. SOLID FUEL USE AND RISK OF RESPIRATORY DISEASE

## 6.1 INTRODUCTION

The respiratory system is the primary route of exposure to HAP from solid fuel use.[4] Not-surprisingly, most previous epidemiological studies on the health effects of solid fuel use had focused on respiratory disease, especially COPD.[4] The majority of the studies on COPD were cross-sectional or case-control in design and mostly examined airflow obstruction defined using spirometry or chronic bronchitis defined based on respiratory symptoms.[9-12,14] Although it has been widely recognised that solid fuel use is associated with excess risk of COPD, substantial uncertainty remains as the magnitude of association varied substantially across studies, from over two-fold in earlier meta-analyses (where significant heterogeneity and evidence of publication bias had been reported)[9-12,14] to no evidence of an association in the more recent large-scale studies.[15-17]

Prior to this thesis, very few studies have prospectively investigated the impact of solid fuel use on hospitalisation or death of COPD, which could be particularly important in assessing the associated public health burden in LMICs, where often a large fraction of airflow obstruction cases are asymptomatic (e.g. 35-60% in China[15,112]). For other respiratory diseases in adults, such as ALRI, the evidence is more limited, with many previous studies having unclear outcome definition and inadequate adjustment for confounders.[12,18] There were only three relevant prospective studies on solid fuel use and respiratory outcomes to date, with one on respiratory death,[19] one on ALRI[20] and another on COPD (regarding improved ventilation but not solid fuel use),[103] all of which reported inconclusive findings based on very small sample sizes and event numbers. The relationship between solid fuel use for heating and respiratory disease is rarely

investigated independently of cooking-related exposure, with only a few non-prospective studies with relatively small sample sizes reporting inconclusive findings.[83-90]

## 6.2 AIMS

This chapter aimed to examine the prospective associations between solid fuel use for cooking and incident hospitalisation and death of a range of acute and chronic respiratory diseases, to assess whether the use of ventilated cookstove or switching to clean fuels could modify the association, and to explore the association of solid fuel use for heating in relation to selected respiratory diseases.

## 6.3 METHODS

### 6.3.1 Study design and data collection

As described in detail in **Chapter 3** and elsewhere,[69,153] the CKB recruited 0.5 million adults aged 30-79 years from ten areas across China. At baseline, trained health workers administered a laptop-based, electronic questionnaire interview on socio-demographic and lifestyle characteristics, health conditions and medical history, and undertook a range of physical measurements, including spirometry.

In the questionnaire interview, participants were being asked whether they had "coughed up sputum after getting up in the morning" during the past 12 months, and those who reported having such symptom for ≥3 months were considered as having chronic phlegm. Participants were also asked about their prior history of doctor-diagnosed chronic diseases (chronic bronchitis, emphysema, tuberculosis, asthma, cancer, stroke, transient ischaemic attack, chronic heart disease).

Spirometry was conducted by trained technicians following the recommendations of the American Thoracic Society,[186] with the detailed procedures described elsewhere.[86]

Briefly, each participant performed at least two successful forced expiratory manoeuvres (determined by the technician) using a handheld Micro Spirometer (MS01; CareFusion UK, Basingstoke, UK) as instructed and supervised by a trained technician. No bronchodilator was administered. The highest values of $FEV_1$ and FVC, not necessarily from the same manoeuvre, were used in all relevant analyses. Possible airflow obstruction at baseline is defined as $FEV_1$:FVC ratio less than LLN calculated using the Global Lung Initiative reference equation for East-Asians.[187]

### 6.3.2 Assessment of solid fuel use

Details of assessment of solid fuel use have been described in **Chapter 4** and elsewhere.[33,35] At baseline, each participant was asked to recall, for up to their three most-recent residences, how many years they had lived there, cooking frequency, ownership of ventilated cookstove winter heating behaviour and primary fuel used for cooking and heating (electricity, gas, coal, wood, other unspecified, and central heating [for heating only]). For cooking fuel use, only those who cooked weekly or daily were considered as regular cooks, whose exposure status in each residence were classified according to their primary cooking fuel. By combining these data, participants were categorised into those who had always used clean fuels (long-term clean fuel users), who had switched from solid to clean fuels and who had always used solid fuels (long-term solid fuel users) during the recall period. As discussed in **Section 2.3.1.1**, participants who did not cook regularly or did not use heating are likely to be substantially different from those who cook or use heating, respectively, not only in terms of exposure to HAP from solid fuel combustion but also other measured and unmeasured characteristics, and they should not be included as part (nor the entirety) of the reference category as some previous studies did. This rationale was verified by comparing the baseline characteristics of participants who had never cooked regularly or used heating with those who did (see **Section 6.4.1** below).

Long-term solid fuel users were further stratified according to 1) specific types of solid fuel used (always coal, always wood, switched between coal and wood), 2) estimated duration of continuous exposure (<20, 20-39, ≥40 years) and 3) the proportion of the recall period during which ventilated cookstoves were used (≥50% and <50%), separately for cooking and heating. As a sensitivity analysis, participants were also classified according to weighted duration of exposure to solid fuel use (cooking: <20, 20-39, ≥40 weighted-year; heating: <10, 10-19, ≥20 weighted-year), based on cooking frequency in each residence and area-specific approximated heating need (details of the calculation were described in **Section 4.1.4**).

### 6.3.3 Follow-up and outcome definitions

All participants were followed-up from the baseline survey to 1st January 2016, through electronic linkage to death and disease registries and to national health insurance databases or standardised verbal autopsy[188] (for a small proportion of deaths that occurred outside the healthcare system), and death and hospitalisation events were coded according to the ICD-10 by trained staff who were blinded to participants' baseline information.[153] The outcome investigated were the first event of major respiratory disease, including CLRD (ICD-10 J40-J47, in which J41-J44 were classified as COPD), ALRI (J12-J18, J20-J22), AURI (J00-J06), other upper respiratory disease (J30-J39), and death from any respiratory diseases (excluding those due to external or post-operative causes: J00-J47, J80-J94, J96-J99). **Table 6.1** shows the details of each endpoint investigated. Participants who had no event of interest were censored upon death, loss to follow-up or the end of follow-up, whichever is earlier.

### 6.3.4 Participant exclusions

To minimise the potential confounding effect from smoking, a profound risk factor of respiratory disease, the main analyses were restricted to never-smokers (n = 317,614), defined as participants who had either never smoked or had smoked <100 cigarettes or

equivalent during their lifetime. Participants with potentially unreliable residential recall information (n = 1,573) and those with self-reported doctor-diagnosis of chronic diseases that could affect lung function and susceptibility to respiratory disease (chronic bronchitis, emphysema, tuberculosis, asthma, cancer, stroke, transient ischaemic attack, or chronic heart disease) (n = 26,095) and those with missing information on BMI (n = 1) were further excluded, resulting in an overall analytical sample of 289,945.

For cooking- and heating-related analyses, participants who reported unspecified fuel type at any residence ($n_{cooking}$ = 2,527; $n_{heating}$ = 1,423), who switched from clean to solid fuels ($n_{cooking}$ = 665; $n_{heating}$ = 2,067), who had cooked regularly (n = 8,925) or used heating (n = 10,902) previously but had stopped at baseline were also excluded, respectively. The heating-related analyses also excluded all participants from tropical Haikou (n = 21,260), where heating is not generally necessary, and Zhejiang (n = 33,679), where <1% of participants reported using heating at baseline. Principally, these analysis-specific exclusions were made to keep the largest possible number of participants from the overall study population to retain comparability while excluding individuals who are likely to be distinctively different from those in the main exposure categories and may introduce bias to the analyses if included. For example, individuals who had cooked previously but stopped at baseline could be elderly who stopped cooking because of poor health. This will be discussed further in **Section 6.4.1**. **Figure 6.1** summarises the exclusions for the main analyses.

Of note, participants with possible airflow obstruction or chronic phlegm at baseline (defined in **Section 6.3.1**) were not excluded from the main analyses because the non-standard definitions used would include a non-trivial proportion of false positive cases (of airflow obstruction and chronic bronchitis), and exclusion of them may introduce bias to the analyses. Nonetheless, to assess the potential reverse causation and residual confounding related to baseline respiratory health problems, they were excluded in the sensitivity analysis.

### 6.3.5 Statistical analyses

Direct standardisation was used to estimate age, gender and study area-adjusted percentages or means of selected baseline characteristics (age [gender and study area-adjusted], gender [age and study area-adjusted], urban residence, education, income, occupation, alcohol consumption, ETS exposure, cookstove ventilation, BMI, self-reported general health, possible airflow obstruction, chronic phlegm) across long-term cooking and heating fuel exposure categories, where appropriate. Same method was used to compare the baseline characteristics between participants included in and excluded from the main analyses and between those who had or had not developed the disease outcome of interest during the follow-up period, as well as to estimate standardised rates (per 100,000 person-years) of each outcome of interest across age, gender and urban-rural residency subgroups.

Cox proportional hazard regression was used to estimate HRs and group-specific 95% CI (using the "floating absolute risk" method described in **Section 4.5.3**[167]) for respiratory disease in relation to long-term fuel use exposure, stratifying for age-at-risk (five-year intervals), gender and study area (10 areas, to account for the potential clustering effect), and adjusted for education level (no formal school, primary school, middle school, high school/college/ university), annual household income (<10,000, 10,000-19,999, 20,000-34,999, ≥35,000 Yuan/ year), occupation (agricultural worker, factory worker, non-manual worker, others), alcohol consumption (never/rarely, occasional, ex-drinker or reduced-intake, weekly regular), BMI (continuous), ETS (<1 day/week, 1-5 days/week, daily or almost every day), cookstove ventilation (none, at least some), length of recall period (continuous), and mutual adjustment for cooking and heating fuel exposure (always clean fuels, solid to clean fuels, always solid fuels, never cooked regularly, others), where appropriate. $\chi^2$ tests for heterogeneity was used to assess the statistical differences across groups of categorical exposure indicators without directly quantifiable trends (e.g. long-term coal use versus wood use), and tests

for trend was used to test the potential dose-response relationship related to duration of solid fuel use. The proportional hazard assumption was assessed by comparing the HRs for the first five years and for the subsequent years of follow-up as well as formal test based on Schoenfeld residuals[165] and no significant evidence of violation was found.

Pre-specified subgroup analyses for major respiratory disease were conducted across categories of age, gender, rural-urban residency, education, alcohol consumption, ETS exposure, BMI, leg length and self-reported health status to assess potential subgroup differences. In particular, leg length was chosen because it may reflect early-life nutritional and socio-economic status and other exposures relevant to lung development. In order to compare the HRs across subgroups, conventional 95% CIs (as opposed to group-specific CIs) were calculated. To avoid type I error inflation, no further subgroup analysis was conducted for specific outcomes.

As a sensitivity analysis, adjusted HRs were estimated across exposure categories defined by weighted duration of exposure to solid fuel use (for cooking: always clean fuels, solid to clean fuels, and <20, 20-39, and ≥40 weighted-year of solid fuels; for heating: always clean fuels, solid to clean fuels, and <10, 10-20, ≥20 weighted-year of solid fuels). Further sensitivity analyses were conducted by repeating the main analysis after further excluding:

i) individuals with <20 years recall information (n = 26,742) – whose long-term exposure status may be more prone to exposure misclassification given the relatively short recall period;

ii) those who used clean fuels for <10 years ($n_{cooking}$ = 54,037; $n_{heating}$ = 28,143) – who are more likely to have greater historical and/or concurrent exposure to solid fuel use since they have only adopted clean fuels for a relatively short period of time;

iii) individuals with spirometry evidence of airflow obstruction or self-reported chronic phlegm at baseline (n = 20,197) – who may have poorer lung function and had developed subclinical respiratory disease prior to the baseline survey, and;

iv) for cooking-related analyses only, those who cooked weekly at baseline (n = 25,466) – who are less regularly exposed to clean or solid fuel use as compared to those who cooked daily.

To assess the potential influence of the multi-stage cluster sampling scheme on the main findings, robust standard error estimates and corresponding 95% CIs were calculated using marginal Cox regression based on a robust sandwich covariance matrix (to account for the study area-level intra-cluster dependency) ,[189] and these were compared to the corresponding estimates from the main analyses.

## 6.4 RESULTS

### 6.4.1 Baseline characteristics by cooking and heating fuel use exposure

**Table 6.2** shows the baseline characteristics of the overall study population of 289,945 never-smoking participants without prior chronic disease (277,838 included in the cooking-related analyses, 221,078 included in the heating-related analyses). Of these participants, the mean (SD) age was 50.3 (10.3) years and 91% were female. The mean total duration of the three most-recent residences was 39.7 (14.5) years, with 91% participants having had at least 20 years of residence covered.

Of the 277,838 participants included in the cooking-related analyses, 91% reported regular cooking during the recall period, 52% of whom used solid fuel throughout. Compared to long-term clean fuel users, those who had switched from solid to clean fuels and the long-term solid fuel users (to a greater extent) tend to be older, to be female, to be rural residents, to have lower education level or household income, to be

an agricultural worker, to be exposed to ETS, not to drink regularly, to have no ventilated cookstove, to use solid fuels for heating long-term, to report poor health, and to have possible airflow obstruction or chronic respiratory symptoms. There was no observable difference in terms of leg length and BMI across the exposure categories. About 60% of the never-regular cooks were men, just above half were urban residents, and, as compared to long-term solid fuel users, they were more similar to long-term clean fuel users or those who had switched from solid to clean fuels in terms of socio-economic, occupational and lifestyle characteristics, but they tend to report poor health and more had possible airflow obstruction. Of the 221,078 participants included in the heating-related analyses, 72% had used heating during the recall period, with 66% of them used solid fuels persistently. The variations of baseline characteristics across long-term heating fuel use exposure categories were similar to that across cooking exposure categories (**Table 6.2**).

**Table 6.3** compares the baseline characteristics of participants included and excluded from the main analyses. Compared to the ever-regular cooks, those excluded from the cooking-related analyses (those who used unspecified fuel types, who switched from clean to solid fuels or who had cooked previously but stopped at baseline) tend to be older, to be urban residents, to have slightly higher education level or household income, to be regular drinkers, more likely to report poor health, and to have possible airflow obstruction or chronic phlegm at baseline. For heating, the characteristics of the excluded participants from Haikou and Zhejiang were presented separately from other excluded participants. Although participants from Haikou and Zhejiang would have been classified as “never used heating” if they were not excluded, they were distinctively different from those who had never used heating. For example, there were markedly less regular drinkers in Haikou but more male drinkers in Zhejiang, and much less participants from these two areas reported poor health or had possible airflow obstruction or chronic phlegm at baseline. As for the excluded participants from the

other eight study areas, they tend to be more educated but had lower household income, to be non-agricultural workers, to drink regularly, to report poor health, and to have possible airflow obstruction or chronic phlegm at baseline.

### 6.4.2 Baseline characteristics in relation to respiratory disease

During 2.6 million person-years of follow-up (median [IQR]: 9.2 [8.3-10.2] years), 23,078 incident major respiratory diseases were recorded in the study population, including 12,346 CLRD, 5,093 COPD, 8,422 ALRI, 3,586 AURI, and 2,049 other upper respiratory disease, and 793 respiratory deaths. **Table 6.4** shows the standardised incidence rates (per 100,000 person-years) of outcomes of interest by age, gender and rural-urban residency. The rates of most respiratory diseases were higher in older participants (except AURI and other upper respiratory disease) and in females (except other upper respiratory disease and respiratory death). In particular, the rates of COPD varied from 78/100,000 person years in participants aged <40 years to 670/100,000 person-years among those aged ≥70 years. For other upper respiratory disease, the rates were the highest among participants aged <50 years. The rates of all respiratory outcomes studied were higher among rural residents, with that of major respiratory disease over two times as high as in urban residents (1,204 versus 560).

Compared to participants who did not develop respiratory disease, those who had any selected respiratory disease event (except for other upper respiratory disease), tend to be older, to be rural residents, to have lower education level or household income, to drink less, to have always used solid fuels for cooking and heating, to report poor health, to have possible airflow obstruction or chronic phlegm at baseline (except for AURI) (**Tables 6.5 and 6.6**). Comparing participants with and without an episode of other upper respiratory disease, in contrast to other respiratory outcomes studied, they were younger, drank more (for males), and used solid fuels for heating less often.

### 6.4.3 Cooking fuel use and risk of respiratory disease

Compared with long-term clean fuel use, long-term solid fuel use for cooking was associated with increased risks of multiple respiratory diseases, with adjusted HRs of 1.37 (group-specific 95% CI 1.33-1.42) for all major respiratory diseases, 1.47 (1.42-1.53) for CLRD, 1.10 (1.03-1.17) for COPD, 1.18 (1.11-1.25) for ALRI, 1.59 (1.48-1.71) for AURI, 1.56 (1.40-1.74) for other upper respiratory disease, and 1.53 (1.26-1.85) for respiratory death (**Figure 6.2**). The HRs were significantly smaller in participants who had switched from solid to clean fuels before baseline compared with those who used solid fuels persistently, with percentage differences ranged from 6% for ALRI to 39% for respiratory death and no statistically significant excess risk was observed for COPD (0.95 [0.88-1.03]), AURI (1.14 [1.04-1.24]), other upper respiratory disease (1.10 [1.00-1.22]) and respiratory death (0.93 [0.75-1.15]) (**Figure 6.2**).

Compared with participants who had always used clean fuels for cooking, the risk of major respiratory diseases was higher in participants who had primarily used solid fuels for longer duration, with HRs of 1.34 (1.28-1.40), 1.42 (1.38-1.47), and 1.56 (1.49-1.62) in those who used solid fuels for <20, 20-39, and ≥40 years, respectively ($P_{trend}$ <0.0001). Similar relationships were observed for each specific respiratory disease ($P_{trend}$ ≤0.007 for all comparisons) (**Figure 6.3**). This was consistent in the sensitivity analysis based on cooking frequency-weighted duration, where the HRs in the exposed groups tend to be higher and with a slightly steeper trend ($P_{trend}$ ≤0.002 for all comparisons) (**Appendix F - Figure F1**).

Amongst long-term solid fuel users, those who used wood had higher HRs for major respiratory diseases than those who used coal (1.38 [1.34-1.42] versus 1.23 [1.16-1.30]; $P_{heterogeneity}$ = 0.0002), and those who had switched between wood and coal had an intermediate risk (1.26 [1.20-1.32]). Similar patterns of association were observed for CLRD, COPD, ALRI and respiratory death but not for other cause-specific respiratory

disease outcomes (**Figure 6.4**). Regarding ventilation, long-term solid fuel users who had no ventilated cookstove for ≥50% of their recall period had significantly higher excess risk of major respiratory diseases than those who had no ventilated cookstove for <50% of their recall period (1.45 [1.40-1.51] versus 1.35 [1.32-1.39]). Similar associations were observed for CLRD (1.63 [1.54-1.72] versus 1.44 [1.39-1.50]), AURI (1.81 [1.66-1.96] versus 1.52 [1.42-1.63]), other upper respiratory disease (1.95 [1.71-2.22] versus 1.43 [1.29-1.59]) and respiratory death (1.70 [1.38-2.08] versus 1.48 [1.26-1.75]), but not for COPD or ALRI (**Figure 6.5**).

For major respiratory diseases, the HRs (conventional 95% CI) comparing long-term solid fuel users with clean fuel users was similar in men and women (1.44 [1.19-1.73] versus 1.38 [1.30-1.46]), and across a range of baseline characteristics except BMI, where the association appeared to be stronger in participants with lower BMI (**Figure 6.6**). The strength of observed associations between solid fuel use for cooking and respiratory diseases did not change materially after excluding frequent movers, participants with poor self-reported health, those who had possible airflow obstruction or chronic phlegm at baseline, or those who only cooked weekly at baseline (**Table 6.7**). Similarly, the associations were not materially different in the sensitivity analyses based on marginal Cox regression (**Appendix F – Table F1**).

### 6.4.4 Heating fuel use and risk of respiratory disease

In contrast to solid fuel use for cooking, long-term solid fuel use for heating was not associated with most respiratory disease outcomes examined, except for CLRD (HR [group-specific 95% CI]: 1.20 [1.08-1.34]) and COPD (1.27 [1.12-1.45]) (**Figure 6.7**). However, there was no clear trend of higher risks of CLRD and COPD in relation to (un-weighted and weighted) duration of solid fuel use for heating (**Table 6.8**). In terms of types of solid fuels, long-term wood use (1.23 [1.11-1.36]) and mix of both wood and coal (1.22 [1.12-1.34]) had significantly higher risk of CLRD but no excess risk was

observed for coal use (**Table 6.9**). The excess risk of COPD appeared to be slightly higher in long-term wood users (1.30 [1.17-1.45]) than those who had used both coal and wood (1.25 [1.10-1.42]) or those used coal persistently (1.19 [1.02-1.40]), but the differences were not statistically significant. The use of ventilated cookstove did not alter the association between solid fuel use for heating and any respiratory disease outcomes examined (**Figure 6.8**). The association between solid fuel use for heating and respiratory diseases did not change significantly in the sensitivity analyses (**Table 6.10; Appendix F – Table F2**).

## 6.5 DISCUSSION

In this prospective cohort study of 290,000 never-smoking Chinese adults who had no known prior history of major chronic diseases at baseline, long-term use of solid fuels for cooking was associated with significant elevated risks of hospitalisation or death from both acute and chronic respiratory diseases, but the evidence for COPD was weak. The excess risks appeared to be greater among those who used solid fuels for longer duration or used wood compared to coal, whereas switching from solid to clean fuels or use of ventilated cookstoves were associated with relatively smaller excess risks for mild respiratory diseases examined. In contrast, long-term solid fuel use for heating was only associated with excess risks of CLRD and COPD, with no consistent evidence of higher risks related to longer duration of exposure or the use of wood as compared to coal.

### 6.5.1 Solid fuel use for cooking and risk of COPD

Most previous epidemiological studies on solid fuel use and respiratory diseases focused on COPD in adults, with the majority of them being relatively small cross-sectional or case-control studies examining airflow obstruction based on spirometry or chronic bronchitis based on self-reported symptoms.[9-14,17] Earlier pooled-analyses of these studies reported a large excess risk (summary odds ratio from 1.94 to 2.80), but

with high levels of heterogeneity and evidence of publication bias.[9-12] Several recent, large population-based cross-sectional studies involving 13,000 to 67,000 participants, including two conducted in China, and a more recent SR and meta-analysis with more stringent inclusion criteria reported much weaker associations (from no association to ~40% excess risk).[13-17] In this large prospective cohort, long-term use of solid fuels for cooking was associated with about 10% excess risk of hospitalisation or death of COPD, which is more consistent with the recent large-scale cross-sectional studies than the earlier pooled estimates. Compared to the previous non-prospective studies, the prospective design enabled the present analyses to take better account of the influence of reverse causation, by excluding those with prior history of major respiratory disease in the main analyses and also those with possible airflow obstruction or chronic phlegm in the sensitivity analyses, and by examining incident hospitalisation or death of COPD. Furthermore, the current analyses were restricted to never-smokers, so the residual confounding from smoking, a leading cause of COPD, should be minimised. Nevertheless, it is possible that our HRs for COPD could be underestimated.

Unlike many previous studies which examined airflow obstruction using spirometry, I used hospitalisation records and death certificates for outcome ascertainment. Spirometry is rarely (7-10%) used in China and a substantial proportion (35-60%) of the screen-detected airflow obstruction cases were found to be asymptomatic, as reported in two recent nationwide Chinese surveys.[15,112] Consistently, although a large proportion (85%) of the COPD diagnoses obtained through electronic health records in CKB were determined to be adequately substantiated by clinical evidence (signs, symptoms, risk exposure, radiological examination or spirometry), only <15% of were supported by spirometry evidence.[190] Therefore, many asymptomatic and mild airflow obstruction cases not requiring imminent medical attention are less likely to have been identified, diagnosed and captured in our records. Under-diagnosis of COPD is disproportionately more common in rural China,[15] where solid fuel use is more prominent. The higher

likelihood of undiagnosed cases in the exposed group means that the observed risks for COPD may well be diluted.

Indeed, a stronger association was found between long-term solid fuel use for cooking and CLRD (HR [group-specific 95% CI]: 1.47 [1.41-1.52]), which included all COPD cases plus mostly unspecified bronchitis (ICD-10 J40; n = 6,830). Six-hundred and forty individuals who had incident unspecified bronchitis also had an episode of COPD during follow-up, with 425 (66%) of them having it after the unspecified bronchitis event. Participants who had an episode of unspecified bronchitis were more similar to those who had COPD than those who had non-CLRD respiratory disease or no respiratory disease in terms of a range of baseline characteristics, except that they were considerably younger (**Appendix F - Table F3**). In particular, more unspecified bronchitis and COPD cases reported poor health, shortness of breath and chronic phlegm, and a greater proportion of them had possible airflow obstruction at baseline compared to those without any respiratory disease or those who had non-CLRD respiratory disease. Additionally, unspecified bronchitis cases were more likely to have a subsequent episode of COPD (adjusted OR: 3.56 [3.17-3.99]), ALRI (3.30 [2.99-3.65]) or AURI (3.12 [2.80-3.48]) but had no significant excess risk of external causes of morbidity (1.05 [0.76-1.45], as a negative control), after adjusting for key confounders (**Appendix F - Table F4**). Altogether, it is possible that many of these unspecified bronchitis cases could be mild, early stages COPD or acute exacerbations of pre-existing, but previously undetected, COPD, given that they are much younger than the recorded COPD cases and spirometry is rarely used for diagnosis in China. However, more extensive adjudication on the unspecified bronchitis cases is needed to verify this speculation.

### 6.5.2 Solid fuel use for cooking and other respiratory diseases

For respiratory disease other than CLRD, previous evidence has been even more limited. Two small cohort studies on respiratory death (with 155 cases) and ALRI (with

229 participants, no case numbers were reported) reported inconclusive findings.[19,20] Despite having included substantially larger number of respiratory deaths (793 cases), the HR estimates had relatively wide CIs, indicating that the corresponding analyses had suboptimal power. For ALRI, a recent SR[18] had identified eight relevant studies and found no consistent evidence. Most of these studies involved less than 1,000 disease events, and many had major methodological limitations, such as unclear outcome definitions,[113,116,118] inadequate adjustment for confounders[113-115] or suboptimal comparison groups (e.g. wood versus charcoal).[113,116-119] The present analyses included much larger numbers of events than all previous studies combined (about 8,400 ALRI; 3,500 AURI), and there was strong evidence that long-term solid fuel use for cooking is associated with significantly elevated risk of both diseases. This complements a larger body of observational evidence on the relationship between HAP and ALRI in infants and young children,[4,18] highlighting the potential need of considering adult ALRI when assessing the disease burden related to HAP exposure. It is worth noting that ALRI and AURI are acute recurring conditions. The observed associations reflect an overall shorter time to the first documented infection during the follow-up in solid fuel users, which may indirectly imply a higher rate of recurrent infection among them. Future analysis focusing on recurrent events should be able to clarify this.

### 6.5.3 Types of solid fuels and risk of respiratory disease

Wood is the commonest type of solid fuels being used worldwide, and most domestic coal users are in China.[2,3] Compared to coal use, wood use has been associated with higher levels of particulate pollution[5,39] and potentially higher risk of COPD.[4,10] While most previous studies had focused on biomass use, I examined both coal and wood (combined as “solid fuels” and separately) in the same study population, and consistently found higher risks of CLRD, COPD, and ALRI amongst those persistently exposed to wood smoke compared with those using coal. Interestingly, an earlier cross-sectional analysis of CKB observed a lower odds of airflow obstruction related to

baseline wood use (OR [95% CI]: 0.91 [0.86-0.98]) and higher odds related to baseline coal use (1.10 [1.02-1.20]) in women.[86] The current and previous CKB studies differ importantly by the disease outcome examined (prevalence of spirometry-detected airflow obstruction[86] versus rate of clinical episodes of COPD), as well as inclusion criteria, exposure classification and analysis strategy. In the current study participants with any prior chronic diseases were excluded. The present analyses classified individuals who cooked weekly or daily as regular users of fuels (clean or solid), whereas the previous analysis also included less frequent (monthly) cooks (who were more likely to be men, factory workers, and clean fuel users compared to the more frequent cooks). Furthermore, the current analyses had additionally adjusted for other important confounders that were not taken into account in the previous published report (e.g. ETS, occupation, BMI).

For upper respiratory disease, the excess risks appeared to be largely similar in the long-term wood and coal users for reasons that are not fully understood. It is possible that the aetiology or mechanisms between COPD and acute respiratory infections in relation to HAP from burning of different fuel types may differ. For example, compared to wood smoke, coal smoke typically contains much higher levels of $SO_2$,[44] a highly water soluble, irritating gas that dissolves in the mucus layer of the upper respiratory tract and has been associated with acute respiratory symptoms and upper airway inflammation.[191] The potentially greater exposure to $SO_2$ associated with coal use may have compensated for the lower exposure to particulate pollutants as compared to wood use, leading to similarly high risk of upper respiratory disease. Further investigation including direct measurement of HAP and characterisation of smoke constituents should help to clarify our findings.

### 6.5.4 The role of ventilated cookstoves

Both observational and intervention studies have consistently shown that HAP exposure and acute respiratory symptoms in adults may be reduced through adequately

maintained cookstove ventilation.[59,120] However, there has been no clear evidence on the long-term respiratory benefits of improved cookstove ventilation on lung function decline or disease development in adults.[59] A retrospective cohort study involving 42,000 Chinese adults from Xuanwei County reported significantly lower risks of pneumonia mortality (225 cases) and recalled physician diagnosis of COPD (1,478 cases) in lifelong coal users for cooking who adopted ventilated cookstove compared to those who did not.[119,133] In contrast, another cohort study of 600 Chinese adults (74 cases) found no significant effect of improved ventilation on the risk of spirometry-defined airflow obstruction.[103] Based on much larger number of clinical events, I found that solid fuel users who used ventilated cookstoves had lower risks of CLRD and upper respiratory diseases, but not ALRI, COPD or respiratory death, compared with those who used unventilated cookstoves. This is in agreement with the existing evidence that improved ventilation generally may have benefits on mild, acute conditions but not on more severe diseases such as COPD or ALRI,[59,120] possibly because the HAP levels after improvement remain substantially above the recommended threshold.[6,59,120] The discrepancy in results on CLRD and COPD, as discussed above, may be related to the unspecified bronchitis (ICD-10: J40) which could be acute exacerbation of early stages of COPD.

Nonetheless, the ownership of ventilated cookstove is associated with higher SES, so it is possible that the observed risk attenuation was affected by residual confounding. It is, however, reassuring that the risk attenuation appeared to be specific to cooking fuel exposure and only to less severe respiratory disease but no similar pattern was observed in the heating-related analyses.

### 6.5.5 The role of switching from solid to clean fuels

Compared to the long-term solid fuel users, participants who had switched their primary cooking fuel from solid to clean fuels prior to the baseline survey had smaller excess risks of all respiratory diseases studied. Although limited, there is consistent evidence

that switching from solid to clean fuels is associated with significantly greater HAP reduction than adopting improved ventilation.[59,60] Findings presented in this chapter offer supportive evidence that clean fuel adoption may be beneficial for the alleviation of the excess risk of both acute and chronic respiratory conditions related to historical exposure to solid fuel use, a phenomenon similar to that of smoking cessation.[192] However, residual confounding from SES is possible, as individuals who could switch from solid to clean fuels are more likely to be at a better socioeconomic position than the long-term solid fuel users, as described in **Chapter 5**. Furthermore, the switching from solid to clean fuels were determined by recall of exposure not prospectively monitored, so the exact timing of fuel switch cannot be clearly distinguished using the data available. Future large-scale RCTs with adequately long follow-up period and appropriately designed intervention are needed to more robustly assess the potential respiratory benefits associated with clean fuel adoption observed in this study.

### 6.5.6 Solid fuel use for heating and risk of respiratory disease

Although solid fuel use for heating has been shown to be associated with distinctively higher exposure to HAP than solid fuel use for cooking alone,[32,39,44,45] very few studies have examined the respiratory risk associated with heating fuel exposure while controlling for the effect of cooking fuel exposure.[83-89] Most of these were cross-sectional studies with <1,000 cases,[83-90] and the findings were conflicting, with several small cross-sectional studies reporting extreme ORs with wide CIs (e.g. 36.2, 13.6-96.8) for chronic bronchitis[84] but a much larger case-control study (1,700 cases of COPD) observed no association.[90] In this first prospective cohort study to explore the role of solid fuel use for heating independently, long-term solid fuel use for heating was only associated with excess risk of CLRD and COPD but not with other respiratory outcomes examined and these associations do not differ significantly by duration of exposure or types of solid fuel used. The reason behind such inconsistency of associations across different respiratory outcomes is unclear. The absence of association with ALRI, AURI

and other upper respiratory diseases may reflect a net balance between the risks from HAP exposure to solid fuel combustion and the general benefits of heating against cold temperature in preventing acute illnesses.[48-54] Conversely, long-term solid fuel use for heating, as a proxy of cumulative HAP exposure, may be more strongly predictive for lung function impairment or development of chronic respiratory disease (CLRD and COPD) than acute conditions, and these associations were therefore less confounded by the hypothesised acute protective effect against cold temperature. In fact, when the disease events were analysed in multivariate logistic regression (with similar adjustment for confounders as the main analyses) separately by cold and non-cold months (defined as area-specific monthly average temperature <10°C during 2005-2017), solid fuel use for heating was only associated with cases that occurred in non-cold months (OR [group-specific 95% CI]: 1.24 [1.09-1.42] for CLRD and 1.35 [1.15-1.58] for COPD) but not those in cold months (1.06 [0.88-1.29] for CLRD and 1.18 [0.94-1.48] for COPD).

### 6.5.7 Strengths and limitations

The key strengths of the present analyses lie in the large number of never-smokers, comprehensive investigation of prospectively documented hospitalization and death of a range of respiratory diseases, and the high consistency of exposure-outcome relationships across these diseases and across different population subgroups in regard of cooking fuel exposure. Moreover, two common limitations of previous research on this topic, namely reverse causality and residual confounding from smoking, were carefully dealt with in these analyses. However, our there are several limitations that merit discussion.

First, hospitalisation records and death certificates were used for outcome ascertainment. Misclassification due to misdiagnosis is possible, especially for COPD due to the low utility of spirometry and high proportion of asymptomatic cases in China.[15,16,112] Clinical episodes of COPD were also unlikely to represent new onset

airflow obstruction as it has a prolonged development period with risk factors that could trace back to pre-conception,[110] meaning that it is difficult to establish temporality accurately. Nonetheless, participants with pre-existing chronic diseases were excluded in the main analyses and the results persisted after exclusion of those with signs of airflow obstruction at baseline or poor self-reported health in the sensitivity analyses.

Second, HAP exposure was estimated by the main type of fuel used as in most previous studies, and there was no direct exposure measurement data for more accurate assessment of the exposure-response relationships. It is possible that historical or concurrent exposure to solid fuel emissions from secondary fuel or neighbourhood fuels could have elevated the background risks in the long-term clean fuel users. Although it has been reported in China that the main fuel types accounted for the majority of the total household fuel consumption and should therefore reasonably reflect an individual's usual HAP exposure,[94] the residual, unaccounted exposure means that we could have underestimated the real excess risk of respiratory disease associated with solid fuel use.

Third, instead of prospectively monitoring lifetime exposure, it was only possible to estimate exposure based on recall information on the three most-recent residences of the participants. This might have resulted in misclassification, especially among clean fuel users who might have used solid fuels in their early life. Furthermore, the present analysis did not take into account of the general transition from solid to clean fuels after the baseline survey as described in **Chapter 5** (especially for cooking fuel). The lack of complete lifetime exposure data as such may have resulted in an underestimation of the associations examined. Nonetheless, the recall period covered on average ~40 years (≥70% of the adulthood in 80% participants), substantially longer than the follow-up period (9 years) where gradual fuel transition occurred, and the findings remained largely similar after exclusion of participants with <20 years of recall information provided.

Fourth, residual confounding from SES and ETS is possible despite the adjustment made on relevant proxy indicators (education level, household income, frequency of exposure to ETS). There was also no direct early-life exposure data, which could play an important role in COPD development in adults. Nonetheless, the associations observed were consistent across subgroups defined by proxies of early-life exposures (e.g. leg length, education level), and additional adjustment for duration of exposure to ETS did not alter the relationship of interest (results not shown). Finally, the current study sample has an imbalanced gender ratio (9:1) and one may argue that the findings may not be generalisable to men. Despite that, in the gender-specific analyses (with >26,000 men), there was no significant heterogeneity by sex.

### 6.6 CONCLUSIONS

In conclusion, in never-smoking Chinese adults, solid fuel use for cooking was associated with higher risks of both acute and chronic respiratory diseases, with the excess risk seemingly greater for wood than coal users, especially for CLRD and COPD, and in those with more prolonged use. Moreover, use of ventilated cookstoves and switching to clean fuels were associated with smaller excess risks of some respiratory diseases associated with solid fuel use, reinforcing the need for strengthening the existing global initiatives to improve access to clean energy and to distribute improved cookstoves in communities where a complete switch to cleaner fuels is not yet feasible. Solid fuel use for heating appeared to be associated with CLRD and COPD but not with other respiratory disease examined, but further investigation is needed to remove the potential confounding effect from cold temperature. Future studies based on directly measured air pollution exposure across multiple seasons are in pressing need to clarify our findings.

**Table 6.1 Details of major respiratory diseases defined by ICD-10 codes**

| Endpoint | ICD-10 Code | ICD-10 description |
|---|---|---|
| Chronic lower respiratory disease | J40-J47 | Chronic lower respiratory diseases (Unspecified bronchitis [J40], simple and mucopurulent chronic bronchitis [J41], unspecified chronic bronchitis [J42], emphysema [J43], other chronic obstructive pulmonary disease [J44], asthma [J45], bronchiectasis [J47]) |
| Chronic obstructive pulmonary disease | J41-J44 | Simple and mucopurulent chronic bronchitis [J41], unspecified chronic bronchitis [J42], emphysema [J43] and other chronic obstructive pulmonary disease [J44] |
| Acute lower respiratory infection | J12-J18, J20-J22 | Pneumonia (J12-J18) and other acute lower respiratory infections (J20-J22) |
| Acute upper respiratory infection | J00-J06 | Acute upper respiratory infections (acute nasopharyngitis [J00], acute sinusitis [J01], acute pharyngitis [J02], acute tonsillitis [J03], acute laryngitis and tracheitis [J04], acute obstructive laryngitis and epiglottitis [J05], acute upper respiratory infections of multiple and unspecified sites [J06]) |
| Other upper respiratory disease | J30-J39 | Other diseases of upper respiratory tract (vasomotor and allergic rhinitis [J30], chronic rhinitis, nasopharyngitis and pharyngitis [J31], chronic sinusitis [J32], nasal polyp [J33], other and unspecified disorders of nose and nasal sinuses [J34], chronic diseases of tonsils and adenoids [J35], peritonsillar abscess [J36], chronic laryngitis and laryngotracheitis [J37], disease of vocal cords and larynx, not elsewhere classified [J38] and others [J39]) |
| Major respiratory diseases | All of the above | All of the above |
| Respiratory death* | J00-J47, J80-J94, J96-J99 | All diseases of the respiratory system except: lung diseases due to external agents (J60-J70), intraoperative and post-procedural complications and disorders of respiratory system, not elsewhere classified (J95) |

* Respiratory death: any death with the underlying cause coded as one of the enlisted ICD-10 codes.

**Table 6.2 Baseline characteristics of participants according to long-term primary cooking and heating fuel exposure***

| | COOKING | | | | HEATING | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Characteristics** | **Always clean** | **Solid to clean** | **Always solid** | **Never cooked** | **Always clean** | **Solid to clean** | **Always solid** | **Never heated** | |
| **Total participants, N** | 53,130 | 66,115 | 131,270 | 27,323 | 23,648 | 29,894 | 105,761 | 61,775 | 289,945 |
| **Age (SD), years** | 45.2 (9.5) | 50.8 (9.8) | 52.9 (10.2) | 45.6 (11.2) | 46.7 (10.2) | 47.9 (10.3) | 52.0 (10.3) | 49.2 (10.3) | 50.3 (10.3) |
| **Women, %** | 86.3 | 96.9 | 95.4 | 40.2 | 90.0 | 90.5 | 92.3 | 88.7 | 90.9 |
| **Urban residency, %** | 88.7 | 79.8 | 8.2 | 51.4 | 79.0 | 88.6 | 15.6 | 54.3 | 44.7 |
| **Education level, %** | | | | | | | | | |
| No formal education | 13.3 | 17.9 | 27.5 | 19.6 | 13.4 | 8.0 | 18.5 | 28.0 | 23.5 |
| Primary | 20.8 | 28.2 | 34.4 | 25.2 | 19.2 | 23.2 | 34.4 | 32.3 | 30.5 |
| Secondary or above | 65.9 | 53.9 | 38.2 | 55.1 | 67.4 | 68.7 | 47.0 | 39.8 | 46.1 |
| **Annual household income, %** | | | | | | | | | |
| <10,000 Yuan | 17.8 | 20.6 | 38.1 | 22.8 | 12.4 | 16.5 | 33.5 | 35.0 | 28.3 |
| 10,000-19,999 Yuan | 26.6 | 31.6 | 32.9 | 28.5 | 28.5 | 29.0 | 34.7 | 29.3 | 29.4 |
| ≥20,000 Yuan | 55.6 | 47.8 | 29.0 | 48.7 | 59.1 | 54.5 | 31.8 | 35.7 | 42.4 |
| **Occupation, %†** | | | | | | | | | |
| Agricultural worker | 19.1 | 26.2 | 47.8 | 30.6 | 18.7 | 24.2 | 41.0 | 41.6 | 40.8 |
| Factory worker | 12.9 | 12.2 | 11.3 | 15.5 | 13.6 | 11.1 | 7.2 | 13.3 | 12.1 |
| Non-manual worker | 18.3 | 14.0 | 6.5 | 16.4 | 21.4 | 19.1 | 5.6 | 7.7 | 10.1 |
| Others | 49.7 | 47.6 | 34.5 | 37.5 | 46.3 | 45.7 | 46.1 | 37.3 | 37.0 |
| **Environmental tobacco smoke, %** | | | | | | | | | |
| <1 day/ week | 44.3 | 39.3 | 38.6 | 41.7 | 45.0 | 38.1 | 38.0 | 48.1 | 40.5 |
| 1-5 days/ week | 17.8 | 19.1 | 18.5 | 17.3 | 15.9 | 17.9 | 15.7 | 16.3 | 19.0 |
| 6-7 days/ week | 37.9 | 41.6 | 42.9 | 41.0 | 39.1 | 44.0 | 46.2 | 35.6 | 40.4 |
| **Regular drinker in male, %** | 22.7 | 21.9 | 18.1 | 19.6 | 27.2 | 23.6 | 20.1 | 14.2 | 19.1 |
| **Regular drinker in female, %** | 2.0 | 1.7 | 1.5 | 2.1 | 2.1 | 2.5 | 1.2 | 1.3 | 1.6 |
| **Always solid fuels for cooking, %‡** | - | - | - | - | 25.6 | 35.6 | 59.3 | 58.9 | 52.4 |
| **No cookstove ventilated, %** | 18.9 | 20.0 | 31.2 | 23.7 | 13.1 | 15.9 | 29.5 | 31.9 | 23.7 |
| **Always solid fuels for heating, %‡** | 48.7 | 50.1 | 89.0 | 62.5 | - | - | - | - | 66.4 |
| **Leg length (SD), cm** | 71.9 (4.2) | 71.7 (3.8) | 71.3 (3.7) | 71.7 (4.6) | 72.0 (4.2) | 71.5 (4.4) | 70.8 (4.0) | 71.4 (4.0) | 71.6 (4.1) |
| **Body mass index (SD), kg/m$^2$** | 23.8 (3.3) | 24.2 (3.4) | 23.6 (3.4) | 23.8 (3.2) | 23.7 (3.2) | 24.0 (3.4) | 24.3 (3.5) | 23.9 (3.3) | 23.8 (3.4) |
| **Self-reported poor health, %** | 8.5 | 8.2 | 10.4 | 9.8 | 9.7 | 9.8 | 11.9 | 11.2 | 9.2 |
| **Possible airflow obstruction, %** | 5.1 | 5.3 | 5.6 | 5.8 | 5.9 | 7.2 | 6.3 | 6.9 | 5.5 |
| **Chronic phlegm, %** | 1.5 | 1.7 | 2.0 | 1.3 | 1.3 | 2.4 | 1.9 | 1.8 | 1.7 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate.

† Non-manual worker: administrator/ manager, professional/ technician or sales/ service worker; others: homemaker, retired, self-employed, not stated or unemployed.

‡ Among participants who did not fit any corresponding cooking- and heating-specific criteria of exclusion.

**Table 6.3. Baseline characteristics of all participants, by categories of cooking and heating-related exposure and exclusion categories***

| | COOKING | | | HEATING | | | | |
|---|---|---|---|---|---|---|---|---|
| **Characteristics** | **Ever cooked regularly** | **Never cooked regularly** | **Excluded†** | **Ever used heating** | **Never used heating** | **Haikou** | **Zhejiang** | **Other excluded†** |
| **Total participants, N** | 250,515 | 27,323 | 12,107 | 159,303 | 61,775 | 21,260 | 33,679 | 13,928 |
| **Age (SD), years** | 50.7 (10.2) | 45.6 (11.2) | 51.4 (4.0) | 49.7 (10.3) | 48.7 (10.2) | 52.2 (11.6) | 51.5 (9.6) | 49.4 (10.3) |
| **Women, %** | 95.5 | 40.5 | 91.0 | 91.2 | 88.5 | 84.5 | 93.9 | 90.2 |
| **Urban residency, %** | 45.4 | 50.0 | 53.3 | 38.8 | 65.4 | - | - | 43.7 |
| **Education level, %** | | | | | | | | |
| No formal education | 23.6 | 20.3 | 21.8 | 17.8 | 25.7 | 18.1 | 53.7 | 14.9 |
| Primary school | 30.7 | 25.6 | 27.6 | 30.0 | 33.6 | 20.3 | 31.1 | 29.8 |
| Middle school or above | 45.7 | 54.0 | 50.7 | 52.2 | 40.7 | 61.6 | 15.1 | 55.3 |
| **Annual household income, %** | | | | | | | | |
| <10,000 Yuan | 28.9 | 22.9 | 24.2 | 28.9 | 40.7 | 22.6 | 6.4 | 32.9 |
| 10,000-19,999 Yuan | 29.4 | 28.3 | 29.8 | 30.7 | 31.2 | 31.8 | 14.7 | 29.4 |
| ≥20,000 Yuan | 41.6 | 48.8 | 46.0 | 40.3 | 28.1 | 45.6 | 78.9 | 37.7 |
| **Occupation, %‡** | | | | | | | | |
| Agricultural worker | 41.2 | 31.0 | 33.9 | 40.2 | 43.7 | 15.5 | 49.2 | 36.9 |
| Factory worker | 11.7 | 15.6 | 14.9 | 10.4 | 12.1 | 3.3 | 27.0 | 11.8 |
| Non-manual worker | 9.7 | 16.1 | 14.5 | 11.0 | 7.2 | 14.7 | 6.1 | 10.9 |
| Others | 37.4 | 37.2 | 36.8 | 38.4 | 37.1 | 66.6 | 17.7 | 40.4 |
| **Environmental tobacco smoke, %** | | | | | | | | |
| <1 day/ week | 40.7 | 42.0 | 39.7 | 35.2 | 44.9 | 58.8 | 61.4 | 37.5 |
| 1-5 days/ week | 19.1 | 17.4 | 19.4 | 17.5 | 14.1 | 21.1 | 27.6 | 16.1 |
| 6-7 days/ week | 40.2 | 40.6 | 40.9 | 47.3 | 41.1 | 20.1 | 11.0 | 46.4 |
| **Regular drinker in male, %** | 18.7 | 19.6 | 21.6 | 19.9 | 14.7 | 7.0 | 23.7 | 22.6 |
| **Regular drinker in female, %** | 1.5 | 2.1 | 2.0 | 1.7 | 1.3 | 0.4 | 1.3 | 2.0 |
| **Always solid fuels for cooking, %§** | - | - | - | 51.2 | 62.7 | 24.4 | 56.5 | 50.2 |
| **No cookstove ventilated, %** | 23.8 | 23.6 | 24.3 | 24.2 | 35.2 | 37.7 | 5.5 | 27.2 |
| **Always solid fuels for heating, %§** | 66.5 | 62.6 | 61.2 | - | - | - | - | - |
| **Leg length (SD), cm** | 71.6 (3.9) | 71.7 (4.6) | 71.6 (4.0) | 71.4 (4.1) | 71.1 (3.8) | 72.3 (4.1) | 72.8 (3.9) | 71.3 (4.0) |
| **Body mass index (SD), kg/m$^2$** | 23.8 (3.4) | 23.7 (3.2) | 23.9 (3.5) | 23.9 (3.5) | 24.0 (3.2) | 23.3 (3.3) | 23.1 (3.2) | 23.9 (3.4) |
| **Self-reported poor health, %** | 9.1 | 9.8 | 11.1 | 10.0 | 12.7 | 6.2 | 4.4 | 14.2 |
| **Possible airflow obstruction, %** | 5.5 | 5.8 | 5.7 | 5.7 | 7.8 | 3.3 | 4.0 | 7.3 |
| **Chronic phlegm, %** | 1.7 | 1.3 | 2.1 | 2.0 | 2.0 | 0.7 | 0.7 | 2.9 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate.
† Participants who used other fuels at any residence, who had switched from clean to solid fuels or who had previously cooked/ heated but stopped at baseline.
‡ Non-manual worker: administrator/ manager, professional/ technician or sales/ service worker; others: homemaker, retired, self-employed, not stated/ unemployed.
§ Among participants who did not fit any corresponding cooking- and heating-specific criteria of exclusion.

**Table 6.4 Distribution and rates (number per 100,000 person-years) of incident respiratory disease according to age, gender and study area***

| | Major respiratory disease | | Chronic lower respiratory disease | | Chronic obstructive pulmonary disease | | Acute lower respiratory infection | | Acute upper respiratory infection | | Other upper respiratory disease | | Respiratory death | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Characteristic** | **No. of events** | **Rate (95% CI)** | **No. of events** | **Rate (95% CI)** | **No. of events** | **Rate (95% CI)** | **No. of events** | **Rate (95% CI)** | **No. of events** | **Rate (95% CI)** | **No. of events** | **Rate (95% CI)** | **No. of events** | **Rate (95% CI)** |
| **Age, years (mean)** | | | | | | | | | | | | | | |
| 30-39 (37.5) | 2,300 | 552 (402 - 703) | 851 | 200 (109 - 291) | 218 | 78 (15 - 141) | 914 | 260 (144 - 376) | 469 | 69 (62 - 77) | 332 | 76 (32 - 120) | 5 | 1 (0 - 2) |
| 40-49 (44.8) | 5,910 | 701 (604 - 798) | 2,696 | 273 (229 - 317) | 682 | 91 (48 - 134) | 2,140 | 347 (252 - 441) | 1,160 | 127 (84 - 171) | 703 | 84 (48 - 120) | 18 | 2 (1 - 3) |
| 50-59 (54.7) | 7,783 | 919 (823 - 1014) | 4,255 | 462 (420 - 504) | 1,541 | 166 (140 - 193) | 2,765 | 351 (270 - 431) | 1,253 | 126 (117 - 134) | 675 | 65 (60 - 71) | 122 | 12 (10 - 15) |
| 60-69 (64.6) | 4,897 | 1271 (1206 - 1335) | 3,077 | 812 (758 - 867) | 1,691 | 415 (367 - 463) | 1,786 | 422 (369 - 474) | 522 | 133 (119 - 146) | 262 | 67 (57 - 77) | 303 | 62 (54 - 69) |
| ≥70 (72.7) | 2,188 | 1597 (1518 - 1677) | 1,467 | 1105 (1037 - 1172) | 961 | 670 (620 - 721) | 817 | 517 (475 - 558) | 182 | 109 (90 - 128) | 77 | 42 (31 - 53) | 345 | 221 (193 - 248) |
| **Gender** | | | | | | | | | | | | | | |
| Male | 1,912 | 823 (780 - 865) | 1,023 | 438 (407 - 469) | 549 | 196 (178 - 214) | 752 | 294 (270 - 317) | 263 | 117 (100 - 133) | 170 | 77 (64 - 91) | 136 | 42 (35 - 50) |
| Female | 21,166 | 932 (919 - 945) | 11,323 | 492 (483 - 501) | 4,544 | 202 (196 - 208) | 7,670 | 329 (322 - 337) | 3,323 | 140 (135 - 145) | 1,879 | 77 (74 - 81) | 657 | 31 (29 - 34) |
| **Residency** | | | | | | | | | | | | | | |
| Rural | 16,299 | 1204 (1185-1223) | 9,314 | 686 (672-701) | 4,011 | 309 (299-319) | 5,466 | 387 (377-398) | 2,373 | 161 (154-167) | 1,211 | 80 (75-84) | 544 | 48 (44-52) |
| Urban | 6,779 | 560 (547-574) | 3,032 | 245 (236-254) | 1,082 | 84 (79-89) | 2,956 | 241 (232-250) | 1,213 | 102 (96-108) | 838 | 70 (65-75) | 249 | 19 (17-21) |

* Rates were standardised to the age, gender and study area structure of the overall study population, where appropriate. Chronic lower respiratory disease (ICD-10: J40-J47); Chronic obstructive pulmonary disease (J41-J44); Acute lower respiratory infection (J12-J18, J20-J22); Acute upper respiratory infection (J00-J06); Other upper respiratory disease (J30-J39); major respiratory disease (all of the above).* Rates were standardised to the age, gender and study area structure of the overall study population, where appropriate. Chronic lower respiratory disease (ICD-10: J40-J47); Chronic obstructive pulmonary disease (J41-J44); Acute lower respiratory infection (J12-J18, J20-J22); Acute upper respiratory infection (J00-J06); Other upper respiratory disease (J30-J39); major respiratory disease (all of the above).

**Table 6.5 Baseline characteristics of participants with and without incident respiratory disease (1)***

| | Chronic lower respiratory disease | | Chronic obstructive pulmonary disease | | Acute lower respiratory infection | |
|---|---|---|---|---|---|---|
| **Characteristic** | **No** | **Yes** | **No** | **Yes** | **No** | **Yes** |
| **Total participants, N** | 277,599 | 12,346 | 284,852 | 5,093 | 281,523 | 8,422 |
| **Age (SD), years** | 50.1 (10.3) | 56.7 (10.5) | 50.2 (10.3) | 60.7 (10.2) | 50.2 (10.3) | 54.3 (10.8) |
| **Women, %** | 90.8 | 92.1 | 90.8 | 90.1 | 90.8 | 91.7 |
| **Urban residency, %** | 45.7 | 22.7 | 45.2 | 15.2 | 45.1 | 32.0 |
| **Education level, %** | | | | | | |
| No formal education | 23.2 | 27.2 | 23.4 | 28.3 | 23.4 | 24.5 |
| Primary | 30.4 | 32.6 | 30.5 | 31.2 | 30.4 | 32.1 |
| Secondary or above | 46.3 | 40.2 | 46.2 | 40.5 | 46.2 | 43.4 |
| **Annual household income, %** | | | | | | |
| < 10,000 Yuan | 28.1 | 30.5 | 28.2 | 29.6 | 28.3 | 29.7 |
| 10,000-19,999 Yuan | 29.3 | 30.6 | 29.4 | 30.3 | 29.3 | 29.7 |
| ≥ 20,000 Yuan | 42.5 | 38.9 | 42.4 | 40.1 | 42.4 | 40.6 |
| **Occupation, %†** | | | | | | |
| Agricultural worker | 40.5 | 44.5 | 40.8 | 42.0 | 40.8 | 42.3 |
| Factory worker | 12.2 | 10.6 | 12.1 | 7.7 | 12.1 | 12.2 |
| Non-manual worker | 10.1 | 8.6 | 10.1 | 10.8 | 10.1 | 9.3 |
| Others | 37.2 | 36.3 | 37.0 | 39.5 | 37.0 | 36.2 |
| **Environmental tobacco smoke, %** | | | | | | |
| <1 day/ week | 40.6 | 39.0 | 40.6 | 37.9 | 40.6 | 39.5 |
| 1-5 days/ week | 19.0 | 18.8 | 19.0 | 20.2 | 19.0 | 18.7 |
| 6-7 days/ week | 40.4 | 42.3 | 40.4 | 42.0 | 40.4 | 41.9 |
| **Regular drinker in male, %** | 19.2 | 14.5 | 19.2 | 14.4 | 19.1 | 18.6 |
| **Regular drinker in female, %** | 1.6 | 1.8 | 1.6 | 1.3 | 1.6 | 1.6 |
| **Always solid fuels for cooking, %‡** | 52.1 | 56.0 | 52.4 | 54.8 | 52.4 | 54.6 |
| **No cookstove ventilated, %** | 23.6 | 25.8 | 23.7 | 25.7 | 23.7 | 24.6 |
| **Always solid fuels for heating, %§** | 66.3 | 68.2 | 66.4 | 68.8 | 66.4 | 66.3 |
| **Leg length (SD), cm** | 71.6 (3.4) | 71.4 (3.6) | 71.6 (3.4) | 71.4 (3.8) | 71.6 (3.4) | 71.6 (3.6) |
| **Body mass index (SD), kg/m$^2$** | 23.8 (4.1) | 23.7 (4.0) | 23.8 (4.1) | 23.8 (4.2) | 23.8 (4.1) | 23.8 (4.1) |
| **Self-reported poor health, %** | 9.0 | 13.4 | 9.1 | 14.1 | 9.1 | 12.2 |
| **Possible airflow obstruction, %** | 5.3 | 9.7 | 5.3 | 13.4 | 5.4 | 6.6 |
| **Chronic phlegm, %** | 1.6 | 3.3 | 1.6 | 3.6 | 1.7 | 2.3 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample.

† Non-manual worker: administrator or manager, professional or technician, or sales or service worker; others: homemaker, retired, self-employed, other no stated or unemployed.

‡ Among participants who had ever cooked regularly and did not fit any criteria of exclusion.

§ Among participants who had ever used heating and did not fit any criteria of exclusion.

**Table 6.6 Baseline characteristics of participants with and without incident respiratory disease (2)***

| | Acute upper respiratory infection | | Other upper respiratory disease | | Respiratory death | |
|---|---|---|---|---|---|---|
| **Characteristic** | **No** | **Yes** | **No** | **Yes** | **No** | **Yes** |
| **Total participants, N** | 286,359 | 3,586 | 287,896 | 2,049 | 289,152 | 793 |
| **Age (SD), years** | 50.3 (10.4) | 51.3 (09.9) | 50.3 (10.4) | 48.9 (09.7) | 50.3 (10.3) | 66.7 (7.5) |
| **Women, %** | 90.8 | 92.7 | 90.8 | 89.5 | 90.9 | 83.4 |
| **Urban residency, %** | 44.9 | 34.4 | 44.8 | 41.9 | 44.8 | 31.5 |
| **Education level, %** | | | | | | |
| No formal education | 23.4 | 23.8 | 23.4 | 22.0 | 23.4 | 35.1 |
| Primary | 30.4 | 32.2 | 30.4 | 33.5 | 30.5 | 33.9 |
| Secondary or above | 46.2 | 44.0 | 46.1 | 44.5 | 46.1 | 30.9 |
| **Annual household income, %** | | | | | | |
| <10,000 Yuan | 28.2 | 28.5 | 28.3 | 26.8 | 28.3 | 39.9 |
| 10,000-19,999 Yuan | 29.3 | 31.8 | 29.3 | 32.4 | 29.4 | 29.9 |
| ≥20,000 Yuan | 42.4 | 39.7 | 42.4 | 40.8 | 42.4 | 30.2 |
| **Occupation, %†** | | | | | | |
| Agricultural worker | 40.7 | 47.7 | 40.8 | 44.7 | 40.8 | 43.2 |
| Factory worker | 12.1 | 11.3 | 12.1 | 10.8 | 12.1 | 6.2 |
| Non-manual worker | 10.1 | 7.2 | 10.1 | 10.5 | 10.1 | 8.3 |
| Others | 37.1 | 33.9 | 37.1 | 34.0 | 37.0 | 42.3 |
| **Environmental tobacco smoke, %** | | | | | | |
| <1 day/ week | 40.6 | 39.0 | 40.6 | 38.9 | 40.5 | 45.5 |
| 1-5 days/ week | 19.0 | 19.5 | 19.0 | 20.5 | 19.0 | 19.0 |
| 6-7 days/ week | 40.4 | 41.6 | 40.4 | 40.5 | 40.4 | 35.5 |
| **Regular drinker in male, %** | 19.1 | 17.9 | 19.1 | 25.7 | 19.1 | 10.4 |
| **Regular drinker in female, %** | 1.6 | 1.6 | 1.6 | 1.0 | 1.6 | 0.4 |
| **Always solid fuels for cooking, %‡** | 52.3 | 60.4 | 52.3 | 55.9 | 52.4 | 61.3 |
| **No cookstove ventilated, %** | 23.6 | 23.5 | 23.7 | 25.5 | 23.7 | 30.2 |
| **Always solid fuels for heating, %§** | 66.4 | 68.3 | 66.4 | 64.6 | 66.4 | 70.6 |
| **Leg length (SD), cm** | 71.6 (3.4) | 71.5 (3.2) | 71.6 (3.4) | 71.6 (3.3) | 71.6 (4.1) | 70.9 (4.6) |
| **Body mass index (SD), kg/m$^2$** | 23.8 (4.1) | 23.5 (3.9) | 23.8 (4.1) | 23.8 (4.0) | 23.8 (3.4) | 22.5 (4.1) |
| **Self-reported poor health, %** | 9.1 | 11.6 | 9.1 | 11.9 | 9.1 | 23.6 |
| **Possible airflow obstruction, %** | 5.5 | 5.1 | 5.5 | 5.6 | 5.4 | 20.3 |
| **Chronic phlegm, %** | 1.7 | 1.5 | 1.7 | 1.8 | 1.7 | 4.5 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample.

† Non-manual worker: administrator or manager, professional or technician, or sales or service worker; others: homemaker, retired, self-employed, other no stated or unemployed.

‡ Among participants who had ever cooked regularly and did not fit any criteria of exclusion.

§ Among participants who had ever used heating and did not fit any criteria of exclusion.

**Table 6.7 Adjusted hazard ratios (HRs) for major respiratory diseases by long-term primary cooking fuel exposure with different exclusion of participants**

| | (1) Excluding those with <20 year recall period | | (2) Excluding those who used clean fuels <10 years | | (3) Excluding those with possible airflow obstruction or chronic phlegm | | (4) Excluding weekly regular cooks | | (5) Excluding 1-4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **N** | **HR (95% CI)*** | **N** | **HR (95% CI)*** | **N** | **HR (95% CI)*** | **N** | **HR (95% CI)*** | **N** | **HR (95% CI)*** |
| **Major respiratory disease** | | | | | | | | | | |
| Always clean | 2,149 | 1.00 (0.95-1.05) | 1,407 | 1.00 (0.95-1.06) | 2,407 | 1.00 (0.96-1.05) | 2,095 | 1.00 (0.95-1.05) | 1,030 | 1.00 (0.94-1.07) |
| Solid to clean | 4,283 | 1.16 (1.12-1.20) | 2,687 | 1.15 (1.10-1.20) | 4,179 | 1.17 (1.13-1.21) | 4,053 | 1.12 (1.08-1.16) | 2,129 | 1.14 (1.09-1.20) |
| Always solid | 12,381 | 1.38 (1.33-1.42) | 12,748 | 1.46 (1.41-1.50) | 11,118 | 1.38 (1.33-1.43) | 11,745 | 1.30 (1.26-1.35) | 9,903 | 1.40 (1.35-1.46) |
| **Chronic lower respiratory disease** | | | | | | | | | | |
| Always clean | 958 | 1.00 (0.93-1.07) | 637 | 1.00 (0.92-1.09) | 985 | 1.00 (0.93-1.07) | 874 | 1.00 (0.93-1.08) | 437 | 1.00 (0.90-1.11) |
| Solid to clean | 2,121 | 1.19 (1.14-1.25) | 1,283 | 1.16 (1.09-1.23) | 2,037 | 1.26 (1.20-1.32) | 2,013 | 1.18 (1.12-1.23) | 992 | 1.20 (1.12-1.28) |
| Always solid | 7,020 | 1.46 (1.40-1.52) | 7,235 | 1.56 (1.50-1.62) | 6,131 | 1.52 (1.46-1.58) | 6,628 | 1.41 (1.36-1.47) | 5,410 | 1.59 (1.51-1.66) |
| **COPD†** | | | | | | | | | | |
| Always clean | 304 | 1.00 (0.88-1.13) | 206 | 1.00 (0.86-1.16) | 297 | 1.00 (0.88-1.13) | 298 | 1.00 (0.88-1.13) | 135 | 1.00 (0.83-1.20) |
| Solid to clean | 739 | 0.97 (0.89-1.05) | 497 | 1.04 (0.94-1.15) | 631 | 0.99 (0.91-1.08) | 698 | 0.94 (0.86-1.02) | 351 | 1.09 (0.97-1.23) |
| Always solid | 3,216 | 1.11 (1.04-1.19) | 3,283 | 1.15 (1.08-1.24) | 2,487 | 1.16 (1.07-1.25) | 3,111 | 1.11 (1.03-1.19) | 2,302 | 1.28 (1.17-1.40) |
| **Acute lower respiratory infection** | | | | | | | | | | |
| Always clean | 842 | 1.00 (0.93-1.08) | 545 | 1.00 (0.91-1.10) | 976 | 1.00 (0.93-1.08) | 875 | 1.00 (0.93-1.08) | 422 | 1.00 (0.90-1.11) |
| Solid to clean | 1,764 | 1.13 (1.07-1.19) | 1,147 | 1.13 (1.06-1.21) | 1,709 | 1.10 (1.04-1.16) | 1,669 | 1.08 (1.02-1.14) | 922 | 1.11 (1.03-1.20) |
| Always solid | 4,333 | 1.19 (1.12-1.27) | 4,445 | 1.24 (1.17-1.32) | 3,894 | 1.17 (1.09-1.25) | 4,188 | 1.13 (1.06-1.20) | 3,574 | 1.17 (1.08-1.26) |
| **Acute upper respiratory infection** | | | | | | | | | | |
| Always clean | 364 | 1.00 (0.90-1.12) | 245 | 1.00 (0.88-1.14) | 429 | 1.00 (0.90-1.11) | 347 | 1.00 (0.89-1.12) | 179 | 1.00 (0.86-1.17) |
| Solid to clean | 547 | 1.16 (1.06-1.27) | 337 | 1.12 (1.00-1.26) | 561 | 1.14 (1.05-1.24) | 510 | 1.13 (1.03-1.23) | 278 | 1.13 (0.99-1.28) |
| Always solid | 1,934 | 1.63 (1.52-1.76) | 1,988 | 1.76 (1.64-1.90) | 1,860 | 1.57 (1.45-1.69) | 1,732 | 1.53 (1.41-1.66) | 1,572 | 1.68 (1.55-1.83) |
| **Other upper respiratory disease** | | | | | | | | | | |
| Always clean | 267 | 1.00 (0.88-1.14) | 165 | 1.00 (0.85-1.18) | 318 | 1.00 (0.88-1.13) | 258 | 1.00 (0.87-1.15) | 122 | 1.00 (0.83-1.21) |
| Solid to clean | 388 | 1.08 (0.97-1.20) | 250 | 1.18 (1.03-1.35) | 404 | 1.10 (0.99-1.22) | 367 | 1.08 (0.97-1.21) | 202 | 1.18 (1.01-1.38) |
| Always solid | 951 | 1.55 (1.39-1.73) | 988 | 1.74 (1.56-1.94) | 905 | 1.52 (1.35-1.69) | 866 | 1.54 (1.36-1.73) | 759 | 1.73 (1.52-1.97) |
| **Respiratory death** | | | | | | | | | | |
| Always clean | 49 | 1.00 (0.74-1.34) | 34 | 1.00 (0.70-1.42) | 39 | 1.00 (0.72-1.39) | 40 | 1.00 (0.72-1.38) | 19 | 1.00 (0.63-1.59) |
| Solid to clean | 117 | 0.83 (0.66-1.04) | 72 | 0.70 (0.52-0.93) | 98 | 0.99 (0.77-1.27) | 113 | 1.01 (0.80-1.27) | 53 | 0.86 (0.60-1.21) |
| Always solid | 453 | 1.44 (1.18-1.76) | 464 | 1.42 (1.16-1.74) | 336 | 1.95 (1.53-2.48) | 432 | 1.56 (1.27-1.91) | 302 | 2.02 (1.54-2.65) |

* Hazard ratios were stratified for age-at-risk, gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, exposure to environmental tobacco smoke, cookstove ventilation, length of recall period and heating fuel exposure.
† COPD: chronic obstructive pulmonary disease.

**Table 6.8 Adjusted hazard ratios (HRs) for chronic lower respiratory disease and chronic obstructive pulmonary disease by unweighted and weighted duration of solid fuel use for heating**

| | Number of events | HR (95% CI)* |
|---|---|---|
| **UNWEIGHTED DURATION** | | |
| **Chronic lower respiratory disease** | | |
| Always clean | 459 | 1.00 (0.87-1.15) |
| Solid to clean | 450 | 0.95 (0.84-1.08) |
| Always solid (<20 years) | 192 | 1.41 (1.21-1.63) |
| Always solid (20-39 years) | 871 | 1.23 (1.13-1.33) |
| Always solid (≥40 years) | 2,167 | 1.16 (1.06-1.27) |
| **Chronic obstructive pulmonary disease** | | |
| Always clean | 288 | 1.00 (0.84-1.18) |
| Solid to clean | 274 | 0.99 (0.84-1.16) |
| Always solid (<20 years) | 89 | 1.22 (0.98-1.51) |
| Always solid (20-39 years) | 478 | 1.29 (1.16-1.43) |
| Always solid (≥40 years) | 1,399 | 1.23 (1.10-1.38) |
| **WEIGHTED DURATION** | | |
| **Chronic lower respiratory disease** | | |
| Always clean | 459 | 1.00 (0.87-1.16) |
| Solid to clean | 450 | 0.96 (0.84-1.09) |
| Always solid (<10 years) | 953 | 1.27 (1.16-1.38) |
| Always solid (10-19 years) | 1,622 | 1.17 (1.08-1.27) |
| Always solid (≥20 years) | 670 | 1.23 (1.04-1.46) |
| **Chronic obstructive pulmonary disease** | | |
| Always clean | 288 | 1.00 (0.84-1.19) |
| Solid to clean | 274 | 0.99 (0.85-1.16) |
| Always solid (<10 years) | 637 | 1.23 (1.10-1.37) |
| Always solid (10-19 years) | 979 | 1.24 (1.12-1.37) |
| Always solid (≥20 years) | 356 | 1.30 (1.03-1.64) |

* Hazard ratios were stratified for age-at-risk, gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, exposure to environmental tobacco smoke, cookstove ventilation, length of recall period and cooking fuel exposure.

**Table 6.9 Adjusted hazard ratios (HRs) for chronic lower respiratory disease and chronic obstructive pulmonary disease by specific types of fuel used for heating**

| | Number of events | HR (95% CI)* |
|---|---|---|
| **Chronic lower respiratory disease** | | |
| Always clean | 459 | 1.00 (0.90-1.12) |
| Always coal | 752 | 0.95 (0.85-1.07) |
| Coal and wood mixed | 838 | 1.23 (1.11-1.36) |
| Always wood | 1,636 | 1.22 (1.12-1.34) |
| **Chronic obstructive pulmonary disease** | | |
| Always clean | 288 | 1.00 (0.87-1.14) |
| Always coal | 316 | 1.19 (1.02-1.40) |
| Coal and wood mixed | 444 | 1.25 (1.10-1.42) |
| Always wood | 1,206 | 1.30 (1.17-1.45) |

* Hazard ratios were stratified for age-at-risk, gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, exposure to environmental tobacco smoke, cookstove ventilation, length of recall period and cooking fuel exposure.

**Table 6.10 Adjusted HRs for major respiratory diseases by long-term primary heating fuel exposure with different exclusion of participants**

| | (1) Excluding those with <20 year recall period | | (2) Excluding those who used clean fuels <10 years | | (3) Excluding those with possible airflow obstruction or chronic phlegm | | (4) Excluding 1-3 | |
|---|---|---|---|---|---|---|---|---|
| | N | HR (95% CI)* | N | HR (95% CI)* | N | HR (95% CI)* | N | HR (95% CI)* |
| **Major respiratory disease** | | | | | | | | |
| Always clean | 1,141 | 1.00 (0.94-1.06) | 747 | 1.00 (0.93-1.07) | 1,170 | 1.00 (0.94-1.06) | 709 | 1.00 (0.93-1.08) |
| Solid to clean | 1,294 | 0.91 (0.84-0.98) | 754 | 0.92 (0.83-1.02) | 1,287 | 0.93 (0.87-1.00) | 816 | 0.92 (0.84-1.01) |
| Always solid | 6,418 | 1.03 (0.96-1.11) | 6,600 | 1.03 (0.95-1.11) | 5,925 | 1.07 (1.00-1.15) | 5,607 | 1.05 (0.96-1.14) |
| **Chronic lower respiratory disease** | | | | | | | | |
| Always clean | 398 | 1.00 (0.91-1.10) | 262 | 1.00 (0.89-1.13) | 352 | 1.00 (0.90-1.11) | 222 | 1.00 (0.88-1.14) |
| Solid to clean | 418 | 0.96 (0.84-1.09) | 238 | 1.00 (0.84-1.19) | 395 | 1.00 (0.88-1.14) | 250 | 0.99 (0.83-1.17) |
| Always solid | 3,137 | 1.20 (1.07-1.34) | 3,226 | 1.23 (1.10-1.39) | 2,787 | 1.24 (1.10-1.40) | 2,654 | 1.21 (1.06-1.39) |
| **COPD†** | | | | | | | | |
| Always clean | 259 | 1.00 (0.89-1.13) | 189 | 1.00 (0.87-1.15) | 200 | 1.00 (0.87-1.15) | 148 | 1.00 (0.85-1.17) |
| Solid to clean | 262 | 1.04 (0.88-1.23) | 157 | 1.05 (0.85-1.31) | 232 | 1.05 (0.89-1.25) | 164 | 1.08 (0.88-1.32) |
| Always solid | 1,924 | 1.31 (1.15-1.49) | 1,966 | 1.27 (1.11-1.45) | 1,629 | 1.35 (1.16-1.56) | 1,565 | 1.31 (1.11-1.54) |
| **Acute lower respiratory infection** | | | | | | | | |
| Always clean | 697 | 1.00 (0.93-1.08) | 467 | 1.00 (0.92-1.09) | 736 | 1.00 (0.93-1.08) | 464 | 1.00 (0.91-1.09) |
| Solid to clean | 776 | 0.86 (0.78-0.95) | 471 | 0.87 (0.76-0.98) | 779 | 0.90 (0.82-0.98) | 504 | 0.87 (0.77-0.99) |
| Always solid | 2,566 | 0.90 (0.82-0.99) | 2,647 | 0.87 (0.79-0.97) | 2,416 | 0.97 (0.87-1.07) | 2,258 | 0.92 (0.82-1.03) |
| **Acute upper respiratory infection** | | | | | | | | |
| Always clean | 86 | 1.00 (0.80-1.24) | 54 | 1.00 (0.77-1.30) | 92 | 1.00 (0.81-1.24) | 57 | 1.00 (0.76-1.31) |
| Solid to clean | 94 | 0.80 (0.62-1.02) | 56 | 1.03 (0.74-1.43) | 98 | 0.87 (0.69-1.11) | 64 | 0.86 (0.64-1.16) |
| Always solid | 771 | 0.98 (0.78-1.24) | 788 | 1.02 (0.79-1.31) | 748 | 1.11 (0.88-1.40) | 727 | 1.11 (0.86-1.43) |
| **Other upper respiratory disease** | | | | | | | | |
| Always clean | 75 | 1.00 (0.79-1.26) | 45 | 1.00 (0.75-1.33) | 99 | 1.00 (0.81-1.23) | 42 | 1.00 (0.73-1.36) |
| Solid to clean | 106 | 1.08 (0.85-1.38) | 52 | 0.92 (0.65-1.30) | 109 | 0.93 (0.74-1.17) | 59 | 1.06 (0.77-1.46) |
| Always solid | 454 | 1.07 (0.83-1.38) | 467 | 1.18 (0.89-1.55) | 436 | 1.01 (0.78-1.31) | 406 | 1.18 (0.88-1.59) |
| **Respiratory death** | | | | | | | | |
| Always clean | 39 | 1.00 (0.73-1.37) | 28 | 1.00 (0.69-1.45) | 30 | 1.00 (0.69-1.45) | 25 | 1.00 (0.67-1.49) |
| Solid to clean | 67 | 1.07 (0.73-1.55) | 37 | 0.83 (0.50-1.36) | 60 | 1.18 (0.81-1.73) | 41 | 0.97 (0.62-1.52) |
| Always solid | 302 | 0.96 (0.69-1.34) | 307 | 0.84 (0.59-1.18) | 252 | 1.15 (0.80-1.66) | 245 | 0.97 (0.65-1.44) |

* Hazard ratios were stratified for age-at-risk, gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, exposure to environmental tobacco smoke, cookstove ventilation, length of recall period and cooking fuel exposure.
† COPD: chronic obstructive pulmonary disease.

**Figure 6.1 Participants exclusion**

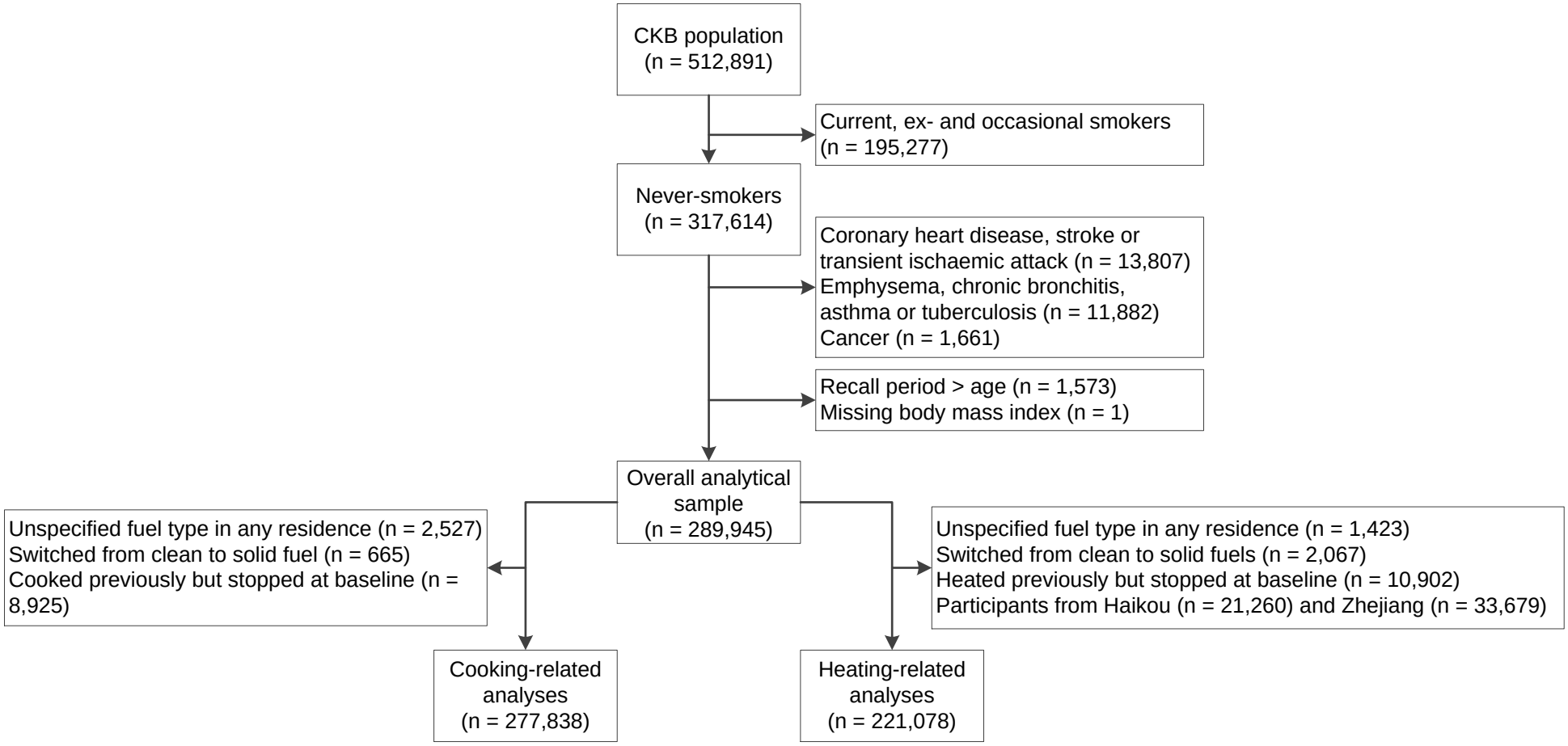


**Figure 6.2 Adjusted hazard ratios for major respiratory diseases by long-term cooking fuel exposure**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke, cookstove ventilation, primary heating fuel exposure and length of recall period. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

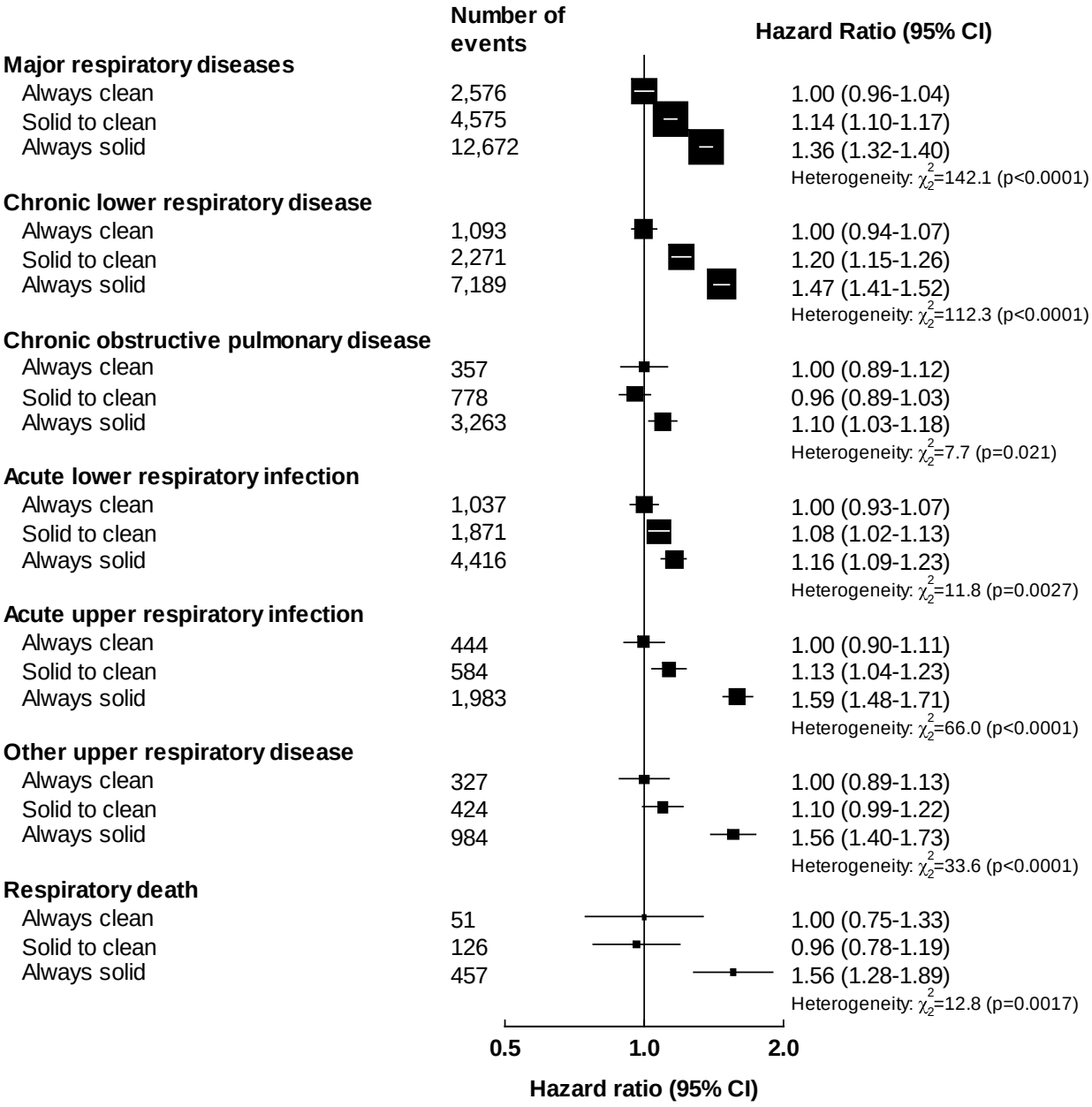


**Figure 6.3 Adjusted hazard ratios for major respiratory diseases by duration of continuous exposure to solid cooking fuel in never-smokers**

Conventions as Figure 6.2.

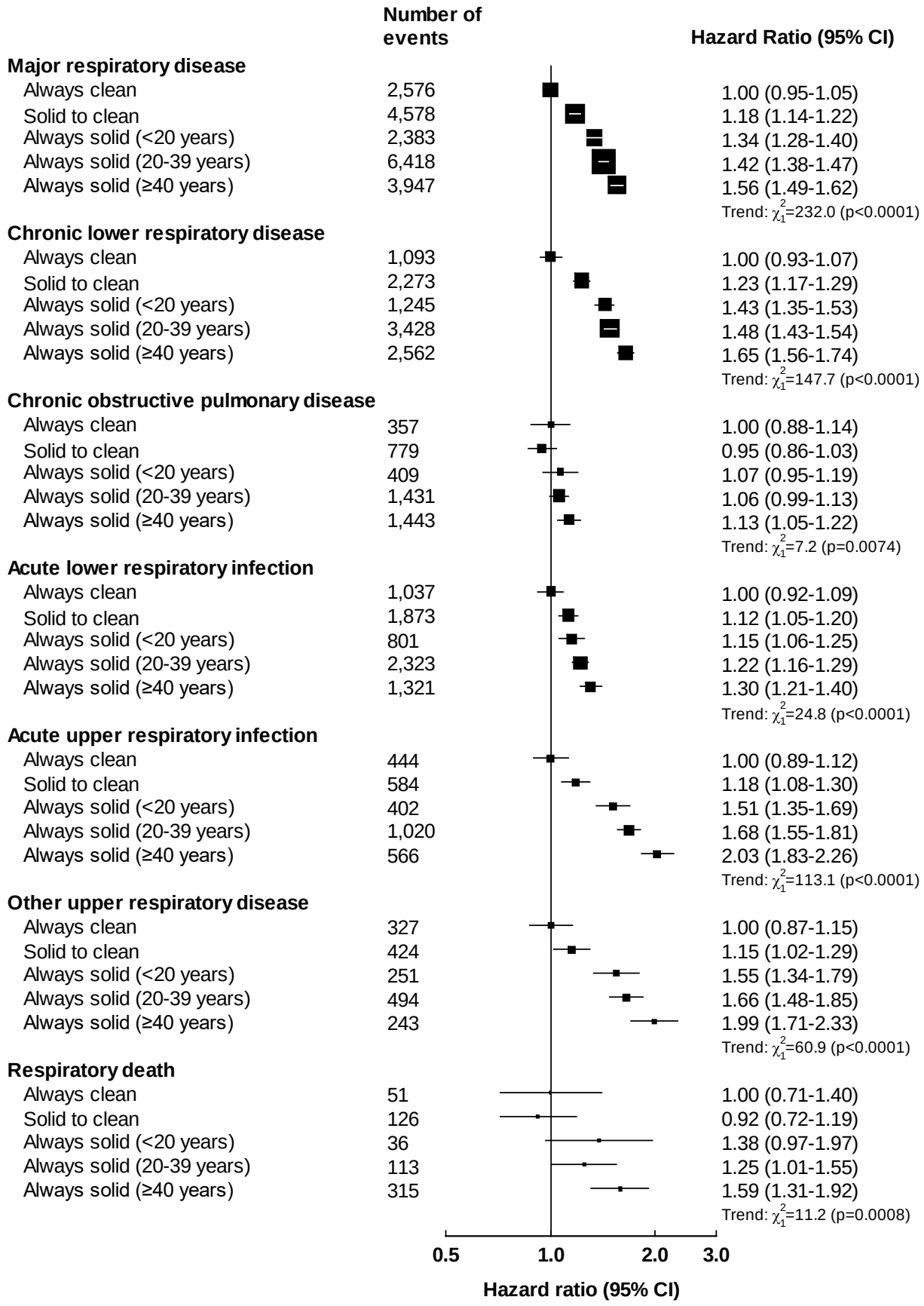


**Figure 6.4 Adjusted hazard ratios for major respiratory diseases by types of primary cooking fuel used in never-smokers**

Conventions as Figure 6.2.

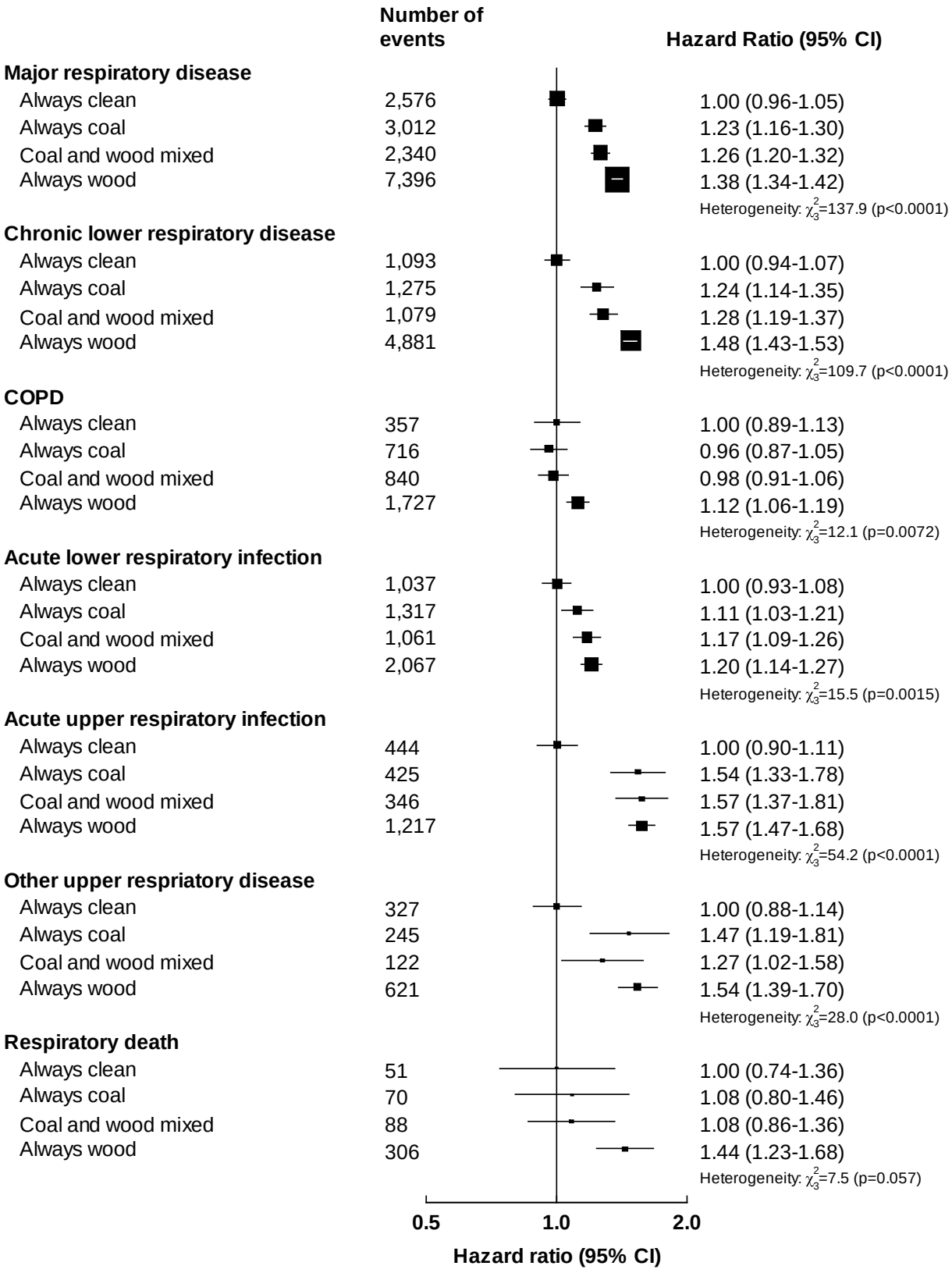


**Figure 6.5 Adjusted hazard ratios for major respiratory diseases by long-term primary cooking fuel and ventilated cookstove ownership in never-smokers**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke, primary heating fuel exposure and length of recall period. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

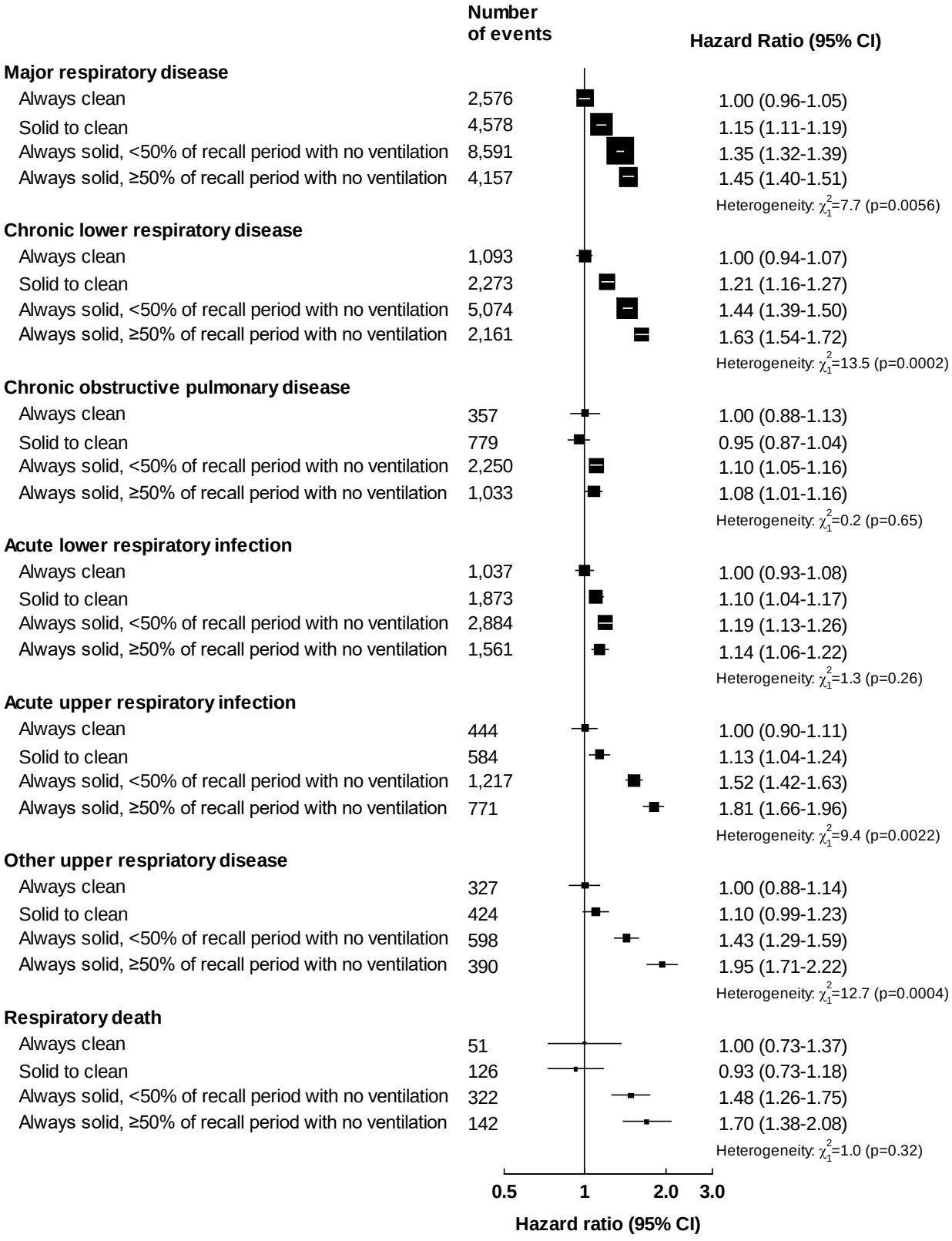


**Figure 6.6 Adjusted hazard ratios for major respiratory diseases associated with long-term solid fuel use for cooking (versus clean fuel use), by subgroups of baseline characteristics**

Hazard ratios (HRs) were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke, primary heating fuel exposure and length of recall period, where appropriate. The black boxes represent HRs, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).The white diamond represent the HRs and 95% CI in the main analysis.

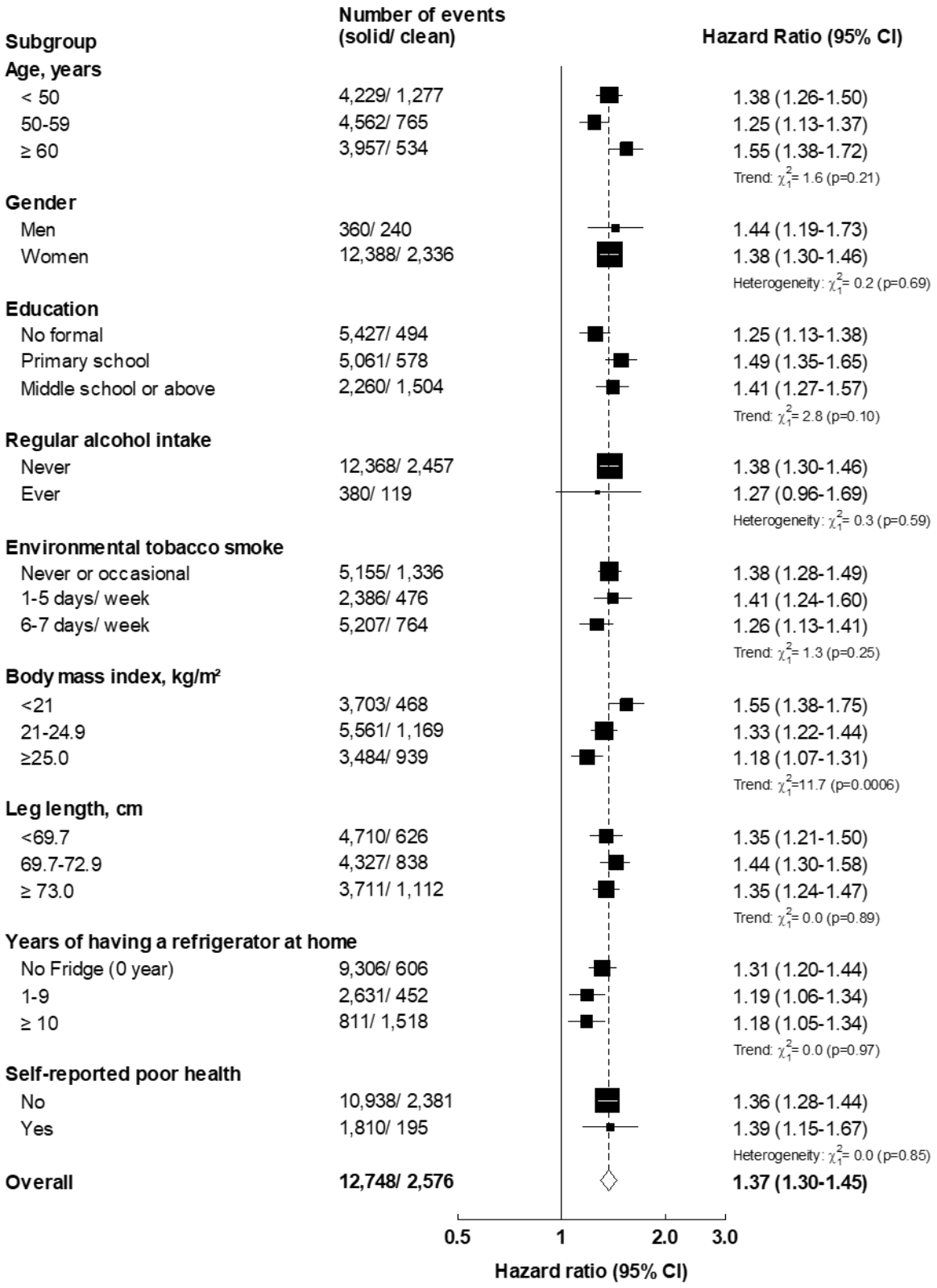


**Figure 6.7 Adjusted hazard ratios for major respiratory diseases by long-term heating fuel exposure**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke, cookstove ventilation, primary cooking fuel exposure and length of recall period. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

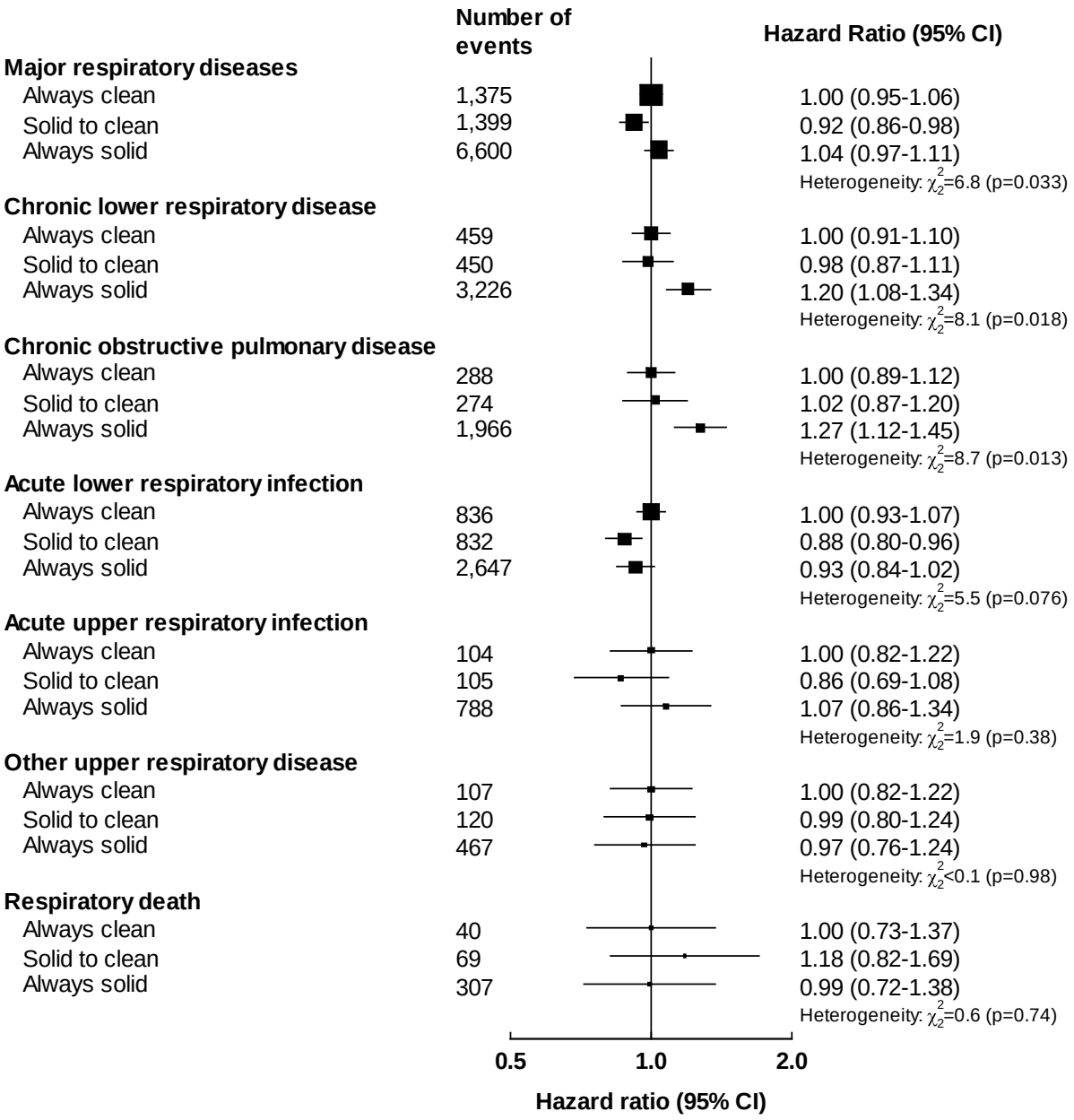
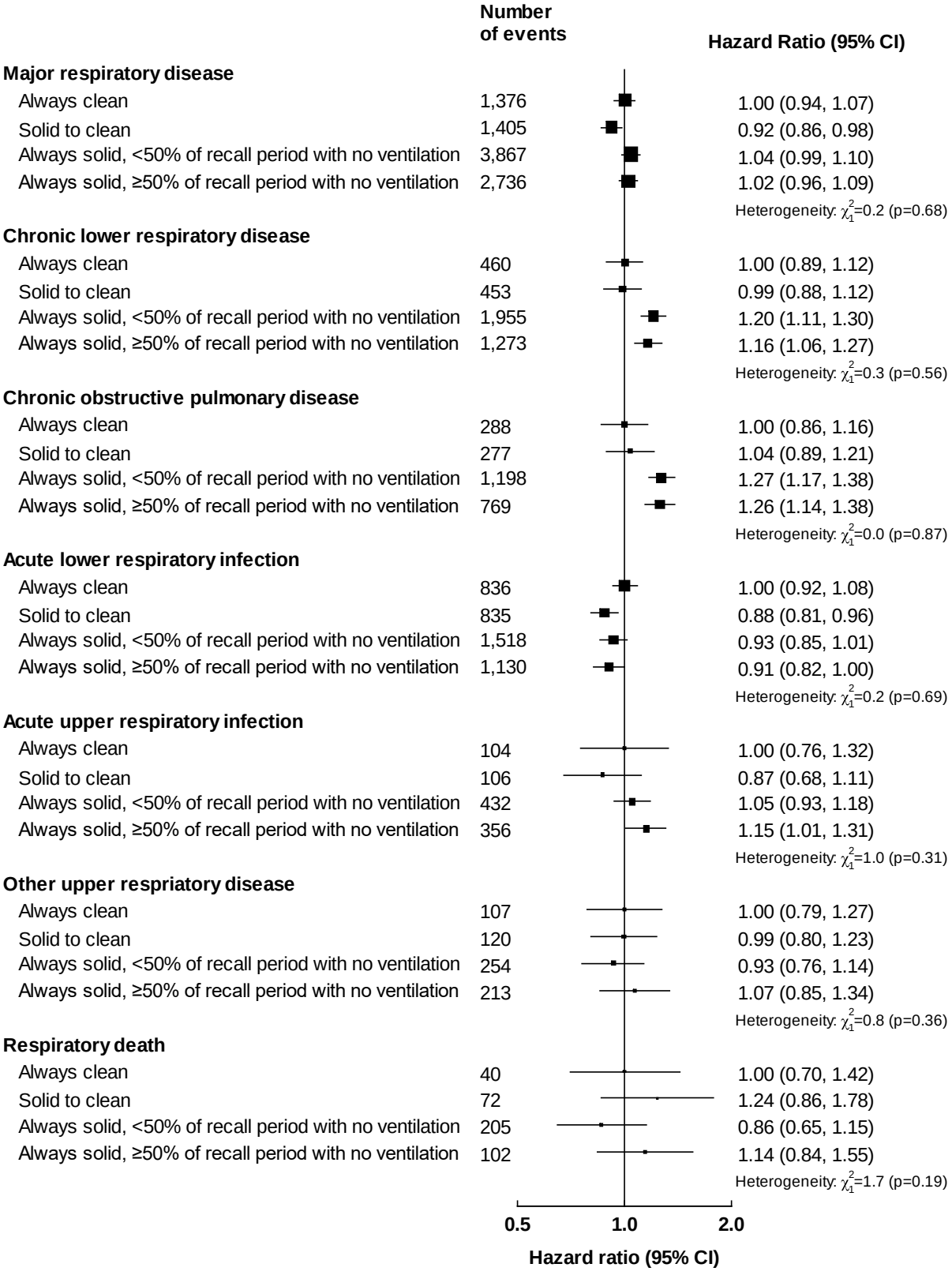


**Figure 6.8 Adjusted hazard ratios for major respiratory diseases by long-term primary heating fuel and ventilated cookstove ownership in never-smokers**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke, primary cooking fuel exposure and length of recall period. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).



# CHAPTER 7. SOLID FUEL USE AND CARDIOVASCULAR RISK

The findings in **Chapter 6** provide supporting evidence that long-term solid fuel use for cooking was associated with excess risks of a range of respiratory diseases. This chapter now look at the evidence of the association of solid fuel use with cardiovascular death.

## 7.1 INTRODUCTION

Despite the abundance of epidemiological studies investigating smoking and AAP with CVD over the past 50 years, investigation on the potential linkage between HAP from solid fuel use and CVD only started recently.[21] Emerging epidemiological evidence, predominately from cross-sectional or case-control studies, suggest that HAP exposure is associated with a range of intermediate vascular health indicators, with more consistent evidence on elevated BP but scattered evidence on development of atherosclerosis, systemic inflammation, elevated oxidative stress and prevalent cardiovascular conditions.[26-28,136,139] Prior to this thesis, the only two relevant prospective cohort studies reported inconsistent results on the relationship between solid fuel use and cardiovascular death, with one showing no association with duration of wood use[19] and another reporting significant excess risk related to ever coal use.[31] Both of these studies assessed only household fuel use without considering personal fuel use behaviour, were restricted to one geographical region and examined a relatively small number of cases (1,500 and 850).[19,31] Due to the lack of consistent empirical evidence, the current global disease burden estimation on CVD attributed to solid fuel use was based on a statistical interpolation method (an IERF) that borrows evidence mainly from prospective cohort studies on smoking and AAP, two qualitatively similar exposures that involves inhalation of airborne combustion products (of differential intensity and nature).[9] However, there has not been epidemiological investigation directly comparing the risk of cardiovascular death related to solid fuel use for cooking

against that associated with smoking in the same study population. To the best of our knowledge, the relationship between solid fuel use for heating and CVD has not been studied independently. Furthermore, few studies have explored the potential cardiovascular benefits of lowering HAP exposure associated with improved ventilation or clean fuel adoption, with suggestive observational evidence linking to attenuated BP elevation.[22,147] More reliable prospective evidence is urgently needed to enhance the understanding of the relationship between solid fuel use and CVD and related health protection strategies.

## 7.2 AIMS

This chapter aimed to examine the prospective associations between solid fuel use for cooking and overall and cause-specific cardiovascular death, to assess whether the use of ventilated cookstoves or switching to clean fuels may modify these associations, and to explore the role of solid fuel use for heating in relation to cardiovascular death. A secondary aim of this chapter was to examine the mean SBP and DBP levels across cooking and heating fuel use exposure groups in cold and non-cold months at baseline.

## 7.3 METHODS

### 7.3.1 Study design and data collection

Details of the study design of CKB have been described in **Chapter 3** and elsewhere.[69,153] Briefly, the CKB recruited 0.5 million adults aged 30-79 years from ten areas across China.[69,153] Trained health workers administered a laptop-based questionnaire to collect data on socio-demographic and lifestyle factors, undertook a range of physical measurements, including BP, and drew blood samples for blood spot tests on random blood glucose and long-term storage.[69,153] As described in **Section 3.7**, hypertension at baseline is defined according to self-reported use of anti-hypertensive medications and measured BP levels (SBP ≥140 mmHg or DBP ≥90 mmHg) and

diabetes is defined according to self-reported prior doctor-diagnosis or measured random or fasting plasma glucose level at baseline.[157]

### 7.3.2 Assessment of solid fuel use

The exposure assessment and classification methods used in this chapter were described in details in **Section 4.4.1** and are largely similar to those highlighted in **Section 6.3.2**. Briefly, participants reported their cooking frequency, primary cooking fuel, ventilated cookstove ownership, winter heating behaviour and primary heating fuel regarding their three most-recent residences, which constituted their "residential recall period". For the main prospective analyses, participants were classified into long-term clean fuel users, having switched from solid to clean fuels and long-term solid fuel users for cooking and heating, respectively, based on the aforementioned information regarding the residential recall period. For further investigations, long-term solid fuel users were categorised by types of solid fuel used (always coal, always wood, switched between coal and wood), duration of continuous exposure (<20, 20-39, ≥40 years) and the proportion of the recall period during which ventilated cookstoves were used (≥50% and <50%), separately for cooking and heating. For sensitivity analysis, the duration of continuous exposure were also weighted by cooking frequency and area-specific approximated heating need (details of the calculation were described in **Section 4.1.4**). Additionally, a composite variable of long-term cooking fuel use and smoking habits (four categories: always clean fuels and never-smoked, always solid fuels and never-smokers, always clean fuels and ever-smoked, always solid fuels and ever-smoked) was derived to examine the potential joint association of solid fuel use for cooking and smoking—two major sources of exposure to inhalable particulates included in the IERF used by the GBD—with cardiovascular death.

For the analyses on SBP and DBP, participants were classified according to self-reported cooking and heating fuel exposure at baseline (clean fuels, coal, wood, non-regular cooking/ no heating). To explore the potential role of cookstove ventilation in the

relationship between cooking fuel exposure and BP, a composite exposure variable was derived by separating solid fuel users who had ventilated cookstoves from those who had no ventilated cookstove at baseline and their BP levels were compared to clean fuel users. Coal and wood were combined as solid fuels to improve statistical power. A similar variable combining heating fuel use and cookstove ventilation was derived as a negative control.

### 7.3.3 Measurement of blood pressure

At baseline, trained health workers undertook two BP measurements for each participant using a daily calibrated digital sphygmomanometer (UA-779; A&D Instruments; Abingdon, UK) after the participant had remained in a seated resting position for at least five minutes.[156] If the SBP from the two measurements differed by over 10 mmHg, a third measurement was taken and the last two measurements were recorded.[156] All analyses presented used the mean of the two documented values of SBP and DBP.

### 7.3.4 Follow-up and outcome ascertainment

As described in **Section 4.3**, the vital status and underlying causes of death of all participants were monitored regularly through electronic linkage to the DSP system[154] and established death registries or standardised verbal autopsy[188] (for the deaths that occurred without prior medical attention), from baseline to 1st January 2016. The causes for all death events recorded were coded according to ICD-10 by trained staff who were blinded to participants' baseline information. The endpoints investigated in this chapter were deaths from cardiovascular causes (ICD-10 I00-I88 and I95-I99) and its key components, namely IHD (I20-I25), stroke (I60-I61 and I63; including ICH [I61] and IS [I63]) and other CVD (I00-I16, I26-I52, I62, I65-I88, I95-I99). **Table 7.1** presents the details of the endpoints examined. Participants without the event of interest were

censored upon death due to causes other than what was studied, loss to follow-up or 1st January 2016, whichever is earlier.

### 7.3.5 Participant exclusions

Participants with potentially unreliable recall information (n = 2,302), those with self-reported doctor-diagnosis of chronic heart disease, stroke or transient ischaemic attack (n = 23,129) or any cancer (n = 2,577) and those with missing information on BMI (n = 2) at baseline were excluded from all analyses, leaving an overall sample size of 485,144. Similar to the analyses described in **Chapter 6**, further exclusions were made for cooking- and heating-related analyses, respectively. For heating-related analyses, participants from Haikou (n = 28,888) and Zhejiang (n = 56,709), two areas where <1% of participants reported using heating in winter, were first excluded. Participants who reported unspecified fuel type at any residence ($n_{cooking}$ = 3,215; $n_{heating}$ = 2,335), who switched from clean to solid fuels ($n_{cooking}$ = 929; $n_{heating}$ = 3,847), who had cooked regularly (n = 17,801) or used heating (n = 17,196) previously but had stopped at baseline were further excluded. The final analytical sample sizes were 463,222 for cooking-related analyses and 376,191 for heating-related analyses. **Figure 7.1** summarises the exclusions described above. Unlike the analyses reported in **Chapter 6**, smokers were not excluded because smoking is a comparatively weaker risk factor and confounder for CVD than for respiratory disease and we were interested to examine the combined effect of solid fuel use for cooking and smoking in relation to CVD death and to compare our findings with the IERF used for global CVD burden estimation.[29]

### 7.3.6 Statistical analyses

*7.3.6.1 Descriptive analyses*

Percentages and means of baseline characteristics relevant to solid fuel use and CVD death were standardised according to the age, gender and study area structure of the CKB population and cross-tabulated with 1) long-term cooking and heating fuel

exposure categories, 2) participants included in and excluded from the exposure-specific analyses and 3) those who died from cardiovascular causes during the follow-up period and those censored. The baseline characteristics examined include age, gender, rural-urban residency, education, household income, alcohol consumption, smoking habit, total physical activity (metabolic equivalent of task [MET-hour/ day]), diet (consumption of fresh fruit, meat, preserved vegetables, poultry, fish, dairy and egg), ETS exposure, long-term solid fuel use for cooking and heating, cookstove ventilation, leg length (cm), BMI (kg/m$^2$), self-reported poor health, prevalent hypertension, self-reported antihypertensive treatment status, diabetes and prior chronic respiratory disease. The same method was used to estimate standardised rates (per 100,000 person-years) of each CVD outcome across age, gender and rural-urban residency categories.

*7.3.6.2 Cross-sectional analyses with blood pressure*

Due to the known gender difference in BP, all analyses on BP were conducted separately in males and females. Exposure to HAP from solid fuel use for heating ought to be related to low outdoor temperature, which is known to be associated with higher BP.[50,193-195] In order to tease out the potential season-specific relationship between cooking and heating fuel use exposure and BP, analyses were further stratified according to the date of BP measurement into cold and non-cold months, defined by a standard cut off of area-specific monthly average outdoor temperature <10°C. The area-specific monthly average temperature was derived from corresponding daily average values (across four measurements taken at 0200, 0800, 1400, 2000 hour) from February 2005 to December 2017 obtained from local offices of the China Meteorological Administration (http://2011.cma.gov.cn/forecasts/). **Table 7.2** shows the calendar months classified as cold months in each study area. Multiple linear regression was used to estimate least-square means of SBP and DBP across baseline cooking and heating fuel exposure categories, as well as the composite exposure of cooking

fuel and ventilated cookstove, with adjustment for age, study area, education, household income, occupation, alcohol consumption, smoking habit, diet (consumption of fresh fruit, preserved vegetables, meat), physical activity, BMI, baseline antihypertensive treatment, ETS exposure, cookstove ventilation, plus mutual adjustment for baseline cooking and heating exposures. To test the sensitivity of the results to the arbitrary cut off used to defined cold and non-cold months, the analyses were repeated using different cut offs of 5°C, 8°C and 12°C.

*7.3.6.3 Prospective analyses*

Cox proportional hazard regression models yielded adjusted HRs, with stratification by age-at-risk (5-year interval), gender and study areas, and adjustment for education (no formal school, primary school, middle school, high school/ college/ university), annual household income (<10,000, 10,000-19,999, 20,000-34,999, ≥35,000 Yuan), occupation (agricultural worker, factory worker, non-manual worker, others), alcohol consumption (never/rarely, occasional, ex-drinker or reduced-intake, weekly regular), smoking habit (never, occasional, ex-regular, current-regular), diet (consumption of fresh fruit, preserved vegetables, meat; frequency per week), physical activity (MET-hour/day, continuous), BMI (continuous), ETS exposure (<1 day/week, 1-5 days/week, daily or almost every day), cookstove ventilation (none, at least some), antihypertensive treatment (yes/ no), length of recall period (continuous), and mutual adjustment for long-term cooking and heating exposures (always clean fuels, solid to clean fuels, always solid fuels, never cooked regularly/ had heating, others), where appropriate. As described in **Section 4.5.3**, group-specific 95% CIs were estimated for HRs of categorical exposures with three or more groups. The proportional hazard assumption was tested by comparing the HRs for each CVD outcome the first five years and latter four years of follow-up and formal test on Schoenfeld residuals,[165] and no evidence of significant violation was found.

Subgroup analyses were conducted for overall cardiovascular death across subpopulations defined by age, gender, rural-urban residency, education, household income, alcohol consumption, smoking habit, ETS exposure, BMI, baseline SBP, self-reported health status, chronic respiratory disease history, baseline diabetes, hypertension and antihypertensive treatment. Sensitivity analyses were conducted by repeating the main analysis after i) additional adjustment for other dietary variables (fish, poultry, dairy, egg, rice) and leg length, and further excluding: ii) individuals with <20 years recall information (n = 42,179) – that is more prone to exposure misclassification because of the short recall period; iii) those who used clean fuels for <10 years ($n_{cooking}$ = 78,081; $n_{heating}$ = 47,993) – who might have greater historical or concurrent exposure to solid fuel use; iv) events occurred during the first three years of follow-up – to remove cases which may be at greater risk of reverse causation bias, and; for cooking-related analyses only, those who cooked weekly at baseline (n = 57,393) – whose exposure to cooking practice is distinctive from the daily-regular cooks, respectively. Similar to **Chapter 6**, sensitivity analyses based on marginal Cox regression[189] were conducted to assess the potential impact of clustering by study area in the study sample on the main findings.

## 7.4 RESULTS

### 7.4.1 Baseline characteristics by cooking and heating fuel use exposure

**Table 7.3** presents the baseline characteristics in the overall analytical sample and by categories of long-term cooking and heating fuel exposure after analysis-specific exclusions. The mean (SD) age of the overall analytical sample of 485,144 participants was 51.1 (10.5) years and 59% were female. The mean length of recall period of three most-recent residences was 39.6 (14.4) years, with 91% participants having had at least 20 years covered.

Among the 463,222 adults included in the cooking-related analyses, 73% reported cooking regularly during the recall period, with 49% of them used solid fuels primarily. Similar to what was observed in the never-smoker subsample in **Chapter 6**, compared to long-term clean fuel users, long-term solid fuel users tend to be older, to be female, to be rural residents, to have no formal education or annual household income <10,000 Yuan (~£1,150), to be an agricultural worker, to drink less regularly but smoke more regularly, to be exposed to ETS, to have no ventilated cookstove, to use solid fuels for heating long term, and to report poor health. They also had the highest physical activity across the four categories and were less likely to consume fresh fruit and meat weekly but more likely to consume preserved vegetables. The prevalence of hypertension and chronic respiratory disease was similar in both groups, but long-term solid fuel users were less likely to be on antihypertensive treatment or to have diabetes. There was no observable difference in terms of leg length or BMI across the exposure groups. Never-regular cooks were predominantly male (88%). Although their mean age was similar to that of long-term clean fuel users, they tend to be less educated, had lower household income, to smoke regularly, to use solid fuels for heating and to report poor health.

Of the 376,191 participants included in the heating-related analyses, 71% had used heating during the recall period, of whom 65% were long-term solid fuels users. Similar patterns of baseline characteristics were observed across heating exposure categories as for cooking exposure, but the differences in gender ratio between long-term clean fuel users and other categories were much smaller. Furthermore, those who had never used heating tend to be less educated, to have lower household income and to be less healthy (highest proportion of self-reported poor health and hypertension but lowest proportion of having antihypertensive treatment) compared to all other categories.

**Table 7.4** shows the baseline characteristics in participants included and excluded from the exposure-specific analyses. Similar to those reported in **Chapter 6**, participants excluded from the cooking-related analyses were more likely to report poor health and

to have diabetes or history of chronic respiratory diseases than those included. For heating-related analyses, those included were more likely to report poor health (10.3% in ever-users and 12.7% in never-users) compared to the overall analytical sample (9.3%) or the cooking-specific subset, possibly because of the exclusion of all participants from Haikou and Zhejiang, where prevalence of self-reported poor health was substantially lower than the population average (6.2% and 4.3%, respectively). However, the prevalence of poor health was even higher in the excluded participants from the other eight study areas (13.3%).

### 7.4.2 Baseline characteristics in relation to CVD outcomes

After 4.2 million person-years of follow-up (median [IQR]: 9.2 [8.3-10.1] years), 11,464 cardiovascular deaths were recorded in the 485,144 participants, including 3,982 from IHD, 5,338 from stroke (1,200 from IS and 3,814 from ICH) and 2,144 from other CVD. As expected, the standardised rates of overall and cause-specific cardiovascular death (per 100,000 person-years) were consistently higher in older participants, males and rural residents (**Table 7.5**). Compared to those who did not die from CVD, those who died from CVD tend to be older, male or rural residents, to have lower education level or household income, to be an agricultural worker, to drink and smoke more, to have lower physical activity, to consume less fresh fruit and meat but slightly more preserved vegetables, to use solid fuels for cooking and heating long-term, to have no ventilated cookstove, to have slightly higher BMI, to report poor health, to have hypertension, diabetes and chronic respiratory disease and to be on antihypertensive treatment at baseline, and these are mostly consistent for all cause-specific cardiovascular deaths (**Tables 7.6 and 7.7**).

### 7.4.3 Fuel use and blood pressure

**Figure 7.2** shows the adjusted SBP levels by baseline cooking and heating fuel use categories in cold and non-cold months for male and female participants. Regardless of

exposure categories, males had consistently higher SBP than females, and SBP levels in cold months were higher than in non-cold months in both genders. In non-cold months, solid fuel use for cooking was associated with modestly higher SBP compared to clean fuel use, especially for wood (mean difference [95% CI]: 0.77 [0.28-1.27] mmHg in females and 0.83 [0.22-1.43] mmHg in males)**,** but no significant difference was observed across heating fuel categories. In contrast, the difference across cooking fuel categories attenuated in cold months, while solid fuel use for heating was associated with significantly higher SBP levels than clean fuels, again with a more pronounced elevation related to wood use (mean difference [95% CI]: 2.3 [1.08-3.46] mmHg in females and 1.90 [1.00-2.80] mmHg in males). Across both cold and non-cold months, non-regular cooking in males was associated with slightly lower SBP, and lack of heating was associated with higher SBP in both males and females, although the elevation in cold months tends to be smaller than wood use for heating. These patterns of association persisted when using different cut offs to define cold and non-cold months (5°C, 8°C and 12°C) as well as after excluding participants who were on antihypertensive treatment or ever-regular smokers (results not shown).

Compared to clean fuel use, solid fuel use for cooking with and without ventilated cookstoves were both associated with significantly elevated SBP in non-cold months in both genders, but with considerably larger elevation among those without ventilated cookstove (mean difference [95% CI]: 1.33 [0.72-1.95] mmHg in females and 1.17 [0.65-1.68] mmHg in males) (**Figure 7.3**). Conversely, there was no significant variation in SBP levels across the corresponding exposure categories in cold months. For the composite exposure of heating fuel and ventilated cookstoves, SBP levels did not vary significantly by exposure categories regardless of gender and season.

The patterns of DBP were less clear (**Figure 7.4**). There was less variation in DBP by gender and season as compared to SBP. There was no significant difference across cooking-related exposure categories in females, but non-regular cooking in non-cold

months and coal use for cooking in cold months were associated with lower DBP in males. For heating-related exposure, both coal and wood use for heating in females were associated with a small elevation of DBP in cold months, but this was not observed in males. Additionally, solid fuel use for heating in males was associated with modestly lower DBP in non-cold months.

### 7.4.4 Cooking fuel use and risk of CVD

Compared with long-term clean fuel use for cooking, long-term solid fuel use was associated with modestly higher risk of overall cardiovascular death, with adjusted HR (group-specific 95% CI) of 1.14 (1.09-1.20). Similar associations were observed with deaths from stroke (1.27 [1.19-1.35]) and its subtypes (ICH: 1.27 [1.18-1.36]; IS: 1.41 [1.22-1.63]) and other CVD (1.25 [1.13-1.39]), but not with IHD death (**Figure 7.5**). There was no statistical significant excess risk of overall and cause-specific cardiovascular death in participants who had switched from solid to clean fuels before baseline (**Figure 7.5**).

Longer duration of continuous exposure to solid fuel use for cooking appeared to be associated with higher risks of overall cardiovascular death, with adjusted HRs of 1.15 (1.06-1.24) and 1.28 (1.20-1.36) in those who used solid fuels for <20 years and ≥40 years, respectively (**Figure 7.6**). Similar patterns of association was observed with IS (1.47 [1.14-1.90] versus 1.66 [1.37-2.01]) and other CVD (1.29 [1.07-1.55] versus 1.46 [1.26-1.69]) but not with overall stroke or ICH. The trend in the association was more pronounced for cooking-frequency weighted duration of exposure, with a clearer tendency of higher risk in relation to longer duration for all cardiovascular death endpoints except IHD death (**Figure 7.7**). In particular, the adjusted HRs for overall cardiovascular death in participants exposed for <20, 20-39 and ≥40 weighted-years were 1.13 (1.04-1.22), 1.16 (1.09-1.23) and 1.33 (1.24-1.42), respectively.

The excess risk of cardiovascular death related to solid fuel use appeared to be mainly driven by wood use, with adjusted HRs of 1.18 (1.12-1.25) for overall cardiovascular death, 1.24 (1.15-1.33) for stroke death, 1.21 (1.11-1.32) for ICH death, 1.40 (1.17-1.66) for IS death and 1.32 (1.16-1.50) for other CVD death (**Figure 7.8**). In terms of ventilated cookstoves, prolonged ownership during the recall period had no significant influence on the relationships between solid fuel use for cooking and overall and cause-specific cardiovascular deaths (all $P_{heterogeneity}$ >0.05) (**Figure 7.9**).

The excess risk of overall cardiovascular death associated with long-term solid fuel use for cooking do not differ significantly by most population subgroups examined, except for smoking habits and BMI. The association appeared to be stronger in never-smokers than in ever-smokers ($P_{heterogeneity}$ =0.0037) and there was suggestive evidence of a stronger association in participants with lower BMI ($P_{trend}$ = 0.0021) (**Figure 7.10**). The main results were largely consistent in the sensitivity analyses with additional adjustment for confounders or exclusions of individuals who are more prone to exposure misclassification or reverse causation bias (**Table 7.8**) as well as in marginal Cox regression models (**Appendix G – Table G1**).

### 7.4.5 Joint association of solid fuel use for cooking and smoking with cardiovascular death

Compared to never-smokers who used clean fuels for cooking long-term, those who used solid fuels had significant excess risk of cardiovascular death (HR [group-specific 95% CI]: 1.29 [1.18-1.40]), but ever-smokers who used clean fuels had even higher risk (1.74 [1.58-1.92]) and the risk in ever-smokers who used solid fuels was somewhat similar (1.77 [1.66-1.88]) (**Figure 7.17**). These patterns of association were largely similar when stratifying by gender, but the number of female smokers was relatively small (n = 14,098; 282 cases) and, therefore, the statistical power was low for female smoking categories (**Appendix G – Figure G1**). There were insufficient event numbers for cause-specific cardiovascular death for subgroup analysis by gender.

### 7.4.6 Heating fuel use and risk of CVD

Long-term solid fuel use for heating was also associated with significant excess risk of overall cardiovascular death (HR [group-specific 95% CI]: 1.21 [1.12-1.31]). Unlike cooking fuel exposure, the association appeared to be primarily driven by stroke death (1.28 [1.12-1.45]), specifically, ICH death (1.46 [1.25-1.69]), and no statistically significant association was observed with other specific causes of cardiovascular death (**Figure 7.11**). There was no clear trend of higher risk of cardiovascular death in relation to longer duration of solid fuel use for heating, with the highest HR in participants who had used solid fuels for heating for <20 years (**Figure 7.12**). Such patterns attenuated slightly for weighted duration of solid fuel use for heating, and, in particular, a clearer positive trend of association was observed for other CVD death (**Figure 7.13**). In terms of specific types of solid fuels, wood use was consistently associated with greater excess risk of overall cardiovascular death and HS death than coal use or mixed use of coal and wood (**Figure 7.14**). The presence of ventilated cookstoves during the recall period did not mediate the excess risk of cardiovascular death related to solid fuel use for heating (**Figure 7.15**).

The association between solid fuel use for heating and overall cardiovascular death do not differ by any population subgroups examined (**Figure 7.16**), but it attenuated towards the null upon sequential exclusion of individuals who used clean fuels for <10 years and deaths that occurred within the first three years of follow-up (**Table 7.9**). Conversely, HR estimates from the marginal Cox regression models were not materially different from the main findings (**Appendix G – Table G2**).

## 7.5 DISCUSSION

In this large prospective cohort study of 460,000 Chinese adults without prior CVD, baseline solid fuel use for cooking and heating were associated with elevated SBP in non-cold and cold months, respectively, and long-term solid fuel use for cooking and

heating were both associated with significant excess risk of overall cardiovascular death. While solid fuel use for cooking was associated with higher risk of death from a range of specific CVD, including ICH, IS and other CVD (e.g. pulmonary heart disease), that for heating appeared to be mostly related to ICH death. Individuals who had used solid fuels previously but switched to clean fuels prior to baseline had no significant excess risk of cardiovascular death, but prolonged ownership of ventilated cookstoves among those who used solid fuels for cooking had no observable influence on the excess risk of cardiovascular death associated with solid fuel use.

### 7.5.1 Solid fuel use and blood pressure

Among the limited studies on the cardiovascular health impact of HAP from solid fuel use, BP is one of the most commonly investigated outcomes.[26] It has been largely consistently shown that solid fuel users or residents of solid fuel-reliant households have significantly elevated SBP or higher odds of hypertension,[27,28,138,141,143-145] and it is believed to be one of the mechanistic pathways through which HAP is associated with higher risk of CVD. However, no previous studies had assessed cooking and heating separately or assessed the potential influence of ambient temperature on the associations, either because their measurements were taken over a short timeframe[138,143,145] or only aggregated metrics were analysed,[27,28,141,144] and only two studies adjusted for ambient temperature or month of measurement.[27,28]

Leveraging the large sample size and long recruitment period of the CKB, I examined the BP measurements taken in cold and non-cold months separately and found a distinctive seasonal pattern. Solid fuel use for cooking was associated with a weak elevation of SBP in non-cold months and no elevation in cold months, whereas solid fuel use for heating was only associated with higher SBP (to a greater extent) in cold months, and there was no clear association with DBP. The magnitude of SBP elevation associated with solid fuel use for heating was similar to what was observed for low fresh fruit consumption (2-3 mmHg), which has been linked to higher risk of CVD and related

deaths in CKB.[196] Regarding solid fuel use for cooking in non-cold months, the SBP elevation observed in this study (wood use: 0.77 mmHg in females) was consistent to that reported (0.58 mmHg after adjusting for ambient temperature) in the largest existing study on this relationship, which involved over 77,000 younger women (15-49 years) from 12 LMICs (where biomass is the predominant solid fuel used).[27] The same study also found no significant association between solid fuel use and DBP,[27] which has been suggested to have less clear predictive value on cardiovascular risk at the relatively low levels that our analyses covered (75-80 mmHg).[197-199] Since these present analyses were mutually adjusted for cooking and heating fuel use, it suggests that while solid fuel use in general may be associated with elevated SBP, that for cooking this was throughout the year whereas that for heating, this only becomes more prominent in colder months when heating is needed. This concurs with current knowledge that measured HAP levels (e.g. $PM_{2.5}$) are markedly higher in households burning solid fuels for heating in winter.[32,39,44,45]

Nonetheless, it is possible that solid fuel use for heating was less effective in providing warmth compared to clean fuels (e.g. electric heater) and the observed greater elevation in SBP may be confounded by cold temperature. Furthermore, it is relatively well-established that temperature has a distributed lag association with BP and cardiovascular risk,[48] which could not be fully accounted by the binary split of calendar time into cold and non-cold months as in this study. Although daily temperature data during the baseline survey period (2004-2008) are partially available (from February 2005 to 2008), no detailed information on heating fuel use behaviour had been collected. As heating is highly correlated with cold temperature, adjustment for the distributed lag effect of daily temperature without considering the corresponding variation of heating fuel use may result in over-adjustment. Future studies involving real-time monitoring of HAP levels, temperature and relative humidity and ambulatory BP using wearable

sensors would be valuable to better understand the complex interrelation between solid fuel use for heating, temperature and BP.

### 7.5.2 Solid fuel use for cooking and risk of cardiovascular death

Before this thesis, only two prospective studies have investigated the associations of solid fuel use with cardiovascular death.[19,31] One study involved about 75,000 Chinese women with 859 cases in Shanghai, China[31] and another included about 50,000 Iranians with 1,578 cardiovascular deaths in Golestan, Iran.[19] The Chinese study found that ever coal use for cooking was associated with significant excess cardiovascular death (HR [95% CI]: 1.18 [1.02-1.37]),[31] but the Iranian study found no association between duration of wood use for cooking and heating (per 10 years) and cardiovascular death (1.03 [0.97-1.08]).[19] The association observed in the Chinese study appeared to be driven by a significant association with IHD death (1.61 [1.14-2.27]) based on only 180 cases but not stroke death (1.01 [0.84-1.22]; 534 cases). Based on over 10,000 cases of cardiovascular deaths (including 4,000 IHD deaths and 5,000 stroke deaths), I found that long-term solid fuel use for cooking was associated with 14% excess risk of overall cardiovascular death, with stronger association with deaths from stroke and other CVD but no significant association with IHD death, and evidence of higher risk related to longer duration of exposure. I also compared wood and coal use in the same study population for the first time, and found that long-term wood use was associated with particularly high risk, which agrees with our findings on SBP as well as the current knowledge that wood use is associated with higher $PM_{2.5}$ exposure. [5,39] The reason behind the discrepancies in the relationships between solid fuel use and death from stroke and IHD is unclear. However, it is known that they have distinctive risk factor profiles, whereby BP is substantially more important for stroke whereas lipid profiles are amongst the strongest risk factors for myocardial infarction, but their linkages with stroke have been inconsistent.[199-203] Similarly, HAP has been largely consistently reported to be associated with elevated BP (including in this

chapter), but little evidence exists on its association with atherosclerosis or its markers.[26-28] It is possible that residual confounding from lipid profiles, which was not accounted for in the analyses due to lack of data, had more prominent influence on the findings on IHD death.

There are several key differences that may explain the disparities between the present and previous analyses. First, both previous studies classified exposure based on household fuel type without accounting for personal fuel use behaviour while these analyses were only conducted among regular cooks using different fuels. The inclusion of non-regular cooks into fuel-based categories, as discussed in previous chapters, may introduce bias to the analysis. The bias may be more prominent in the Iranian study which included 42% male, who tend to have higher risk of cardiovascular death and are less likely to cook regularly than females in LMIC settings.[19] Although the Chinese cohort included only women, it was conducted in Shanghai, one of the most developed cities in China, and virtually all participants had a non-agricultural job (~50% were factory workers) and coal use in 99% households had stopped prior to baseline,[31] leaving substantial uncertainty about the accuracy of exposure classification (ever coal use or not). Furthermore, as opposed to using established death registries (in the Chinese study and our study), the Iranian study used verbal autopsy in determining causes of death, which may be subject to greater extent of non-differential misclassification that would dilute the actual assocaition.[19]

The association between long-term solid fuel use for cooking and cardiovascular death were not modified by most characteristics, except that it tends to be stronger in individuals with lower BMI and in never-smokers. Although different fuel users did not differ by BMI at baseline, those with lower BMI had on average longer exposure to solid fuel use (BMI <21 kg/m$^2$: 18.6 years; 21-24.9 kg/m2: 14.4 years; ≥25 kg/m$^2$: 12.0 years; P <0.0001). As we have shown that longer duration of exposure was associated with greater excess risk, it is likely that the subgroup differences by BMI were driven by the

differences in duration of exposure. The subgroup findings on smoking will be discussed in **Section 7.5.3** in conjunction with the findings on cooking-smoking composite exposure.

### 7.5.3 Comparison with smoking

Tobacco is a type of biomass which generates extremely high concentrations of $PM_{2.5}$ (among other toxic chemicals) when burning. While tobacco smoking is a well-established major cause of cardiovascular death, it supports a plausible link between exposure to $PM_{2.5}$ from solid fuel combustion and cardiovascular risk.[30] Before sufficient empirical epidemiological evidence become available, the GBD used an IERF for $PM_{2.5}$ exposure built on relative risk estimates from mostly prospective cohort studies on tobacco smoking and AAP to approximate the potential cardiovascular impact of solid fuel use for cooking.[9,29,30] The IERF is supralinear such that the relative risk increase more rapidly at lower concentration (AAP or HAP from cooking) but plateau at extreme high concentration (tobacco smoking).[30] For the first time, I have examined the potential joint association of solid fuel use for cooking and tobacco smoking in the same cohort and found evidence that corroborates the IERF. Compared to never-smoking long-term clean fuel users, solid fuel use alone was associated with significant excess risk of cardiovascular death (HR = 1.29) and smoking alone was associated with markedly higher risk (HR = 1.74), but combined exposure to both solid fuel use and smoking had comparable risk as smokers (HR = 1.77), suggesting that the combined effect may be dominated by smoking. Further work to quantify $PM_{2.5}$ levels associated with solid fuel use and smoking in the CKB or other similar studies would generate more direct evidence in evaluating the validity of the IERF.

### 7.5.4 The role of switching to clean fuels and ventilated cookstoves

Little consistent evidence exists on the potential cardiovascular benefits of reducing HAP exposure through adopting clean fuels or ventilated cookstoves.[22,147-150] In the

present study, for both cooking and heating, individuals who had switched from solid to clean fuels before baseline had no significant excess risk of cardiovascular death compared to long-term clean fuel users while long-term solid fuel users were at significantly higher risk. Conversely, we found no evidence of risk attenuation in relation to prolonged ownership of ventilated cookstoves among long-term solid fuel users. Nevertheless, use of a ventilated cookstove appeared to attenuate the elevated SBP related to solid fuel use for cooking (in non-cold months). These are consistent with the findings in **Chapter 6** where prolonged ownership of ventilated cookstoves was only associated with attenuated risk of mild, acute conditions such as URTI (**Sections 6.4.3 and 6.5.4**). As discussed previously, clean fuels interventions have been associated with significantly greater reduction of HAP exposure than ventilated cookstove interventions,[59,60] which may explain the contrasting results. However, it is important to note that there has been very limited RCTs on clean fuel interventions,[147,204] and previous HAP reduction RCTs suffered from a range of methodological and practical challenges (e.g. poor compliance and sustainability) that hamper the value of their findings.[134] There has been growing effort in improving these interventions through more systematic programme evaluation and adaptive design informed by local knowledge.[204] Future RCT involving larger sample, longer follow-up and more carefully designed and implemented clean fuels intervention would be valuable to verify our observations.

### 7.5.5 Solid fuel use for heating and risk of cardiovascular death

No previous study had examined solid fuel use for heating in relation to cardiovascular death independently. I found 21% and 46% excess risks of overall cardiovascular death and ICH death related to long-term solid fuel use for heating, respectively, and these associations do not differ significantly by population subgroups. Compared to IHD or IS, ICH has a higher case fatality rate and is more common in Asia and in LMIC, but the pathogenesis of HS is also less well-understood.[205] One of the most recognised risk factors for ICH is hypertension.[205] In the CKB, SBP was over two times more strongly

associated with death and hospitalisation for ICH (68% excess risk per 10 mmHg higher SBP) than IS (30%) or IHD (31%).[201] Solid fuel use for heating was associated with significant elevated SBP in cold months, and prolonged exposure may in turn increase the long-term, cumulative risk of ICH. However, the association between solid fuel use for heating and ICH death attenuated to the null after excluding those who used clean fuels for <10 years and deaths occurred during the first three years of follow-up. Individuals who used clean fuels for <10 years might have switched from solid fuels or started to use heating recently due to underlying health problems that prompted greater need of warmth in cold weather, and those who died early during the follow-up period might have subclinical illnesses before the baseline survey, both suggesting reverse causation bias. It is however worth noting that the case number in the reference group (clean fuel users) reduced markedly by 50% (from 117 to 62) upon the stringent exclusions, and we had even more limited statistical power for those analyses. Further investigation with longer follow-up and larger case number would help to clarify this.

### 7.5.6 Strengths and limitations

The main strengths of this study are the prospective nature, large sample size and comprehensive follow-up, which granted us the capacity to examine both overall and cause-specific cardiovascular death in detail. Unlike the previous prospective studies, we classified individuals exposure based not only on household fuel type but also personal fuel use behaviour, which should reduce misclassification. I also examined both coal and wood use and compared solid fuel use for cooking and tobacco smoking in relation to cardiovascular death in the same cohort study for the first time.

The limitations related to HAP exposure were discussed in detail in **Section 6.5.7**. Briefly, I used self-reported primary fuel use in assessing HAP exposure, which is subject to misclassification due to changes in fuel use patterns within each residence or parallel exposure to solid fuel smoke in clean fuel users. Moreover, I classified an individual's exposure based on recalled data collected from baseline survey, and the

general transition from solid to clean fuels (especially for cooking) observed in **Chapter 5** was not taken into account. These constraints could all result in underestimation of the association of interest. Additionally, the lack of directly measured HAP exposure data in CKB prevents us from directly assessing the dose-response relationship or make comparison to the IERF for $PM_{2.5}$ and cardiovascular death. However, when considering external data on $PM_{2.5}$ associated with different fuel types (higher levels from wood than coal burning) and smoking (higher than wood use), the relative risks of cardiovascular death observed in CKB (smoking > wood > coal) were broadly consistent with the IERF.[30] Due to the relatively low prevalence of long-term clean fuel use in the study population, we had limited cases in the reference group and hence low statistical power for our heating-related analyses, especially for cause-specific mortality. Because solid fuel use is strongly linked to lower SES, which is in turn associated with higher risk of cardiovascular death,[206] residual confounding is possible despite the adjustment made (education, household income, occupation, dietary exposures, leg length).

## 7.6 CONCLUSIONS

In this prospective study of Chinese adults, solid fuel use for cooking was associated with higher risks of overall cardiovascular death and, specifically, death from stroke and other CVD but not IHD. The risks appeared to be higher with longer duration of exposure or with long-term wood use, but lower in those who had switched from solid to clean fuels despite historical exposure. The association observed appeared to be consistent with the IERF used to estimate global burden of cardiovascular death. Solid fuel use for heating was associated with excess risk of overall cardiovascular death and ICH death, but these analyses included relatively small case numbers and there is possibility of reverse causation bias. Future study involving enhanced exposure classification based on directly measured HAP exposure data is in need to clarify our findings.

**Table 7.1 Details of cardiovascular endpoints defined by ICD-10 codes**

| Underlying cause of death | ICD-10 Code | ICD-10 description |
|---|---|---|
| Ischaemic heart disease | I20-I25 | Angina pectoris (I20), acute myocardial infarction (I21), subsequent ST elevation and non-ST elevation myocardial infarction (I22), certain current complications following ST elevation and non-ST elevation myocardial infarction (within the 28 day period; I23), other acute ischaemic heart diseases (I24), chronic ischaemic heart disease (I25) |
| Stroke | I60-I61, I63 | Non-traumatic subarachnoid haemorrhage (I60), non-traumatic intracerebral haemorrhage (I61), cerebral infarction (I63) |
| Intracerebral haemorrhage | I61 | Non-traumatic intracerebral haemorrhage |
| Ischaemic stroke | I63 | Cerebral infarction |
| Other cardiovascular disease | I00-I16, I27-I52, I62, I65-I88, I95-I99 | Acute rheumatic fever (I00-I02), chronic rheumatic heart diseases (I05-I09), hypertensive diseases (I10-I16), pulmonary heart disease and diseases of pulmonary circulation (I26-I28), other forms of heart disease (I30-I52), cerebrovascular diseases excluding stroke (I62, I65-I69), diseases of arteries, arterioles and capillaries (I70-I79), diseases of veins, lymphatic vessels and lymph nodes, not elsewhere classified except "other non-infective disorders of lymphatic vessels and lymph nodes (I80-I88), other and unspecified disorders of the circulatory system (I95-I99) |
| Overall cardiovascular disease | All of the above | All of the above |

**Table 7.2 Calendar month(s) where overall monthly average temperature during 2005-2017 was less than 10°C**

| Study area | Calendar month* |
|---|---|
| Qingdao | 1 2 3 11 12 |
| Harbin | 1 2 3 4 10 11 12 |
| Haikou | - |
| Suzhou | 1 2 12 |
| Liuzhou | 1 |
| Sichuan | 1 2 12 |
| Gansu | 1 2 3 11 12 |
| Henan | 1 2 11 12 |
| Zhejiang | 1 2 12 |
| Hunan | 1 2 12 |

*1= January , 2= February , 3= March, 4= April, 5= May, 6 = June, 7= July, 8= August, 9= September, 10 = October, 11= November, 12= December.

**Table 7.3 Baseline characteristics of participants according to long-term primary cooking and heating fuel exposure***

| Characteristics | COOKING | | | | HEATING | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Always clean | Solid to clean | Always solid | Never cooked | Always clean | Solid to clean | Always solid | Never heated | |
| **Total participants, N** | 82,710 | 88,295 | 167,550 | 124,667 | 41,018 | 51,328 | 174,919 | 108,926 | 485,144 |
| **Age (SD), years** | 46.7 (9.8) | 51.2 (9.9) | 53.8 (10.5) | 47.9 (10.8) | 47.0 (10.5) | 49.7 (10.5) | 52.8 (10.5) | 49.6 (10.3) | 51.1 (10.5) |
| **Female, %** | 50.3 | 83.4 | 77.4 | 11.9 | 54.1 | 58.9 | 62.4 | 54.7 | 59.1 |
| **Urban residency, %** | 86.3 | 82.0 | 9.7 | 41.9 | 77.0 | 88.5 | 14.8 | 62.4 | 43.3 |
| **No formal education, %** | 10.9 | 14.1 | 22.6 | 16.8 | 8.3 | 7.3 | 14.6 | 19.9 | 18.7 |
| **Household income <10,000 Yuan/ year, %** | 19.4 | 19.8 | 38.6 | 24.2 | 15.0 | 17.4 | 35.4 | 40.0 | 28.3 |
| **Agricultural worker, %** | 23.8 | 27.0 | 48.9 | 36.7 | 20.7 | 24.9 | 45.6 | 45.4 | 42.8 |
| **Factory worker, %** | 15.5 | 15.7 | 13.8 | 16.6 | 16.2 | 14.1 | 10.8 | 14.7 | 14.7 |
| **Lifestyle behaviour** | | | | | | | | | |
| **Regular drinker in male, %** | 36.3 | 40.6 | 33.4 | 33.6 | 39.2 | 37.9 | 32.0 | 29.4 | 34.0 |
| **Regular drinker in female, %** | 2.6 | 2.1 | 2.0 | 3.1 | 2.2 | 3.0 | 2.3 | 1.9 | 2.1 |
| **Regular smoker in male, %** | 59.4 | 57.5 | 61.8 | 63.1 | 58.6 | 60.0 | 65.2 | 60.1 | 62.1 |
| **Regular smoker in female, %** | 1.8 | 2.4 | 3.3 | 2.6 | 2.6 | 3.1 | 4.1 | 2.4 | 2.3 |
| **Total physical activity (SD), MET-hr/d †** | 19.8 (12.3) | 21.0 (13.2) | 23.0 (13.2) | 20.8 (15.8) | 19.4 (11.6) | 18.9 (11.3) | 20.4 (13.9) | 22.3 (13.7) | 21.5 (13.9) |
| **Weekly intake of fresh fruit, %** | 71.0 | 68.2 | 51.8 | 61.1 | 77.1 | 73.5 | 60.0 | 61.3 | 59.5 |
| **Weekly intake of meat, %** | 86.3 | 87.3 | 80.4 | 83.8 | 89.9 | 89.1 | 79.7 | 75.7 | 82.9 |
| **Weekly intake of preserved vegetables, %** | 48.5 | 51.2 | 51.8 | 50.2 | 52.1 | 49.2 | 52.3 | 51.5 | 51.0 |
| **Environmental exposure, %** | | | | | | | | | |
| **Daily environmental tobacco smoke** | 40.1 | 42.5 | 41.9 | 42.7 | 44.1 | 46.2 | 49.0 | 40.6 | 41.9 |
| **Always solid fuels for cooking‡** | - | - | - | - | 22.2 | 24.7 | 43.7 | 43.9 | 36.2 |
| **No ventilated cookstove** | 20.3 | 20.2 | 30.3 | 23.6 | 15.6 | 16.9 | 29.2 | 35.1 | 23.9 |
| **Always solid fuels for heating§** | 35.1 | 32.2 | 62.2 | 45.1 | - | - | - | - | 46.5 |
| **Anthropometric measures** | | | | | | | | | |
| **Leg length (SD), cm** | 73.7 (4.8) | 73.4 (4.3) | 73.1 (4.3) | 73.5 (4.3) | 73.5 (4.9) | 73.5 (5.1) | 72.9 (4.8) | 73.0 (4.6) | 73.4 (4.8) |
| **Body mass index (SD), kg/m$^2$** | 23.8 (3.3) | 24.0 (3.4) | 23.3 (3.4) | 23.6 (3.2) | 23.9 (3.2) | 24.0 (3.4) | 23.7 (3.4) | 23.6 (3.2) | 23.6 (3.4) |
| **Health condition, %** | | | | | | | | | |
| **Self-reported poor health** | 8.3 | 8.2 | 10.7 | 9.8 | 11.2 | 10.2 | 12.4 | 12.7 | 9.3 |
| **Hypertension** | 30.3 | 31.5 | 30.7 | 30.0 | 28.4 | 29.1 | 28.2 | 29.5 | 31.0 |
| **Antihypertensive treatment** | 4.5 | 4.1 | 2.8 | 4.1 | 5.7 | 5.5 | 4.1 | 3.7 | 3.6 |
| **Diabetes** | 6.6 | 6.2 | 5.0 | 6.1 | 6.4 | 6.7 | 6.3 | 5.4 | 5.4 |
| **Chronic respiratory disease¶** | 4.3 | 4.4 | 4.2 | 4.8 | 4.8 | 5.3 | 5.0 | 4.6 | 4.2 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate.
† MET: metabolic equivalent of tasks.
‡ Among participants who had ever cooked regularly and did not fit any criteria of exclusion.
§ Among participants who had ever used heating and did not fit any criteria of exclusion.
¶ Chronic respiratory disease: emphysema, chronic bronchitis, asthma, tuberculosis.

**Table 7.4 Baseline characteristics of participants by categories of cooking and heating-related exposure and exclusion categories ***

| | COOKING | | | HEATING | | | | |
|---|---|---|---|---|---|---|---|---|
| **Characteristics** | **Ever cooked regularly** | **Never cooked regularly** | **Excluded†** | **Ever used heating** | **Never used heating** | **Haikou** | **Zhejiang** | **Other excluded†** |
| **Total participants, N** | 338,555 | 124,667 | 219,221 | 267,265 | 108,926 | 28,888 | 56,709 | 23,356 |
| **Age (SD), years** | 51.5 (10.4) | 47.9 (10.8) | 51.8 (10.9) | 50.5 (10.5) | 49.6 (10.3) | 52.3 (11.6) | 52.2 (9.9) | 50.5 (10.7) |
| **Female, %** | 77.5 | 11.9 | 60.4 | 59.0 | 54.7 | 63.9 | 58.6 | 58.3 |
| **Urban residency, %** | 49.9 | 41.9 | 59.4 | 38.5 | 62.4 | - | - | 43.0 |
| **No formal education, %** | 18.9 | 16.8 | 17.2 | 13.9 | 19.9 | 14.7 | 43.9 | 11.6 |
| **Household income <10,000 Yuan/ year, %** | 29.9 | 24.2 | 23.9 | 28.9 | 40.0 | 22.1 | 6.7 | 32.0 |
| **Agricultural worker, %** | 42.5 | 36.7 | 36.2 | 42.0 | 45.4 | 15.0 | 49.5 | 37.9 |
| **Factory worker, %** | 14.6 | 16.6 | 16.1 | 13.1 | 14.7 | 3.9 | 28.2 | 14.7 |
| **Lifestyle behaviour** | | | | | | | | |
| **Regular drinker in male, %** | 34.4 | 33.6 | 34.5 | 33.9 | 29.4 | 16.1 | 38.6 | 34.2 |
| **Regular drinker in female, %** | 2.0 | 3.1 | 2.7 | 2.2 | 1.9 | 0.4 | 1.5 | 2.6 |
| **Regular smoker in male, %** | 60.7 | 63.1 | 61.1 | 62.9 | 60.1 | 42.2 | 65.1 | 61.0 |
| **Regular smoker in female, %** | 2.3 | 2.6 | 2.6 | 2.7 | 2.4 | 0.3 | 1.1 | 3.0 |
| **Total physical activity (SD), MET-hr/d ‡** | 21.8 (13.0) | 21.1 (15.8) | 21.5 (14.8) | 20.3 (13.2) | 22.3 (13.7) | 13.8 (9.1) | 30.4 (15.3) | 20.5 (13.9) |
| **Weekly intake of fresh fruit, %** | 59.6 | 61.1 | 62.0 | 62.9 | 61.3 | 61.5 | 55.8 | 61.7 |
| **Weekly intake of meat, %** | 82.3 | 83.8 | 83.3 | 81.2 | 75.7 | 99.0 | 92.2 | 78.4 |
| **Weekly intake of preserved vegetables, %** | 51.1 | 50.2 | 50.6 | 54.1 | 51.5 | 12.0 | 49.1 | 52.5 |
| **Environmental exposure, %** | | | | | | | | |
| **Daily environmental tobacco smoke** | 41.0 | 42.7 | 42.6 | 47.9 | 40.6 | 22.6 | 17.0 | 46.0 |
| **Always solid fuels for cooking§** | - | - | - | 35.1 | 43.9 | 16.9 | 36.5 | 35.9 |
| **No ventilated cookstove** | 24.4 | 23.6 | 23.6 | 24.6 | 35.1 | 38.3 | 5.2 | 26.9 |
| **Always solid fuels for heating¶** | 46.1 | 45.1 | 43.2 | - | - | - | - | - |
| **Anthropometric measures** | | | | | | | | |
| **Leg length (SD), cm** | 73.4 (4.5) | 73.6 (4.3) | 73.5 (4.7) | 73.3 (4.9) | 73.0 (4.6) | 73.6 (4.6) | 74.8 (4.7) | 73.2 (4.8) |
| **Body mass index (SD), kg/m$^2$** | 23.6 (3.4) | 23.7 (3.2) | 23.8 (3.4) | 23.8 (3.4) | 23.6 (3.2) | 23.3 (3.3) | 22.9 (3.2) | 23.8 (3.4) |
| **Health condition, %** | | | | | | | | |
| **Self-reported poor health** | 9.5 | 9.8 | 11.0 | 10.3 | 12.7 | 6.2 | 4.3 | 13.3 |
| **Hypertension** | 31.5 | 30.0 | 30.6 | 29.5 | 29.5 | 23.2 | 41.2 | 29.7 |
| **Antihypertensive treatment** | 3.6 | 4.1 | 3.9 | 4.0 | 3.7 | 4.4 | 1.9 | 4.2 |
| **Diabetes** | 5.4 | 6.1 | 6.4 | 5.3 | 5.4 | 6.7 | 5.0 | 5.6 |
| **Chronic respiratory disease‖** | 4.2 | 4.8 | 5.2 | 4.6 | 4.6 | 2.8 | 3.8 | 4.8 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate.

† Excluded: participants who used other fuels at any residence, who had switched from clean to solid fuels or who had previously cooked but stopped at baseline.

‡ MET: metabolic equivalent of tasks.

§ Among participants who had ever cooked regularly and did not fit any criteria of exclusion.

¶ Among participants who had ever used heating and did not fit any criteria of exclusion.

|| Chronic respiratory disease: emphysema, chronic bronchitis, asthma, tuberculosis.

**Table 7.5 Distribution and rates of cardiovascular death according to age, gender and study area**

| | Overall cardiovascular death | | Ischaemic heart disease death | | Any stroke death | | Ischaemic stroke death | | Intracerebral haemorrhage death | | Other cardiovascular disease death | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Characteristic** | **No. of events** | **Rate (95% CI)*** | **No. of events** | **Rate (95% CI)*** | **No. of events** | **Rate (95% CI)*** | **No. of events** | **Rate (95% CI)*** | **No. of events** | **Rate (95% CI)*** | **No. of events** | **Rate (95% CI)*** |
| **Age, years (mean)** | | | | | | | | | | | | |
| 30-39 (37.5) | 179 | 20 (17-24) | 63 | 7 (5-9) | 83 | 9 (7-11) | 8 | 1 (0-2) | 69 | 7 (5-9) | 32 | 4 (2-6) |
| 40-49 (44.8) | 903 | 96 (40-152) | 313 | 19 (16-21) | 447 | 41 (19-62) | 67 | 5 (3-6) | 360 | 35 (13-56) | 141 | 36 (-15-88) |
| 50-59 (54.7) | 2,292 | 196 (144-248) | 742 | 78 (35-120) | 1,170 | 94 (64-124) | 203 | 13 (11-15) | 909 | 77 (47-107) | 375 | 24 (21-27) |
| 60-69 (64.6) | 4,481 | 625 (556-695) | 1,541 | 230 (189-272) | 2,073 | 262 (242-281) | 443 | 55 (49-60) | 1,511 | 193 (174-211) | 864 | 133 (80-185) |
| ≥ 70 (72.7) | 3,609 | 1176 (1132-1221) | 1,323 | 413 (387-438) | 1,565 | 546 (514-577) | 479 | 147 (132-162) | 965 | 354 (328-380) | 717 | 217 (199-235) |
| **Sex** | | | | | | | | | | | | |
| Male | 6,294 | 339 (330-347) | 2,185 | 119 (114-124) | 2,935 | 156 (151-162) | 677 | 37 (34-39) | 2,111 | 112 (107-117) | 1,167 | 63 (59-66) |
| Female | 5,170 | 231 (224-237) | 1,797 | 81 (77-85) | 2,403 | 105 (101-110) | 523 | 24 (22-26) | 1,703 | 74 (70-78) | 962 | 44 (41-47) |
| **Residency** | | | | | | | | | | | | |
| Rural | 7,971 | 361 (352-369) | 2,515 | 115 (110-119) | 4,133 | 184 (178-190) | 766 | 36 (33-39) | 3,200 | 141 (136-146) | 1,318 | 62 (58-65) |
| Urban | 3,493 | 182 (176-188) | 1,467 | 77 (73-81) | 1,205 | 62 (59-66) | 434 | 23 (20-25) | 614 | 32 (29-35) | 811 | 42 (39-45) |

*Rates (per 100,000 person-years) were mutually standardised for age, gender and study area structure.

**Table 7.6 Baseline characteristics of participants with and without overall and cause-specific cardiovascular death (1)***

| | Overall cardiovascular death | | Ischaemic heart disease death | | Any stroke death | |
|---|---|---|---|---|---|---|
| **Characteristics** | **No** | **Yes** | **No** | **Yes** | **No** | **Yes** |
| **Total participants, N** | | | | | | |
| **Age (SD), years** | 50.8 (10.4) | 63.8 (9.2) | 51.0 (10.5) | 64.2 (9.2) | 50.9 (10.5) | 63.2 (10.5) |
| **Women, %** | 59.3 | 41.9 | 59.1 | 37.8 | 59.2 | 43.5 |
| **Urban residency, %** | 43.7 | 28.4 | 43.4 | 30.4 | 43.5 | 22.5 |
| **No formal education, %** | 18.6 | 23.2 | 18.7 | 24.4 | 18.6 | 23.9 |
| **Household income <10,000 Yuan/ year, %** | 28.1 | 36.8 | 28.2 | 37.3 | 28.2 | 35.7 |
| **Agricultural worker, %** | 42.9 | 44.4 | 42.8 | 46.0 | 42.8 | 45.4 |
| **Factory worker, %** | 14.7 | 11.3 | 14.7 | 11.4 | 14.7 | 11.7 |
| **Lifestyle behaviour** | | | | | | |
| **Regular drinker in male, %** | 34.0 | 35.9 | 34.0 | 35.0 | 34.0 | 39.4 |
| **Regular drinker in female, %** | 2.1 | 2.6 | 2.1 | 2.8 | 2.1 | 2.9 |
| **Regular smoker in male, %** | 62.0 | 67.1 | 62.1 | 69.3 | 62.1 | 66.7 |
| **Regular smoker in female, %** | 2.3 | 3.6 | 2.3 | 3.9 | 2.3 | 3.7 |
| **Total physical activity (SD), MET-hr/d †** | 21.6 (13.9) | 20.4 (11.7) | 21.6 (13.9) | 21.0 (11.0) | 21.6 (13.9) | 21.2 (9.2) |
| **Weekly intake of fresh fruit, %** | 59.6 | 51.9 | 59.5 | 48.5 | 59.5 | 51.5 |
| **Weekly intake of meat, %** | 83.0 | 78.8 | 82.9 | 78.9 | 82.9 | 79.8 |
| **Weekly intake of preserved vegetables, %** | 51.0 | 52.5 | 51.0 | 51.0 | 51.0 | 53.7 |
| **Environmental exposure, %** | | | | | | |
| **Daily exposure to ETS** | 41.9 | 42.0 | 41.9 | 41.9 | 41.9 | 41.1 |
| **Always solid fuels for cooking‡** | 36.1 | 39.8 | 36.2 | 38.8 | 36.1 | 41.2 |
| **No ventilated cookstove** | 23.8 | 27.0 | 23.9 | 28.5 | 23.9 | 27.7 |
| **Always solid fuels for heating§** | 46.5 | 48.3 | 46.5 | 51.9 | 46.5 | 49.2 |
| **Anthropometric measures** | | | | | | |
| **Leg length (SD), cm** | 73.4 (4.8) | 73.4 (4.8) | 73.4 (4.8) | 73.8 (4.9) | 73.4 (4.8) | 73.3 (4.8) |
| **Body mass index (SD), kg/m$^2$** | 23.6 (3.3) | 24.0 (3.8) | 23.6 (3.3) | 24.4 (4.0) | 23.6 (3.4) | 24.1 (3.7) |
| **Health condition, %** | | | | | | |
| **Self-reported poor health** | 9.1 | 19.6 | 9.2 | 18.0 | 9.2 | 18.6 |
| **Hypertension** | 30.5 | 59.4 | 30.9 | 53.7 | 30.8 | 68.7 |
| **Antihypertensive treatment** | 3.5 | 8.6 | 3.6 | 6.6 | 3.5 | 11.3 |
| **Diabetes** | 5.2 | 12.0 | 5.3 | 12.7 | 5.3 | 12.3 |
| **Chronic respiratory disease¶** | 4.2 | 5.0 | 4.2 | 5.8 | 4.2 | 4.1 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate.
† MET: metabolic equivalent of tasks.
‡ Among participants who had ever cooked regularly and did not fit any criteria of exclusion.
§ Among participants who had ever used heating and did not fit any criteria of exclusion.
¶ Chronic respiratory disease: emphysema, chronic bronchitis, asthma, tuberculosis.

**Table 7.7 Baseline characteristics of participants with and without overall and cause-specific cardiovascular death (2)***

| | Ischaemic stroke death | | Intracerebral haemorrhage death | | Other cardiovascular disease death | |
|---|---|---|---|---|---|---|
| **Characteristics** | **No** | **Yes** | **No** | **Yes** | **No** | **Yes** |
| **Total participants, N** | | | | | | |
| **Age (SD), years** | 51.0 (10.5) | 65.4 (8.4) | 51.0 (10.5) | 62.1 (9.3) | 51.0 (10.5) | 64.0 (8.8) |
| **Women, %** | 59.1 | 43.1 | 59.1 | 41.2 | 59.1 | 43.9 |
| **Urban residency, %** | 43.3 | 35.4 | 43.5 | 18.1 | 43.3 | 40.5 |
| **No formal education, %** | 18.7 | 33.7 | 18.6 | 22.8 | 18.7 | 21.3 |
| **Household income <10,000 Yuan/ year, %** | 28.3 | 41.8 | 28.2 | 35.0 | 28.2 | 40.9 |
| **Agricultural worker, %** | 42.8 | 47.2 | 42.8 | 46.0 | 42.8 | 41.2 |
| **Factory worker, %** | 14.7 | 7.3 | 14.7 | 12.8 | 14.7 | 10.1 |
| **Lifestyle behaviour** | | | | | | |
| **Regular drinker in male, %** | 34.0 | 35.8 | 34.0 | 41.1 | 34.0 | 30.5 |
| **Regular drinker in female, %** | 2.1 | 1.4 | 2.1 | 2.2 | 2.1 | 3.6 |
| **Regular smoker in male, %** | 62.1 | 71.6 | 62.1 | 65.0 | 62.1 | 62.1 |
| **Regular smoker in female, %** | 2.3 | 4.0 | 2.3 | 3.0 | 2.3 | 2.5 |
| **Total physical activity (SD), MET-hr/d†** | 21.6 (13.9) | 20.4 (10.7) | 21.6 (13.9) | 21.7 (12.6) | 21.6 (13.9) | 19.2 (11.3) |
| **Weekly intake of fresh fruit, %** | 59.5 | 46.2 | 59.5 | 52.1 | 59.5 | 52.5 |
| **Weekly intake of meat, %** | 82.9 | 76.6 | 82.9 | 79.6 | 82.9 | 74.5 |
| **Weekly intake of preserved vegetables, %** | 51.0 | 54.1 | 51.0 | 53.9 | 51.0 | 53.0 |
| **Environmental exposure, %** | | | | | | |
| **Daily exposure to ETS** | 41.9 | 41.5 | 41.9 | 41.4 | 41.9 | 38.3 |
| **Always solid fuels for cooking‡** | 36.2 | 44.5 | 36.2 | 42.3 | 36.2 | 38.6 |
| **No ventilated cookstove** | 23.9 | 31.5 | 23.9 | 27.9 | 23.9 | 26.5 |
| **Always solid fuels for heating§** | 46.5 | 50.3 | 46.5 | 49.3 | 46.5 | 50.1 |
| **Anthropometric measures** | | | | | | |
| **Leg length (SD), cm** | 73.4 (4.8) | 73.5 (4.9) | 73.4 (4.8) | 73.3 (4.8) | 73.4 (4.8) | 73.8 (4.8) |
| **Body mass index (SD), kg/m$^2$** | 23.6 (3.4) | 23.7 (3.8) | 23.6 (3.4) | 24.2 (3.6) | 23.6 (3.4) | 23.9 (3.7) |
| **Health condition, %** | | | | | | |
| **Self-reported poor health** | 9.3 | 19.7 | 9.2 | 18.8 | 9.3 | 25.2 |
| **Hypertension** | 31.0 | 59.9 | 30.8 | 71.3 | 31.0 | 51.7 |
| **Antihypertensive treatment** | 3.6 | 11.4 | 3.6 | 10.8 | 3.6 | 7.5 |
| **Diabetes** | 5.4 | 15.2 | 5.3 | 11.4 | 5.4 | 9.7 |
| **Chronic respiratory disease¶** | 4.2 | 4.5 | 4.2 | 4.1 | 4.2 | 5.3 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate.
† MET: metabolic equivalent of tasks.
‡ Among participants who had ever cooked regularly and did not fit any criteria of exclusion.
§ Among participants who had ever used heating and did not fit any criteria of exclusion.
¶ Chronic respiratory disease: emphysema, chronic bronchitis, asthma, tuberculosis.

**Table 7.8 Adjusted hazard ratios (HRs) for major cardiovascular death by long-term primary cooking fuel exposure with different exclusion of participants**

| | (1) Additional adjustment* | | + Excluding those with <20 year recall period | | + Excluding those who used clean fuels <10 years | | + Excluding events occurred within the first 3 years of follow-up | | + Excluding weekly regular cooks | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cause of death** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** |
| **All cardiovascular disease** | | | | | | | | | | |
| Always clean | 893 | 1.00 (0.93-1.08) | 757 | 1.00 (0.92-1.08) | 507 | 1.00 (0.91-1.10) | 403 | 1.00 (0.90-1.11) | 284 | 1.00 (0.88-1.14) |
| Solid to clean | 1,441 | 0.99 (0.92-1.06) | 1,372 | 1.04 (0.96-1.12) | 900 | 1.02 (0.94-1.12) | 752 | 1.07 (0.97-1.18) | 627 | 1.08 (0.97-1.20) |
| Always solid | 4,581 | 1.13 (1.07-1.18) | 4,404 | 1.16 (1.10-1.22) | 4,404 | 1.15 (1.10-1.21) | 3,524 | 1.20 (1.14-1.27) | 3,103 | 1.25 (1.17-1.33) |
| **Ischaemic heart disease** | | | | | | | | | | |
| Always clean | 399 | 1.00 (0.89-1.12) | 335 | 1.00 (0.88-1.13) | 234 | 1.00 (0.86-1.16) | 191 | 1.00 (0.85-1.18) | 136 | 1.00 (0.83-1.21) |
| Solid to clean | 578 | 0.95 (0.85-1.07) | 559 | 1.02 (0.90-1.16) | 378 | 0.97 (0.84-1.13) | 315 | 1.00 (0.85-1.17) | 264 | 1.01 (0.84-1.21) |
| Always solid | 1,410 | 0.94 (0.86-1.04) | 1,362 | 1.00 (0.91-1.10) | 1,362 | 0.98 (0.89-1.08) | 1,106 | 1.02 (0.92-1.14) | 979 | 1.09 (0.97-1.23) |
| **Stroke** | | | | | | | | | | |
| Always clean | 301 | 1.00 (0.88-1.14) | 264 | 1.00 (0.87-1.15) | 171 | 1.00 (0.85-1.18) | 127 | 1.00 (0.83-1.21) | 90 | 1.00 (0.80-1.25) |
| Solid to clean | 513 | 1.05 (0.94-1.18) | 487 | 1.06 (0.94-1.20) | 309 | 1.07 (0.92-1.24) | 254 | 1.17 (0.99-1.37) | 214 | 1.19 (1.00-1.42) |
| Always solid | 2,348 | 1.25 (1.17-1.33) | 2,265 | 1.22 (1.15-1.31) | 2,265 | 1.22 (1.14-1.30) | 1,739 | 1.31 (1.22-1.42) | 1,541 | 1.35 (1.24-1.47) |
| **Intracerebral haemorrhage** | | | | | | | | | | |
| Always clean | 174 | 1.00 (0.84-1.19) | 151 | 1.00 (0.83-1.20) | 94 | 1.00 (0.80-1.25) | 67 | 1.00 (0.77-1.30) | 45 | 1.00 (0.73-1.37) |
| Solid to clean | 288 | 1.12 (0.96-1.30) | 276 | 1.16 (0.99-1.35) | 173 | 1.23 (1.01-1.49) | 135 | 1.29 (1.03-1.61) | 116 | 1.38 (1.09-1.75) |
| Always solid | 1,766 | 1.24 (1.15-1.33) | 1,713 | 1.21 (1.13-1.31) | 1,713 | 1.25 (1.16-1.34) | 1,282 | 1.28 (1.17-1.40) | 1,145 | 1.40 (1.27-1.55) |
| **Ischaemic stroke** | | | | | | | | | | |
| Always clean | 99 | 1.00 (0.80-1.25) | 89 | 1.00 (0.80-1.26) | 61 | 1.00 (0.76-1.31) | 49 | 1.00 (0.74-1.35) | 39 | 1.00 (0.71-1.40) |
| Solid to clean | 154 | 0.94 (0.76-1.17) | 144 | 0.91 (0.73-1.13) | 102 | 0.91 (0.70-1.18) | 92 | 1.06 (0.81-1.40) | 75 | 0.97 (0.72-1.32) |
| Always solid | 458 | 1.41 (1.22-1.62) | 433 | 1.37 (1.18-1.58) | 433 | 1.32 (1.13-1.53) | 359 | 1.48 (1.26-1.75) | 308 | 1.31 (1.09-1.57) |
| **Other cardiovascular disease** | | | | | | | | | | |
| Always clean | 190 | 1.00 (0.85-1.17) | 158 | 1.00 (0.84-1.19) | 102 | 1.00 (0.81-1.23) | 85 | 1.00 (0.79-1.26) | 58 | 1.00 (0.76-1.32) |
| Solid to clean | 345 | 1.00 (0.87-1.16) | 326 | 1.04 (0.90-1.21) | 213 | 1.09 (0.91-1.30) | 183 | 1.10 (0.91-1.34) | 149 | 1.09 (0.88-1.35) |
| Always solid | 822 | 1.23 (1.11-1.37) | 777 | 1.30 (1.17-1.45) | 777 | 1.35 (1.21-1.50) | 679 | 1.36 (1.21-1.53) | 583 | 1.38 (1.21-1.58) |

***** Additional adjustment: adjustment for extra diet variables (fish, poultry, dairy, egg, rice) and leg length in addition to those in the main analyses.

† Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, heating exposure, length of recall period and antihypertensive treatment plus additional adjustment on extra diet variables (fish, poultry, dairy, egg, rice) and leg length.

**Table 7.9. Adjusted HRs for major cardiovascular death by long-term primary heating fuel exposure with different exclusion of participants**

| | (1) Additional adjustment* | | + Excluding those with <20 year recall period | | + Excluding those who used clean fuels <10 years | | + Excluding events occurred within the first 3 years of follow-up | |
|---|---|---|---|---|---|---|---|---|
| **Cause of death** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** | **N** | **HR (95% CI)†** |
| **All cardiovascular disease** | | | | | | | | |
| Always clean | 522 | 1.00 (0.92-1.09) | 439 | 1.00 (0.91-1.10) | 295 | 1.00 (0.89-1.12) | 246 | 1.00 (0.88-1.13) |
| Solid to clean | 1,027 | 0.97 (0.89-1.06) | 983 | 0.97 (0.89-1.07) | 589 | 0.94 (0.83-1.06) | 471 | 0.87 (0.76-0.99) |
| Always solid | 5,993 | 1.18 (1.09-1.28) | 5,790 | 1.17 (1.07-1.26) | 5,790 | 1.11 (1.02-1.21) | 4,511 | 1.04 (0.94-1.14) |
| **Ischaemic heart disease** | | | | | | | | |
| Always clean | 217 | 1.00 (0.87-1.15) | 172 | 1.00 (0.86-1.17) | 116 | 1.00 (0.83-1.20) | 96 | 1.00 (0.82-1.23) |
| Solid to clean | 542 | 0.96 (0.86-1.08) | 520 | 0.98 (0.86-1.11) | 323 | 0.93 (0.79-1.10) | 252 | 0.87 (0.72-1.04) |
| Always solid | 2,178 | 1.15 (1.02-1.31) | 2,103 | 1.13 (1.00-1.29) | 2,103 | 1.04 (0.91-1.19) | 1,680 | 1.02 (0.88-1.19) |
| **Stroke** | | | | | | | | |
| Always clean | 195 | 1.00 (0.87-1.15) | 171 | 1.00 (0.86-1.16) | 118 | 1.00 (0.84-1.19) | 98 | 1.00 (0.82-1.22) |
| Solid to clean | 321 | 0.97 (0.83-1.13) | 307 | 0.95 (0.81-1.12) | 171 | 0.90 (0.72-1.12) | 140 | 0.81 (0.63-1.04) |
| Always solid | 2,910 | 1.22 (1.08-1.39) | 2,843 | 1.21 (1.06-1.38) | 2,843 | 1.15 (1.00-1.32) | 2,124 | 1.01 (0.86-1.19) |
| **Intracerebral haemorrhage** | | | | | | | | |
| Always clean | 117 | 1.00 (0.83-1.20) | 105 | 1.00 (0.83-1.21) | 73 | 1.00 (0.80-1.25) | 62 | 1.00 (0.78-1.28) |
| Solid to clean | 174 | 0.97 (0.79-1.19) | 165 | 0.91 (0.73-1.13) | 83 | 0.81 (0.60-1.10) | 64 | 0.69 (0.49-0.98) |
| Always solid | 2,275 | 1.38 (1.18-1.60) | 2,227 | 1.33 (1.13-1.56) | 2,227 | 1.29 (1.09-1.54) | 1,628 | 1.09 (0.89-1.33) |
| **Ischaemic stroke** | | | | | | | | |
| Always clean | 53 | 1.00 (0.76-1.32) | 42 | 1.00 (0.73-1.36) | 30 | 1.00 (0.70-1.44) | 26 | 1.00 (0.68-1.48) |
| Solid to clean | 125 | 0.87 (0.67-1.13) | 121 | 0.97 (0.74-1.28) | 78 | 0.92 (0.65-1.31) | 69 | 0.87 (0.60-1.25) |
| Always solid | 560 | 0.89 (0.70-1.15) | 543 | 0.97 (0.75-1.25) | 543 | 0.76 (0.58-0.99) | 436 | 0.73 (0.54-0.97) |
| **Other cardiovascular disease** | | | | | | | | |
| Always clean | 109 | 1.00 (0.83-1.21) | 96 | 1.00 (0.82-1.22) | 61 | 1.00 (0.78-1.28) | 52 | 1.00 (0.76-1.31) |
| Solid to clean | 158 | 0.99 (0.79-1.24) | 156 | 0.99 (0.79-1.24) | 95 | 0.99 (0.74-1.33) | 79 | 0.96 (0.69-1.33) |
| Always solid | 900 | 1.15 (0.96-1.37) | 844 | 1.13 (0.94-1.37) | 844 | 1.16 (0.95-1.41) | 707 | 1.09 (0.88-1.35) |

***** Additional adjustment: adjustment for extra diet variables (fish, poultry, dairy, egg, rice) and leg length in addition to those in the main analyses.

† Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, cooking exposure, length of recall period and antihypertensive treatment plus additional adjustment on extra diet variables (fish, poultry, dairy, egg, rice) and leg length.

**Figure 7.1 Participant exclusions**

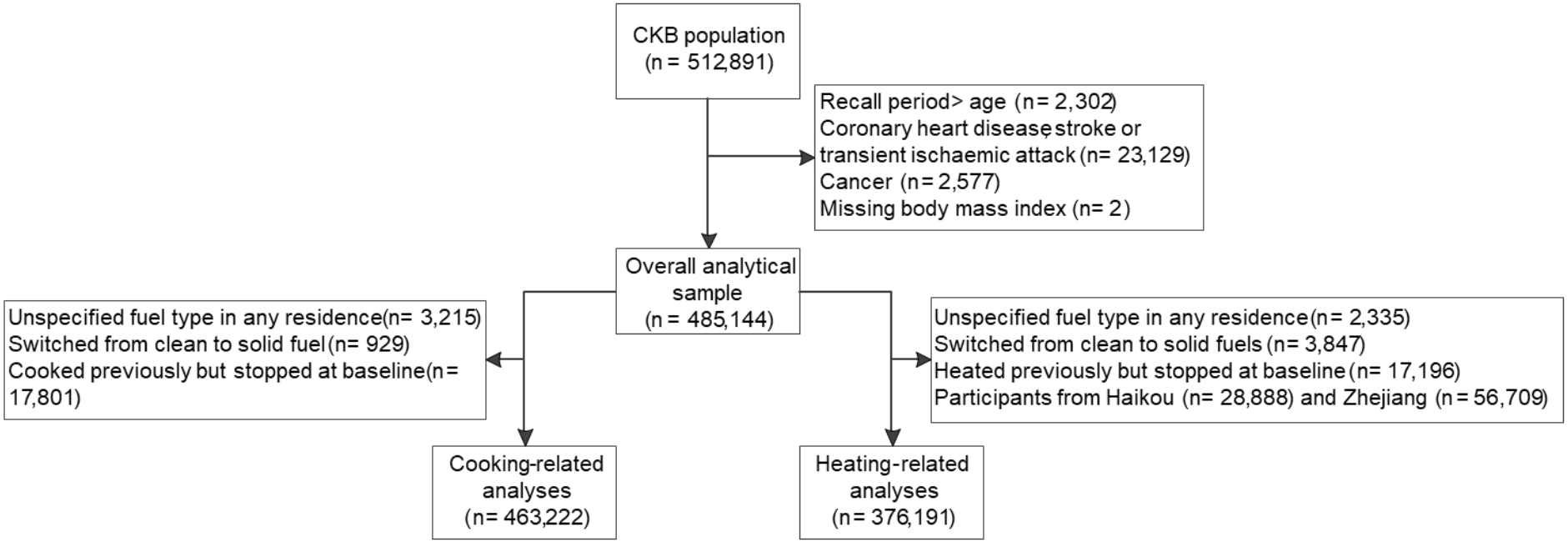


**Figure 7.2 Adjusted mean systolic blood pressure (SBP) by cooking and heating exposure groups, stratified by gender and season.**

Mean SBP were adjusted for age, study area, education level, household income, alcohol consumption, smoking habit, environmental tobacco smoke, cookstove ventilation, diet (fresh fruit, preserved vegetables, meat, dairy products), physical activity, body mass index, antihypertensive treatment, plus mutual adjustment for cooking and heating fuel exposure.

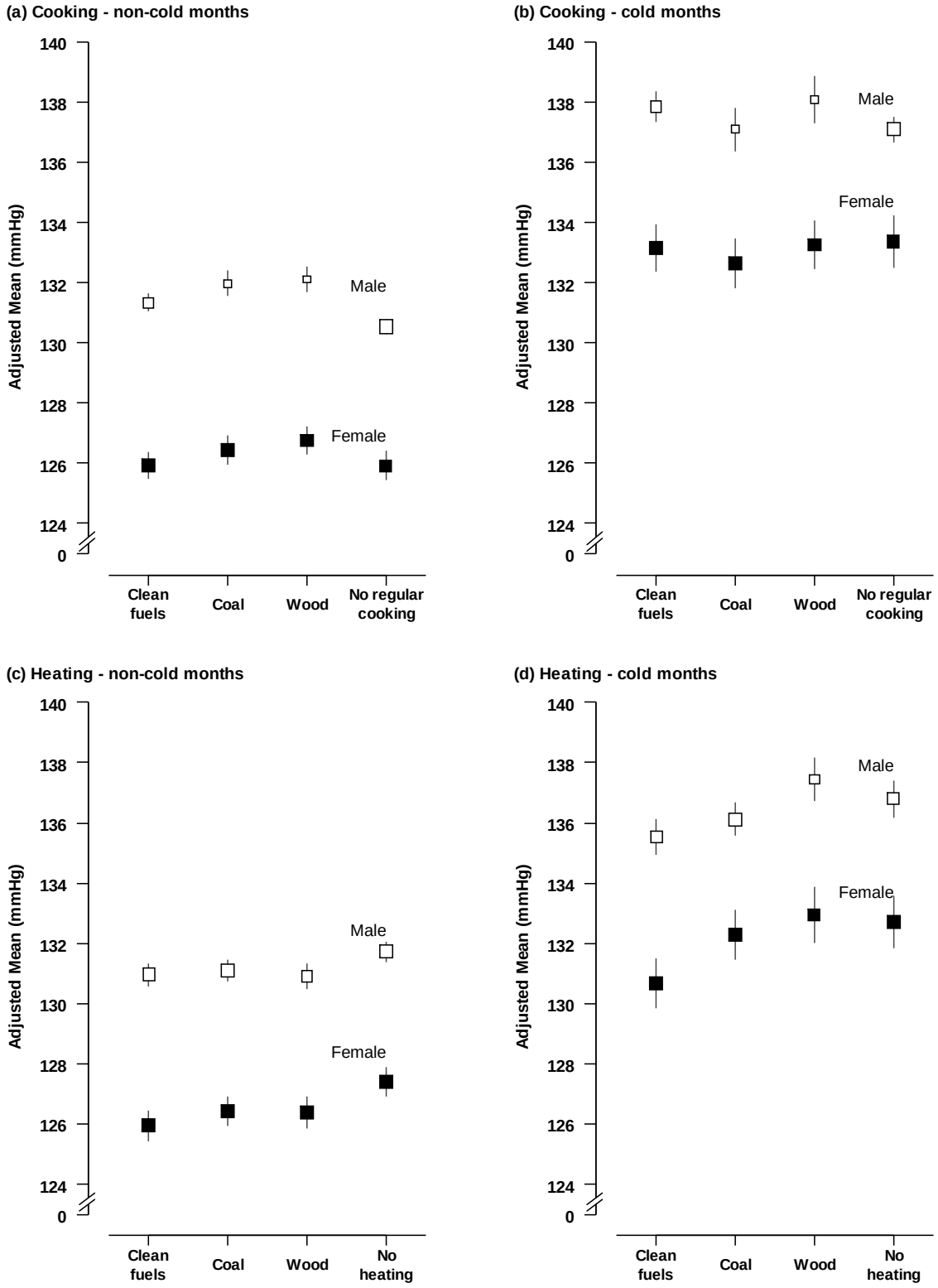


**Figure 7.3 Adjusted mean systolic blood pressure (SBP) by fuel-cookstove ventilation groups, stratified by gender and season.**

Mean SBP were adjusted for age, study area, education level, household income, alcohol consumption, smoking habit, environmental tobacco smoke, diet (fresh fruit, preserved vegetables, meat, dairy products), physical activity, body mass index, antihypertensive treatment, plus mutual adjustment for cooking and heating fuel exposure.

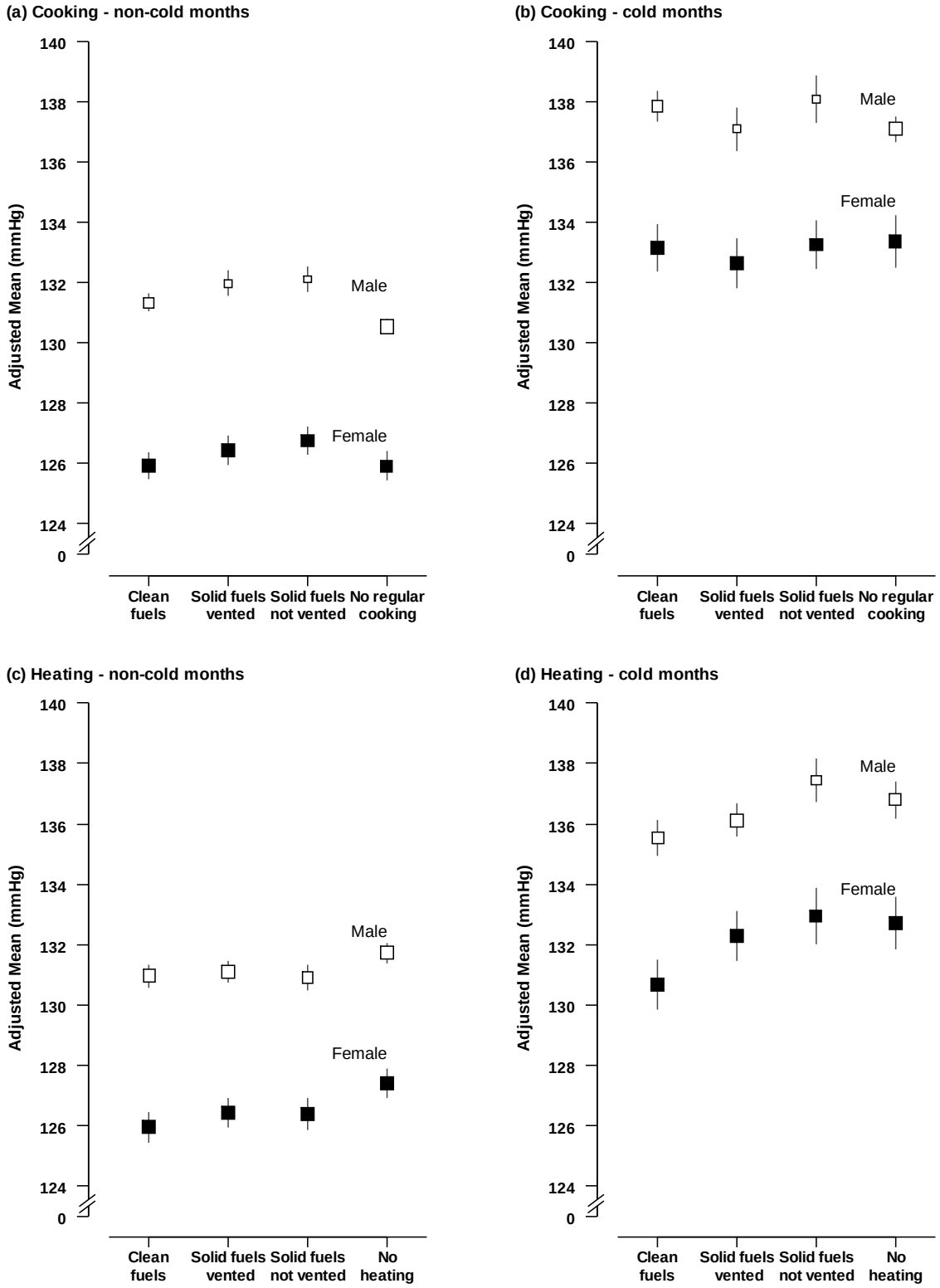


**Figure 7.4 Adjusted mean diastolic blood pressure (DBP) by cooking and heating exposure groups, stratified by gender and season.**

Mean SBP were adjusted for age, study area, education level, household income, alcohol consumption, smoking habit, environmental tobacco smoke, cookstove ventilation, diet (fresh fruit, preserved vegetables, meat, dairy products), physical activity, body mass index, antihypertensive treatment, plus mutual adjustment for cooking and heating fuel exposure.

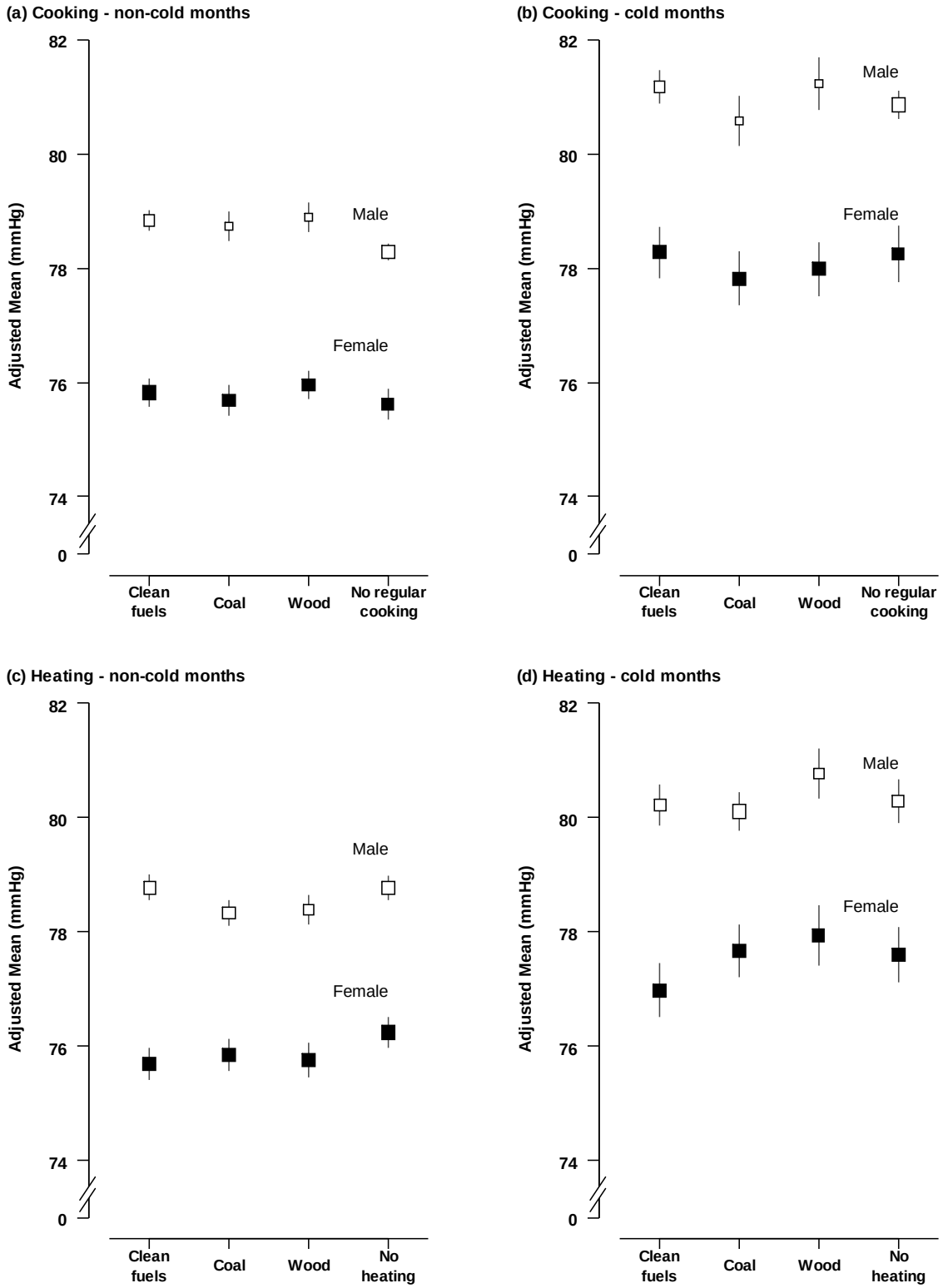


**Figure 7.5 Adjusted hazard ratios for cardiovascular death by long-term cooking fuel exposure**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, heating exposure, length of recall period and antihypertensive treatment. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

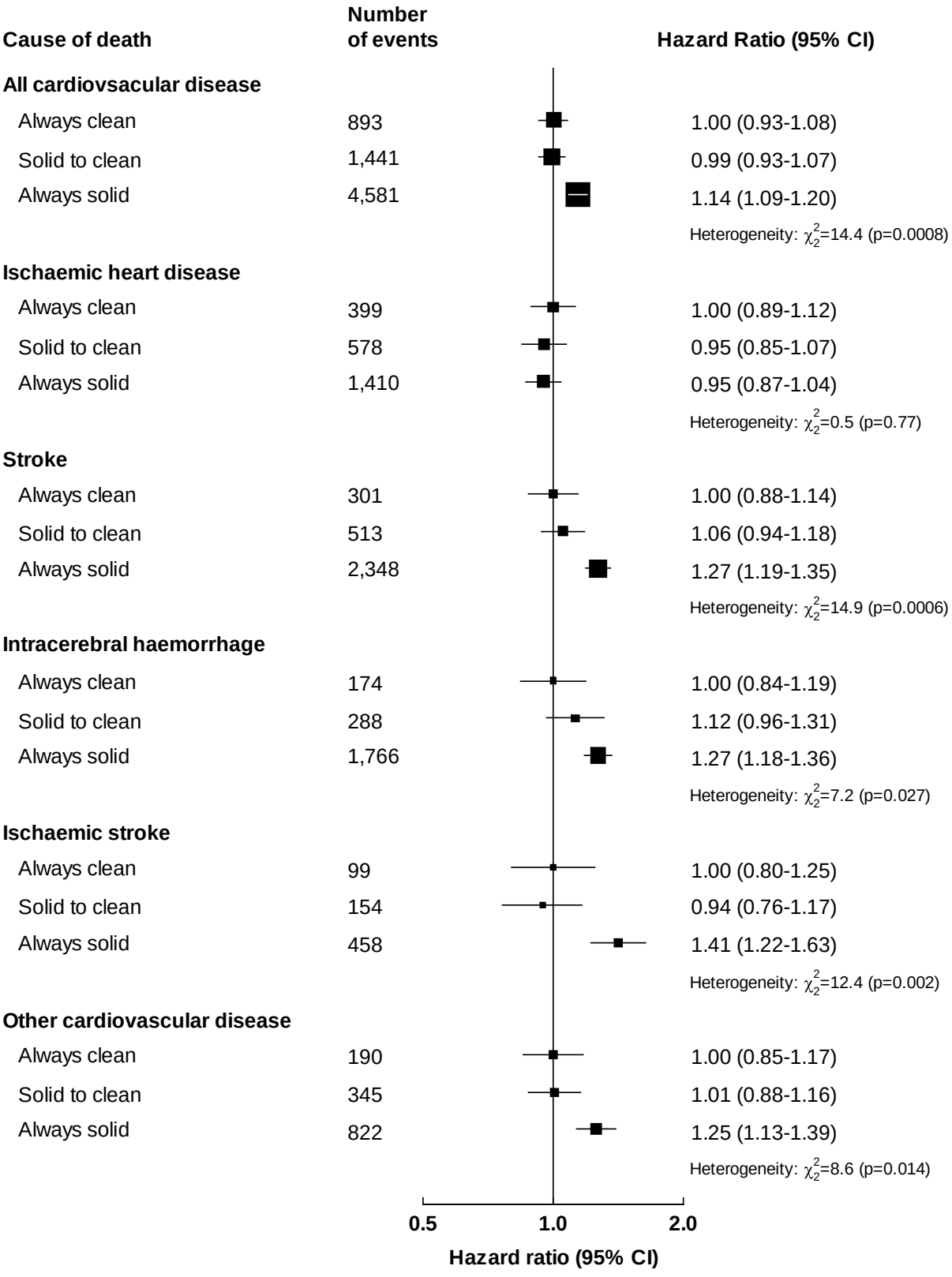


**Figure 7.6 Adjusted hazard ratios for cardiovascular death by duration of continuous exposure to solid cooking fuel**

Conventions as Figure 7.5.

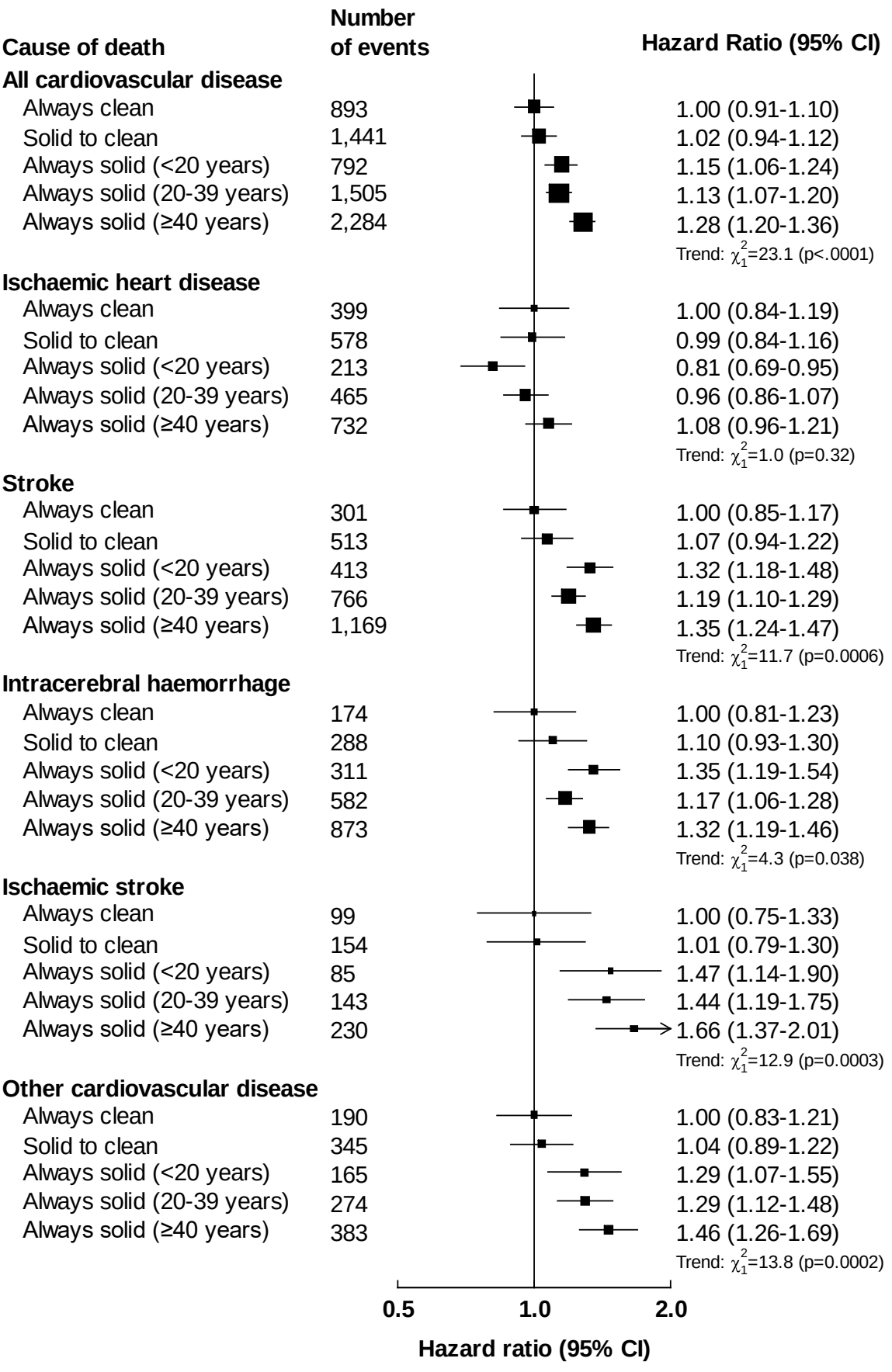


**Figure 7.7 Adjusted hazard ratios for cardiovascular death by weighted-duration of continuous exposure to solid cooking fuel**

Conventions as Figure 7.5.

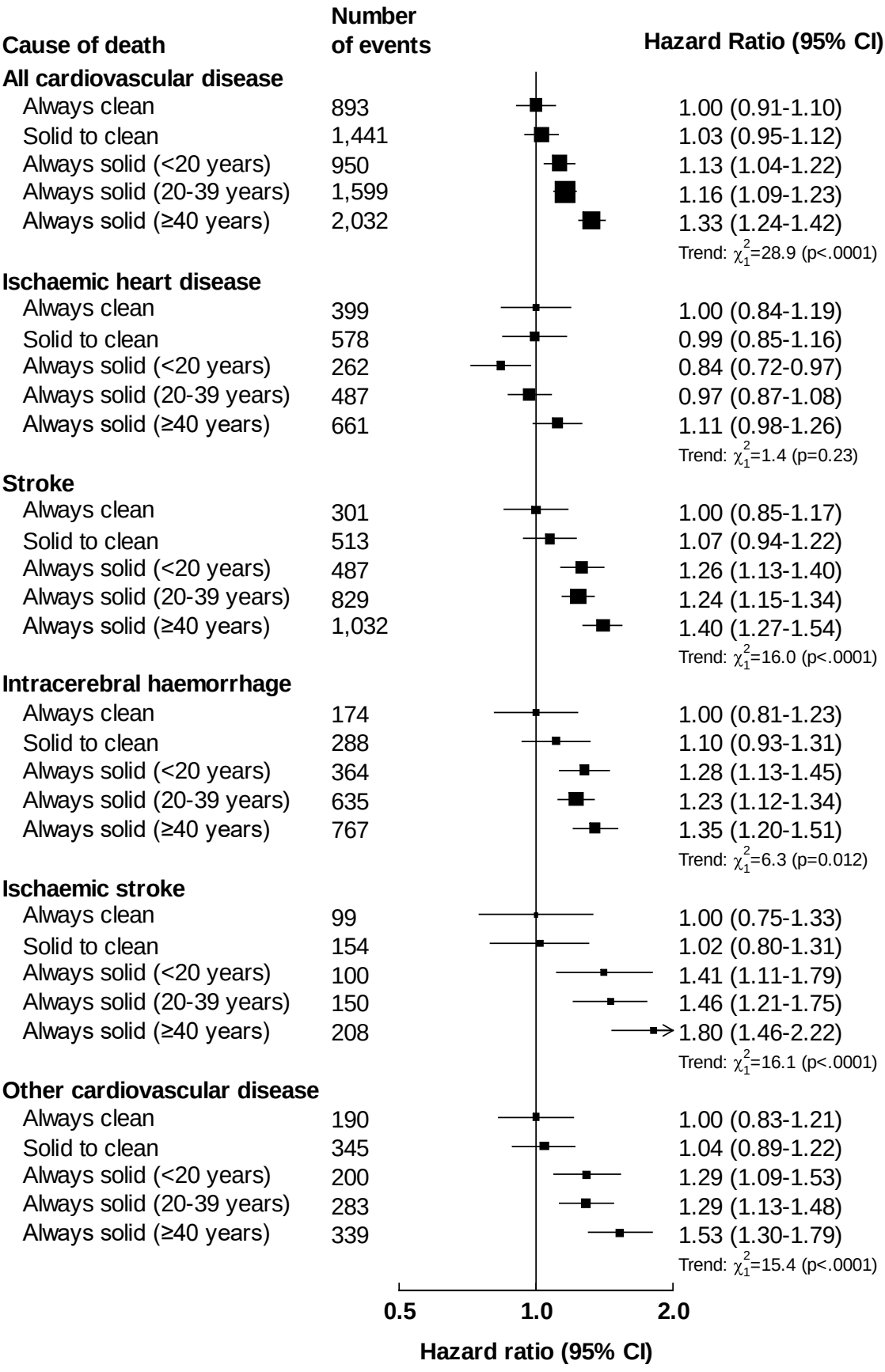


**Figure 7.8 Adjusted hazard ratios for cardiovascular death by types of long-term primary cooking fuel used**

Conventions as Figure 7.5.

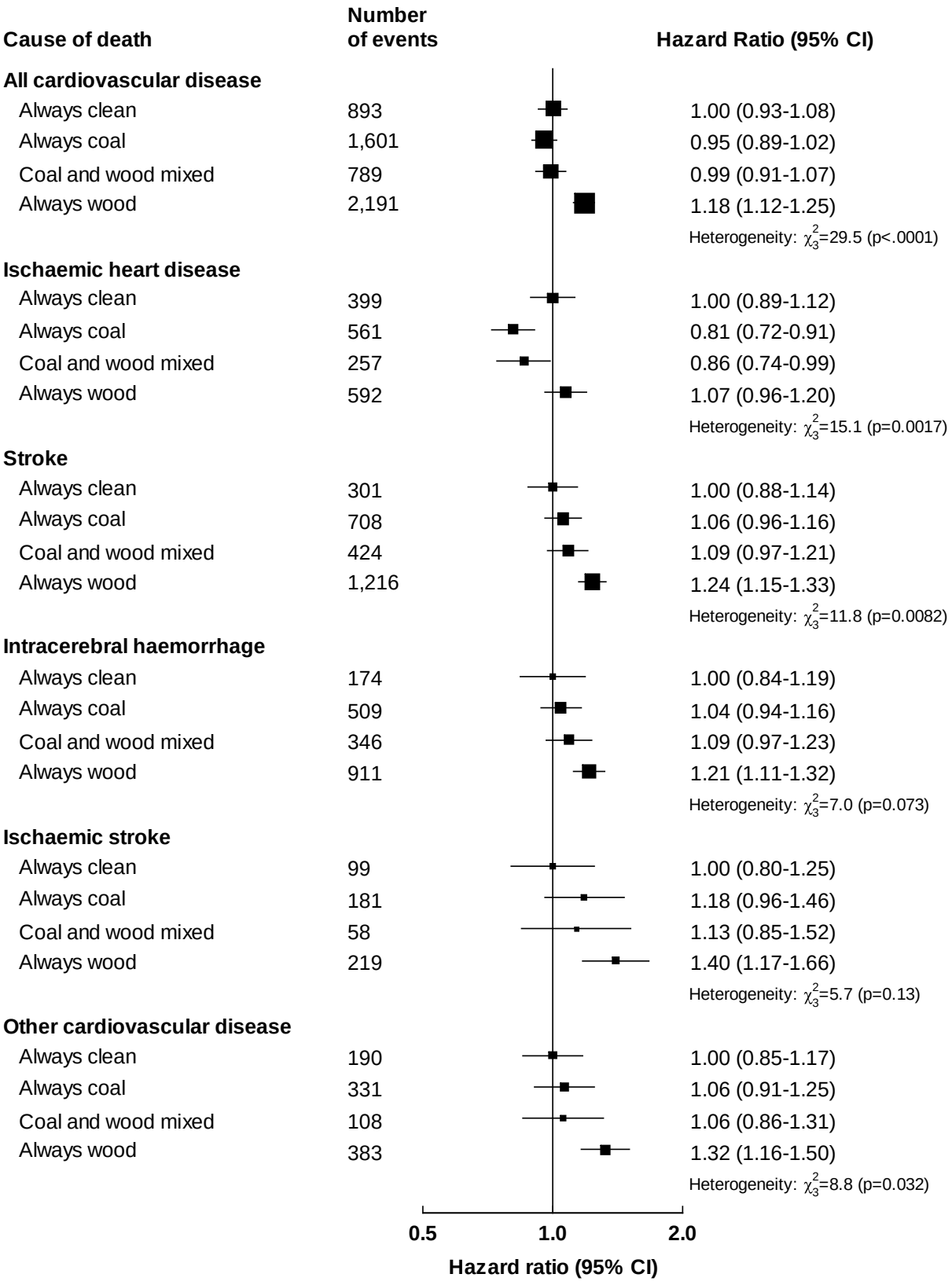


**Figure 7.9 Adjusted hazard ratios for cardiovascular death by long-term primary cooking fuel and ventilated cookstove ownership**

*Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, heating exposure, length of recall period and antihypertensive treatment. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

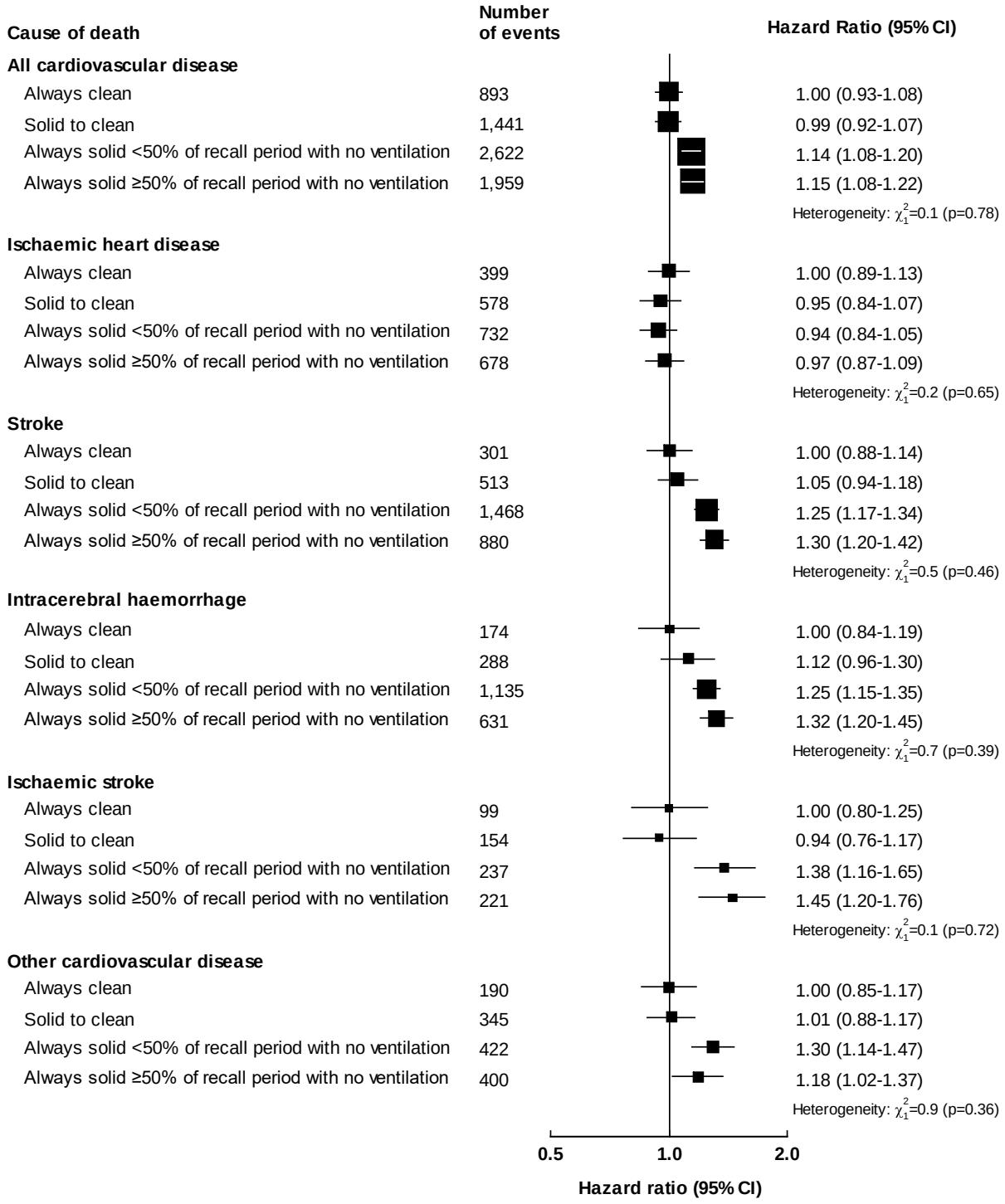


**Figure 7.10 Adjusted hazard ratios for cardiovascular death associated with long-term solid fuel use for cooking (versus clean fuel use), by subgroups of baseline characteristics**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, heating exposure, length of recall period and antihypertensive treatment, where appropriate. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI). The white diamond represents the HRs and 95% CI in the main analysis.

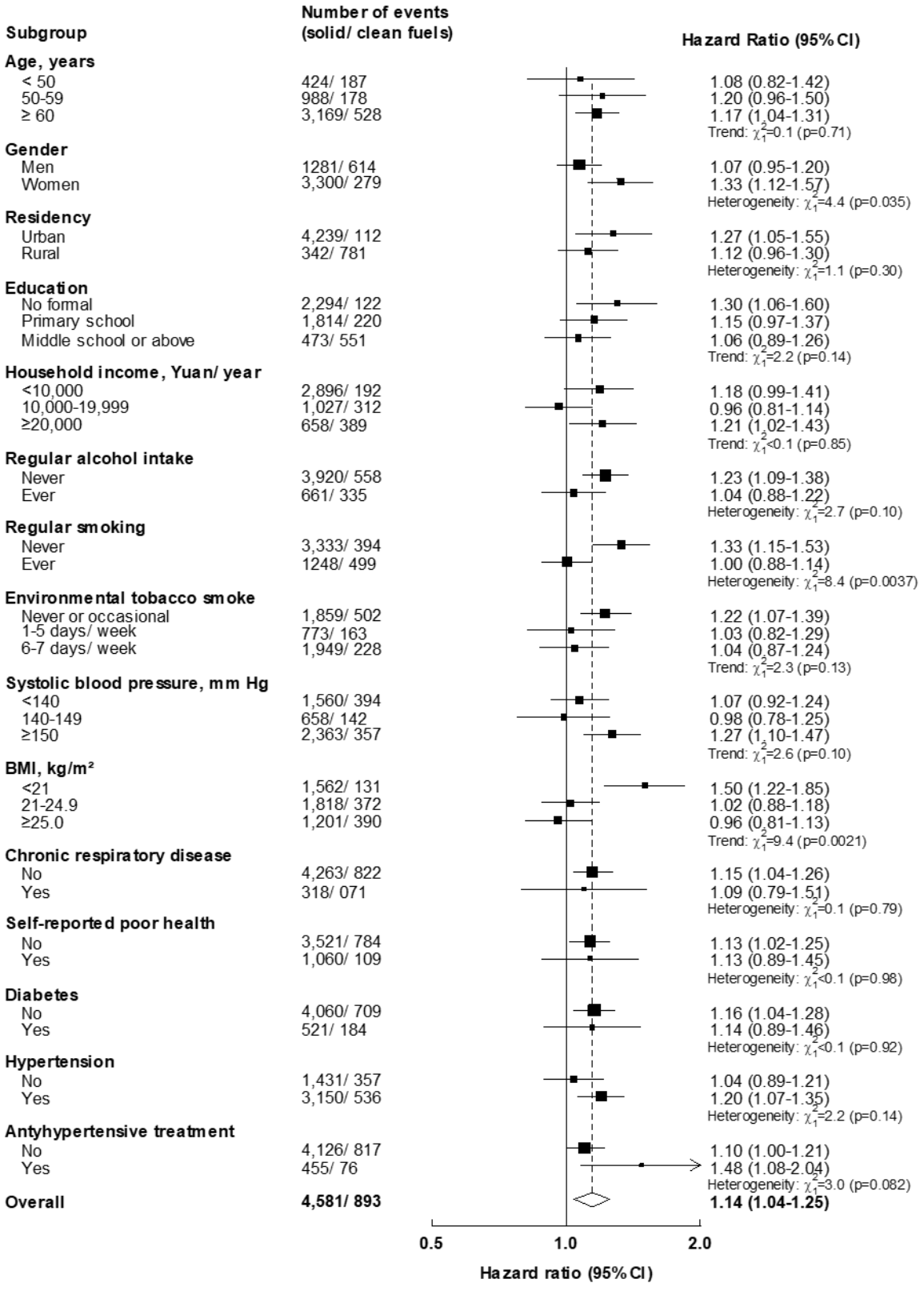


**Figure 7.11 Adjusted hazard ratios for cardiovascular death by long-term heating fuel exposure**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, cooking exposure, length of recall period and antihypertensive treatment. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

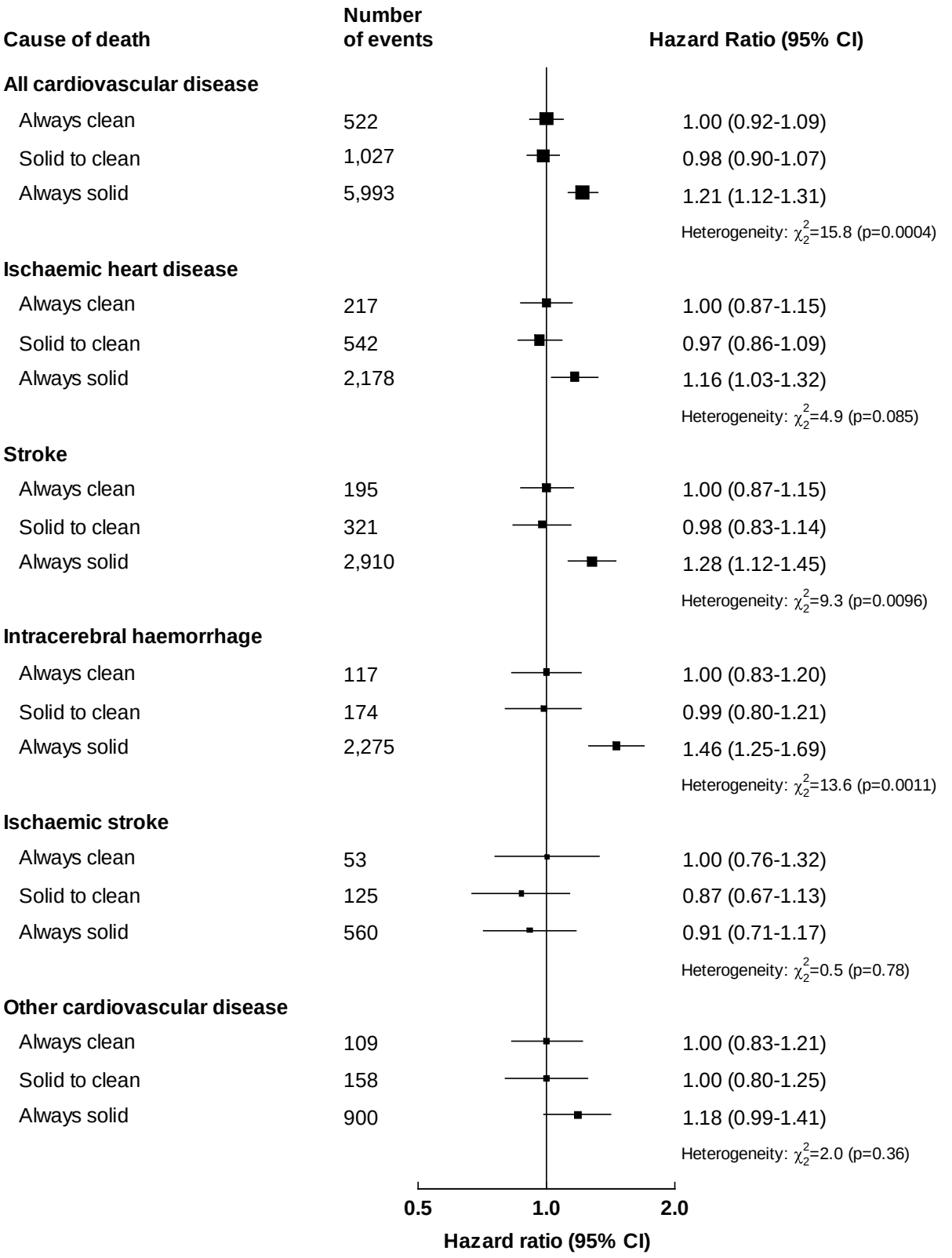


**Figure 7.12 Adjusted hazard ratios for cardiovascular death by duration of continuous exposure to solid heating fuel**

Conventions as Figure 7.11.

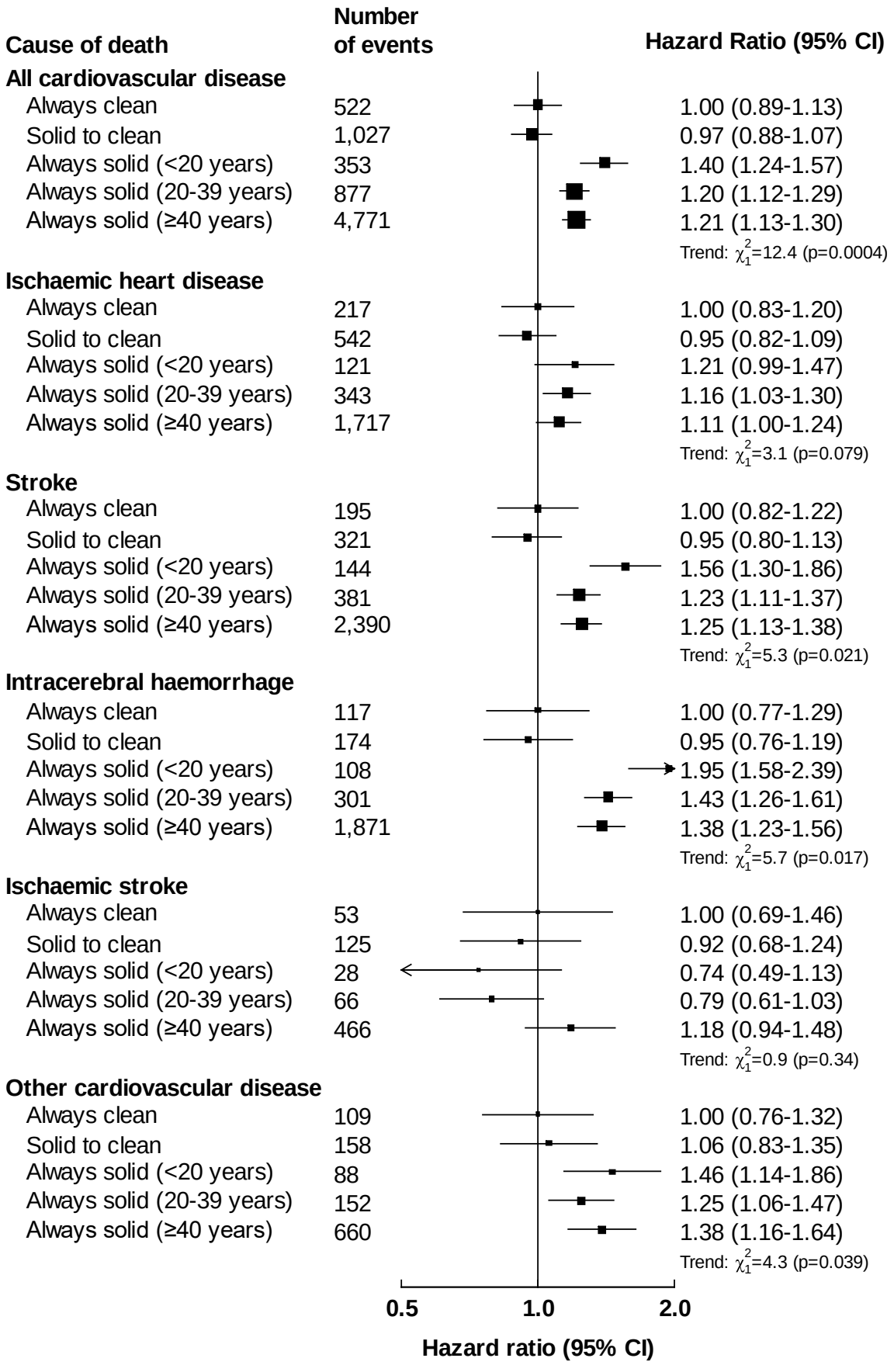


**Figure 7.13 Adjusted hazard ratios for cardiovascular death by weighted-duration of continuous exposure to solid heating fuel**

Conventions as Figure 7.11.

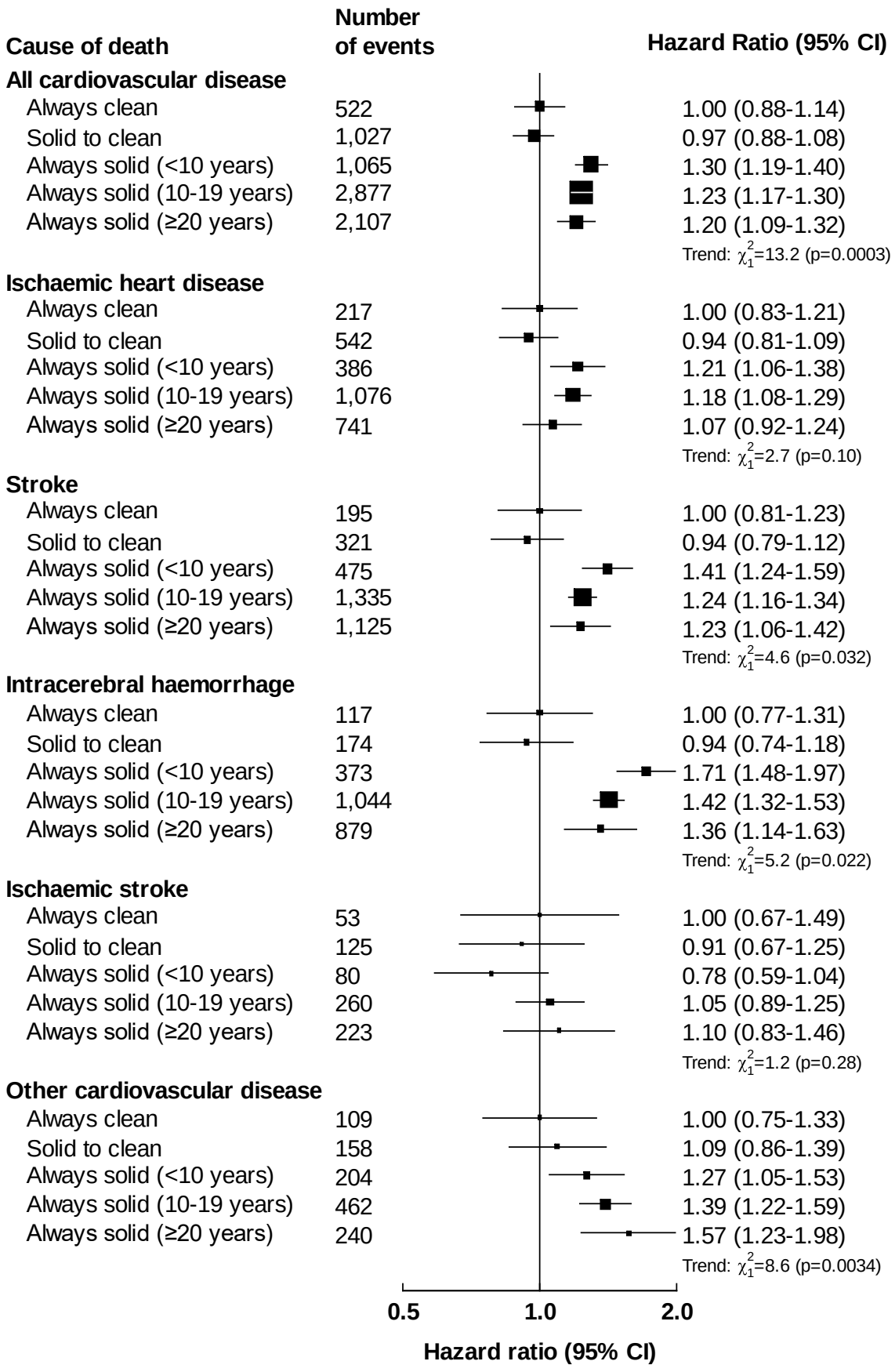


**Figure 7.14 Adjusted hazard ratios for cardiovascular death by types of long-term primary heating fuel used**

Conventions as Figure 7.11.

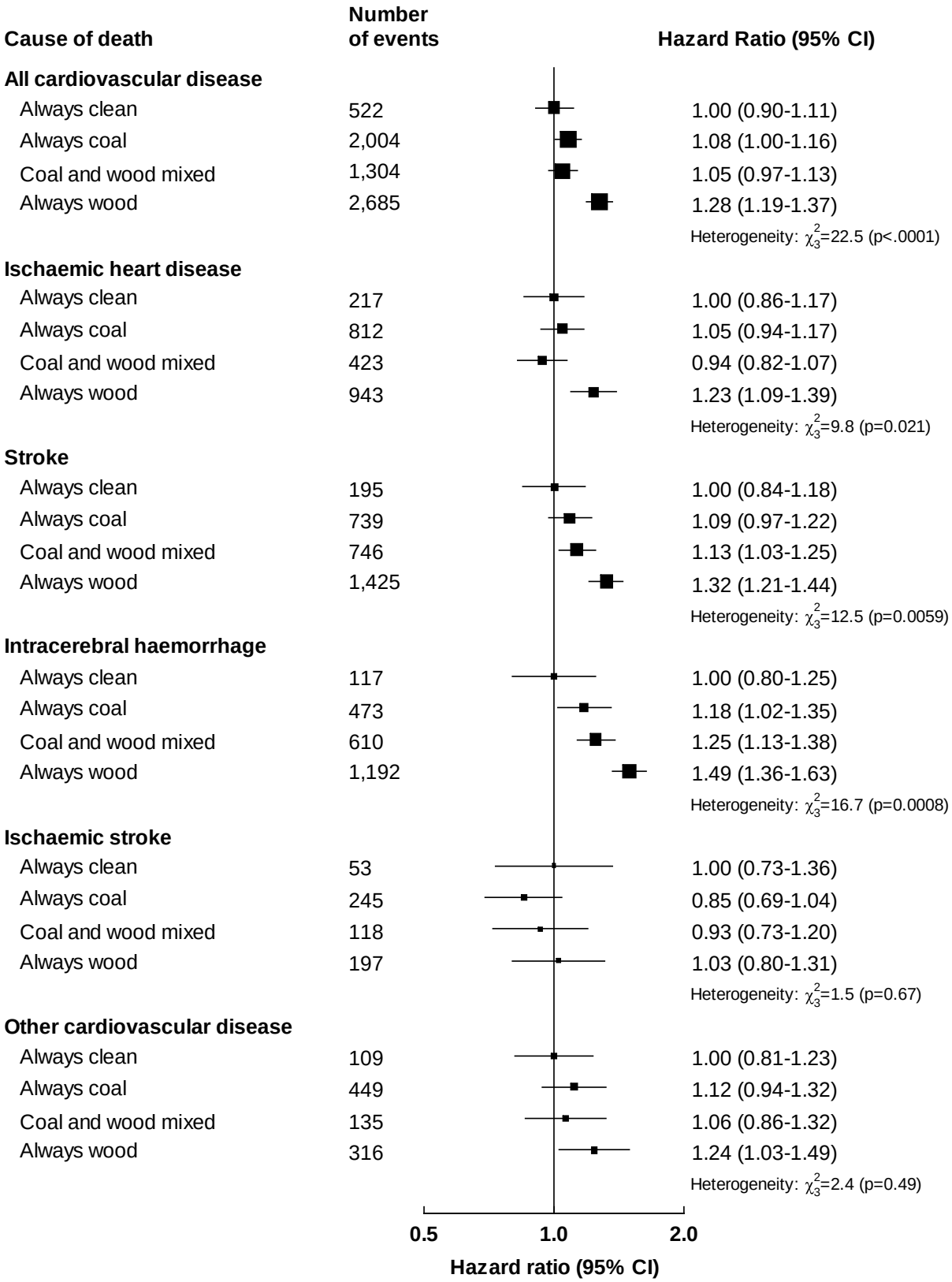


**Figure 7.15 Adjusted hazard ratios for cardiovascular death by long-term primary heating fuel and ventilated cookstove ownership**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cooking exposure, length of recall period and antihypertensive treatment. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).

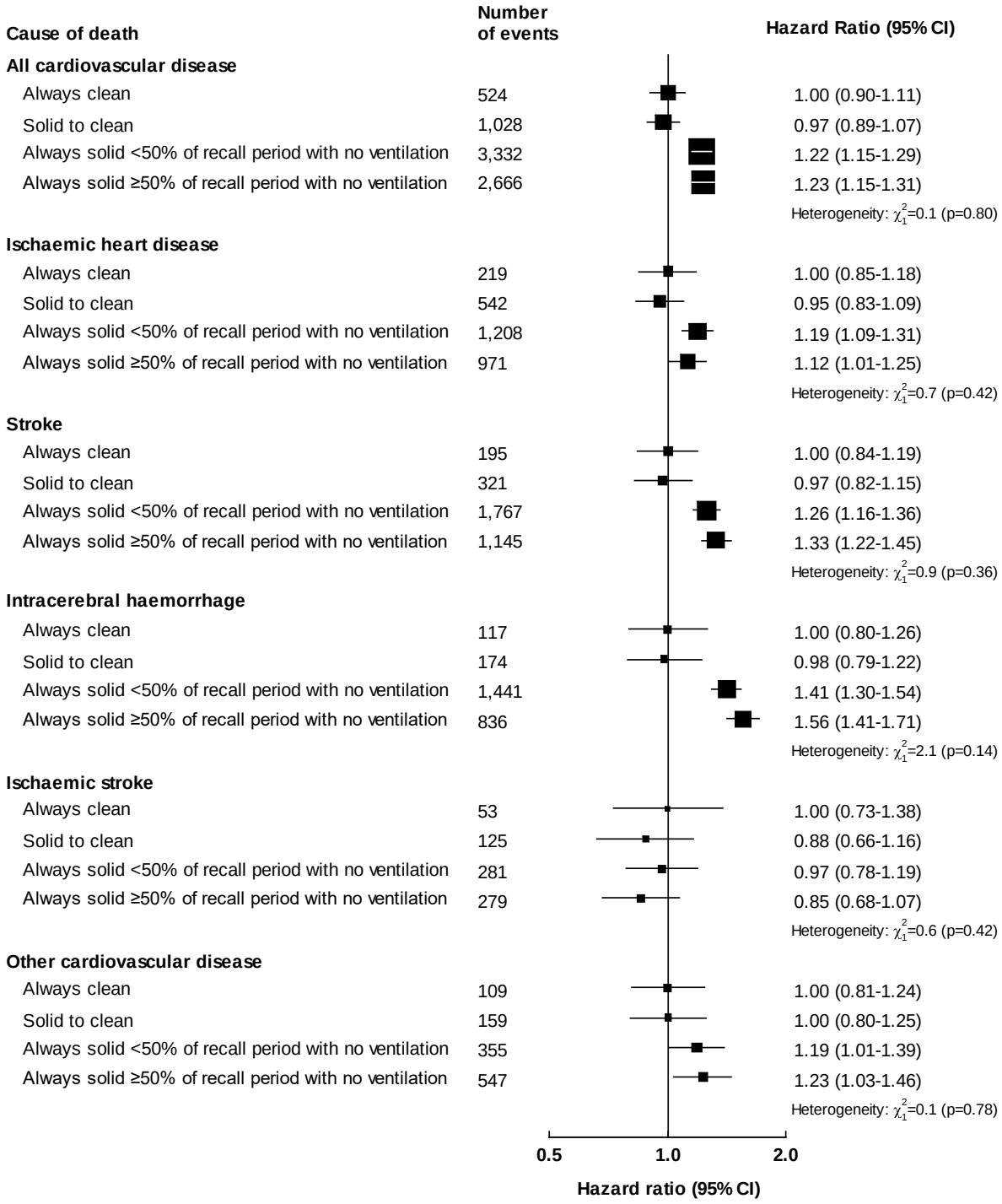


**Figure 7.16 Adjusted hazard ratios for cardiovascular death associated with long-term solid fuel use for heating (versus clean fuel use), by subgroups of baseline characteristics**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, smoking habit, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, cooking exposure, length of recall period and antihypertensive treatment, where appropriate. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI). The white diamond represents the HRs and 95% CI in the main analysis.

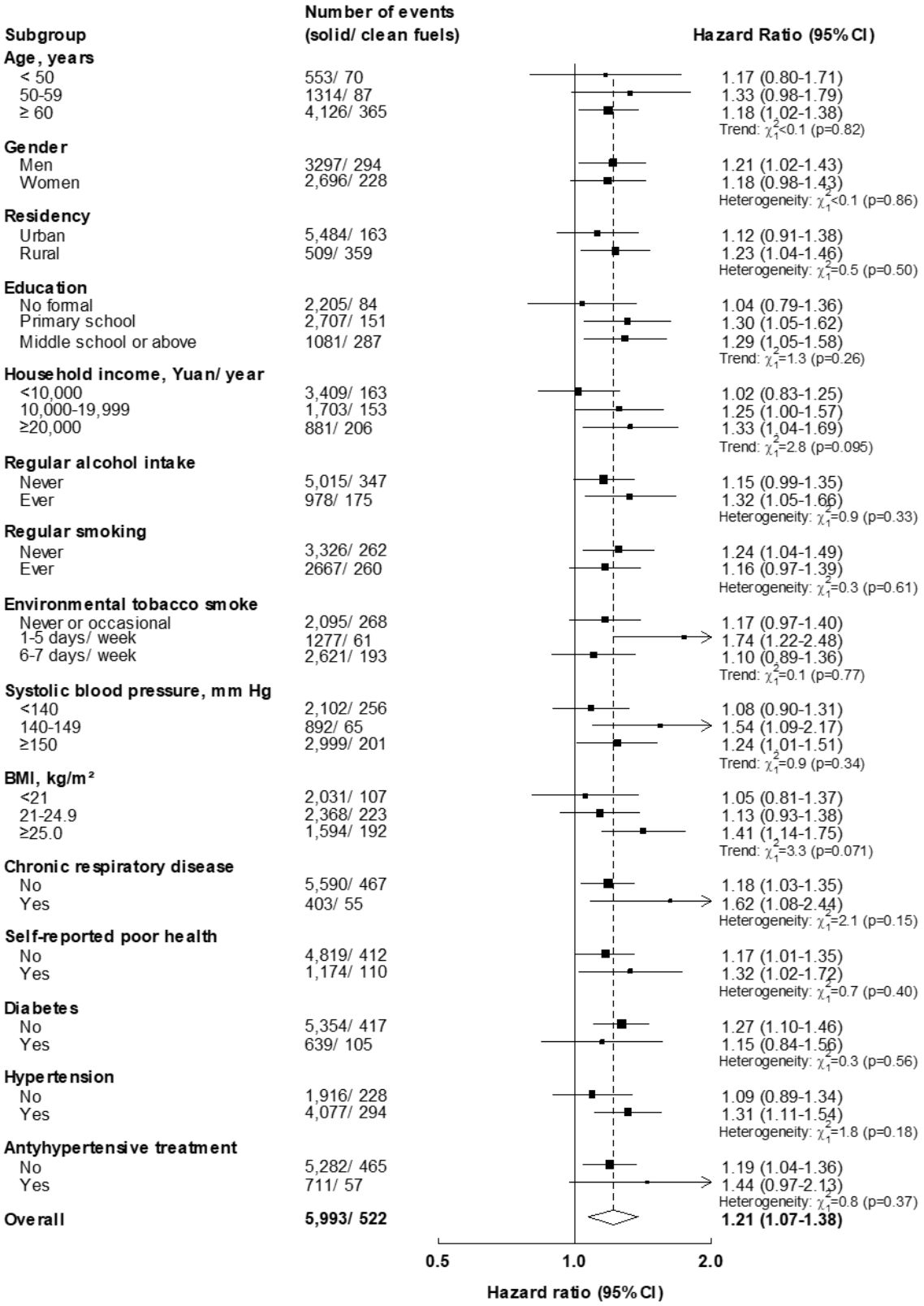
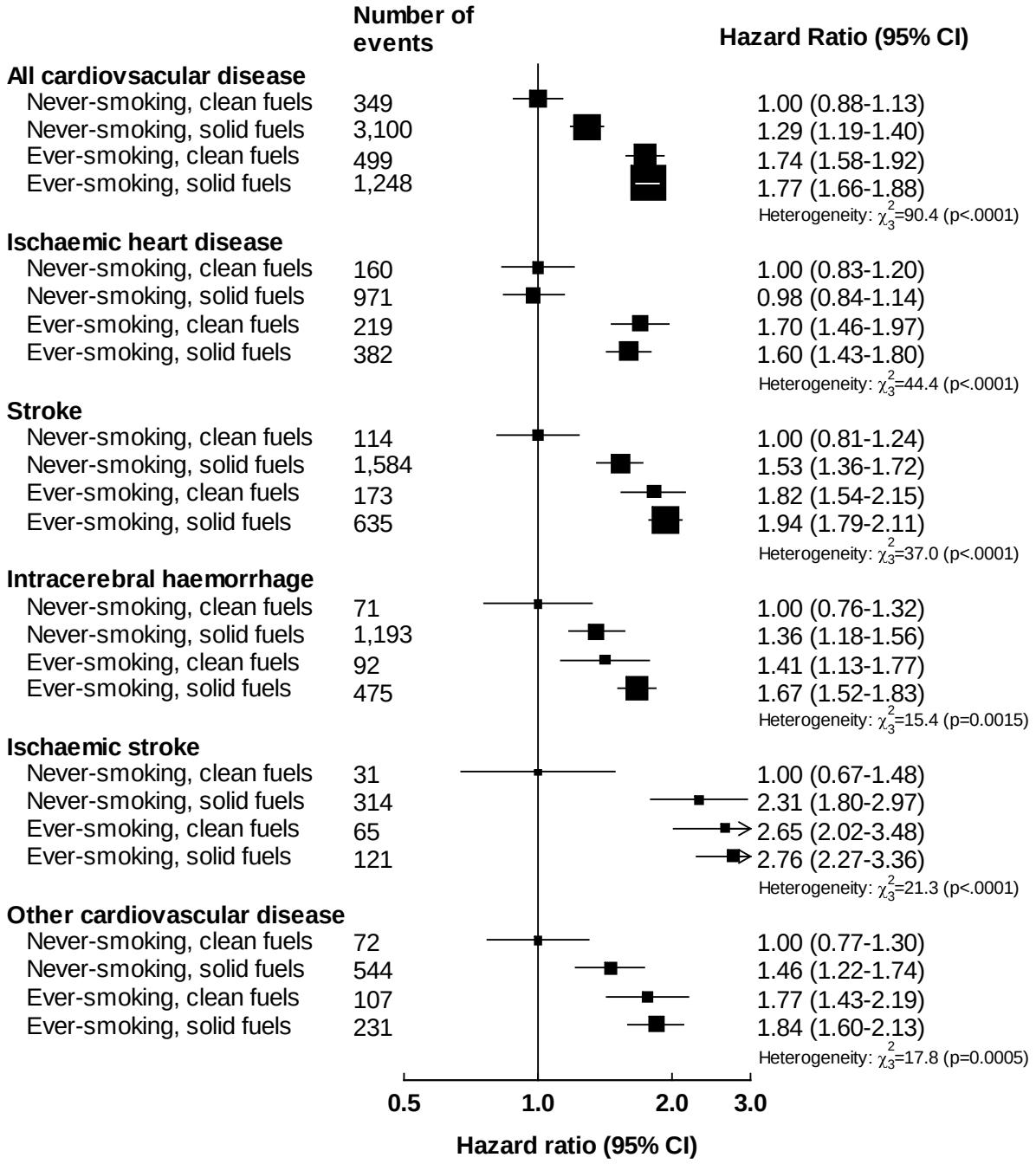


**Figure 7.17 Adjusted hazard ratios for cardiovascular death by composite exposure of cooking fuel use and smoking habit**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, diet (fresh fruit, preserved vegetables, meat), physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, heating fuel exposure, length of recall period and antihypertensive treatment, where appropriate. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).



# CHAPTER 8. DIRECT MEASUREMENT OF AIR POLLUTION EXPOSURE IN THE CHINA KADOORIE BIOBANK: A FEASIBILITY STUDY

## 8.1 INTRODUCTION

Based on the existing questionnaire data from the CKB study, I have investigated the long-term fuel use (for cooking and heating) and cookstove ventilation patterns in the study population in **Chapter 5** and their relationships with risks of hospitalisation and death of respiratory diseases and overall and cause-specific cardiovascular death in **Chapters 6 and 7**, respectively. While these findings have addressed some important knowledge gaps, the analyses was based on self-reported primary fuel use data, (as with many other studies), and there were no directly measured HAP exposure data to allow for more accurate quantification of the dose-response relationships with the disease outcomes examined.

As discussed in **Section 2.2.3**, although direct measurement of HAP exposure has proven to be challenging, advancing technologies and established large-scale cohort studies such as the CKB offer opportunities to more accurately assess the exposure-response relationships between HAP and chronic diseases, by combining self-reported and directly measured data. As such, a pilot study was devised to test the feasibility of obtaining multi-dimensional exposure data in a small subset of CKB participants in 2017.

## 8.2 AIMS AND OBJECTIVES

While the project is still ongoing at the time of writing, this chapter aimed to describe the design and development of the study, my involvement and some preliminary findings that could enrich the final discussion in **Chapter 9**.

The pilot study chiefly aimed to evaluate the feasibility of collecting objectively measured personal air pollution exposure by combining data from questionnaire, biomarker, as

well as stationary and personal air quality monitors. The specific objectives were: 1) to better understand the logistics and organisational issues of measuring air pollution exposure in rural and urban China relevant for scaling up in the future; 2) to measure personal and indoor $PM_{2.5}$, CO, temperature and relative humidity (RH) for five consecutive days (120 hours) during two seasons (warm and cool) and the background ambient AAP levels ($PM_{2.5}$, CO, $NO_2$, $SO_2$, $O_3$) in the study area for the duration of the air pollution monitoring survey; 3) to collect data on time-activity patterns and greater details of fuel use behaviour and other exposures for validation and enhancements to the HAP section of the existing CKB questionnaire; and 4) to measure potential biomarkers for HAP, namely COex, blood oxygen saturation ($SpO_2$) and heart rate.

## 8.3 METHODS

### 8.3.1 Study design overview

The study involved a sample of 451 surviving CKB participants from three study sites. In order to capture seasonal variation in fuel use behaviours and related exposures, the fieldwork involved two phases of data collection, first in warm (May – September 2017) and then in cool (November 2017 – January 2018) seasons, respectively in two rural (Gansu and Henan) and one urban site (Suzhou) (**Figure 8.1**). For logistical convenience, an arbitrary cut off of 10°C for monthly average temperature was selected to determine the appropriate time frame for warm and cool season fieldwork for each study site. Each data collection campaign consisted of three common components, namely air pollution exposure assessment, time-activity questionnaire and measurement of biomarkers (COex, $SpO_2$ and heart rate). The cool season campaign involved an additional household questionnaire to collect self-reported information on SES, lifestyle and HAP-related exposure (**Figure 8.2**). All data collection procedures were computer-based, with the questionnaires and biomarker measurements recorded in the existing CKB software, “SINPUT” and the air quality monitors operated via

manufacturer software coupled with a CKB software, “GadgetManager”, developed for this study (**Figure 8.3**).

Ethical approvals were obtained from the OxTREC (reference: 5109-17) and the institutional review board of Fuwai Hospital, Chinese Academy of Medical Sciences, Beijing, China (reference: 2018-1038). In order to ensure the quality of the data collected, an extensive list of standard operation procedures (SOPs) were developed for all fieldwork procedures (**Table 8.1**). Some of these SOPs were initially developed in English and were translated into Chinese and some were prepared in Chinese directly due to time constraints. I was responsible for developing the first drafts of most SOPs except for those on the DustTrak$^{TM}$ DRX Aerosol Monitor (TSI, Inc., Shoreview, MN, USA), the use of the SINPUT electronic questionnaire software and ICEGPS110 Tracker (ICEGPS, Shenzhen, China).

### 8.3.2 Study population and participant recruitment

A multi-stage cluster-quota sampling was employed to recruit participants from three of the ten study areas (Suzhou, Gansu and Henan) of the CKB to capture a large variety of fuel types (gas, electricity, wood and coal) being used for cooking or heating in typical rural and urban areas. Given the general trend of fuel modernisation (as described in **Chapter 5**), the proportion of solid fuel users has declined over time. In order to account for this, one to two of the largest administrative units (Gansu and Henan: villages; Suzhou: street committees) with the highest prevalence of solid fuel use at baseline were selected for recruitment in order to recruit sufficiently large numbers of solid fuel users.

To be eligible for being invited to the study, individuals had to: 1) have taken part in the baseline CKB survey; 2) not known to have a major disability, died or permanently moved out of the study area; 3) be aged <70 years at the time of recruitment and; 4) be living in their current address for at least one year before recruitment. Individuals who

were older or had major disability were not included because their behaviours (e.g. cooking) are likely to be distinct from an average CKB participant. The criterion for residential history was set in order to exclude migrant workers or individuals who might have changed their fuel types or fuel use behaviour recently due to changes in residence.

Participants were recruited in one administrative unit at a time, and the recruitment ended when the targeted sample size of 150 was reached. With an expected response rate of ~75%, we randomly selected up to 200 eligible participants from each selected administrative unit for recruitment. One unit was selected from Suzhou and Henan and two units were selected from Gansu, because the two largest available units in Gansu only included about 150 and 100 eligible participants, respectively. Participant lists were generated centrally at NDPH and sent to a regional coordinator for recruitment. Local community leaders or health workers distributed initiation letters and information leaflets to targeted participants approximately one week before the targeted fieldwork commencement date, and phone calls or household visits were conducted to encourage participation.

In each study site, about 38-39 participants were recruited each week, and the recruitment ended after five weeks. Overall, a total of 638 participants were invited and 451 participated (response rate = 70.7%) in the warm season who were invited for repeated assessment in the cool season. Thirty-seven warm season participants were not available for the cool season campaign and were replaced by other eligible CKB participants living in the same community. The baseline characteristics (age, sex, education, household income, smoking, drinking, cooking and heating fuel use, self-reported general health and medical history) of the participants included in the two seasons were compared and no statistically significant difference was observed (**Table 8.2**).

### 8.3.3 Training and logistics

For each data collection campaign, eight to ten local fieldworkers (divided into three teams) were recruited from the local CDC or universities in each study site, with one senior staff of the local CDC as the regional coordinator. At the start of each campaign, fieldworkers were trained for three days in order to become familiar with the data collection procedures following established SOPs, including 1) the use and maintenance of air quality monitors and their corresponding software, 2) the use of biomarker measurement devices and 3) the use of CKB in-house electronic data collection platform and related questionnaires.

Upon completion of the initial training, a team leader was selected for each team based on performance. In each campaign, participants were visited four times in six days (**Figure 8.4**), and the materials needed varied by visit, so a "Household visit materials checklist" (see **Appendix H1**) was issued to each team. On a typical working day, fieldworkers arrived at the study site at about 7:30am, completed all necessary fieldwork by 3:00pm and returned to the regional coordinating centre for data transfer (if necessary) and preparation of the next visit.

The first visit was always scheduled on a Thursday so that the five-day exposure assessment period covered both weekend and weekday (**Figure 8.4**). In the first visit, fieldworkers first verified the participant's identity, introduced the study purpose and design and obtained written informed consent. They then set up the personal and household monitors and provided instructions on the use of the devices to the participant. For the cool season campaign, a different fieldworker administered a household questionnaire interview with the participant in parallel. In the second and third visits (Friday and Monday), fieldworkers administered the time-activity questionnaire to collect information on the activities that occurred in the past 24 hours, measured COex, $SpO_2$ and heart rate and checked the air quality monitors were working satisfactorily. In the fourth visit (Tuesday), they retrieved the monitors and downloaded the data to a

laptop computer on-site. After returning to the local regional coordinating centre, fieldworkers transferred the data from the laptops to a desktop computer, maintain equipment (e.g. cleaning, charging batteries) and prepared for the next week's visits. **Table 8.3** shows the number of individuals who did not undertake each of the four visits and those with missing data on biomarkers.

### 8.3.4 Household questionnaire

A household questionnaire (**Appendix H2**) was developed to collect self-reported information on SES (e.g. household income, occupation), lifestyle (e.g. smoking) and HAP-related exposures (cooking, heating and other sources). Compared to the baseline questionnaire of CKB, additional information on HAP-related exposures was obtained to better understand some of the limitations of the existing data, such as the lack of secondary fuel use data. In particular, participants were asked to report all fuel types in use for cooking and heating in the household (as opposed to only the primary fuel type used by the participant personally in the baseline questionnaire). For each reported fuel type, the frequency (for cooking: "most meals" versus "sometimes") or duration (for heating: hours of use for heating on a typical day) of use and number of years of use throughout their life were assessed. Other additional metrics include usual location of cooking (indoor/ outdoor), use of windows when cooking, smoky kitchen when cooking, heating frequency and duration, heat stove ventilation, reason of not using heating, use of mosquito coils and incense.

### 8.3.5 Time-activity questionnaire and biomarker measurement

Each participant was asked to recall their activities during the past 24 hours twice, first on the Friday (recall for Thursday) and second on Monday (recall for Sunday) of the 5-day monitoring period (**Figures 8.4 and 8.5**). The aim of the time-activity questionnaire was to capture the type, location and length of time spent on each distinctive activity and whether the participant smoked or was exposed to ETS during each activity

reported. The visit schedule was designed to capture the potential variability of time spent on activities on weekdays and weekends.

In the same visit where time-activity interviews were conducted, COex and $SpO_2$ (and heart rate) were measured twice for each participant, using MicroCO meter (CareFusion, Basingstoke, UK) and Onyx Vantage 9590 pulse oximeter (Nonin Medical Inc., Plymouth, MN, USA), respectively (**Figure 8.6**). Details of the procedures to take COex measurements have been published elsewhere and are summarised in **Appendix H3**.[207] All MicroCO meters were calibrated using standard 20 ppm CO gas at the start of the fieldwork in each study site in each season. For $SpO_2$ and heart rate, the participants should have been in resting position for at least three minutes and they were asked to insert their index finger flatly into the oximeter and wait until a green indicator light flashes for four consecutive seconds (as instructed by the manufacturer).

To cross-validate the time-activity and household questionnaire data on cooking frequency and duration, a small button-type data-logging temperature sensor "Stove Use Monitoring System" (SUMS; **Figure 8.7**) was attached to the most frequently used cookstove, or in closest proximity wherever possible. The SUMS measures the surface temperature of the object that it is attached to, and a logging interval of four minutes (as opposed to 10 seconds as the air quality monitors) was specified because of memory constraints.

### 8.3.6 Air pollution exposure measurement

Air pollution exposure measurement involved three key aspects, namely personal, static household environment and ambient environment **(Figure 8.2)**. All personal and household measurements were done using real-time air quality monitors over five consecutive days (120 hours) and ambient measurement was done throughout the fieldwork period in each study site (4-5 weeks) in each data collection campaign. An in-house software "GadgetManager" was developed to track and facilitate the deployment,

collection and data transfer of all air quality monitors. The following sections briefly describe the functionality of the air quality monitors used and the operating procedures. Technical details of the monitors used are available in **Appendix H4**.

*8.3.6.1 Personal monitoring*

Each participant was instructed to wear a cross-body harness (**Figure 8.8a**) or waist belt (**Figure 8.8b**) carrying a "Particle and Temperature Sensor plus Carbon Monoxide Sensor" (PATS+CO; Berkeley Air Monitoring Group, CA, USA), a low cost, light-weighted (110 grams) real-time monitor of $PM_{2.5}$ ($\mu g/m^3$) and CO (ppm) concentration, temperature (°C), RH (%) and motion (yes/ no) (**Figure 8.9**).[208] The PATS+CO has been validated against gold standard gravimetric samples in both laboratory and real-world settings (used in kitchens where solid fuels are the main energy source), with $R^2$ ranging from 0.90 to 0.99,[208] and our own devices were all factory-calibrated against wood smoke by the manufacturer before the fieldwork. At the beginning of each measurement campaign, the CO sensors of all PATS+COs were calibrated using 60 ppm CO gas following standardised protocol (**Appendix H5**).

For deployment, the PATS+COs were connected to a survey laptop computer for initialisation using the "Platform for Integrated Cookstove Assessment" (PICA) software (Berkeley Air Monitoring Group, CA, USA), and a 10 second logging interval was selected. Then, the monitors were calibrated by logging in a "zeroing box" (filled with HEPA-filtered air) with minimal level of PM for 10 minutes (**Figure 8.10**) before being registered in GadgetManager and distributed to participants for personal monitoring or to designated location for static monitoring. A small external battery (140 grams) was attached to each personal PATS+CO to provide sufficient energy for continuous measurement for ≥120 hours together with the internal battery. The participants were asked to wear the monitor during all activities except bathing and sleeping (participant was advised that it needs to be placed within 1 metre of the participant). Upon collection,

the monitors were recalibrated using the same methods described above, and data were downloaded using PICA.

*8.3.6.2 Static household environment monitoring*

In each household, two PATS+CO (each connected to an external battery) were set up following the aforementioned procedures to measure $PM_{2.5}$ and CO levels in the kitchen and living room. The monitors were placed at a height of 1.5 metres and ≥1 metre away from any doors or other openings in the walls, and were required to be left running and undisturbed for at least 120 hours. In the kitchen the device was placed about 1 metre from the edge of the most frequently used cookstove. Participants were advised not to move the sensors.

Three households were randomly selected each week to receive a set of three established monitors, including RTI MicroPEM v3.2 (RTI International, Research Triangle Park, NC, USA) (**Figure 8.11**), Lascar EL-USB-CO CO and EL-USB-2-LCD temperature and RH data logger (Lascar Electronics Ltd, Wiltshire, UK) (**Figure 8.12**), to be co-located with the PATS+CO in the kitchen to collect data on $PM_{2.5}$, CO and temperature and RH, respectively to cross-validate the readings from PATS+CO. Similar to PATS+CO, a logging interval of 10 seconds was set for these data loggers. Collaborators at CUHK also collected gravimetric samples in these households for validation (details of the procedures available in **Appendix H6**).

*8.3.6.3 Ambient environment monitoring and residential geocoding*

To quantify the background AAP level in local community, one DustTrak™ DRX Aerosol Monitor (TSI, Inc., Shoreview, MN, USA) and two Community Air Station-A1 (CAS-A1; City University of Hong Kong, Hong Kong, China) were placed in a location considered representative of the residential community (usually the rooftop of a building in a central location of the community where no obvious sources of pollution was found) for at least the whole duration for which HAP sampling was implemented in that community (**Figure**

**8.13**). DustTrak™ measures different sizes of PM ($PM_1$, $PM_{2.5}$, $PM_{10}$), whereas CAS-A1 measures PM ($PM_1$, $PM_{2.5}$, $PM_{10}$), gaseous pollutants (CO, $O_3$, NO and $NO_2$), temperature and RH. A logging interval of 1 minute was set for both devices. Data from DustTrak™ were stored in a SD card and were downloaded monthly, whereas those from the CAS-A1s were wirelessly transmitted to a secured cloud-based server using GSM network.

Both devices were calibrated in laboratory settings before deployment. Gravimetric sampling was done following established procedures described previously.[209,210] The CAS-A1s were monitored regularly through the cloud-based server, and were sent to manufacturer for formal check-up and re-calibration at the end of the data collection fieldwork. To link AAP data with individual participants, the longitude and latitude of the participants' residences were obtained using a ICEGPS locator (ICEGPS, Shenzhen, China) and recorded in the PATS+CO in the first household visit when the monitors were deployed.

### 8.3.7 Data management

There data were collected via three different routes. First, data from the household and time-activity questionnaires and biomarker measurements were recorded using SINPUT, an electronic data collection platform used for both the baseline and resurveys of CKB with built-in logic and error checks. Second, data from personal and static air pollution monitors were collected through the manufacturer software for each corresponding device and the deployment and collection of them were coordinated with GadgetManager. The ambient air pollution data from DustTrak™ and CAS-A1 were obtained directly from the SD card and through a cloud-based server, respectively, as described in **Section 8.3.6.3**. All data collected on the laptops were transferred to the designated computers at the regional coordinating offices after every visit, and the data were then encrypted and transferred to a protected server in Beijing and subsequently to Oxford for secured storage and further processing.

## 8.4 STUDY PROGRESS AND PRELIMINARY DATA

### 8.4.1 Study progress

The data collection fieldwork was finished in January 2018 and the data were curated and processed in Oxford. At the time of writing, the initial exploration and cleaning were completed for the household and time-activity questionnaires, and work on biomarkers and air pollution data were in the initial stages. For the purpose of this thesis, findings from the exploratory descriptive analyses conducted on the two questionnaires are presented, followed by the initial investigations on the air pollution exposure data. These results, together with fieldwork experiences, are discussed to inform future analysis plans and highlight the potential added value of the data collected.

### 8.4.2 Data processing and analysis

#### *8.4.2.1 Household questionnaire*

Of the 450 participants in the cool season campaign, 449 completed the household questionnaire. The household questionnaire interview on average took 2.5 minutes for each participant to complete. Percentages and means of selected participant characteristics (background, cooking, heating, other HAP exposure) were compared across the three study sites. The CKB baseline questionnaire only assessed personal cooking frequency, which left ambiguity to the cooking-related exposure among non-regular cooks who could be exposed to elevated HAP due to household solid fuel use. With the extra data collected in this study, frequency of household cooking was combined with personal cooking frequency as a composite variable (personal regular cooking, personal non-regular but household regular cooking and non-regular personal and household cooking), with regular cooking defined as cooking for at least a few times a week (as in **Chapters 6 and 7**).

To explore the previously not captured fuel stacking phenomenon, the number and types of cooking fuels used in each household were examined. A composite variable of cooking fuel combination was derived based on the types of fuels used for most meals or all reported fuel types if none was noted as used for most meals. Similarly, the number and types of fuel used for heating in winter were examined, and the duration (hour) used on a typical heating day for each reported fuel type were compared to identify the one used most intensely. A composite variable of heating fuel combination based on the most intensely used heating fuel(s) was derived. In this chapter, clean fuels refer to electricity, gas (natural gas/ town gas/ liquefied petroleum gas/ biogas) or solar, and solid fuels refer to coal, charcoal, wood or crop residue.

*8.4.2.2 Time-activity questionnaire*

From the time-activity questionnaire, a range of variables related to HAP exposure were derived, including frequency and duration of cooking, duration of heating, frequency of smoking and ETS exposure, time spent on different activities and locations. These were compared across the weekday and weekend visits and between the two seasons for the three study sites. The total duration and proportion of assessed duration (total and awake time) during which the participants were wearing the personal PATS+CO were also computed to assess the self-reported compliance of wearing the monitor.

*8.4.2.3 Device data*

The PATS+CO data from 35 participants with typical cooking fuel combinations were inspected qualitatively to understand the diversity and complexity of the HAP exposure patterns and to identify potential signs of device problems to inform future analyses. For each of these participant, data from the three PATS+CO (personal, kitchen, living room) in each season were first truncated to remove the pre- and post-sampling zeroing period (10 minutes each). Then, the extreme values that exceeded the upper detection limits of the sensors ($PM_{2.5}$: 30,000 μg/$m^3$; CO: 500 ppm) were replaced by the corresponding

detection limit values, and the data files were merged by date and time, and the $PM_{2.5}$ and CO data were plotted on two time series graphs. For the purpose of this thesis, graphical examples of typical features identified through the inspection exercise are presented. Data from other monitors (e.g. calibration monitors, ambient monitors, SUMS) are yet to be processed or are being processed by collaborators at the time of writing.

### 8.4.3 Preliminary findings

#### *8.4.3.1 Household questionnaire*

**Table 8.4** shows the background and lifestyle characteristics (ascertained via the household questionnaire) of the study participants by three study sites. The mean (SD) age of the 449 participants interviewed in cool season was 58.0 (6.8) years and about 72% were females, with participants from Suzhou being slightly older and less likely to be female. Participants from urban Suzhou had substantially higher household income (79% ≥100,000 Yuan/ year versus 73% and 83% <50,000 Yuan/ year in Gansu and Henan, respectively) and none of them were agricultural workers while the majority of those from rural Gansu and Henan were either agricultural workers or homemakers. Except for a small proportion of participants from Suzhou, most participants lived in a house (as oppose to an apartment). Smoking prevalence was low in the study sample (~15% current regular, 64/65 were men), but ETS exposure was common (42% 6-7 days/ week).

The majority (76%) of the participants cooked weekly or daily and about a quarter (24%, n = 107) cooked a few times a month or less, but about half (n = 53) of them lived in households where cooking was done regularly (**Table 8.5**). Personal regular cooking was less common in Suzhou (73% versus 78% in Gansu and Henan). Among those who cooked regularly, the mean (SD) time spent in front of stove while cooking was 2.7 (0.7) hours per day, with little variation across study sites. Of participants who lived in regular cooking households, over 60% of those from Suzhou reported using only one

fuel type, and the rest used two types. In contrast, most participants from Gansu (90%) and Henan (95%) used two to three types of fuels. In terms of fuel used for most meals, 50% of the participants from Suzhou reported no relevant types; 65% from Gansu reported two types and 20% reported three types; and 45% from Henan reported one type and 34% reported two types. In terms of fuel combination, 89 participants (23%) reported no fuel used for most meals (i.e. all reported fuels were used “sometimes”), with the majority from Suzhou (n = 66) and most used clean fuels only (n = 79). Among the remaining participants, the commonest combination was clean fuels only (n = 155, 39%), followed by clean fuels and wood (n = 64, 16%; all in Gansu) and clean fuels and coal (n = 46, 12%; mostly in Henan). Sole use of coal for most meals was also common in Henan (n = 33), whereas use of mixed solid fuels or sole use of wood were both uncommon across three sites. Most participants from Suzhou had a ventilated kitchen (98%), but it was relatively less common in Gansu (70%) and Henan (45%). The majority of those from Gansu (93%) and Henan (69%) always opened windows when cooking, but this was less common in Suzhou (61%). About 12% of all participants (the majority from Gansu) reported that their kitchen always became smoky while cooking.

Winter heating was common in Gansu (91% daily) and Henan (74% daily) but relatively rare in Suzhou (17% daily, 71% no heating) (**Table 8.6**). The main reason for not having heating was that heating was considered unnecessary (96%), but a few participants found it inconvenient and only one said it was unaffordable. Most of the participants from Gansu (97%) and Henan (92%) who used heating in winter reported whole-day heating (24 hours), whereas most of those from Suzhou heated their home for up to three hours only (81%). Multiple fuel use for heating was much less common than for cooking, with 78% of all participants (n = 231) reported using only one fuel type, including all participants who used heating in Suzhou (n = 43). Among those who reported having heating at home, all those from Suzhou used clean fuels, those from Henan primarily used coal (86%) and those from Gansu used either coal (46%), wood

(35%) or a mix of solid fuels (17%). Most heat stoves used in Gansu and Henan were ventilated (>90%), unlike in Suzhou where 79% had no ventilation. A large proportion of participants from Gansu (82%) reported that sometimes their home became smoky while heating but it is very rare in other sites.

Sustained use of slow burning stove was uncommon in this study sample (n = 41, 9%), with most reported from Henan (n = 36) (**Table 8.7**). In contrast, use of mosquito coils in summer was more common in Gansu (86% at least a few times a week) but less so in Suzhou or Henan. Indoor incense burning was generally rare in all three sites.

*8.4.3.2 Time-activity questionnaire*

During the warm season, one and three participants did not undertake the weekday and weekend time-activity questionnaire, respectively. The corresponding numbers in cool season were one and two participants, respectively. All participants included in each season had undertaken at least one time-activity questionnaire interview. While SINPUT included a logic check to ensure the recall period covered at least 24 hours, a large fraction of participants had a recall period exceeding 24 hours (**Table 8.8**), and there was strong digit preference in self-reported duration spent on each activity such that 99.9% of the values were multiples of five minutes.

The cooking frequency and duration in the weekday and weekend assessments were largely similar within each season, but cooking was practiced more frequently and for longer total duration during the cool season (**Table 8.8**). In particular, 56% and 73% participants cooked at least twice on each day in warm and cool season, respectively, and the median (IQR) duration of cooking were 1.7 (1.0-2.5) hours and 2.5 (1.7-3.0) hours, respectively. Consistent with the household questionnaire data, most participants who used heating had their heating turned on throughout the day, with a median duration of 24 hours (100% of the recall period). Of note, 12 participants reported using heating during the warm season and 264 used heating in the cool season assessment.

While about 15% of the participants reported current regular smoking in the household questionnaire (**Table 8.4**), about 10% reported smoking during the time-activity recall period in both warm and cool season campaign (**Table 8.8**). About 16% and 14% of participants in the warm and cool season were exposed to ETS, respectively. The reported duration of carrying the personal PATS+CO were largely similar in both seasons, with a median duration of 12.5 hours. After taking into account of sleeping time during which participants would remove the PATS+CO, the percentages of awake time wearing PATS+CO were up to 83% in the two seasons, with consistently greater values observed for the weekend assessment.

Some participants spent time in the kitchen not only for cooking (e.g. eating), hence the total time spent in kitchen appeared to be slightly higher than the total cooking duration reported, particularly in warm season (median [IQR]: 1.8 [1.0-2.5] hours) (**Table 8.9**). Participants also tended to spend the majority of their time at home (median 83% in warm season, 88% in cool season) and indoors (home, indoor workplace or public spaces; 90% in warm season, 95% in cool season) and less outdoors, especially in the cool season. Only a small fraction (<25% in the warm season and 17% in the cool season) of the participants spent time on road transportation (bicycle, car or bus), and the median time spent was <1 hour. **Figure 8.14** shows the average percentages of time spent on different activities across the three study sites, on weekday and weekend assessments in the two seasons. For most cases, the distribution of time-activity patterns were largely similar on weekday and weekend in the same season, except that participants from Gansu reported a greater proportion of time spent on other activities on the weekend (48%) than on weekdays (39%) in the warm season. Additionally, Gansu participants spent larger proportion of time sitting (8-9%) or working (15-16%) in cool season than in the warm season (5-8% and 3-8%, respectively). In contrast, Henan participants reported smaller proportion of time working (2-3%) but greater proportion

on other activities (28-29%) in the cool season compared to the warm season (8% and 20-21%, respectively).

*8.4.3.3 Directly measured exposure*

The measured air pollution exposure patterns were highly heterogeneous both within and between individuals and over time, but the data from the three PATS+COs of the same participant in each season were generally consistent with each other and some common patterns were identified. First, there were general patterns of peaks of $PM_{2.5}$ (>500 μg/$m^3$) and CO (>10 ppm) at around 05:00-07:00 (morning, less common), 11:00-13:00 (noon) and 18:00-20:00 (evening) in all three monitors in both seasons across most cases (**Figure 8.15a**). Usually, these spikes started with a drastic rise that peaked within five minutes and followed by a gradual exponential decline. Generally, the spikes for those who used solid fuels for cooking or heating tend to have a higher peak and longer duration (before declining to background levels) than those who used clean fuels. In homes that reported primarily using solid fuels for heating, the evening peaks recorded in the cool season tend to be followed by a long tail of elevated levels of $PM_{2.5}$ that last until early morning of the next day (**Figure 8.15b**). In some cases from Suzhou who used clean fuels for cooking, somewhat regular “domes” of prolonged slight elevation of $PM_{2.5}$ (>50 μg/$m^3$) were observed from late evening to mid-day of the second day (**Figure 8.16**).

Several potentially important signs of problematic data were identified. First, there were cases with prolonged elevation of $PM_{2.5}$ that deviate from the expected background levels (**Figure 8.17**). Second, some cases had extended period of readings at the detection threshold recorded in one PATS+CO (mostly the personal monitor) while the other two recorded elevated levels (**Figure 8.18**). There were also cases recording sudden extreme peaks that are neither preceded by an increasing trend nor followed by

an exponential decline, some of these happened just before the PATS+CO were collected at the end of the monitoring period (**Figure 8.18)**.

## 8.5 DISCUSSION

### 8.5.1 Self-reported exposure

#### *8.5.1.1 Cooking-related exposure*

This study assessed both household and personal cooking frequency, and found that a considerable number (n = 53; 12%) of individuals who reported no regular cooking being "exposed" to regular cooking in the household. It has been emphasised in the previous chapters that classification of non-cooking individuals as "unexposed" (alone or together with clean fuel users) to HAP may be inappropriate, because they may also have elevated HAP exposure. As recorded, of the non-regular cooks who lived in household with regular cooking in this study, 43% reported a mix of clean and solid fuels for cooking most meals in their households, and they are likely to have elevated HAP exposure compared to those cooking using clean fuels or living in households using clean fuels.[211,212] This provides preliminary evidence within the CKB dataset to support the exposure classification methods used in the previous chapters, whereby non-regular cooks were isolated in the cooking-related analyses instead of included as part of the reference category.

Most previous studies on HAP from solid fuel use, including those reported in the previous chapters in this thesis, examined only primary fuel use.[9-12,14,18,19,26,31,33,35,169] In **Chapter 5**, I showed that over 95% of individuals from Gansu and Henan and almost a quarter of those from Suzhou used solid fuels for cooking primarily at baseline (2004-2008), and a rapid transition to clean fuels was observed during 2008-2014, with about 50%, 30% and 98% of the baseline participants from Gansu, Henan and Suzhou, respectively, reported using clean fuels primarily. In this study, all fuel types in use reported by each participant were recorded, and a fuel stacking phenomenon was

observed alongside increased clean fuel use, as described in a few recent studies in China.[158,213] In this feasibility study, fuel stacking was exclusive to rural participants, who were still undergoing fuel transition, whilst virtually all urban participants used clean fuels only. Even for rural participants, a substantial proportion of them reported using clean fuels for cooking most meals, either exclusively (Gansu and Henan: 35%) or in combination with solid fuels (Gansu: 58%; Henan: 28%), although over a quarter of those from Henan still used coal exclusively. Consistent with the previous CKB surveys (**Chapter 5**), wood remained the commonest type of solid fuel used in Gansu, and most solid fuel users from Henan used coal. Consistent with previous nationwide studies in China,[158] charcoal was rarely used in the study sample, supporting that the exposure category "wood" (defined in the previous CKB questionnaires to include both wood and charcoal) analysed in the previous chapters should be reasonably specific to actual wood use.

About 70% of the participants who lived in regular-cooking households had a ventilated kitchen (with a chimney or extractor), with the highest percentage in Suzhou (98%) and the lowest in Henan (45%). These percentages were comparable to those observed in the second resurvey (2013-2014), coinciding with the relatively slower trend of ventilation adoption described in **Chapter 5**. Interestingly, participants from Suzhou and Henan were less likely to open windows or report having a smoky kitchen when cooking, while most from Gansu would always open windows and a large proportion (77%) reported having a smoky kitchen when cooking. This may reflect behaviour adaptations to mitigate against high levels of HAP, which are not commonly assessed for HAP exposure classification. Future analyses on directly measured exposure levels in relation to these two factors would provide more objective evidence in understanding the implications of opening windows and subjectively reported "smokiness" of a microenvironment on estimating HAP exposure.

*8.5.1.2 Heating-related exposure*

Compared to cooking fuel, fuel stacking is much less common for heating, and the majority of individuals from Gansu and Henan remained reliant on solid fuels. This is consistent with the delayed modernisation trend for heating fuel described in **Chapter 5**, again highlighting that heating is an under-recognised source of HAP in China. There was little detailed information about heating fuel use behaviour or relevant ventilation conditions at baseline, and no information on the reasons for lack of heating. In this small subsample, we observed a large contrast whereby most participants from Gansu and Henan reported using heating daily and for the entire day in winter, whereas those from Suzhou used heating much less frequently and for shorter duration (typically ~3 hours). The main reason for not having heating was no perceived need, whereas inconvenience or problem of affordability were rarely reported as an issue. It is reasonable to expect less people in Suzhou would have heating needs because of the relatively short and mild winter (one month with average temperature ≤5°C during 2005-2017). It is somewhat surprising to see about 10% and 20% of participants from Gansu and Henan (three months with average temperature ≤5°C during 2005-2017), respectively, felt heating was unnecessary. Although this was only assessed in a very small subset of the CKB population, it leads to a question as to whether the perceived need of heating matches with the actual need in coping with cold temperatures and the associated health risks.[48,50,57,194,195,214,215]

Most participants who used solid fuels for heating had ventilated heat stoves, but it is possible that these individuals were still exposed to prolonged elevated HAP in the household environment, especially in the case of inefficient ventilation. In fact, over 80% of Gansu participants who had heating (mostly using solid fuels) reported that their homes would become smoky when the heating was in use even though almost all of their heat stoves were ventilated. This could be further explored by examining the directly measured HAP exposure data in the future.

*8.5.1.3 Other exposures*

Exposure to non-cooking and non-heating sources of HAP was uncommon and largely region-specific. Most of those who used slow burning stoves were from Henan, where people use a type of traditional stove that burns coal bricks very slowly (especially in a low-oxygen environment, e.g. when the combustion chamber is partially covered) throughout the day to maintain an energy source for burning new coal bricks (**Figure 8.19**). This relatively low-temperature, oxygen-deprived, slow burning characteristic may result in higher tendency of incomplete combustion and higher emission of CO and coarse PM. Mosquito coils and incense are two other slow-burning materials that have been associated with high levels of HAP (e.g. $PM_{2.5}$, CO, VOCs) and a range of health concerns have been raised, but existing epidemiological evidence is scattered.[216-220] Incense burning was uncommon in the study sample, but a large proportion of participants from Gansu used mosquito coils at least a few times a week in summer. Future investigations on HAP exposure in areas like Gansu may need to take into consideration of the potential confounding from mosquito coil burning.

*8.5.1.4 Time-activity patterns*

In this small study sample of older adults (mean age 58 years), participants spent up to 90% of their time indoors (mostly at home), with higher proportion in the cool season than in the warm season. The high proportion of time spent indoors is consistent with what was reported in the NHANES in the United States (~87%)[221] and the Chinese Exposure Factors Handbook (~80%),[222] but the CKB participants spent significantly greater proportion of their indoors time at home, possibly because of the relatively old age and high proportion of home-makers and retirees. If verified in a larger study sample, this would have important implications on assessing personal air pollution exposure to household and ambient sources.

Previous studies on the health effects of air pollution exposure often focus on either AAP or HAP while omitting or crudely adjusting for the potential confounding effects of

each type of pollution. Conventional exposure classification methods on AAP depend primarily on residential addresses,[223] and one major criticism has been the inability to account for varying time-activity patterns across individuals and communities and over time, as well as exposure in locations distant from individuals' residential addresses.[224-226] The high proportion of time spent at home means that the above conventional residential-based approach to estimate AAP exposure may be subject to less misclassification in settings where AAP is the primary source of personal air pollution exposure (e.g. urban cities). However, in solid fuel-reliant communities where HAP also contribute significantly to AAP, exposure to HAP from solid fuel use must be taken into account, ideally by directly measuring HAP levels.

It is reassuring that the cooking duration reported in the household questionnaire (as an aggregated duration) was largely similar across study sites and consistent with that ascertained via the time-activity questionnaire in cool season (as a sum of duration of all cooking episodes). Comparing across the two seasons, participants tend to cook more frequently (two versus three times daily) and for longer duration (1.7 versus 2.5 hours) in cool than in warm season, consistently in both rural and urban sites. We collected no further information that could explain the changes in cooking duration and frequency, but this may reflect a habit of having hot food when it is cold in the Chinese population.

Although empirical evidence is limited, it has been shown that HAP levels in solid fuel-reliant households would be higher in the cool season.[32,39,44-46] However, the variability of time-activity patterns and its influence on HAP exposure in different seasons is rarely taken into account. It is intuitive to expect solid fuel combustion for heating to be the major contributor to an elevated HAP levels in the cool season, but little is known about the extent to which changing cooking behaviour may also contribute. Future work has been planned to annotate the time-series air pollution data using the time-activity information of each participant. This would allow better characterisation and

understanding of the relationships between various activities (e.g. cooking, heating) and air pollution levels, both qualitatively (e.g. by inspecting time-series graphs annotated with activity types and locations) and quantitatively (e.g. by estimating the geometric means of $PM_{2.5}$ and CO associated with selected activities). Consequently, we can evaluate the relative contribution of the increased cooking time in relation to measured HAP levels while taking other sources such as heating into account. This can inform future work in modelling personal air pollution exposure in the wider CKB population based on multi-dimensional data.

### 8.5.2 Directly measured exposure and air quality monitors

Although the data from the cases inspected showed that HAP exposure was highly heterogeneous both within and between individuals, some commonalities were identified. There were somewhat regular patterns of significantly elevated levels of $PM_{2.5}$ (and CO in some cases) at times corresponding to typical cooking time (morning, noon, evening) in the study population (as shown on **Figure 8.15a**). Consistent with existing literature on cooking-related exposure, the shape of these spikes are characterised by a sharp increase at start (e.g. when fuels are being ignited, or the “ignition stage”) and a gradual exponential decline after the peak as fuel combustion ends and pollutants disperse or settle depending on ventilation and human activity.[58,211,227-229]

Interestingly, similar spikes were also observed for individuals who used clean fuels for cooking or heating. It is worth noting that Chinese style cooking, which typically involving high-temperature stir-frying, have been consistently associated with markedly elevated levels of $PM_{2.5}$ (also known as cooking fumes), especially at the initial stage when cooking oil is being heated to above the smoking point before food ingredients are cooked.[230-235] Unlike the $PM_{2.5}$ from solid fuel combustion, cooking fumes usually consist of greater proportion of fatty acids and PAHs but lower levels of elemental carbon.[230,232] Future studies could collect data on black carbon (based on real-time monitor or gravimetric analysis) in parallel to clarify the relative contribution of cooking

fumes to the measured $PM_{2.5}$ levels. Another feature observed in urban households using clean fuels was occasional “domes” where $PM_{2.5}$ level increased slowly from late evening until early morning of the second day and declined to background level by mid-day. This likely reflects infiltration of ambient $PM_{2.5}$ which tends to increase slowly during evening and over mid-night in urban cities, as air pollutants accumulate alongside less human activities and temperature inversion effect.

Consistent with the existing literature,[32] the air pollution levels appeared to be substantially greater in the cool than in the warm season in solid fuel using households. Although extreme spikes were recorded near expected cooking time in both seasons, a common feature of the cool season data in solid fuel using households is that the recorded air pollution levels were elevated for a much greater percentage of time, often characterised by a longer tail of sustained high levels or slowly declining $PM_{2.5}$ from the evening peak through the morning or noon of the second day (as shown on **Figure 8.15b**). Apart from solid fuel use for heating, the presence of these long tails may reflect the use of slow burning stoves (in Henan cases) or mosquito coils (in Gansu) or infiltration from ambient environment, where air pollutant concentration tends to increase during the midnight due to relatively stagnant air current and temperature inversion effect (especially in cities).[236-238] Further investigations to integrate and compare the data from the time-activity questionnaire, ambient, household and personal monitors would better clarify this.

The data inspection exercise had identified several potentially important signs of problematic data. First, prolonged elevation of $PM_{2.5}$ that deviated from the expected background variation likely suggest that there were debris inside the photoelectric chamber, as the readings were usually elevated by certain values while the shape of the curve remains consistent with other monitors. One possible solution is to quantify the faulty elevation by comparing the lowest background values recorded during normal

and erroneous period and then the readings could be brought down by subtracting the estimate error values.

Extended period of readings at the detection threshold, which was frequently observed in the personal monitor, may suggest that the device was being kept at locations where $PM_{2.5}$ levels are very low or that the air inlet was blocked. The first condition can be verified by examining the motion sensor data during the same period. Another possible reason could be due to unstable energy supply when the internal battery drop to below 3.5 V, which is believed to disproportionately influence the performance of the $PM_{2.5}$ sensor but less so for the CO sensor.

While certain activities (e.g. smoking, beginning of cooking) could result in records of extremely high $PM_{2.5}$, sudden peaks that are not preceded or followed by exponential increase or decline are likely to be due to sudden temperature change, direct light shining into the photoelectric chamber or physical shock to the device. An algorithm will be developed to automatically identify these peaks, by comparing the peaking value against a projected value (with pre-specified error margin) calculated from the slopes of the curve before and after the peak, and any potentially faulty peaks would be replaced by the projected value. It was also realised that the $PM_{2.5}$ or CO sensor may give unexpected peak values near the end of the monitoring period when the device was being collected. Therefore, future analysis should truncate at least 10 minutes at the beginning and end of the monitoring period in addition to the pre- and post-zeroing period to ensure that the monitors were sampling at a stable condition.

### 8.5.3 Experience and lesson learned

The primary aim of this study was to establish the infrastructure and gain experience in objectively measuring air pollution exposure in a subset of the CKB population. The experience of preparation, implementation and data processing in this study has

provided important insight into how feasible is it to scale-up these measurements for future research.

*8.5.3.1 Training, logistics and fieldwork implementation*

The data collection fieldwork was a highly labour intensive undertaking, which involved a relatively complex weekly schedule and a wide range of devices and software that were unfamiliar to local fieldworkers who had little command of English. I played a leading role in the development of SOPs and multi-media training materials in Chinese to train local fieldworkers. An adaptive approach was employed such that the training materials were revised repeatedly based on the feedback and our observations during the data collection fieldwork. The three-day training workshops involved guided exercises and role play in carrying out all data collection and device maintenance procedures, and fieldworkers were supervised during the implementation of these procedures during the first week of fieldwork. It was proved to be effective in training inexperienced fieldworkers to an adequate standard of performance.

Fieldworkers were asked to document any unsolvable problems encountered in the field, such as mislabelling of data files, malfunctioning of instruments or software failure, but this was rarely done according to the guided procedures (to fill in an error report form). Fieldworkers tend to report problems via an instant messaging application on their mobile phones (“Wechat”) to get immediate feedback from mentors in Oxford or Beijing or the fieldwork coordinator in China. It is worth-noting that mobile phone applications are now an integral part of the daily life of many Chinese residents, and all of our fieldworkers use these for communication, shopping, banking and more. There is an opportunity to develop a comprehensive mobile phone-based application to improve fieldwork management and remote communication for future studies in general. Nonetheless, it may be more cost-efficient to add a troubleshooting-helper function or more detailed step-by-step guide for device and software operation into

GadgetManager, the software that was already in place to guide and coordinate various data collection tasks (to be discussed further in **Section 8.6.4.3**).

*8.5.3.2 Participant recruitment and feedback*

Regarding participants, it appeared that most of the data collection procedures were well-accepted, including the use of air quality monitors for personal and household monitoring. The self-reported compliance of carrying the personal PATS+CO was high (82-83% of awake time). However, some participants found the cross-body harness used for carrying personal PATS+CO difficult to put on and may hinder agricultural work. The harness was designed to position the PATS+CO on the chest of the participant to allow sampling within the participant's breathing zone. However, the integrity of the harness declined very quickly and it could barely hold the device at the designated position after the warm season fieldwork. Based on participants' feedback, we have designed a waist belt with stronger materials as an alternative option in the cool season campaign. Most participants preferred to use the waist belt option over the original harness for its convenience. However, the PATS+CO carried using a waist belt would be further away from one's breathing zone. Future studies may need to further improve the design to strike a balance between accurate measurement and participant acceptability and compliance.

At the design stage of the study, there were concerns about the feasibility of following the relatively rigid weekly data collection schedule which started on a Thursday and ended on a Tuesday. The schedule was designed to capture both weekday and weekend exposure and time-activity patterns, while avoiding overtime work during the weekend. The plan was implemented successfully given the tight time frame of 4-5 weeks for each study site (restricted by seasonality and resources available), any delay or loss of contact with participant would hinder us from achieving the targeted sample size. One key determinant behind the success was that local fieldwork coordinators and

community leaders contacted eligible participants about one week in advance to conduct pre-enrolment, which involved a brief introduction of the study objectives and contents, and arranged specific time for household visits for formal recruitment. The pre-recruitment was done to “over-recruit” 5-8 participants each week, who were reserved for replacement for those who had initially agreed to participate but declined upon formal recruitment or became unavailable on the day of visit. This is particularly important for studies that require careful scheduling of household visits and has more restricted timeframe, as opposed to the previous CKB surveys which invited participants to a centralised location for assessment over a longer period of time. For future studies involving household visits, the above recruitment process could be formalised and facilitated by using or developing an interactive electronic participant recruitment platform.

*8.5.3.3 Air pollution measurement*

Air pollution measurement is a key component of this study, and we encountered a range of problems that brought us important insight into designing future studies.

One key challenge concerning all devices was that most of the devices used had to be operated on an English-medium software from the device manufacturer and some of the procedures could be quite complex for fieldworkers with little or no command of English. The GadgetManager provided a relatively simple Chinese-medium platform to guide fieldworkers through various procedures in device deployment, collection and data transfer, and it was proven to be effective in most (but not all) situations. Ideally, if we could obtain the application programming interface (API) of any manufacturer software, we could programme GadgetManager to communicate with the software and automate the procedures of device registration, setup, deployment, collection and data transfer. We can also include built in error checks that would generate a warning message to fieldworkers and flag for attention in the meta-data database of

GadgetManager, thus reducing human error and facilitating quality control of the data collection processes. We have been attempted to obtain the API from the manufacturers, but most of the devices used are commercialised and the manufacturers have been reluctant to share their developmental information. A more feasible solution is to enhance the current GadgetManager to incorporate more sophisticated error checks, warning system and interactive SOPs (akin software installation wizards) that could be demonstrated to fieldworkers and used in parallel with their operation via the manufacturer software.

For PATS+CO, we have identified several mechanical design problems such as some of the CO sensors can be detached from the circuit board easily upon shock, and the indicator LED bulb (which shows the operation model of the device by flashing different colours at different frequency) was soldered at a position that is prone to be broken by external pressure. The manufacturer was informed about these problems and modified the design of those parts, such as to solder the LED bulb further away from the casing. However, problems such as the CO sensor becoming detached still occurred, as identified from inspecting the time series data. We have also identified several problems with the PICA software, including the inability to connect and setup SUMS and a range of bugs which caused the software to crash or failed to download processed data. All these were communicated to the manufacturer and the software has since been updated once during the course of the fieldwork, but some problems persisted. Further software updates are underway.

For MicroPEM, one major issue was that the HAP levels in some households were too high and the 25 mm filters became overloaded and the flowrate would have been reduced during the course of sampling, thus giving erroneous readings. This led to sequential changes of the sampling period where MicroPEM is co-located with the corresponding PATS+CO, from 120 to 72 hours initially, and then to 48 or 24 hours (for households with particularly high levels of HAP), as a 72-hour period was still too long.

In the future, it may be necessary to consider using traditional air pump and cyclone sampler with filters of larger capacity (e.g. 37 mm) in households expected to have higher HAP levels (e.g. wood-burning households) to minimise loss of gravimetric data.

## 8.6 CONCLUSIONS

This chapter described the design and methods of an on-going study conducted to test the feasibility of obtaining multi-dimensional data to assess personal air pollution exposure in a small subset of CKB participants. Despite some challenges in terms of training, logistics and data collection, it was feasible to conduct a study of this kind at the given scale. Use of various air quality monitors was well-accepted by local residents, and compliance of carrying personal monitor appeared to be high. We have captured a sample with a reasonably wide range of HAP-related exposures and the electronic time-activity questionnaire was implemented successfully. Exploration of the air quality monitor data have informed plans for further data cleaning and analysis. Experience gained from this study will provide valuable insights into designing similar larger-scale studies and inform new ideas on how to further develop fieldwork and device management software to facilitate future studies.

**Table 8.1 List of standard operating procedures developed for the feasibility study**

| No. | Title | Contents |
|---|---|---|
| 1 | **Participant registration** | • Instructions for using the CKB in-house participant registration software "ParticipantDetails" and procedures to register recruited participant |
| 2 | **PATS+CO** | • Structure and function of the "Particle and Temperature Sensor plus carbon monoxide sensor" (PATS+CO)<br>• Pre-household visit preparation and device maintenance procedures<br>• Procedures to deploy, check, retrieve and download data from the device, using "GadgetManager" and "PICA" software<br>• Notes for trouble-shooting and repairing |
| 3 | **SUMS** | • Structure and function of the “Stove Use Monitoring System” (SUMS)<br>• Procedures to deploy, check, retrieve and download data from the device, using "GadgetManager" and "OneWireViewer" software |
| 4 | **Calibration set** | • Structure and function of the "MicroPEM" particle sensor, "EL-USD-CO" carbon monoxide monitor and "EL-USB-2-LCD" temperature and relative humidity monitor, a set of three established monitors for calibration of PATS+CO data<br>• Pre-household visit preparation and device maintenance procedures<br>• Procedures to deploy, check, retrieve and download data from the devices, using "GadgetManager", "MicroPEM Docking Station" and "Lascar EasyLog" software |
| 5 | **Use of questionnaire software** | • Procedures to use the CKB in-house SINPUT software in conducting household and time-activity questionnaire and recording biomarker measurements |
| 6 | **Household and time-activity questionnaire** | • Purposes of the household and time-activity questionnaire<br>• Detailed meaning and rationale of each question and answer option included in the questionnaires, and standardised approach to administer the question<br>• Quality control measures<br>• Tips for proper conduct |
| 7 | **Nonin Oximeter** | • Structure and function of the "Nonin Onyx Vantage 9590" used to measure heart rate and blood oxygen saturation<br>• Procedures to measure heart rate and blood oxygen saturation<br>• Tips for proper usage and common mistakes<br>• Device maintenance |
| 8 | **MicroCO meter** | • Structure and function of the "MicroCO meter" used to measure exhaled carbon monoxide<br>• Procedures to calibrate the device and measure exhaled carbon monoxide |
| 9 | **GPS locator** | • Structure and function of the ICEGPS locator<br>• Procedures to obtain and record longitude and latitude |
| 10 | **Weekly workflow** | • Descriptions of the weekly workflow by tasks on each working day |
| 11 | **Household visit procedures** | • Step by step guide to conduct each of the four household visits for each participant |
| 12 | **Trouble shooting for device deployment and common problems** | • Lists of common problems related to study equipment and software<br>• Methods of trouble-shooting and reporting problems |

**Table 8.2 Selected baseline characteristics of participants included in the warm and cool season campaign***

| Baseline characteristics | Warm season (N = 451) n (%) | Cool season (N = 450) n (%) |
|---|---|---|
| **Age - years** | | |
| <40 | 79 (17.6) | 83 (18.4) |
| 40-49 | 203 (45.1) | 202 (44.9) |
| 50-59 | 158 (35.1) | 154 (34.2) |
| 60-69 | 10 (2.2) | 11 (2.4) |
| ≥70 | | |
| **Female** | 329 (73.1) | 326 (72.4) |
| **Education** | | |
| No formal | 111 (24.7) | 112 (24.9) |
| Primary school | 164 (36.4) | 159 (35.3) |
| Middle school | 125 (27.8) | 126 (28.0) |
| High school or above | 50 (11.1) | 53 (11.8) |
| **Household income - Yuan/ year** | | |
| <10,000 | 208 (46.2) | 209 (46.4) |
| 10,000 - 19,999 | 95 (21.1) | 95 (21.1) |
| ≥20,000 | 147 (32.7) | 146 (32.4) |
| **Smoking** | | |
| Never-regular | 341 (75.8) | 338 (75.1) |
| Occasional | 12 (2.7) | 11 (2.4) |
| Ex-regular | 14 (3.1) | 13 (23.9) |
| Current-regular | 83 (18.4) | 88 (19.6) |
| **Alcohol consumption** | | |
| Never-regular | 232 (51.6) | 230 (51.1) |
| Occasional or monthly | 160 (35.6) | 157 (34.9) |
| Ex-regular or reduced intake | 14 (3.1) | 14 (3.1) |
| Current-regular | 44 (9.8) | 49 (10.9) |
| **Primary cooking fuel** | | |
| No cooking | 103 (22.9) | 108 (24.0) |
| Clean fuels | 111 (24.7) | 112 (24.9) |
| Coal | 167 (37.1) | 162 (36.0) |
| Wood | 64 (14.2) | 63 (14.0) |
| Other | 5 (1.1) | 5 (1.1) |
| **Primary heating fuel** | | |
| No heating | 128 (28.4) | 128 (28.4) |
| Clean fuels | 33 (7.33) | 31 (6.9) |
| Coal | 212 (47.1) | 214 (47.6) |
| Wood | 67 (14.9) | 67 (14.9) |
| Other | 10 (2.2) | 10 (2.2) |
| **Self-reported poor health** | 54 (12.0) | 51 (11.3) |
| **Diabetes†** | 29 (6.4) | 30 (6.7) |
| **Prior cardiovascular disease‡** | 8 (1.8) | 6 (1.3) |
| **Prior hypertension** | 47 (10.4) | 46 (10.2) |

* All $\chi^2$ p-value comparing between the two samples were >0.05.

† Self-reported prior doctor diagnosis of diabetes or screen-detected diabetes based on random blood glucose test (as stated in Section 4.2).

‡ Self-reported prior doctor diagnosis of chronic heart disease, transient ischaemic attack or stroke.

**Table 8.3 Missing data in warm and cool season campaign**

| | Warm season (N = 451) | | | | Cool season (N = 450) | | | |
|---|---|---|---|---|---|---|---|---|
| | **Thu** | **Fri** | **Mon** | **Fri** | **Thu** | **Fri** | **Mon** | **Fri** |
| **Types of missing** | | | | | | | | |
| **Did not undertake time-activity questionnaire** | 0 | 1 | 3 | 0 | 0 | 1 | 2 | 0 |
| **Missing $SpO_2$* and heart rate data** | - | 16 | 16 | - | - | 33 | 41 | - |
| **Missing COex† data** | - | 25 | 26 | - | - | 34 | 41 | - |
| **Did not undertake household questionnaire** | - | - | - | - | 1 | - | - | - |
| **Only participated in one season** | 37 | | | | 37 | | | |

*$SpO_2$: blood oxygen saturation.

†COex: exhaled carbon monoxide

**Table 8.4 Background characteristics of study participants by study area**

| Characteristics | Suzhou (urban) n (%) | Gansu (rural) n (%) | Henan (rural) n (%) | Overall n (%) |
|---|---|---|---|---|
| **Age - years, mean (SD)** | 59.8 (7.0) | 57.4 (7.3) | 56.8 (5.6) | 58.0 (6.8) |
| **Female** | 103 (69.1) | 110 (73.3) | 112 (74.7) | 325 (72.4) |
| **Annual household income, Yuan** | | | | |
| <35,000 | 2 (1.3) | 63 (42.0) | 100 (66.7) | 165 (36.8) |
| 35,000-49,999 | 12 (8.1) | 47 (31.3) | 24 (16.0) | 83 (18.5) |
| 50,000-74,999 | 9 (6.0) | 33 (22.0) | 18 (12.0) | 60 (13.4) |
| 75,000-99,999 | 9 (6.0) | 4 (2.7) | 2 (1.3) | 15 (3.3) |
| ≥100,000 | 117 (78.5) | 3 (2.0) | 6 (4.0) | 126 (28.1) |
| **Occupation** | | | | |
| Agricultural worker | 0 (0.0) | 67 (44.7) | 101 (67.3) | 168 (37.4) |
| Factory worker | 16 (10.7) | 0 (0.0) | 6 (4.0) | 22 (4.9) |
| Non-manual labour | 6 (4.0) | 1 (0.7) | 5 (3.3) | 12 (2.7) |
| Retired | 99 (66.4) | 2 (1.3) | 0 (0.0) | 101 (22.5) |
| Home-maker | 15 (10.1) | 79 (52.7) | 34 (22.7) | 128 (28.5) |
| Self/ un-employed or other | 13 (8.7) | 1 (0.7) | 4 (2.7) | 18 (4.0) |
| **Type of dwelling** | | | | |
| Apartment | 16 (10.7) | 0 (0.0) | 0 (0.0) | 16 (3.6) |
| House | 133 (89.3) | 150 (100.0) | 150 (100.0) | 433 (96.4) |
| **Current smoking** | | | | |
| Do not smoke now | 122 (81.9) | 122 (81.3) | 129 (86.0) | 373 (83.1) |
| Only occasionally | 4 (2.7) | 2 (1.3) | 5 (3.3) | 11 (2.5) |
| Yes, on most days | 0 (0.0) | 1 (0.7) | 1 (0.7) | 2 (0.5) |
| Yes, daily or almost every day | 23 (15.4) | 25 (16.7) | 15 (10.0) | 63 (14.0) |
| **Frequency of ETS* exposure** | | | | |
| Never | 75 (51.0) | 30 (20.4) | 45 (30.6) | 150 (34.0) |
| <1 day/ week | 4 (2.7) | 18 (12.2) | 11 (7.5) | 33 (7.5) |
| 1-2 day/ week | 5 (3.4) | 12 (8.2) | 21 (14.3) | 38 (8.6) |
| 3-5 day/ week | 3 (2.0) | 19 (12.9) | 14 (9.5) | 36 (8.2) |
| 6-7 day/ week | 60 (40.8) | 68 (46.3) | 56 (38.1) | 184 (41.7) |
| **Duration of ETS* exposure, hours/ week (mean)** | | | | |
| Never or rarely exposed (<1 day/ week) | 82 (55.0) | 51 (34.0) | 77 (51.3) | 210 (46.8) |
| ≤3 hours (1.7) | 11 (7.4) | 25 (16.7) | 25 (16.7) | 61 (13.6) |
| 3.1 to 20 hours (14.5) | 29 (19.5) | 29 (19.3) | 10 (6.7) | 68 (15.1) |
| 20.1 to 37 hours (28.4) | 2 (1.3) | 32 (21.3) | 18 (12.0) | 58 (12.9) |
| >37 hours (50.0) | 25 (16.8) | 13 (8.7) | 20 (13.3) | 58 (12.9) |

*ETS: environmental tobacco smoke.

**Table 8.5 Cooking-related characteristics of study participants by study area**

| Characteristics | Suzhou (urban) n (%) | Gansu (rural) n (%) | Henan (rural) n (%) | Overall n (%) |
|---|---|---|---|---|
| **Cooking frequency** | | | | |
| Daily or almost every day | 100 (67.1) | 114 (76.0) | 113 (75.3) | 327 (72.8) |
| A few times a week | 8 (5.4) | 3 (2.0) | 4 (2.7) | 15 (3.3) |
| A few times a month | 2 (1.3) | 1 (0.7) | 4 (2.7) | 7 (1.6) |
| Never or rarely | 39 (26.2) | 32 (21.3) | 29 (19.3) | 100 (22.3) |
| **Cooking exposure** | | | | |
| Personal regular | 108 (72.5) | 117 (78.0) | 117 (78.0) | 342 (76.2) |
| Household regular, personal non-regular | 23 (15.4) | 21 (14.0) | 9 (6.0) | 53 (11.8) |
| Non-regular | 18 (12.1) | 12 (8.0) | 24 (16.0) | 54 (12.0) |
| **Cooking duration - hours, mean (SD)*** | 2.7 (0.7) | 2.8 (0.8) | 2.5 (0.7) | 2.7 (0.7) |
| **Number of cooking fuel reported, median (IQR)*** | 1 (1-2) | 3 (2-3) | 2 (2-3) | 2 (2-3) |
| One | 80 (61.1) | 4 (2.9) | 5 (3.9) | 89 (22.4) |
| Two | 51 (38.9) | 56 (40.6) | 73 (56.6) | 180 (45.2) |
| Three | 0 (0.0) | 68 (49.3) | 49 (38.0) | 117 (29.4) |
| Four | 0 (0.0) | 7 (5.1) | 2 (1.6) | 9 (2.3) |
| Five | 0 (0.0) | 2 (1.5) | 0 (0.0) | 2 (0.5) |
| Eight | 0 (0.0) | 1 (0.7) | 0 (0.0) | 1 (0.3) |
| **Cooking fuel combination for any meals*** | | | | |
| Clean fuels only | 130 (99.2) | 54 (39.1) | 50 (39.7) | 234 (59.2) |
| Clean fuels and coal | 0 (0) | 11 (8.0) | 43 (34.1) | 54 (13.7) |
| Clean fuels and mixed solid fuels | 0 (0) | 5 (3.6) | 0 (0) | 5 (1.3) |
| Clean fuels and wood | 0 (0) | 66 (47.8) | 0 (0) | 66 (16.7) |
| Coal only | 0 (0) | 1 (0.7) | 33 (26.2) | 34 (8.6) |
| Mixed solid fuels | 0 (0) | 1 (0.7) | 0 (0) | 1 (0.3) |
| Wood only | 1 (0.8) | 0 (0) | 0 (0) | 1 (0.3) |
| **Cooking fuel combination for most meals*** | | | | |
| No fuel used for most meals | 66 (50.4) | 8 (5.8) | 15 (11.9) | 89 (22.5) |
| Clean fuels only | 64 (48.9) | 48 (34.8) | 43 (34.1) | 155 (39.2) |
| Clean fuels and coal | 0 (0) | 11 (8.0) | 35 (27.8) | 46 (11.7) |
| Clean fuels and mixed solid fuels | 0 (0) | 5 (3.6) | 0 (0) | 5 (1.3) |
| Clean fuels and wood | 0 (0) | 64 (46.4) | 0 (0) | 64 (16.2) |
| Coal only | 0 (0) | 1 (0.7) | 33 (26.2) | 34 (8.6) |
| Mixed solid fuels | 0 (0) | 1 (0.7) | 0 (0) | 1 (0.3) |
| Wood only | 1 (0.8) | 0 (0) | 0 (0) | 1 (0.3) |
| **Fuel use in those reported no fuel for most meals*,†** | | | | |
| Clean fuels | 66 (100) | 6 (75.0) | 7 (46.7) | 79 (88.8) |
| Clean fuels and coal | 0 (0) | 0 (0) | 8 (53.3) | 8 (9.0) |
| Clean fuels and wood | 0 (0) | 2 (25.0) | 0 (0) | 2 (2.3) |
| **Household indoor cooking*** | 128 (97.7) | 137 (99.3) | 129 (100.0) | 394 (99.0) |
| **Kitchen ventilation*** | 126 (98.4) | 96 (70.1) | 58 (45.0) | 280 (71.1) |
| **Open windows when cooking*** | | | | |
| Always | 78 (60.9) | 128 (93.4) | 89 (69.0) | 295 (74.9) |
| Sometimes | 17 (13.3) | 8 (5.8) | 22 (17.1) | 47 (11.9) |
| Rarely/ never/ no window in the kitchen | 33 (25.8) | 1 (0.7) | 18 (14.0) | 52 (13.2) |
| **Smoky kitchen when cooking*** | | | | |
| Always | 1 (0.8) | 38 (27.7) | 7 (5.4) | 46 (11.7) |
| Sometimes | 6 (4.7) | 68 (49.6) | 31 (24.0) | 105 (26.7) |
| Rarely/ never | 121 (94.5) | 31 (22.6) | 91 (70.5) | 243 (61.7) |

*Only among participants who live in households where regular cooking occurred.

†Reported as fuel used for cooking sometimes.

**Table 8.6 Heating-related characteristics of study participants by study area**

| Characteristics | Suzhou (urban) n (%) | Gansu (rural) n (%) | Henan (rural) n (%) | Overall n (%) |
|---|---|---|---|---|
| **Heating frequency** | | | | |
| Daily or almost every day | 25 (16.8) | 136 (90.7) | 111 (74.0) | 272 (60.6) |
| A few times a week | 10 (6.7) | 0 (0.0) | 3 (2.0) | 13 (2.9) |
| A few times a month | 8 (5.4) | 0 (0.0) | 3 (2.0) | 11 (2.5) |
| No heating | 106 (71.1) | 14 (9.3) | 33 (22.0) | 153 (34.1) |
| **Reason of no heating** | | | | |
| No such need | 106 (100.0) | 12 (85.7) | 29 (87.9) | 147 (96.1) |
| Cannot afford | 0 (0.0) | 1 (7.1) | 0 (0.0) | 1 (0.7) |
| Inconvenience | 0 (0.0) | 1 (7.1) | 4 (12.1) | 5 (3.3) |
| **Typical heating duration*** | | | | |
| ≤ 1 hour | 0 (0.0) | 0 (0.0) | 0 (0.0) | 0 (0.0) |
| 1.1 to 3 hours | 33 (80.5) | 0 (0.0) | 2 (1.7) | 35 (11.9) |
| 3.1 to 8 hours | 7 (17.1) | 2 (1.5) | 4 (3.4) | 13 (4.4) |
| 8.1 to 23.9 hours | 1 (2.4) | 2 (1.5) | 3 (2.6) | 6 (2.0) |
| 24 hours | 0 (0.0) | 132 (97.1) | 108 (92.3) | 240 (81.6) |
| **Central heating system*** | 1 (2.3) | 6 (4.4) | 5 (4.3) | 12 (4.1) |
| **Number of heating fuel reported*** | | | | |
| One | 43 (100.0) | 87 (64.0) | 101 (86.3) | 231 (78.0) |
| Two | 0 (0.0) | 46 (33.8) | 15 (12.8) | 61 (20.6) |
| Three | 0 (0.0) | 3 (2.2) | 1 (0.9) | 4 (1.4) |
| **Heating fuel combination (used for longest hour)*** | | | | |
| Clean fuels only | 43 (100) | 3 (2.2) | 6 (5.1) | 52 (17.6) |
| Coal only | 0 (0) | 62 (45.6) | 100 (85.5) | 162 (54.7) |
| Charcoal only | 0 (0) | 0 (0) | 9 (7.7) | 9 (3.0) |
| Wood only | 0 (0) | 48 (35.3) | 0 (0) | 48 (16.2) |
| Mixed solid fuels | 0 (0) | 23 (16.9) | 0 (0) | 23 (7.8) |
| Others | 0 (0) | 0 (0) | 2 (1.7) | 2 (0.7) |
| **Heat stove ventilation*** | | | | |
| Yes, all | 0 (0.0) | 133 (97.8) | 104 (88.9) | 237 (80.1) |
| Yes, but not all | 9 (20.9) | 0 (0.0) | 3 (2.6) | 12 (4.1) |
| None | 34 (79.1) | 3 (2.2) | 10 (8.6) | 47 (15.9) |
| **Smoky home while heating*** | | | | |
| Always | 0 (0.0) | 1 (0.7) | 0 (0.0) | 1 (0.3) |
| Sometimes | 0 (0.0) | 111 (81.6) | 2 (1.7) | 113 (38.2) |
| Rarely/ never | 43 (100.0) | 24 (17.7) | 115 (98.3) | 182 (61.5) |

*Only among those reported using heating for at least a few times a month.

**Table 8.7 Other household air pollution-related characteristics of study participants by study area**

| Characteristics | Suzhou (urban) n (%) | Gansu (rural) n (%) | Henan (rural) n (%) | Overall n (%) |
|---|---|---|---|---|
| **Slow burning stove*** | | | | |
| Yes, always | 0 (0.0) | 5 (3.3) | 36 (24.0) | 41 (9.1) |
| Yes, sometimes | 0 (0.0) | 8 (5.3) | 0 (0.0) | 8 (1.8) |
| No | 149 (100.0) | 137 (91.3) | 114 (76.0) | 400 (89.1) |
| **Mosquito coils in summer** | | | | |
| Daily or almost every day | 8 (5.4) | 36 (24.0) | 10 (6.7) | 54 (12.0) |
| A few times a week | 5 (3.4) | 93 (62.0) | 9 (6.0) | 107 (23.8) |
| A few times a month | 6 (4.0) | 9 (6.0) | 22 (14.7) | 37 (8.2) |
| Never or rarely | 130 (87.3) | 12 (8.0) | 109 (72.7) | 251 (55.9) |
| **Incense burning indoors** | | | | |
| Daily or almost every day | 2 (1.3) | 7 (4.7) | 5 (3.3) | 14 (3.0) |
| A few times a month | 0 (0.0) | 40 (26.7) | 15 (10.0) | 55 (12.3) |
| Never or rarely | 147 (98.7) | 103 (68.7) | 130 (86.7) | 380 (84.6) |

*Slow burning stove: stove burning fuel all day neither for cooking nor heating.

**Table 8.8 Selected 24-hour time-activity characteristics by household visit in warm and cool season**

| | Warm season | | | Cool season | | |
|---|---|---|---|---|---|---|
| | **Weekday (n = 450)** | **Weekend (n = 448)** | **Overall (n = 898)** | **Weekday (n = 449)** | **Weekend (n = 448)** | **Overall (n = 897)** |
| **COOKING** | | | | | | |
| **Cooking frequency, n (%)** | | | | | | |
| Zero | 121 (26.9) | 123 (27.5) | 244 (27.2) | 89 (19.8) | 83 (18.5) | 172 (19.2) |
| One | 82 (18.2) | 59 (13.2) | 141 (15.7) | 33 (7.4) | 36 (8.0) | 69 (7.7) |
| Two | 139 (30.9) | 152 (33.9) | 291 (32.4) | 117 (26.1) | 111 (24.8) | 228 (25.4) |
| Three or above | 108 (24.0) | 114 (25.5) | 222 (24.7) | 210 (46.8) | 218 (48.7) | 428 (47.7) |
| **Duration of cooking - hours, median (IQR)*** | 1.6 (1.0-2.3) | 1.8 (1.0-2.5) | 1.7 (1.0-2.5) | 2.5 (1.5-3.0) | 2.5 (1.8-3.0) | 2.5 (1.7-3.0) |
| **% of recall period for cooking, median (IQR)*** | 6.5 (4.2-9.7) | 7.5 (4.2-10.2) | 6.9 (4.2-10.0) | 10.2 (6.3-12.5) | 10.2 (7.2-12.4) | 10.2 (6.9-12.5) |
| **HEATING*** | | | | | | |
| **Duration of heating - hours, median (IQR)** | - | 24.2 (24.0-24.5) | 24.2 (24.0-24.5) | 24.0 (24.0-24.5) | 24.0 (24.0-24.5) | 24.0 (24.0-24.5) |
| **% of recall period for heating, median (IQR)** | - | 100 (100-100) | 100 (100-100) | 100 (100-100) | 100 (100-100) | 100 (100-100) |
| **Smoking frequency, n (%)** | | | | | | |
| Zero | 406 (90.2) | 402 (89.7) | 808 (90.0) | 402 (89.5) | 403 (90.0) | 805 (89.7) |
| One to five times | 23 (5.1) | 28 (6.3) | 51 (5.7) | 31 (6.9) | 28 (6.3) | 59 (6.6) |
| Six times or above | 21 (4.7) | 18 (4.0) | 39 (4.3) | 16 (3.6) | 17 (3.8) | 33 (3.7) |
| **ETS exposure frequency, n (%)†** | | | | | | |
| Zero | 383 (85.1) | 371 (82.8) | 754 (84.0) | 380 (84.6) | 388 (86.6) | 768 (85.6) |
| One to four times | 43 (9.6) | 54 (12.1) | 97 (10.8) | 37 (8.2) | 39 (8.7) | 76 (8.5) |
| Five times or above | 24 (5.3) | 23 (5.1) | 47 (5.2) | 32 (7.1) | 21 (4.7) | 53 (5.9) |
| **PATS+CO*** | | | | | | |
| **Duration wearing PATS+CO - hours, median (IQR)** | 12.0 (9.3-14.2) | 13.0 (10.2-15.0) | 12.5 (9.5-14.7) | 12.0 (9.9-14.0) | 13.2 (11.0-15.0) | 12.5 (10.2-14.5) |
| **% of recall period wearing PATS+CO, median (IQR)** | 49.0 (37.5-58.3) | 54.2 (41.7-62.5) | 51.0 (39.6-60.4) | 50.0 (40.0-57.1) | 54.2 (45.0-61.6) | 52.1 (41.7-58.9) |
| **% of awake time wearing PATS+CO, median (IQR)** | 79.0 (60.4-93.5) | 86.7 (49.3-100) | 81.8 (56.7-100) | 80.8 (61.8-93.3) | 86.4 (57.1-100) | 83.0 (60.0-100) |

*Median (IQR) only among those who practiced the activity during the designated recall period.

†ETS: environmental tobacco smoke, defined as presence of a third person smoking next to the participant for at least five minutes.

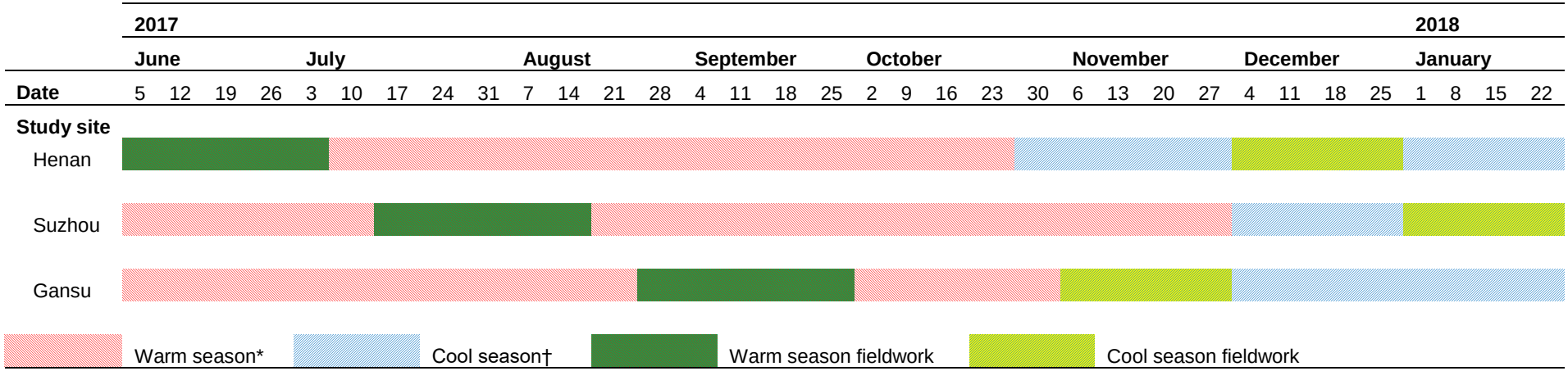
**Table 8.9 Mean and standard deviation of duration and proportion of recall period spent at different locations, by household visit in warm and cool season**

| | Weekday | | Weekend | | Overall | |
|---|---|---|---|---|---|---|
| | N* | Median (IQR) | N* | Median (IQR) | N* | Median (IQR) |
| **WARM SEASON** | | | | | | |
| **Time spent in kitchen - hours** | 328 | 1.7 (1.0-2.3) | 327 | 2.0 (1.0-2.7) | 655 | 1.8 (1.0-2.5) |
| **% of recall period spent in kitchen** | | 6.8 (4.2-9.7) | | 7.8 (4.1-10.9) | | 7.3 (4.2-10.2) |
| **Time spent at home - hours** | 449 | 20.3 (16.2-23.3) | 445 | 20.2 (16.5-23.6) | 894 | 20.3 (16.5-23.5) |
| **% of recall period spent at home** | | 83.4 (66.7-95.8) | | 83.4 (68.8-95.9) | | 83.4 (67.3-95.9) |
| **Time spent indoors - hours** | 418 | 21.5 (18.0-23.8) | 421 | 21.8 (19.0-24.0) | 839 | 21.7 (18.5-24.0) |
| **% of recall period spent indoor** | | 89.6 (74.5-97.9) | | 89.7 (77.1-98.7) | | 89.6 (75.5-98.0) |
| **Time spent outdoors - hours** | 333 | 4.0 (2.0-7.0) | 318 | 4.0 (2.0-6.5) | 651 | 4.0 (2.0-6.8) |
| **% of recall period spent outdoor** | | 15.8 (8.00-29.2) | | 16.5 (8.16-26.2) | | 16.4 (8.05-28.1) |
| **Time spent at roadside - hours** | 191 | 2.0 (1.0-4.0) | 173 | 2.0 (1.0-4.0) | 364 | 2.0 (1.0-4.0) |
| **% of recall period spent at roadside** | | 8.3 (4.2-16.2) | | 8.3 (4.1-16.5) | | 8.3 (4.2-16.4) |
| **Time spent for road surface transportation - hours** | 112 | 0.7 (0.5-1.3) | 96 | 0.9 (0.5-1.3) | 208 | 0.7 (0.5-1.3) |
| **% of recall period spent for road surface transportation** | | 2.8 (2.0-5.5) | | 3.6 (2.1-5.5) | | 2.9 (2.0-5.5) |
| **COOL SEASON** | | | | | | |
| **Time spent in kitchen - hours** | 363 | 2.5 (2.0-3.0) | 365 | 2.5 (1.8-3.0) | 728 | 2.5 (2.0-3.0) |
| **% of recall period spent in kitchen** | | 10.2 (7.8-12.5) | | 10.3 (7.5-12.5) | | 10.3 (7.6-12.5) |
| **Time spent at home - hours** | 449 | 21.5 (18.3-24.0) | 446 | 21.0 (18.3-24.0) | 895 | 21.3 (18.3-24.0) |
| **% of recall period spent at home** | | 88.0 (75.0-100) | | 87.5 (75.0-100) | | 87.5 (75.0-100) |
| **Time spent indoors - hours** | 389 | 23.0 (20.5-24.0) | 386 | 23.0 (20.0-24.0) | 775 | 23.0 (20.0-24.0) |
| **% of recall period spent indoor** | | 95.8 (83.6-100) | | 93.8 (82.5-100) | | 94.7 (83.3-100) |
| **Time spent outdoors - hours** | 267 | 3.0 (1.5-5.0) | 269 | 3.0 (1.5-5.5) | 536 | 3.0 (1.5-5.4) |
| **% of recall period spent outdoor** | | 12.5 (6.12-20.8) | | 12.5 (6.25-22.8) | | 12.5 (6.25-22.2) |
| **Time spent at roadside - hours** | 144 | 2.0 (1.0-3.7) | 113 | 1.8 (1.0-3.0) | 257 | 2.0 (1.0-3.3) |
| **% of recall period spent at roadside** | | 8.2 (4.1-15.2) | | 7.2 (4.1-12.5) | | 7.8 (4.1-13.4) |
| **Time spent for road surface transportation - hours** | 75 | 1.0 (0.5-1.3) | 76 | 1.0 (0.5-1.3) | 151 | 1.0 (0.5-1.3) |
| **% of recall period spent for road surface transportation** | | 4.0 (2.1-5.5) | | 4.0 (2.1-5.5) | | 4.0 (2.1-5.5) |

*N: number of participants with non-zero duration reported for the corresponding location.

**Figure 8.1 Gantt chart for data collection fieldwork**

Originally created by Associate Professor KBH Lam. Used with permission.




*Usual monthly average temperature ≥10 °C

†Usual monthly average temperature <10 °C

**Figure 8.2 Multi-dimensional data collection on air pollution related exposures**

PM: particulate matter; CO: carbon monoxide; O3: ozone; NO: nitric oxide; NO2: nitrogen dioxide; temp: temperature; RH: relative humidity; COex: exhaled carbon monoxide; $SpO_2$: blood oxygen saturation.

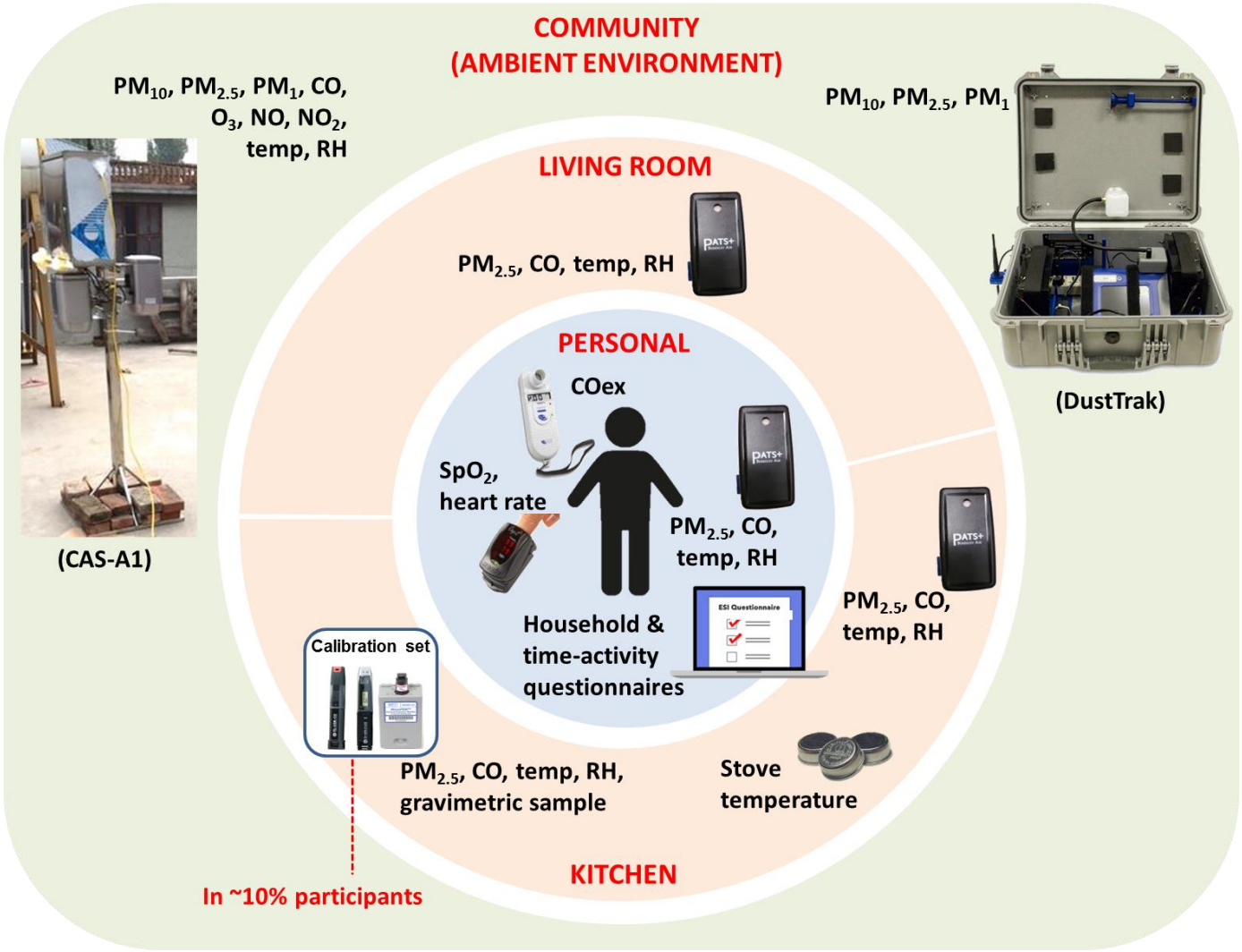


**Figure 8.3 Screen shots of the GadgetManager software developed for device and data management**

English (top) and simplified Chinese (bottom) interface



**Figure 8.4 Fieldwork workflow each week**

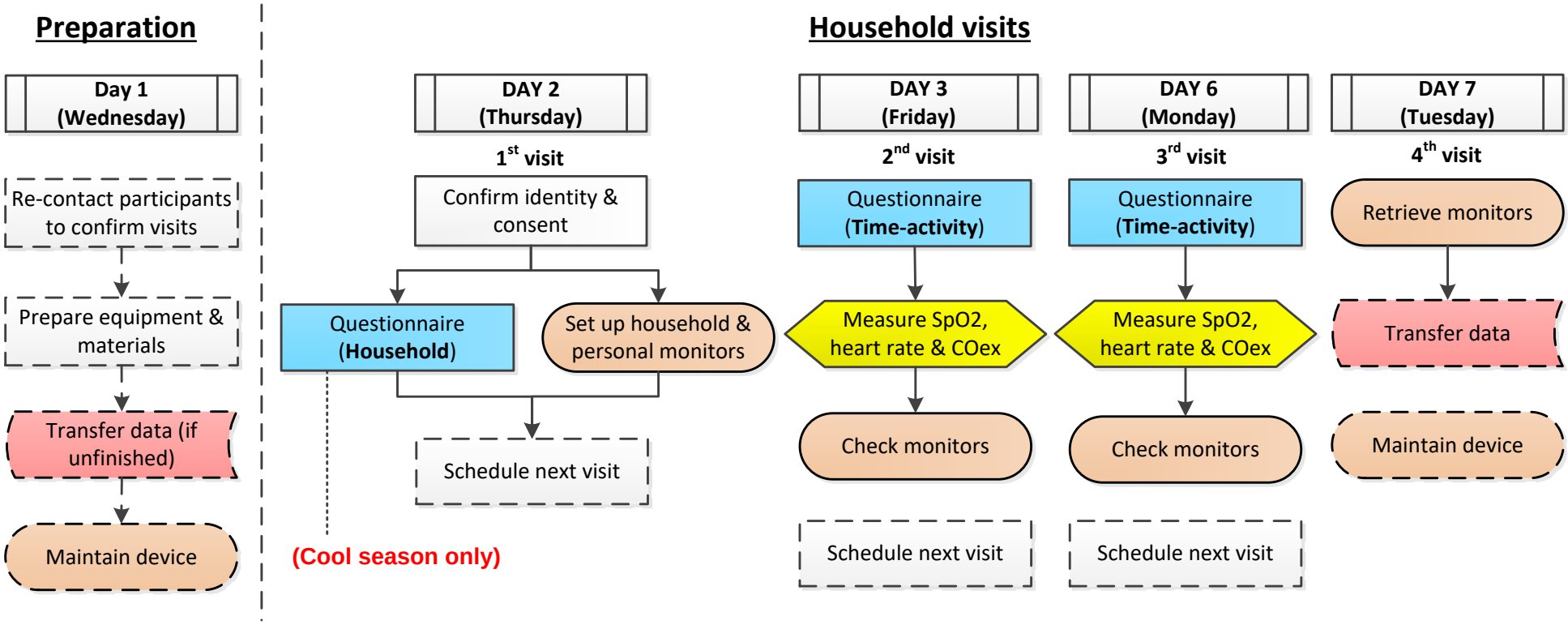


**Figure 8.5 Electronic time-activity questionnaire**

English (top) and Chinese (bottom) interface

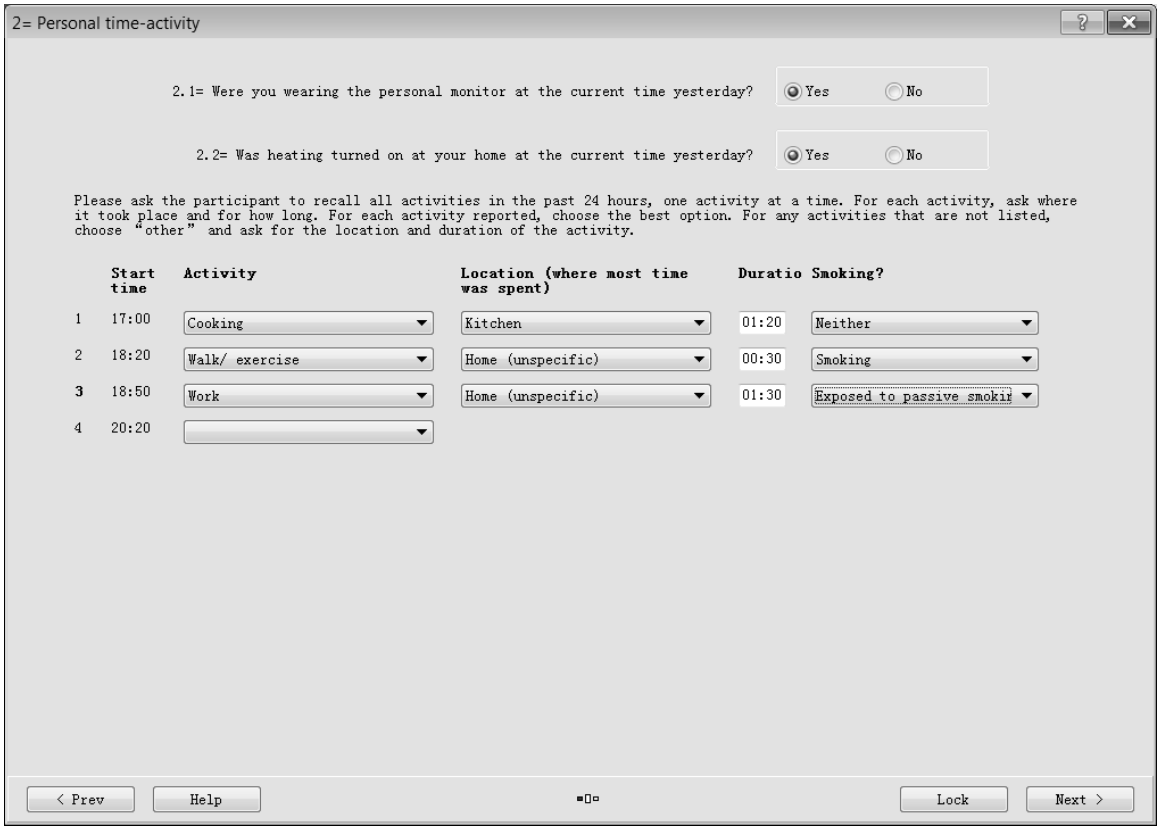





**Figure 8.6 (a) MicroCO meter (left) and (b) Onyx Vantage 9590 pulse oximeter (right)**



**Figure 8.7 Stove use monitoring system (stove temperature logger)**



**Figure 8.8 (a) Cross-body harness (left) and (b) waist belt (right) carrying PATS+CO**



**Figure 8.9 PATS+CO**

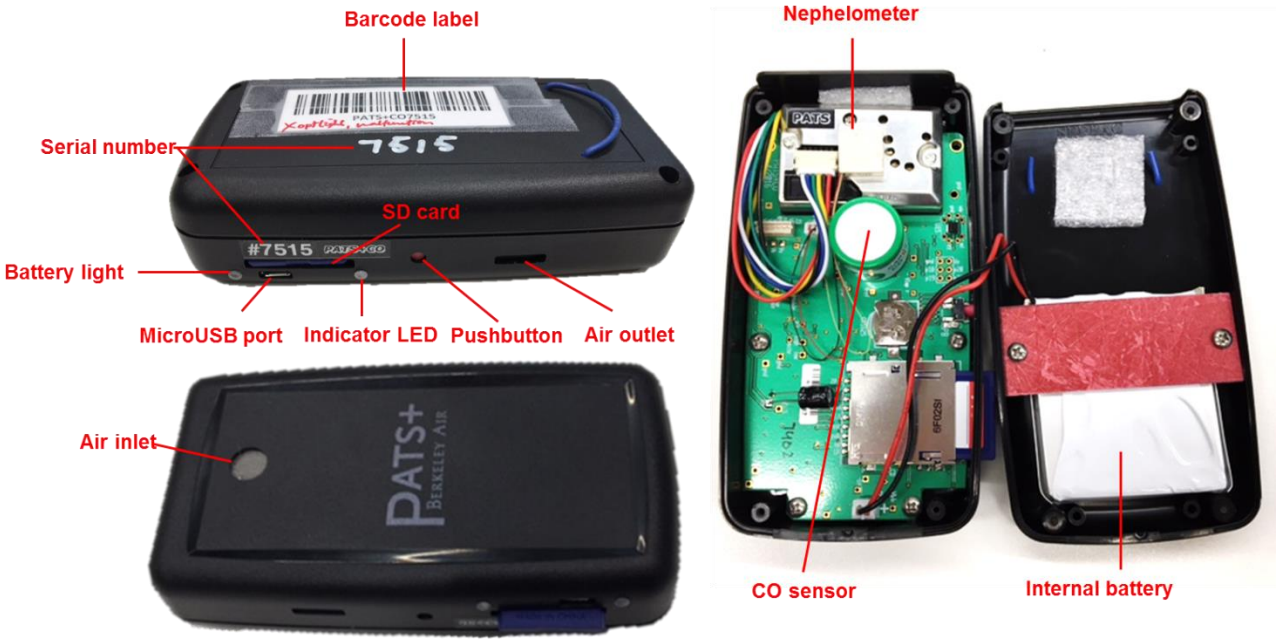


**Figure 8.10 Calibration of PATS+CO**



**Figure 8.11 MicroPEM and accessories**

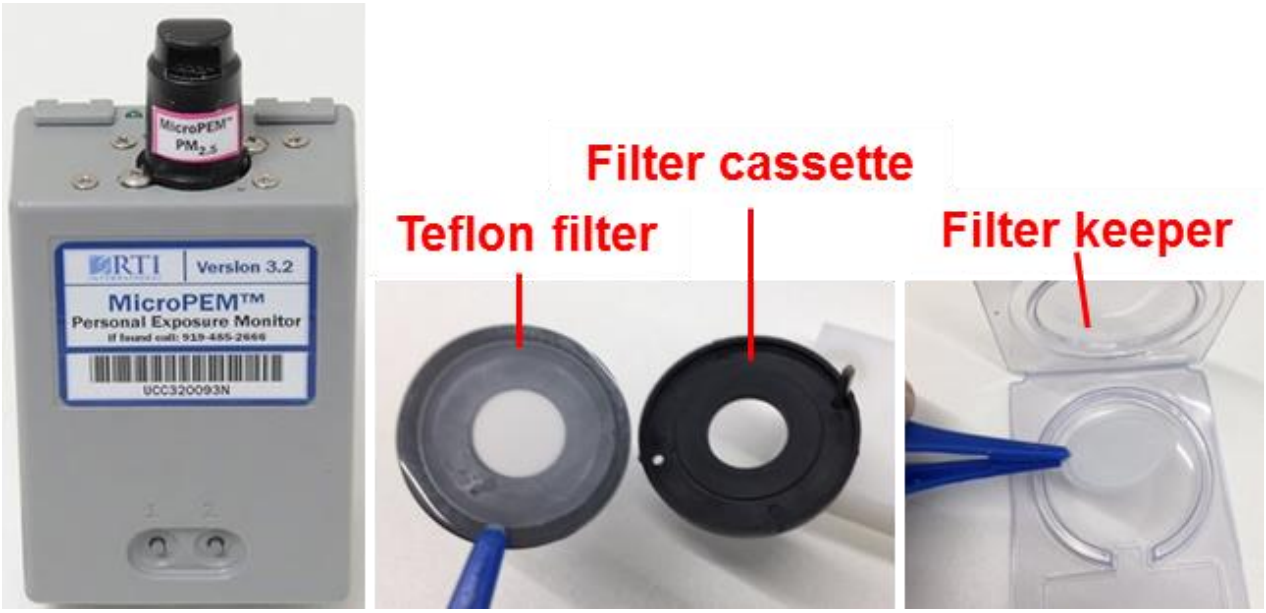


**Figure 8.12 (a) EL-USB-CO (left) and (b) EL-USB-2-LCD (right)**



**Figure 8.13 Ambient air pollution monitors**

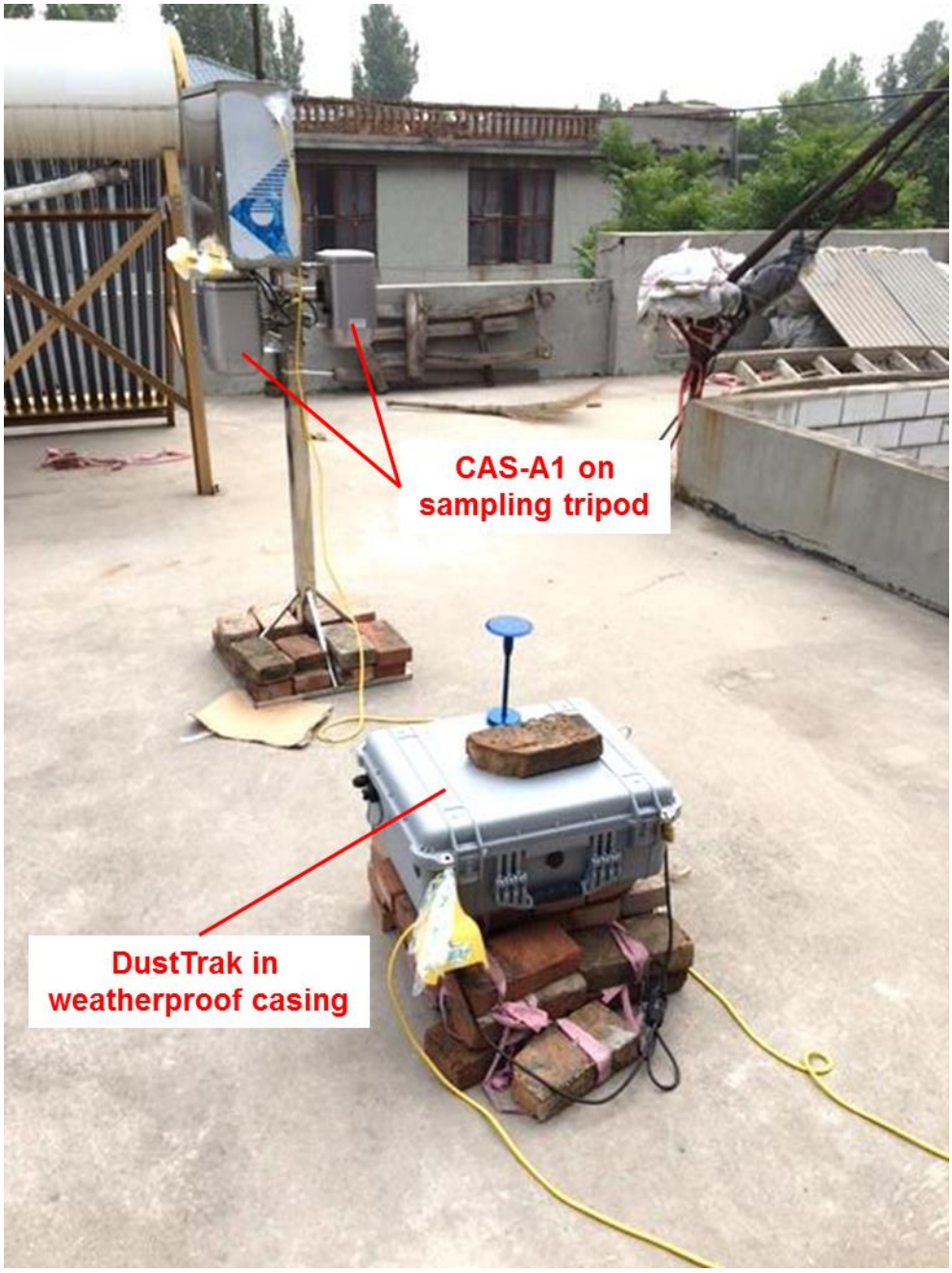


**Figure 8.14 Average percentage of time spent on assessed activities on weekday and weekend in warm and cool season, by study sites**

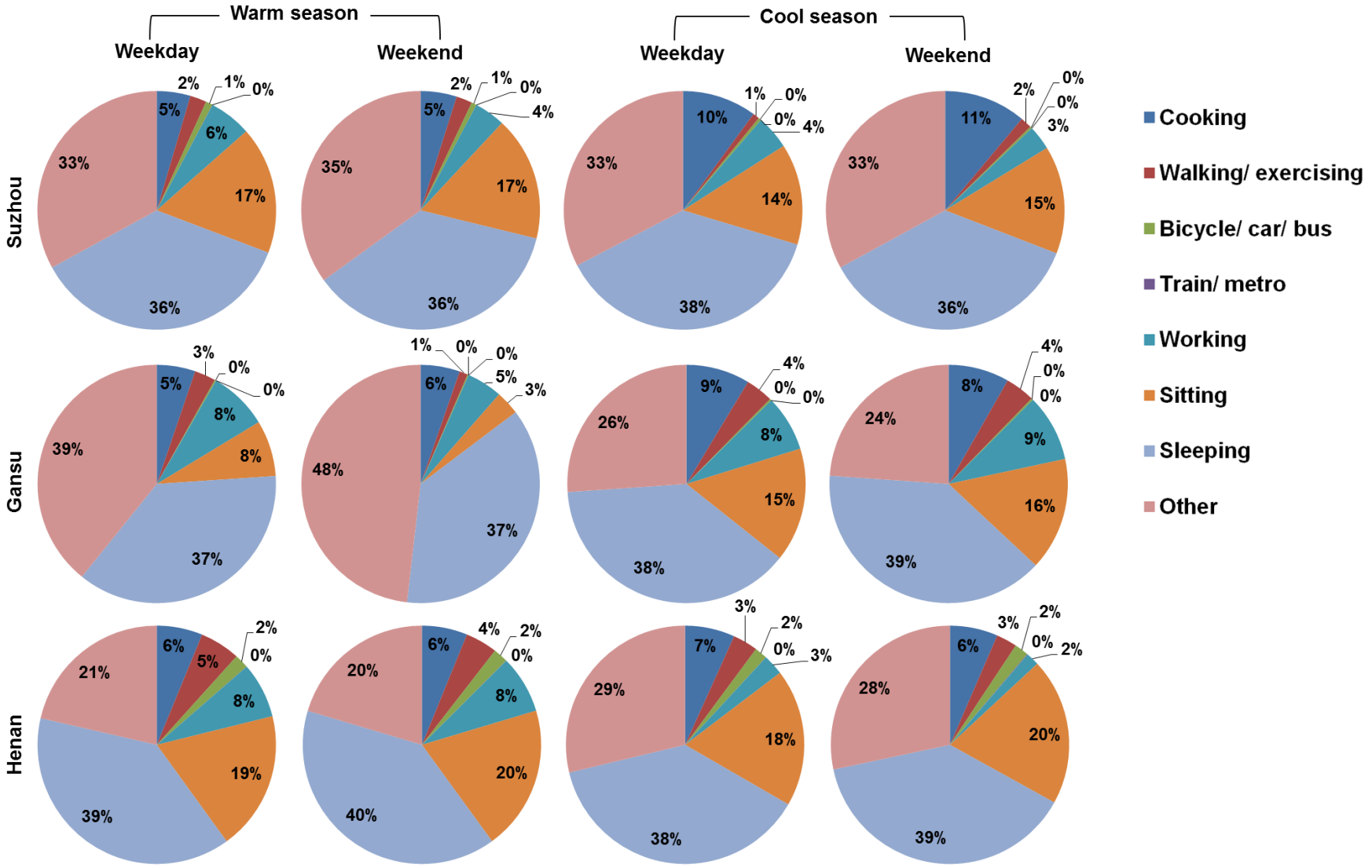
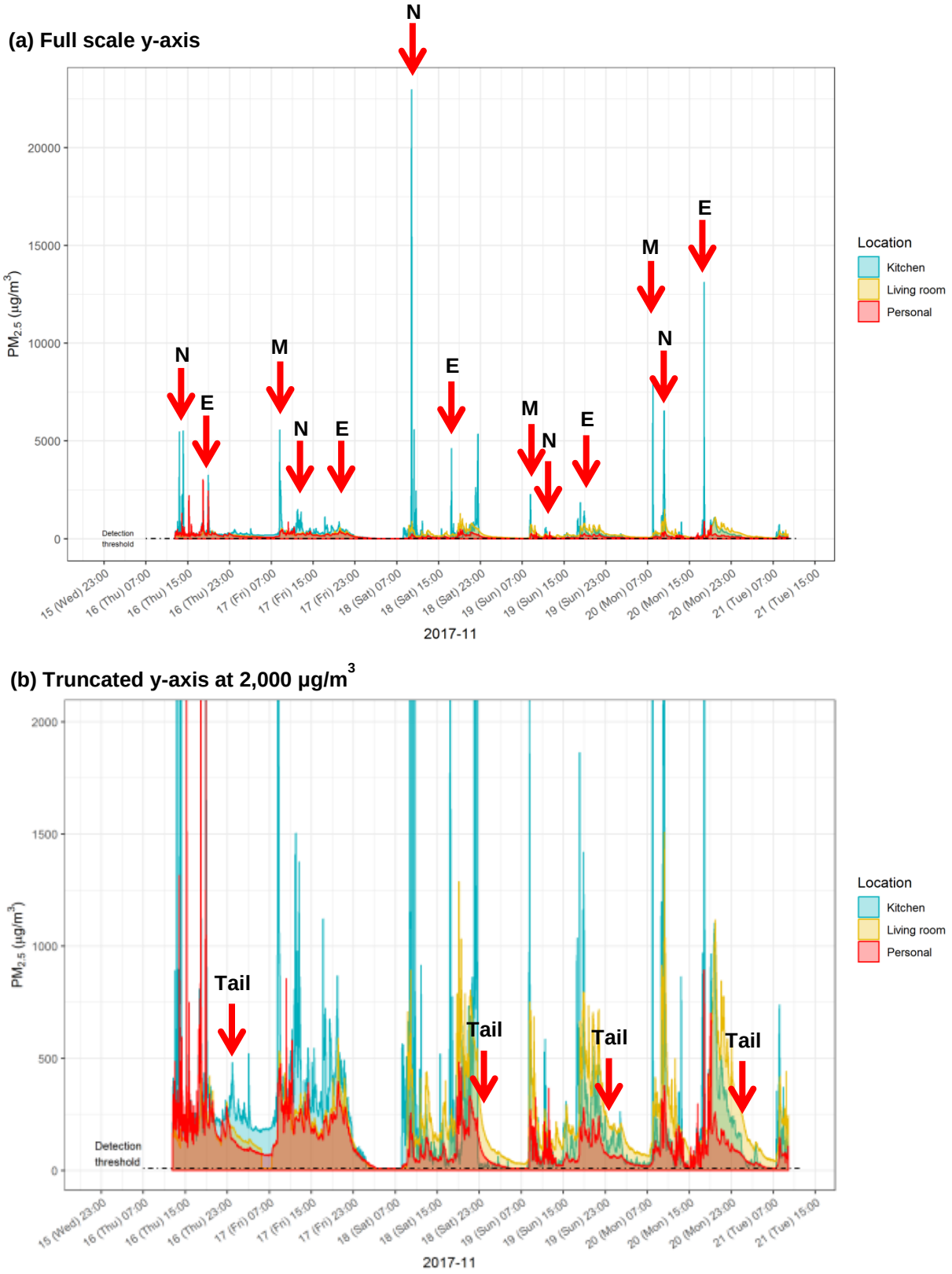


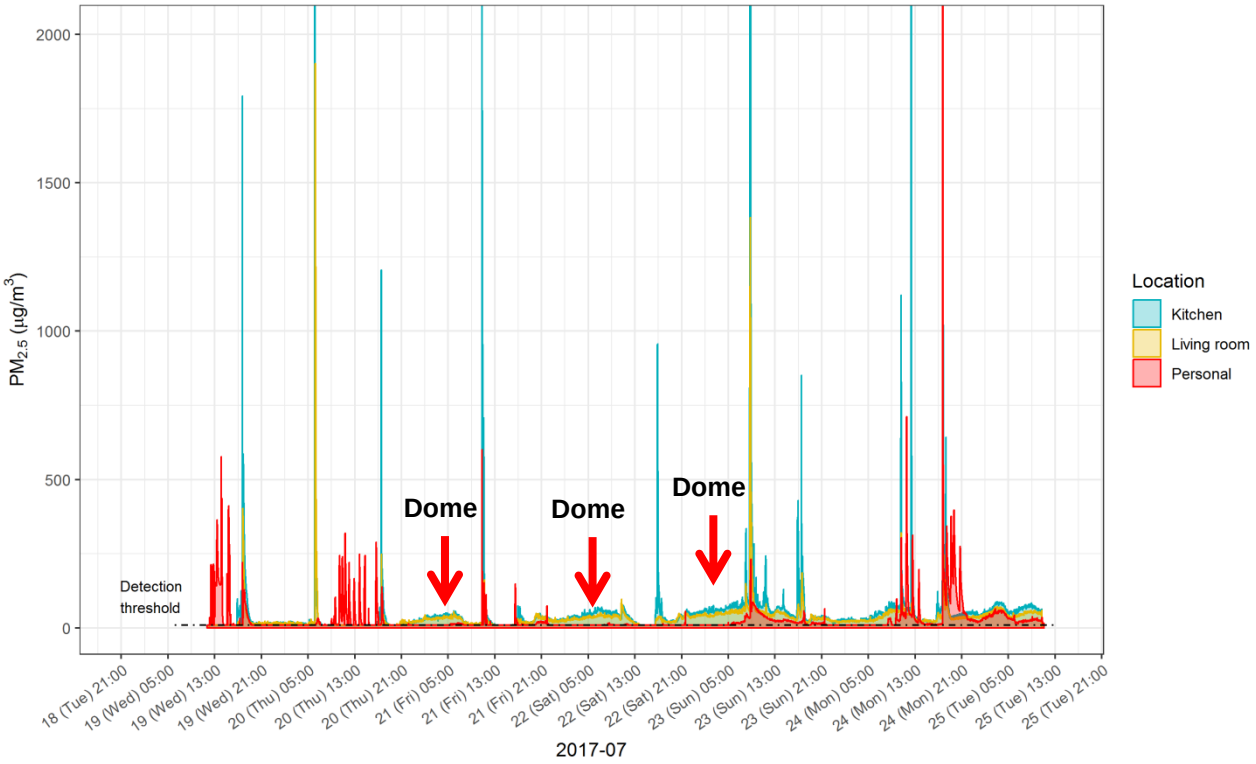
**Figure 8.15 Example of PATS+CO data – Gansu non-smoking female who cooked regularly using clean fuels and wood and used coal for heating in cool season***




*N: noon; E: evening; M: morning; tail: period of exponential decline of $PM_{2.5}$ levels from late evening until the morning of the second day.

**Figure 8.16 Example of PATS+CO data – Suzhou non-smoking female who cooked regularly using clean fuels and had no heating***

Y-axis truncated at 2,000 μg/m$^3$




***** Dome: flat, inversed concave curve of slow increase of $PM_{2.5}$ from evening (~21:00) to early morning (05:00-07:00) of the second day, followed by gradual decline until mid-day.

**Figure 8.17 Example of PATS+CO data – Suzhou non-smoking female who cooked regularly using clean fuels and had no heating in cool season**

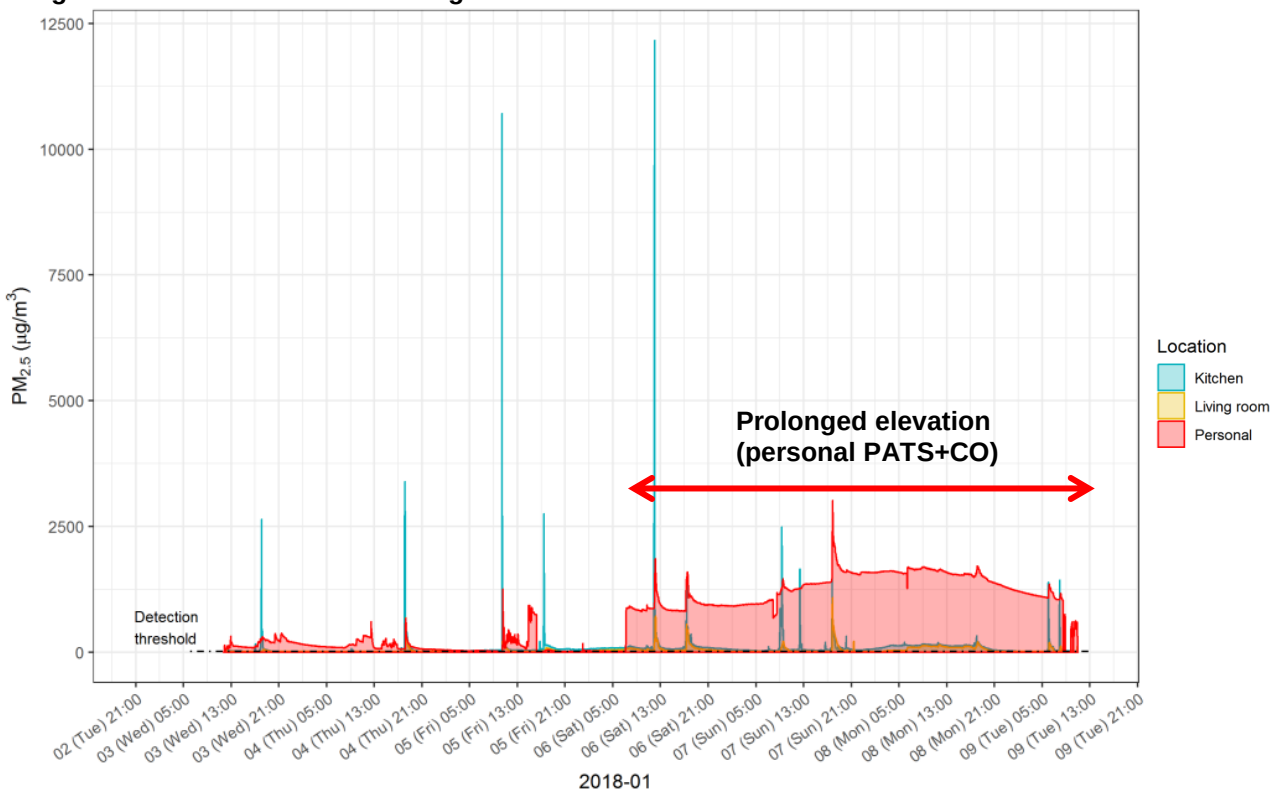
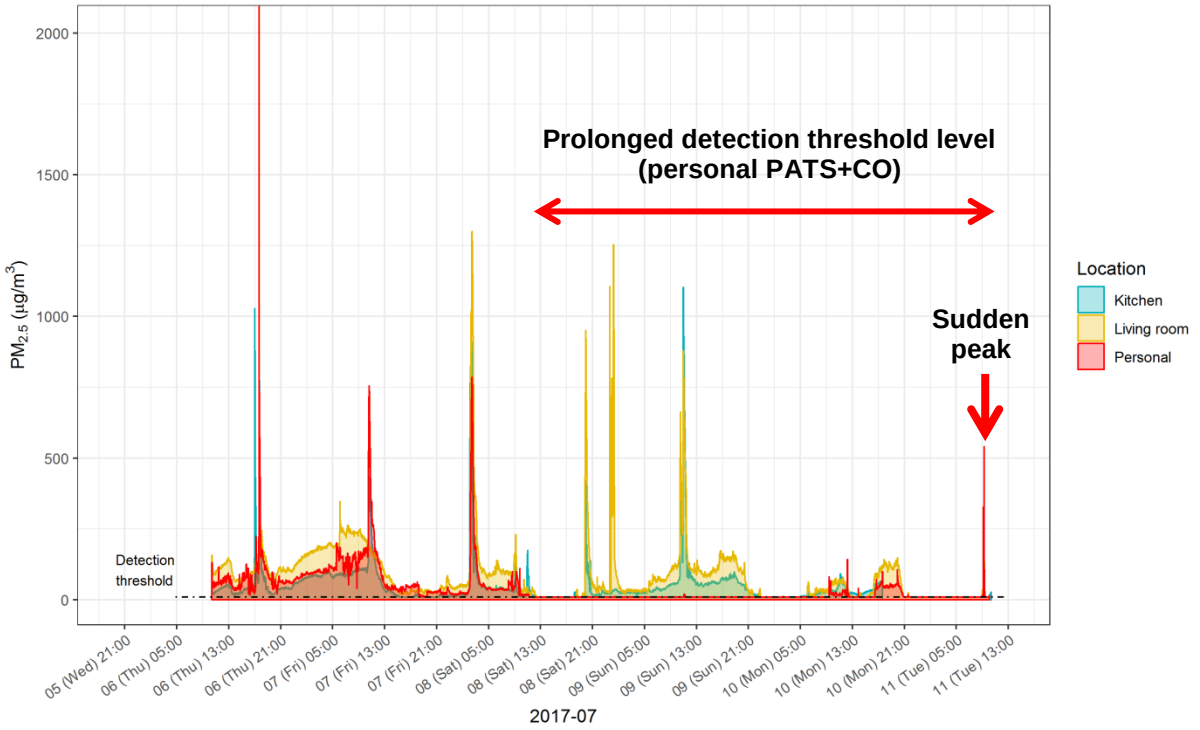


**Figure 8.18 Example of PATS+CO data – Gansu non-smoking female who cooked regularly using clean fuels and coal and used clean fuels for heating***

Y-axis truncated at 2,000 μg/m$^3$




*Prolonged detection threshold level: prolonged period with $PM_{2.5}$ recorded at detection threshold level of 10μg/m$^3$.

**Figure 8.19 Slow burning coal stove used in Henan**



# CHAPTER 9. DISCUSSION

## 9.1 THESIS OVERVIEW

This thesis first examined the regional variation and long-term secular trends of fuel use for cooking and heating and ownership of ventilated cookstoves across ten study areas (**Chapter 5**). These helped to inform subsequent prospective analyses of the association of long-term solid fuel use for cooking and heating with hospitalisation and death from acute and chronic respiratory diseases (**Chapter 6**) and overall and cause-specific cardiovascular death (**Chapter 7**). **Chapter 8** described the design and development of an on-going feasibility study conducted to collect multi-dimensional exposures data to validate and enhance the existing questionnaire-based HAP exposure data. This chapter summarises the key findings from the previous chapters and discusses their implications in a broader context. The key strengths and limitations of the work reported in this thesis are also discussed, followed by recommendations for future research.

## 9.2 KEY FINDINGS

### 9.2.1 Exposure patterns

It is estimated that >2.7 billion individuals use solid fuels for cooking globally, and China has one of the largest population of solid fuel users.[2] However, little is known about the long-term trends and regional variation of solid fuel use in China, and data on heating fuel use has been scarce. Using recall data from the CKB baseline survey (2004-2008) and prospectively collected data from the two subsequent resurveys (2008, 2013-2014), I have examined the long-term trends of self-reported primary fuel use for cooking and heating and ownership of ventilated cookstoves in the CKB population from the 1960's to 2010's.

Consistent with the previous nationwide studies in China,[158,169-173] a general transition from solid to clean fuels for cooking was observed, but with substantial rural-urban disparities. Solid fuel use for cooking was common in both rural and urban areas five decades ago (rural: 98%; urban: 75%), but urban residents switched to clean fuels swiftly and the majority of them used clean fuels at baseline, while rural residents continued to use solid fuels. Cooking fuel in rural areas have been modernising rapidly during 2008-2014, which may be attributed to the rapid expansion of the national electricity grid and continuously decreasing price of electricity over the past decade.[174] Despite this, by 2014 almost 50% of the rural participants still used solid fuels for cooking, compared with 3% of the urban participants. At this rate of modernisation, it is unlikely that China will be able to achieve universal access to clean and affordable energy for cooking by 2030 (as part of the United Nations Sustainable Development Goal Seven[3]) unless more rigorous strategies are put in place.

Although heating is seasonal and climate dependent, emerging evidence suggest that it is a major contributor to HAP exposure and previous disease burden estimation based on cooking fuel use alone might have been underestimated.[32,239] In China, however, the types of fuel used for heating have been changing at a much slower pace than cooking fuel both in rural and urban areas (where 75% and 4% participants still used primarily solid fuels, respectively by 2014), potentially reflecting the cooking-centric research and policy agenda on HAP and domestic energy both in China and globally in the past three decades.[3] As cooking fuels and cookstoves continue to modernise with a growing number of global and national programmes in place,[59,60,204] solid fuel use for heating will become an increasingly important contributor to HAP exposure and a major barrier to achieving universal access to clean energy. Greater attention from both researchers and policymakers is needed to address this problem.

The life-course trajectories of primary fuel use and ventilated cookstove ownership constructed across birth cohorts enabled the assessment of the heterogeneity of

domestic energy modernisation across different generations. In general, older generations adopted clean fuels at a slower pace. As older generations moved away from wood, they tended to switch to coal (as a transitional fuel) before switching to clean fuels, whereas the younger generations tend to adopt clean fuels directly. This demonstrated the possibility of an expedited fuel modernisation that does not follow the traditional energy transition model. Lessons learned in China could help other less developed LMICs to take on a similar route of swift transition, and the country's existing South-South Cooperation programmes across Asia and Africa[240,241] with most of the LMICs provide an ideal platform for knowledge transfer and investment. It is also important to realise that individuals who primarily used clean fuels at baseline could have been exposed to solid fuel use in the past, especially the older generations. Exposure assessment based on current fuel use could result in substantial misclassification.

The descriptive findings from this chapter enabled in-depth understanding about the exposure patterns in the study population, formed the basis of the analysis strategies employed in **Chapters 6 and 7** and prompted the establishment of the feasibility study presented in **Chapter 8**. A systematic exposure classification method based on long-term fuel use experience was developed to distinguish individuals who had always used clean fuels, those who switched from solid to clean fuels and those who had always used solid fuels and to exclude individuals who had more complex and potentially less reliable exposure patterns (e.g. switching from clean to solid fuels). Given the heterogeneity of exposure across study areas, all prospective analyses were stratified by areas; and the varying life-course trajectories of exposure across birth cohorts supported the need of stratification by age-at-risk.

### 9.2.2 Solid fuel use and respiratory disease

Solid fuel use for cooking has been considered as an established risk factor for COPD in adults, but this was based on cross-sectional or case-control studies with small sample sizes,[9-12,14] and recent evidence from large, population-based cross-sectional studies suggested that the magnitude of the association may be largely overestimated.[15-17] To the best of our knowledge, no previous studies have investigated the prospective association between solid fuel use and hospitalisation or death from COPD, which could more directly reflect the imminent burden on the health system. Studies on non-COPD respiratory diseases are scattered and, again, based on very small sample sizes and cross-sectional designs.[12,18,19]

In a subset of 290,000 never-smoking CKB participants without prior history of chronic diseases, long-term solid fuel use for cooking was associated with a range of acute and chronic respiratory diseases, but the association with COPD was much closer to the null compared to the previous meta-analysis estimates,[9-12,14] as reported in several recent large scale cross-sectional studies.[15-17] However, we found significantly stronger association with CLRD, which included mostly COPD and unspecified bronchitis. Indirect evidence in CKB suggested that at least some of these unspecified bronchitis cases may be mild COPD presented to hospitals with inadequate symptomatic or risk exposure information to enable more accurate diagnosis (as spirometry is rarely done in China[15,112]). Therefore, it is possible that the actual strength of association of solid fuel use for cooking with COPD hospitalisation and death lies between those observed with COPD and CLRD.

The excess risks of ALRI related to solid fuel use in this adult Chinese population compliments an abundance of observational evidence linking HAP with childhood ALRI,[4,18] highlighting a potentially underappreciated major disease outcome relevant to HAP exposure in adults. Conversely, although upper respiratory diseases tend to be

mild, the observed HRs were among the highest across all outcomes studied. Given the high background incidence and the recurrent nature of these conditions, the related disease and economic (e.g. loss of productivity) burden could be substantial. Altogether, our findings call for more studies investigating the association between solid fuel use and non-COPD respiratory outcomes, and these may need to be taken into account when evaluating the associated health and economic burden (and benefits of phasing out solid fuels) to better inform policymakers.

Improving ventilation and switching to clean fuels are two common strategies to reduce HAP exposure, but little evidence existed on the long-term respiratory benefits of these interventions, as most previous studies focused on either acute respiratory symptoms or lung function measurements.[59,120] We found suggestive evidence that the use of ventilated cookstoves may attenuate the excess risks of CLRD and upper respiratory diseases related to solid fuel use for cooking, but it had no influence on those of COPD, ALRI or respiratory death. In contrast, individuals who switched their primary fuel from solid to clean fuels had no statistically significant excess risk of any of the respiratory outcomes studied. These are consistent with the existing literature that the decrease of HAP exposure associated with ventilated cookstove interventions in real-life settings (where mixed use of traditional and improved stoves is common) may only be translated to improvements of mild, acute conditions such as respiratory symptoms.[6,59,120] In contrast, clean fuel interventions have been associated with markedly greater reduction of HAP exposure,[59,120] and it is increasingly recognised as a priority strategy to tackle both HAP and AAP in rapidly evolving LMICs such as India and China.[204,242]

Existing evidence on the relationship between solid fuel use for heating and respiratory disease is scarce and inconsistent.[83-90] In CKB, long-term solid fuel use for heating was associated with significantly elevated risks of CLRD and COPD but not with other respiratory diseases after adjusting for cooking fuel exposure and other risk factors. The null associations with diseases other than CLRD and COPD may reflect a net balance

between the excess risks associated with HAP exposure and the potential mediation effect of heating against the elevated risk of acute respiratory disease related to cold temperature.[48-54] However, we had comparatively limited statistical power for these analyses. Further investigation on the potential health effects of heating fuel use and its interaction with indoor and outdoor temperature is needed to clarify this.

### 9.2.3 Solid fuel use and cardiovascular mortality

While there has been decades of effort investigating the relationship between HAP from solid fuel use and respiratory disease, interest on CVD only emerged recently.[21] Most previous studies were based on cross-sectional investigations on the link between solid fuel use for cooking and history of CVD or intermediate cardiovascular conditions such as BP.[26-28,136,139] The limited prospective studies were based on relatively small case numbers and showed inconsistent findings.[19,31]

In 460,000 CKB participants without prior CVD, long-term solid fuel use for cooking was associated with significant excess risk of overall cardiovascular death. The previous prospective studies classified an individual's exposure based on household fuel types without considering personal cooking behaviour,[19,31] whereas our analyses compared the risk associated with different fuel types among regular cooks. Leveraging the large sample size of the CKB, I also explored the relationship with specific causes of cardiovascular mortality and found largely consistent associations with deaths from stroke and other CVD but null association with IHD death. Nonetheless, there could be residual confounding from lipid profiles, which are amongst the strongest risk factors of myocardial infarction (but less so for stroke, especially ICH), as these were not accounted for in the main analyses due to the lack of data. Further investigation into subtypes of IHD (e.g. myocardial infarction versus other IHD) and inclusion of additional data on lipid profiles may offer additional insight into this.

Use of ventilated cookstoves did not appear to alter the excess risks of cardiovascular death associated with solid fuel use for cooking, which is consistent with the observations on respiratory outcomes that improved ventilation may only be relevant to mild, acute conditions. In contrast, those who switched from solid to clean fuels during the recall period had no significantly elevated risk of cardiovascular death, again (as for respiratory outcomes) coinciding with the existing literature that clean fuel adoption is associated with bigger reduction of HAP exposure and, possibly, greater risk attenuation.

Solid fuel use for heating was also found to be associated with significant excess risk of cardiovascular death, but the association appeared to be driven primarily by HS, a highly fatal subtype of stroke.[205] Cold temperature and elevated SBP are some of the most important risk factors of HS, [48-54,57 205] and a specific association of solid fuel use for heating and elevated SBP was observed only in cold months (an indirect approach to capture the effect of heating on SBP). These three factors are closely intertwined with each other, and the current analyses could not clearly distinguish whether solid fuel use for heating interact with cold temperature synergistically (thus the observed association was a combination of excess risk associated with the two factors) or it is confounded by exposure to cold temperature due to poorer heating efficiency as compared to clean fuels. Data from the feasibility study (air pollution exposure, indoor and outdoor temperature) would offer a starting point for further investigation in this complex relationship between heating and temperature, and future studies to collect ambulatory BP would further enhance the mechanistic pathway between these and BP and CVD.

Exploratory analysis examining the joint effect of solid fuel use and smoking on cardiovascular mortality found an approximately log-linear relationship with a tendency of levelling-off at higher risk. This agrees with the IERF of $PM_{2.5}$ used for GBD estimation, which was constructed from multiple independent studies in both HICs and LMICs.[30] However, because of the drastic gender difference in smoking prevalence and cooking

frequency in the CKB, we had limited statistical power to confirm the joint effect in the subgroup analysis by gender, especially for cause-specific cardiovascular death.

### 9.2.4 Feasibility of direct measurement of air pollution exposure

Recognising the limitations of the lack of directly measured HAP exposure data in the prospective studies conducted, a pilot study was established to test the feasibility of collecting multi-dimensional data on personal air pollution exposure for validating and enhancing the existing exposure classification method.

Preliminary findings showed that in 2017-2018 virtually all urban participants in the study used clean fuels exclusively for cooking and heating and mixed use of clean and solid fuels was common in rural areas for cooking, but a large proportion of participants still used mainly solid fuels for heating. This agrees with the slower modernisation trends of heating fuel observed in the whole CKB population. We have also highlighted the heterogeneity of non-cooking individuals, who could be either living in households where cooking is infrequent (and hence low cooking-related HAP exposure) or where cooking is practiced regularly (and potentially elevated cooking-related HAP exposure, depending on specific fuel types used). This supports our analytical approach to isolate individuals who did not cook regularly from clean fuel users, as opposed to including them as part of the reference group as done in some previous studies.

As observed in **Chapter 5**, it was common for participants from Gansu to use either wood or coal for cooking or heating whereas most solid fuel users from Henan used coal only. Wood has been consistently associated with significantly higher levels of $PM_{2.5}$, and consistently, a greater proportion of participants reported their kitchen and homes tend to become smoky during cooking and heating, respectively. The distribution of alternative sources of HAP, such as mosquito coils and slow burning stoves, were also highly site-specific, and future analysis on direct exposure data and personal exposure modelling may need to take into account of these

From the time-activity data, we found that the participants spent the vast majority of their time at home (>80%) in both seasons, suggesting that their air pollution exposure may be reasonably approximated by monitors in their residences. We also observed significantly higher frequency and duration of cooking in the cool season than the warm season, which may account for the generally higher $PM_{2.5}$ and CO levels recorded in the cool season in addition to the use of solid fuels for heating. The cooking frequency and duration reported in the household questionnaire were highly consistent with those reported in the time-activity questionnaire in the same season.

Preliminary inspection of the time-series data from PATS+CO found reasonably reassuring patterns with high consistency across the three monitors of each participant, such as regular peaks of elevated $PM_{2.5}$ and CO levels at typical cooking time (morning, noon, evening) and prolonged elevated levels in homes using solid fuels for heating. Extreme spikes of $PM_{2.5}$ were also recorded in some kitchens of clean fuel users from Suzhou, but these spikes tend to last for a much shorter duration as compared to those observed in homes using solid fuels for cooking, suggesting that the $PM_{2.5}$ recorded may be cooking fumes. We have also identified several key indicators of potential problems of the time-series data of air pollution and devised possible solutions for further data cleaning. The experience from conducting this feasibility study and developing the study materials (e.g. SOPs, device management software) generated important insights into designing future studies of larger scale.

## 9.3 STRENGTHS AND LIMITATIONS

### 9.3.1 Strengths

In **Chapter 5**, I have described one of the largest studies of the regional variation and temporal trends of solid fuel use for cooking and heating as well as ventilated cookstove ownership in rural and urban areas of the CKB. Although CKB was not designed to be nationally representative, our findings were highly consistent with the recent nationwide

studies. This was the first study to examine the long-term trends of heating fuel use or ventilated cookstove ownership, and we revealed a long-overlooked research and policy gap on these two factors. A novel method was applied to construct the life-course trajectories of the three key exposures and revealed important variations across different birth cohorts.

In **Chapters 6** and **7**, I presented two of the largest investigations on the prospective relationships between solid fuel use and respiratory disease and cardiovascular mortality. The prospective design allowed us to carefully deal with reverse causation bias, which has been a major limitation of most previous studies on this topic. Unlike many previous studies that crudely classified exposure based on household fuel use or cooking practice, we isolated non-regular cooks and made comparisons on primary fuel use among regular cooks, thus achieving a less confounded assessment of the associations of interest. Furthermore, these studies were among the first to investigate the role of solid fuel use for heating and the potential joint effect of solid fuel use and smoking in relation to risks of cardiorespiratory disease.

The feasibility study presented in **Chapter 8** utilised state-of-the-art air quality monitors to measure time-resolved personal, household and ambient air pollution levels. We have collected relatively longer-term exposure data (120 hours) covering both weekdays and weekends and across both warm and cool seasons, while most previous studies had only collected data over a 24 to 48 hours period and often without repeat measurement in different seasons.[5,32] All data collection procedures were computer-based and were coordinated by a range of in-house software with built-in logic and error checks to minimise human error. Furthermore, while most previous studies assessed only primary fuel use, we collected a wide range of data relevant to HAP exposure, including all fuel types used for cooking and heating, and the frequency or duration of usage.

### 9.3.2 Limitations

One of the most important limitations that have been highlighted throughout the thesis is the use of on self-reported, residence-based primary fuel use data and lack of directly measured HAP exposure. Self-reported primary fuel use has been a conventional exposure classification method for studying the health effects of HAP from solid fuel use,[5] and earlier studies supported its dominance on household energy consumption and it was considered as a reasonable proxy of HAP exposure.[243] However, emerging evidence shows that a fuel stacking phenomenon is increasingly common in LMICs, especially in areas (of rural China) where the fuel transition is at an intermediate stage (as opposed to early or late stage of transition when most individuals use solid or clean fuels, respectively).[158,244] While data on secondary fuel use remain scarce globally, preliminary data from the feasibility study presented in **Chapter 8** indicated that fuel stacking was indeed common for cooking but less so for heating in the small subset of CKB participants in 2017-2018. The reliance on primary fuel type would be likely to result in underestimation of the associations of interest, because mixed fuel use would attenuate the difference in exposure between the clean and solid fuel users defined according to primary fuel use data.

Even if there were additional data on secondary fuel use, it would be impossible to directly quantify the dose-response relationship between HAP exposure and disease outcomes studied because of the lack of direct exposure data. As presented in **Chapter 8**, direct measurement of HAP is highly resource-intensive, and it is infeasible to be conducted at the scale of CKB. Although the feasibility study included a comparatively small sample size, future analysis to establish the relationship between various fuel combinations and $PM_{2.5}$ and CO would provide important insight into the extent of measurement error in the fuel-based analyses. It would also lay the foundation for conducting future study of greater scale to collect data for personal air pollution

exposure modelling, which would allow direct assessment of the dose-response relationship of interest.

Apart from the above problems, the residential-based recall approach is subject to misclassification from recall bias and within-residence mixed use of fuels or transition of fuel choice. Nonetheless, although the time point of switching primary fuel may be inaccurate at an individual level, the arbitrariness of moving home and changing primary fuel types means that the error at individual level may compensate for each other at a population level, and therefore giving reasonably reliable approximation of the overall temporal trends. This problem also means that the results on total duration of solid fuel use should be interpreted with care that the estimation duration was an approximation of cumulative exposure instead of precise quantification of time.

Another limitation on exposure assessment is the lack of more detailed information on heating fuel use behaviour such as frequency and duration of heating. For example, the current classification based only on primary fuel type used would group individuals who used solid fuels for heating daily and those who used monthly together, potentially resulting in underestimation of the associations of interest. Nonetheless, data from the feasibility study suggested that most participants spent the majority of their time at home and most of the rural participants (Gansu and Henan) heated their home daily and throughout the day, indicating little heterogeneity in heating within these areas. Additional data on heating frequency and duration from all ten study areas would be needed to further clarify this.

In terms of outcome ascertainment, the use of hospitalisation and death records for chronic disease outcomes such as COPD that may suffer from outcome misclassification (e.g. due to under-diagnosis) could result in underestimation of the associations of interest, because the observed risk of solid fuel users (who tend to be at a lower SES and more prone to mis- or under-diagnosis) would be lower than the

actual risk.[190] There would also be inevitable time lags between disease manifestation and the hospitalisation or death events recorded in the record linkage system, and it would be impossible to establish definite temporality for COPD which has prolonged disease development.

As expected for most observational studies, the findings of this thesis are potentially subject to residual confounding. In particular, solid fuel use is strongly linked to SES, which is in turn a strong predictor of cardiorespiratory disease.[245,246] Despite the extensive adjustment made in the main and sensitivity analyses, residual confounding from SES is possible. Furthermore, this thesis included no data on several potential confounders, such as AAP and early life exposure, lipid profiles and detailed occupational exposure history, and we were not able to assess how these factors may influence the associations of interest.

Finally, it is known that HAP exposure varies widely across different populations. The findings in this thesis may not be generalisable to other populations with distinctive fuel use patterns. For example, use of dung and open fire stoves, both of which are associated with extremely high exposure to $PM_{2.5}$, are rare in China but much more common in sub-Saharan Africa.[4,151] Although global HAP exposure modelling data exist,[247] population-based empirical epidemiological evidence would be valuable to better understand the impact of solid fuel use in different countries.

## 9.4 IMPLICATIONS FOR FUTURE RESEARCH

While the work presented in this thesis might have addressed some important knowledge gaps, it has also generated more questions to be answered. Informed by the preceding chapters, this section discusses the need for future research in three key areas, namely exposure assessment, disease outcome and study design.

### 9.4.1 Exposure assessment

As many LMICs and their energy markets continue to develop, fuel stacking will become increasingly common. As such, the current convention of using primary fuel use data in approximating HAP exposure will become less reliable, especially in the younger generations or populations in the middle of the energy transition. There will be a growing need of shifting the basic, questionnaire-based classification method from assessing single primary fuel type to fuel combination. It is also crucial to consider the potential contribution of heating fuel use and stove- and housing-ventilation conditions, as well as the possible seasonal variation of cooking practices in order to more accurately approximate overall HAP exposure. At the same time, more evidence on how different combinations of fuel types, ventilation conditions, time-activity patterns and climate are associated with objectively measured air pollution exposure is needed to construct personal exposure models to further enhance HAP exposure assessment. Beyond HAP, as wearable real-time air quality and activity monitors (e.g. accelerometers and cameras for time-activity patterns) become more reliable and affordable, there are opportunities to reliably capture total personal air pollution exposure to both HAP and AAP sources, and how these interact with other environmental risk factors (e.g. temperature) in relation to cardiorespiratory disease. This could be based on the existing framework used in previous studies on GBD estimation,[75,247] and more comprehensive models could be developed with additional data on population-specific mixed fuel use and time-activity patterns. There is also a pressing need to devise standards for more streamlined and reliable collection of these data, as well as to develop standardised methods to better process, analyse and understand the data collected, given the complexity and volume of the data.

Established large-scale cohort studies[70,73,74,248] offer valuable opportunities for more cost-efficient development of personal air pollution exposure models. Given the large sample size, diverse populations and pre-existing data on participant characteristics in

these cohorts, exposure models can be developed in subset of the cohort and cross-validated in the same study population. The long-term follow-up design of these studies will also enable continuous refinement of the models developed (e.g. to take into account of changing fuel use behaviour), as repeated exposure assessment can be integrated into the existing resurvey structure.

### 9.4.2 Disease outcome

Regarding respiratory disease, there remains a major gap in understanding the relationship between HAP from solid fuel use and respiratory infection in adults, especially on how prolonged solid fuel use may influence the risk of recurrent infection, and whether change of fuel type or improved ventilation could modify the relationship. There is also a need to adjudicate hospitalisation coded as unspecified bronchitis (ICD-10 J40) in the CKB (and future similar studies in LMICs where use of spirometry in COPD diagnosis is rare) in order to better understand the association of HAP exposure with chronic lower respiratory disease.

For CVD, despite having a large sample size, the regional variability in fuel use exposure means that this thesis is underpowered to investigate deaths from specific subtypes of IHD (e.g. myocardial infraction versus angina pectoris) and stroke (e.g. subarachnoid haemorrhage versus intracerebral haemorrhage), which could be highly heterogeneous.[249] Further analysis based on CKB data with longer follow-up or pooling data from other established cohort studies will enable more in-depth investigations into the above specific subtypes of cardiovascular death. Apart from death, there is also a need to better understand the relationships between HAP exposure and pathophysiological markers of the cardiovascular system (e.g. carotid-intima media thickness, BP and lipid profiles) as well as non-fatal cardiovascular events.

It is also important to realise that cardiovascular and respiratory diseases are closely related to each other and, often, characterised by co-morbidity (especially in elderly).

[250] Further study of multi-morbidity may provide a more comprehensive understanding on the overall cardiorespiratory health effects of HAP exposure.

### 9.4.3 Study design

The observational nature of cohort studies makes it impossible to eliminate residual confounding and reverse causation bias. Nonetheless, the suggestive evidence on the possible cardiorespiratory benefits of ventilated cookstoves and clean fuel adoption encourages more investigation based on RCT. It is however important to note that future RCTs must be carefully designed with local knowledge as well as information from conducting pilot studies, and meticulously implemented to minimise the range of challenges that have severely undermined the reliability and validity of the previous RCTs. For disease outcomes with relatively small case numbers, a nested case-control design with study site-specific or propensity score matching based on large cohort studies may be worth exploring as an efficient analytical strategy.[251,252]

## 9.5 CONCLUSIONS

Based on existing data from the CKB, an ongoing prospective cohort study of 0.5 million adult Chinese, we found drastic disparities in cooking and heating fuel modernisation trends across rural and urban areas, different education and income levels and birth cohorts. Rural residents, those with lower education or income level and older generations were significantly slower in adopting clean fuels, and the rate of modernisation of heating fuel was markedly slower than that of cooking fuel. Compared to long-term clean fuel use, long-term solid fuel use for cooking was broadly consistently associated with excess risks of a range of respiratory disease and cardiovascular mortality, but there was suggestive evidence that clean fuel adoption may largely attenuate these risks whereas use of ventilated cookstoves was related to attenuation of risks of mild, acute conditions such as AURI. The lesson learned from the questionnaire-based data prompted the establishment of a feasibility study to obtain

multi-dimensional data to quantify total personal air pollution exposure. Preliminary findings from the feasibility study enabled more in-depth understanding of the limitations of the main analyses described in this thesis and will inform the design and development of future studies on a larger scale, from which personal air pollution exposure models could be developed to validate the main findings of this thesis and quantify the exposure-response relationships of interest more accurately.

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# APPENDICES

## Appendix A. List of publications related to this thesis

**Chan KH**, Lam KBH, Kurmi OP, et al. Trans-generational changes and rural-urban inequality in household fuel use and cookstove ventilation in China: A multi-region study of 0.5 million adults. *Int J Hyg Environ Health* 2017; 220(8): 1370-81.

Yu K*****, Qiu G*****, **Chan KH***, et al. Association of Solid Fuel Use With Risk of Cardiovascular and All-Cause Mortality in Rural China. *JAMA* 2018; 319(13): 1351-61. **Co-first authors*

**Chan KH**, Kurmi OP, Bennett DA, et al. Solid fuel use and risks of respiratory diseases: a cohort study of 280,000 Chinese never-smokers. *Am J Respir Crit Care Med* 2018 (in press).

**Appendix B1. Baseline questionnaire of the China Kadoorie Biobank Study (paper representation)**

## Section 1: Background information

**1.1 Study ID:** ☐☐☐☐☐☐☐☐☐☐☐☐☐ *(The date & time of interview will be recorded by computer)*

**1.2 Name_____, Sex :** Male ☐ Female ☐ , **Name of spouse**_____

**1.3 Date of birth:** ☐☐☐☐ Year ☐☐ Month ☐☐ Day

**1.4 National ID number (if no, put #)** ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

**1.5 Home address :** _____ Province _____ City_____ District/County _____ Street/Village

**Home telephone:** Not available ☐ , ☐☐☐-☐☐☐☐☐☐☐☐

---

**1.6 What is the highest level of school education you ever received?**

- ☐ No formal school
- ☐ Primary School
- ☐ Middle School
- ☐ High School
- ☐ Technical school / college
- ☐ University

---

**1.7 What is your current occupation?**

- ☐ Agriculture & related workers
- ☐ Factory worker
- ☐ Administrator / manager
- ☐ Professional / technical
- ☐ Sales & service workers
- ☐ Retired
- ☐ House wife / husband
- ☐ Self-employed
- ☐ Unemployed
- ☐ Other or not stated

---

**1.8 How many people living together in the household?** ☐☐ persons

**1.9 What is your current marital status?**

- ☐ Married
- ☐ Separated / divorced
- ☐ Widowed
- ☐ Never married

**1.10 What is the total income last year in your household?**

- ☐ <2,500 yuan
- ☐ 2,500-4,999 yuan
- ☐ 5,000-9,999 yuan
- ☐ 10,000-19,999 yuan
- ☐ 20,000-34,999 yuan
- ☐ ≥35,000 yuan

**1.11 Do you have any health care cover and following items in your household?**

| Yes | No | |
|---|---|---|
| ☐ | ☐ | Health care cover |
| ☐ | ☐ | Own house / apartment |
| ☐ | ☐ | Toilet for private use |
| ☐ | ☐ | Telephone or mobile phone |
| ☐ | ☐ | Motor vehicle (e.g. car or motorbike) |
| ☐ | ☐ | Holiday during last five years |

## Section 2: Tea drinking

**2.1 During the past 12 months, how often did you drink any tea?**

- ☐ Never or almost never
- ☐ Only occasionally
- ☐ Only at certain seasons
- ☐ Every month but less than weekly
- ☐ Usually at least once a week → ***Go to Q2.3*** (were2.2)

**2.2**(were 2.1a) **In the past, did you ever have a period of at least 1 year during which you usually drank tea at least once a week?**

- ☐ Yes, → (were 2.1b) if so, how long ago did it end? ☐☐ Years } ***Go to section 3***
- ☐ No

**2.3**(were 2.2) **During the past 12 months, on how many days did you drink tea in a typical week?**

- ☐ 1-2 days/week
- ☐ 3-5 days/week
- ☐ Daily or almost every day

**2.4**(were2.3)**At about what age did you start drinking tea in most weeks?** ……. ☐☐ Years

**2.5**(were2.4)**On days when you drink tea, how many cups do you usually drink?** (choose one only)

Green /Jasmine tea …… ☐☐ cups/day

Oolong tea …… ☐☐ cups/day

Black tea …… ☐☐ cups/day

Other tea …… ☐☐ cups/day

---

**2.6**(were2.5) **How often do you change tea leaves during a day?** …… ☐☐ times

---

**2.7**(were2.6) **About how much tea leaves do you usually add each time?** ☐☐ Grams

---

**2.8**(were2.7) **What strength of tea do you usually prefer to drink?**

☐ Weak
☐ Moderate
☐ Strong

---

**2.9**(were2.8) **At about what temperature do you usually drink your tea?**

☐ Room temperature / warm
☐ Hot
☐ Burning hot

---

**2.10**(were2.9)**Has your tea consumption changed significantly compared with that some years ago?**

☐ About the same as before, ☐ Has increased a lot, ☐ Has decreased a lot

---

## Section 3: Alcohol consumption

**3.1**(were3.0) **Have you drunk any alcohol today?** ☐ Yes , ☐ No

**3.2**(were3.1)**During the past 12 months, how often did you drink any alcohol?**

☐ Never or almost never
☐ Only occasionally
☐ Only at certain seasons
☐ Every month but less than weekly

☐ Usually at least once a week → ***Go to Q3.4*** (wereQ3.2)

---

**3.3**(were3.1a)**In the past, did you ever have a period of at least 1 year, during which you usually drank some alcohol at least once a week?**

☐ Yes, →(were 3.1b) If so, how long ago did it end? ☐☐ Years } ***Go to section 4***
☐ No

---

**3.4**(were3.2)**During the past 12 months, on how many days did you drink alcohol in a typical week?**

☐ 1-2 days/week
☐ 3-5 days/week
☐ Daily or almost every day

---

**3.5**(were3.3)**At about what age did you start drinking some alcohol in most weeks?** ☐☐ Years

---

**3.6**(were3.4) **On days when you drink, how much alcohol do you usually drink in a day?**

**(**Can choose up to 3 types of alcohol for special occasions; for beer, 1 large bottle=2 small ones**)**

| **Alcohol type** | **On a typical day (choose one)** | **On a special day when you drink a lot** | **Last time when you drank** |
|---|---|---|---|
| Beer (large) | ☐☐ Bottle | ☐☐ Bottle | ☐☐ Bottle |
| Rice Wine | ☐☐ liang | ☐☐ liang | ☐☐ liang |
| Wine | ☐☐ liang | ☐☐ liang | ☐☐ liang |
| Spirit (≥50% alcohol) | ☐☐ liang | ☐☐ liang | ☐☐ liang |
| Spirit (<50% alcohol) | ☐☐ liang | ☐☐ liang | ☐☐ liang |

---

**3.7**(were3.5)**On a typical day when you drink alcohol, when do you usually take the drink?**

☐ Usually drink with the meal
☐ Usually drink between or after the meals
☐ No regular pattern

---

**3.8**(were3.6)**After drinking alcohol, do you usually experience hot flushes or dizziness?**

☐ Yes, soon after first mouthful

- ☐ Yes, after drinking small amount of alcohol
- ☐ Yes, but only after drinking large amount of alcohol
- ☐ No

---

**3.9**(were3.7)**During the past month, how often have you drunk alcohol in the morning?**

- ☐ Never
- ☐ <1 day/week
- ☐ A few days a week
- ☐ Daily or almost daily

---

**3.10**(were3.8)**During the past month, have you ever had the following experiences?**

| **Yes** | **No** | |
|---|---|---|
| ☐ | ☐ | Unable to work or to do anything because of drinking |
| ☐ | ☐ | Felt depressed, irritated or couldn't control yourself after drinking |
| ☐ | ☐ | Could not keep away from drinking |
| ☐ | ☐ | Had shakes when you stopped drinking |

---

**3.11**(were3.9) **Has your alcohol consumption changed significantly compared with that some years ago?**

- ☐ About the same as before
- ☐ Has increased a lot
- ☐ Has decreased a lot

---

## Section 4: Smoking history

**4.1**(were4.0) **Have you smoked any tobacco today?☐ Yes , ☐ No,** →if yes, how many: __ total, __in last hour

**4.2**(were4.1)**How often do you smoke tobacco now?**

☐ Do not smoke now
☐ Only occasionally
☐ Yes, on most days
☐ Yes, daily or almost every day } → ***Go to Q4.7*** ( were Q4.5)

---

**4.3**(were4.2)**In the past, how frequently did you smoke?**

☐ Did not smoke
☐ Smoked only occasionally
☐ Smoked on most days
☐ Smoked daily or almost every day } → ***Go to Q 4.5*** (were Q4.3)

**4.4**(were4.2a)**In your life time, have you smoked a total of at least 100 cigarettes or equivalent?**

☐ Yes
☐ No } ➔ ***Please go to section 5***

---

**4.5**(were4.3)**How many years ago did you last stop smoking regularly?** ☐☐ Years

**4.6**(were4.4)**What was your main reason for stopping?**

☐ Physical illness that you already had
☐ Money
☐ Health concerns (about future illness)
☐ Family against
☐ Other

---

**4.7**(were4.5)**At about what age did you first start smoking on most days?** ☐☐ Years

**4.8**(were4.6)**What tobacco did you use when you first started smoking on most days?**

Mainly cigarette ☐, Mainly non-cigarette ☐, Mixed types ☐

↳( 4.6a ) If so, have you always smoked some cigarettes on most days, never having a month or more without them? Yes ☐, No ☐

---

**4.9**(were4.7)**How much tobacco do you usually smoke (or did you smoke before giving up)?**

Filter cigarettes (factory) …… ☐☐ number/day

Non-filter cigarettes (factory)…… ☐☐ number/day

Hand-rolled cigarettes …… …… …… ☐☐ liang/month

Pipe or water pipe …… ☐☐ liang/month

Cigars …… ☐☐ number/day

---

**4.10**(were4.9) **How deeply do you usually inhale the smoke?**

☐ Mouth only
☐ Throat
☐ Lung ➔ 4.9a Have you always inhaled the smoke into your lung when smoking? Yes ☐, No ☐

---

**4.11**(were4.10)**Has your tobacco consumption changed significantly compared with that some years ago?**

☐ About the same as before, ☐ Has increased a lot, ☐ Has decreased a lot

---

## Section 5: Diet

**5.1**(were5.2)**During the past 12 months, about how often did you eat the following foods?**

| | Daily | 4-6 days per week | 1-3 days per week | Monthly | Never/rarely |
|---|---|---|---|---|---|
| Rice | ☐ | ☐ | ☐ | ☐ | ☐ |
| Wheat | ☐ | ☐ | ☐ | ☐ | ☐ |
| Other staple food (corn, millet etc.) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Meat | ☐ | ☐ | ☐ | ☐ | ☐ |
| Poultry | ☐ | ☐ | ☐ | ☐ | ☐ |
| Fish/sea food | ☐ | ☐ | ☐ | ☐ | ☐ |
| Fresh eggs | ☐ | ☐ | ☐ | ☐ | ☐ |
| Fresh vegetables | ☐ | ☐ | ☐ | ☐ | ☐ |
| Soybean products | ☐ | ☐ | ☐ | ☐ | ☐ |
| Preserved vegetables | ☐ | ☐ | ☐ | ☐ | ☐ |
| Fresh fruit | ☐ | ☐ | ☐ | ☐ | ☐ |
| Dairy products (milk, yogurt) | ☐ | ☐ | ☐ | ☐ | ☐ |

---

**5.2**(were5.3)**During the past 12 months, have you taken the following supplements regularly?**

| Yes | No | |
|---|---|---|
| ☐ | ☐ | Fish oil/cod liver oil |

☐ ☐ Vitamins

☐ ☐ Calcium/iron/zinc

☐ ☐ Ginshen (at least 5 or more times during a year)

☐ ☐ Other herbal products

---

**5.3**(were5.3a)**Have you ever experienced any severe food shortage?** ☐Yes, ☐ No → ***Go to Q5.6(wereQ5.3c)***

**5.4**(were5.3a1)**What year was the worst food shortage you experienced? _____ years**

**5.5**(were5.3b)**During the most severe food shortage you experienced:**

**5.5.1− did you lose weight?** ☐ Yes, ☐ No, → If yes, about how much? _____ ***jin*,**

**5.5.2− did you develop any specific disease related to food shortage?** ☐ Yes, ☐ No

**5.6**(were5.3c)**How many years have you had a refrigerator in your home?** ☐☐ Years

---

**5.7**(were5.4) **During the past month, about how often did you eat hot spicy food?**

☐ Never or almost never
☐ Only occasionally
☐ 1-2 days/week
} → ***Go to section 6***
☐ 3-5 days/week
☐ Daily or almost every day

---

**5.8**(were5.5)**At what age did you start to eat spicy food at least once a week?** ☐☐ Years

**5.9**(were5.6)**What strength of spicy food do you usually prefer to eat?**

☐ Weak, ☐ Moderate, ☐ Strong

**5.10**(were5.7)**On day when you eat spicy food, what are the main sources of spice usually used?**

**Yes No**

☐ ☐ Chili sauce

☐ ☐ Chili oil

☐ ☐ Dried chili pepper

☐ ☐ Fresh chili pepper

☐ ☐ Other or don't know

---

## Section 6: Passive smoking & indoor air pollution

**6.1 Have you ever lived with smoker in the same house for at least 6 months?**

☐ Never
☐ Yes, but not now
☐ Yes, at present } → ***If yes, duration of living together*** ☐☐ years

---

**6.2 How frequently are you exposed to other people's tobacco smoke either at home, workplace or in public places?** *(i.e. a minimum of 5 consecutive minutes each time)*

☐ Never or almost never } → ***Go to Q6.4***
☐ Occasionally (<1 time/week) }
☐ 1-2 days/week
☐ 3-5 days/week
☐ Daily or almost every day

---

**6.3 What is the usual duration of your exposure per week?** ☐☐ Hours

---

**6.4 During past year, how long did you store pesticides at home?** ☐☐ Months

---

**6.5**(were6.4a)**Please tell us the duration you lived in 3 most recent houses** (each for at least 1 year)?

**Present house** ☐☐ years
**Previous house** ☐☐ years
**The house before previous** ☐☐ years

---

**6.6**(were6.5) **In your present & two previous houses, how often did you cook at home?**

☐ Daily
☐ Weekly
☐ Monthly
☐ Never/Rarely → ***Go to Q6.10*** **(wereQ6.8)**
☐ No cooking facility → ***Go to Q6.11*** (wereQ6.11)

---

**6.7**(were6.6)**In your present & two previous houses, what was the main cooking fuel used?**

☐ Gas
☐ Coal
☐ Wood
☐ Electricity
☐ Other

**6.8**(were6.7)**In your present & two previous houses, what was the main cooking oil used?**

☐ Rapeseed ☐ Lard

☐ Peanut ☐ Other

☐ Soybean

**6.9**(were6.7a)**How much time have you spent on cooking so far today?** | | minutes

---

**6.10**(were6.8)**In your present & two previous houses, did your stove(s) all have a chimney / extractor?**

☐ Yes ☐ Not all stoves ☐ No

---

**6.11**(were6.9)**In your present & two previous houses, was your stove always kept under slow burning throughout the day?**

☐ Yes, always ☐ Yes, sometimes ☐ No → if ticked, ***Go to Q6.14***

**6.12**(were 6.9a) **If yes , types of the fuel most commonly used?**

☐ Smokeless coal ☐ Coal brick / Coalite

☐ Smoky coal ☐ Other

**6.13**(were 6.9b) **And , the place where stove was usually kept?**

☐ Inside the house ☐ Outside the house

---

**6.14**(were6.11)**In winter, did you normally heat your house?**

☐ Yes, ☐ No

**6.15 If yes, what was the main heating fuel used?**

☐ Central heating ☐ Wood

☐ Gas ☐ Electricity

☐ Coal ☐ Other

---

**6.16**(were6.12)**From what year did the inside of your house tend to be coal-smoky in winter?**

☐ Never → if ticked, ***Go to section 7***

☐ Ever since childhood

☐ Since the year: _____ year

**6.17**(were6.13)**In what year did the inside of your house stop being really coal-smoky in winter?**

☐ In the year: _____ year

☐ Still is

---

## Section 7: Personal & family medical history

### 7.1 How is your current general health status?

7.1.1 Self-rated health status?

- ☐ Excellent
- ☐ Good
- ☐ Fair
- ☐ Poor

7.1.2. Compared to someone of your own age?

- ☐ Better
- ☐ About the same
- ☐ Worse
- ☐ Don't know

---

### 7.2 If you were walking on level ground with other healthy people of the same age, would you usually:

7.2.1 Become short of breath? ☐ Yes ☐ No ☐ Disabled

7.2.2 Slow down due to chest discomfort? ☐ Yes ☐ No ☐ Disabled

---

### 7.3 During the past 12 months, have you usually had the following symptoms?

7.3.1 Cough frequently?

- ☐ No
- ☐ Yes, for <3 months
- ☐ Yes, for ≥3months

7.3.2 Cough up sputum after getting up in the morning?

- ☐ No
- ☐ Yes, for <3 months
- ☐ Yes, for ≥3 months

---

### 7.4 Has a doctor EVER told you that you had had the following disease?

| | Diagnosed disease? | | Age at first | Still on treatment? | |
|---|---|---|---|---|---|
| | **Yes** | **No** | **diagnosis** | **Yes** | **No** |
| Diabetes | ☐ | ☐ | _____ | ☐ | ☐ |
| CHD | ☐ | ☐ | _____ | ☐ | ☐ |
| Stroke or TIA | ☐ | ☐ | _____ | ☐ | ☐ |
| Hypertension | ☐ | ☐ | _____ | ☐ | ☐ |
| Rheumatic heart dis. | ☐ | ☐ | _____ | ☐ | ☐ |

| | | | | | | |
|---|---|---|---|---|---|---|
| TB | ☐ | ☐ | _____ | ☐ | ☐ | For CHD, stroke, and hypertension what is the current medication: |
| Emphysema/bronchitis | ☐ | ☐ | _____ | ☐ | ☐ | |
| Asthma | ☐ | ☐ | _____ | ☐ | ☐ | 1. Aspirin |
| Cirrhosis/chronic hepatitis | ☐ | ☐ | _____ | ☐ | ☐ | 2. ACE-I |
| Peptic ulcer | ☐ | ☐ | _____ | ☐ | ☐ | 3. Beta-blocker |
| Gallstone/gallbladder dis. | ☐ | ☐ | _____ | ☐ | ☐ | 4. Statins |
| Kidney disease | ☐ | ☐ | _____ | ☐ | ☐ | 5. Diuretics |
| Fracture | ☐ | ☐ | _____ | ☐ | ☐ | 6. $Ca^{++}$ antagonist |
| Rheumatoid arthritis | ☐ | ☐ | _____ | ☐ | ☐ | |
| Psychiatric disorders | ☐ | ☐ | _____ | ☐ | ☐ | |
| Neurasthenia | ☐ | ☐ | _____ | ☐ | ☐ | |
| Head injury | ☐ | ☐ | _____ | ☐ | ☐ | |
| Cancer* | ☐ | ☐ | _____ | ☐ | ☐ | |

***If yes, please indicate the site of cancer** ☐ *(If more than one, choose the one that occurred first)*

0. Lung 1. Esophagus 2. Stomach 3. Liver 4. Intestine 5. Breast 6. Prostate 7. Cervix 8. Other

---

**7.5 Have many blood transfusions have you ever received?** *(If none, put 0)* ☐☐ times

---

**7.6**(were7.5a)**How many times have you ever donated blood for financial payment?**

*(If none, put 0)* ☐☐ times

---

**7.7**(were7.6)**About how often do you have bowel movements each week?**

- ☐ More than once on most days
- ☐ About daily
- ☐ Once every 2-3 days
- ☐ Less than 3 times a week

---

**7.8**(were7.7)**How often do your gums bleed when you brush your teeth?**

- ☐ Occasionally, rarely or never
- ☐ Sometimes
- ☐ Always
- ☐ Brush teeth rarely or never

---

**7.9**(were7.8)**How many brothers & sisters do you have?(***Including half siblings. If unknown, put#)*

**7.10**(were7.9)**How many children do you have?** *(Including only biological ones)*

---

**7.11**(were7.9a)**Is your mother still alive?**

- ☐ Yes → If ticked, current age:
- ☐ No → If ticked, age at death:
- ☐ Unknown

**7.12**(were7.9b)**Is your father still alive?**

- ☐ Yes → If ticked, current age:
- ☐ No → If ticked, age at death:
- ☐ Unknown

---

**7.13**(were7.10) **Did any of your parents, siblings or children have following diseases?** *(For sibling and children, please record the number with disease***)**

| | **Stroke** | **Heart attack** | **Diabetes** | **Mental disorder** | **Cancer** |
|---|---|---|---|---|---|
| **Mother** *(tick box)* | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Father** *(tick box)* | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Siblings** *(inclu. half)* | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Children** | ☐ | ☐ | ☐ | ☐ | ☐ |

---

## Section 8U: Physical activities (Urban)

**8.1 During the past 12 months, how active were you at work?**

☐ Mainly sedentary (e.g. office worker)

☐ Standing occupation (e.g. guard, shop assistant)

☐ Manual work (e.g. plumber, carpenter)

☐ Heavy manual work (e.g. miner, construction worker)

☐ Retired or housewife/husband or unemployed or disabled → ***If ticked, please go to Q8.8***

**8.2**(were8.1a) **In a typical week, about how many hours did you usually work? _____ hours**

---

**8.3**(were8.2) **During the past 12 months, how did you usually get to work?**

☐ Mainly walk

☐ By motorbike

☐ By bicycle

☐ By bus/car/ferry/train

☐ Mainly stay at home or work near home

↳***If ticked, please go to Q8.8***

---

**8.4**(were8.3) **How much time did you spend each day on journey to & from work? ____minutes**

---

## Section 8F: Physical activities (New section for rural farmers)

**8.1 During the past 12 months, did your farming work change seasonally?**

☐ No → ***go to Q8.3***

☐ Yes

---

**8.2 During the farming season in the last 12 months:**

8.2.1 How many months did it usually last? ☐☐ month

8.2.2 What types of work did it usually involve?

☐ manual ☐ Semi-mechanized ☐ Fully mechanized

8.2.3 How many hours did you usually work each day? ☐☐ hours

8.2.4 Of which , how many hours did you sweat or have a much faster heartbeat?

| | | hours

---

**8.3 In a typical week, how many hours did you usually work in the field?** | | hours

---

**8.4 Apart from agriculture work, did you have any other job?**

☐ No → ***go to Q8.7***

☐ Yes

---

**8.5 How active were you at work with other job?**

☐ Mainly sedentary

☐ Mainly standing

☐ Mainly general manual work

☐ Mainly heavy manual work

---

**8.6 In a typical week, about how many hours did you work at other job?** | | hours

---

**8.7 In a typical day how much time did you usually spend on the journey to and from work on foot or by bicycle?** | | | minutes

---

## Section 8C: Physical activities (Common to both rural farmers and urban)

**8.8 During the past 12 months, how often did you do exercise in your leisure time?**

☐ Never or almost never } → ***If ticked, please go to Q8.11***

☐ 1-3 times/month

☐ 1-2 times/week

☐ 3-5 times/week

☐ Daily or almost every day

---

**8.9 What is your main type of exercise?** *(tick one box only)*

☐ Taichi / Qigong

☐ Walking

☐ Jogging/aerobic exercise ☐ Swimming

☐ Ball games (basketball, table tennis, etc) ☐ Other (eg. mountain climbing)

**8.10 About how many hours per week did you do such exercise in leisure time? ___ hours**

---

**8.11 In a typical week during the past 12 months, how often did you sweat or have a much faster heartbeat because of heavy physical activities/exercise?**

☐ Never or almost never } → ***If ticked, please go to Q8.13***

☐ <1 time / week ☐ 3-5 times/week

☐ 1-2 times/week ☐ Daily or almost every day

---

**8.12 About how many hours per week did you do such activities? _____ hours**

---

**8.13 About how many hours per week did you do house work? _____ hours**

**8.14 About how many hours per week did you watch TV or read? _____hours**

---

**8.15 During the past 12 months, has your weight changed significantly?**

☐ About the same as before ☐ Yes, gained ≥2.5 kg ☐ Yes, lost ≥2.5 kg

---

**8.16 Have you tried to reduce weight in the past 12 months?** No ☐, Yes ☐

---

**8.17 How much did you weigh when you were at age 25?** (If unknown put #) ☐☐☐ jin

---

## Section 9: Reproductive history (for women)

**9.1 How old were you when you had your first menstrual period?** ☐☐ Year

---

**9.2 Have you had your menopause?**

☐ No
☐ Yes, currently
☐ Yes, had menopause → If so, age of completion of menopause: ☐☐ Year

---

**9.3 How many times have you ever been pregnant?** ( if none, put 0. Go to Q9.6 ) ☐☐ times

**— Of which,**

Live birth ☐☐ times → If none, Go to Q9.5 (wereQ9.6)

Still birth ☐ times, Spontaneous abortion ☐☐ times, Induced abortion ☐☐ times

---

**9.4 Age and length of breastfeeding at each live birth (twins=one birth)?**

| Live Birth | Age at end of pregnancy | Months of breastfeeding |
|---|---|---|
| 1st | ☐☐ | ☐☐ |
| 2nd | ☐☐ | ☐☐ |
| 3rd | ☐☐ | ☐☐ |
| 4th | ☐☐ | ☐☐ |
| 5th | ☐☐ | ☐☐ |

---

**9.5**(were9.6)**Have you ever used oral contraceptive pills?**

☐ Never → ***If ticked, please go to Q9.8*** (were Q9.9)

☐ Past use → **if ticked,** age when you last stopped the pill: ☐☐ Year

☐ Current use

**9.6**(were9.7)**How old were you when you first used oral contraceptives**? | | | Year

**9.7**(were9.8)**For how long altogether have you used oral contraceptives?** | | | Year

---

**9.8**(were9.9)**Have you had a hysterectomy**?

☐ No **,** ☐ Yes → If yes, age when you had the operation | | | Year

---

**9.9**(were9.10)**Have you had one or both ovaries removed?**

☐ No **,** ☐ Yes → If yes, age when you had the most recent operation | | | Year

---

**9.10**(were9.11) **Have you ever had surgery to remove a breast lump?**

☐ No, ☐ Yes → If yes, age when you most recently had the operation | | | Year

---

## Section 10: Sleeping, mood & mental situation

**10.1 In general, how satisfied are you with your life?**

- ☐ Very satisfied
- ☐ Satisfied
- ☐ Neither satisfied nor dissatisfied
- ☐ Unsatisfied
- ☐ Very unsatisfied

---

**10.2 Over the past two years have you had any of the following major events in your life?**

| Yes | No | | Yes | No | |
|---|---|---|---|---|---|
| ☐ | ☐ | Marital separation/divorce | ☐ | ☐ | Major injury or traffic accident |
| ☐ | ☐ | Loss of job/retirement | ☐ | ☐ | Death /major illness of spouse |
| ☐ | ☐ | Business bankrupt | ☐ | ☐ | Death/major illness of other close family member |
| ☐ | ☐ | Violence | ☐ | ☐ | Major natural disaster (e.g. flood & drought) |
| ☐ | ☐ | Major conflict within family | ☐ | ☐ | Loss of income / living on debt |

---

**10.3 During the past month, did you have any of the following for ≥3 days each week?**

| Yes | No | |
|---|---|---|
| ☐ | ☐ | Taking >30 minutes to fall asleep after going to bed or waking up in the middle of the night |
| ☐ | ☐ | Waking up early and not being able to go back to sleep |
| ☐ | ☐ | Needing to take medicine (including herbal or sleeping pills) at least once a week to help sleep |
| ☐ | ☐ | Having difficulty staying alert while at work, eating or meeting people during daytime |

---

**10.4 Do you usually take a daytime nap?** ☐ Yes usually, ☐ Yes ,but only in summer , ☐ No

**10.5**(were10.4a) **Do you snore during sleep?** ☐ Yes, Frequently, ☐ Yes, Sometimes, ☐ No / Don't know

**10.6**(were10.5)**How many hours do you typically sleep per day (incl. naps)?** ☐☐ Hours

---

**10.7**(were10.6)**During the past 12 months, have you had following situations for 2 or more weeks?** *(If answer yes to any of the questions, complete CIDI-A)*

| Yes | No | |
|---|---|---|
| ☐ | ☐ | Feeling much more sad, or depressed than usual |
| ☐ | ☐ | Loss of interest in most things like hobbies or activities that usually give you pleasure |

☐ ☐ Felt so hopeless that you had no appetite to eat even your favourite food

☐ ☐ Feeling worthless and useless, everything went wrong was your fault and life is very difficult that there was no way out

---

**10.8**(were10.7) **During the past 12 months, have you experienced the following situations?**

**Yes No**

☐ ☐ Having a period lasting one month or longer when most of time you felt worried, tense, or anxious and it interfered your life *(if yes, complete CIDI-B)*

☐ ☐ Having a pain or discomfort in your body lasting ≥3 months that interfered with your life

☐ ☐ Having had a spell or an attack when all of sudden felt frightened, anxious, or very uneasy

☐ ☐ Having had inexplicable strong fear in situations such as closed space (cave, elevator, airplane etc), in the crowds or public such that you would avoid such situations

---

## Section 11: Physical examination

**11.1** **Standing height** (without shoes) …… ☐☐☐.☐ cm

**11.2** **Sitting height** …….…… ☐☐☐.☐ cm

**11.3** **Waist** …… ☐☐☐.☐ cm

**11.4** **Hip** …… ☐☐☐.☐ cm

**11.5** **Weight** (without shoes, but in light clothing) …… ☐☐☐.☐ Kg

**11.6** **BMI** …… ☐☐.☐ $Kg/m^2$

**11.7** **Impedance** …… ☐☐☐ **Ω**

*Staff code*

**11.8** **Fat %** (with one decimal point) …… ☐☐.☐ ☐☐☐

---

**11.9** **Did you take any drugs to lower blood pressure in the last 2 days?** ☐ Yes ☐ No

**11.10** **Blood pressure & heart rate** (to be measured after 5 minutes in the seated position)

| | First | Second | |
|---|---|---|---|
| **SBP** | ☐☐☐ | ☐☐☐ | mmHg |

**DBP** ☐☐☐ ☐☐☐ mmHg

**Heart rate** ☐☐☐ ☐☐☐ bpm

**11.11**(were11.10a)**Hours since last ate anything (ignore any drinks)? _____ hours** *Staff code*

**11.12**(were11.11)**Blood sample collected:** Yes (, □ Failed ( ☐☐☐

---

**11.13**(were11.12) **Lung function & CO levels:**

| | First | Second | |
|---|---|---|---|
| **CO** | ☐☐☐ | ☐☐☐ ppm | |
| **%COHB** | ☐☐.☐ | ☐☐.☐ % | *Staff code* |
| **FEV1** | ☐.☐☐ Liter | ☐.☐☐ | ☐☐☐ |
| **FVC** | ☐.☐☐ | ☐.☐☐ Liter | |

---

**11.14(were11.13)Assessment of subject's cooperation and the reliability of data collected?**

Assessment of subject's cooperation? 11.15 Assessment of the reliability of the information collected?

| | |
|---|---|
| ☐ Good | ☐ Good |
| ☐ Fair | ☐ Fair |
| ☐ Poor | ☐ Poor |

---

**Date of interview** _____Year_____Month____Day, **Signature of interviewer**_____

## Appendix B2. Excerpt of the first resurvey questionnaire of the China Kadoorie Biobank Study (paper representation)

### Section 6: Passive smoking & indoor air pollution

**6.1 Have you ever lived with smoker in the same house for at least 6 months?**

☐ Never
☐ Yes, but not now
☐ Yes, at present } → ***If yes, duration of living together*** ☐☐
Years

---

**6.2 How frequently are you exposed to other people's tobacco smoke either at home, workplace or in public places?** *(i.e. a minimum of 5 consecutive minutes each time)*

☐ Never or almost never
☐ Occasionally (<1 time/week) } → ***Go to Q6.4***
☐ 1-2 days/week
☐ 3-5 days/week
☐ Daily or almost every day

---

**6.3 What is the usual duration of your exposure per week?** ☐☐ Hours

---

**6.4 During past year, how long did you store pesticides at home?** ☐☐ Months

---

**6.5 Please tell us the duration you lived in 3 most recent houses** (each for at least 1 year)?

| | | |
|---|---|---|
| Present house | ☐☐ | Years |
| Previous house | ☐☐ | Years |
| The house before previous | ☐☐ | Years |

---

**6.6 In your present & two previous houses, how often did you cook at home?**

☐ Daily ☐ Never/Rarely → ***Go to Q6.10***
☐ Weekly ☐ No cooking facility → ***Go to Q6.11***
☐ Monthly

---

**6.7 In your present & two previous houses, what was the main cooking fuel used?**

☐ Gas ☐ Electricity
☐ Coal ☐ Other
☐ Wood

---

**6.8 In your present & two previous houses, what was the main cooking oil used?**

☐ Rapeseed ☐ Lard

☐ Peanut ☐ Other

☐ Soybean

**6.9 How much time have you spent on cooking so far today?** | | | Minutes

---

**6.10 In your present & two previous houses, did your stove(s) all have a chimney / extractor?**

☐ Yes ☐ Not all stoves ☐ No

---

**6.11 In your present & two previous houses, was your stove always kept under slow burning throughout the day?**

☐ Yes, always ☐ Yes, sometimes ☐ No → if ticked, *Go to Q6.14*

**6.12 If yes , types of the fuel most commonly used?**

☐ Smokeless coal ☐ Coal brick / Coalite

☐ Smoky coal ☐ Other

**6.13 And , the place where stove was usually kept?**

☐ Inside the house ☐ Outside the house

---

**6.14 In winter, did you normally heat your house?**

☐ Yes, ☐ No

**6.15 If yes, what was the main heating fuel used?**

☐ Central heating ☐ Wood

☐ Gas ☐ Electricity

☐ Coal ☐ Other

---

**6.16 From what year did the inside of your house tend to be coal-smoky in winter?**

☐ Never → if ticked, ***Go to section7***

☐ Ever since childhood

☐ Since the year: _____ year

**6.17 In what year did the inside of your house stop being really coal-smoky in winter?**

☐ In the year: _____ year

☐ Still is

## Appendix B3. Excerpt of the second resurvey questionnaire of the China Kadoorie Biobank study (paper representation)

**Section 6: Passive smoking & air pollution**

**6.1 Have you ever lived with a smoker in the same house for at least 6 months?**

☐ Never
☐ Yes, but not now
☐ Yes, at present

} →***If yes, Q6.1a duration of living together*** ☐☐ Years

*If 1st box is ticked, then* ***Go to Q6.3.*** *If 2nd box is ticked, then* ***Go to Q6.3*** *after answering duration*

---

**6.2 During the past 12 months, how frequently have you been exposed to tobacco smoke from a family member at home or someone you shared a room with?** *(i.e. a minimum of 5 consecutive minutes each time)*

☐ Occasionally (<1 day / week) → ***If ticked, Go to Q6.3***
☐ 1-2 days/week
☐ 3-5 days/week
☐ Daily or almost every day

**6.2.1 What is the usual duration of your exposure per week?** ☐☐ Hours

---

**6.3 During the past 12 months, about how frequently have you been exposed to other people's tobacco smoke in workplace or public places?** *(i.e. a minimum of 5 consecutive minutes each time)*

☐ Never or almost never
☐ Occasionally (<1 time/week)

} → ***If ticked, Go to Q6.4***

☐ 1-2 days/week
☐ 3-5 days/week
☐ Daily or almost every day

**6.3.1 What is the usual duration of your exposure per week?** ☐☐ Hours

---

**6.4 During past year, how long did you store pesticides at home?** ☐☐ Months

---

**6.5 Please tell us the duration you lived in 3 most recent houses** (each for at least 1 year)?

Present house ☐☐ years
Previous house ☐☐ years
The house before previous ☐☐ years

---

**6.6 How far are your present & previous houses from any main/busy road with traffic?**

Present house: ☐ <50m, ☐ 50-100m, ☐ 100-200m, ☐ >200m

Previous house1: ☐ <50m, ☐ 50-100m, ☐ 100-200m, ☐ >200m (skip if #)

Previous house2: ☐ <50m, ☐ 50-100m, ☐ 100-200m, ☐ >200m (skip if #)

---

**6.7 Are your present & previous houses within 10 kilometres of heavily air-polluted (with smoke/gas/dust) industry/industrial zone?**

Present house: ☐ Yes ☐ No

Previous house1: ☐ Yes ☐ No (skip if Previous house1 is #)

Previous house2: ☐ Yes ☐ No (skip if Previous house2 is #)

---

**6.8 During the past 12 months, how often did you cook at home?**

☐ Daily or almost every day
☐ A few times a week
☐ A few times a month
☐ Never or rarely → ***If ticked, Go to <u>Q6.9</u>***
☐ No cooking facility → ***If ticked, Go to Q6.11***

**6.8.1 How much time on average do you spend in front of the fire/stove while cooking per week?** _____ Hours

**6.8.2 At about what age did you start cooking regularly at home?** ☐☐ Years

**6.8.3 What is the main cooking oil used now?**

☐ Rapeseed ☐ Lard
☐ Peanut ☐ Other
☐ Soybean

---

**6.9 In your household, what is the main cooking fuel used now?**

☐ Gas ☐ Electricity
☐ Coal →***If ticked, Go to <u>Q6.9a</u>*** ☐ Other
☐ Wood

**6.9a Please specify the main type of coals used?**

☐ Smokeless coal ☐ Coal brick / Coalite (smokeless)
☐ Smoky coal ☐ Other

---

**6.10 In your household, do all stoves have a chimney / extractor?**

☐ Yes ☐ Not all stoves ☐ No

**6.10.1 Apart from cooking, is your stove always kept under slow burning throughout the day?**

☐ Yes, always ☐ Yes, sometimes ☐ No → ***If ticked, Go to <u>Q6.11</u>***

**6.10.2 Where is the stove usually kept?**

☐ Inside the house ☐ Outside the house

---

**6.11 In winter, do you normally heat your house?**

☐ Yes, ☐ No → ***If No, Go to <u>Q6.12</u>***

**6.11.1 What is the main heating fuel?**

☐ Central heating ☐ Wood

☐ Gas ☐ Electricity

☐ Coal →***If ticked, Go to <u>Q6.11.2</u>*** ☐ Other

**6.11.2 Please specify the main type of coals used:**

☐ Smokeless coal ☐ Coal brick / Coalite (smokeless)

☐ Smoky coal ☐ Other

**6.11.3 When you heat the house in winter, do you still need to wear plenty of warm clothes at home?** ☐ Yes, ☐ No

---

**6.12 From what year did the inside of your house tend to be coal-smoky in winter?**

☐ Never → ***If ticked, Go to <u>Q6.13</u>***

☐ Ever since childhood

☐ Since the year: _____ year

**6.12.1 In what year did the inside of your house stop being really coal-smoky in winter?**

☐ In the year: _____ year

☐ Still is

---

**6.13 During your working life, have you ever been exposed to any of the following for at least 6 consecutive months?**

Gas/Vapour/Fume/Mist ☐ Yes, ☐ No;

→if Yes, then **<u>Q6.13a</u>** total years of exposure? ___years

Dust (eg. silica/coal/cotton) ☐ Yes, ☐ No;

→if Yes, then **Q6.13b** total years of exposure? ___years

Fibres (eg, asbestos/textile) ☐ Yes, ☐ No;

→if Yes, then **Q6.13c** total years of exposure? ___years

---

## Appendix C. Supplementary methods to Chapter 4: estimation of duration of continuous exposure to solid fuels

To approximate the potential dose-response relationship between duration of solid fuel use and disease outcomes of interest, a semi-quantitative indicator of duration of continuous exposure to solid fuels for cooking was developed. Among participants who reported primarily using solid fuels for cooking throughout the recall period (i.e. up to three most-recent residences), the duration of continuous exposure to solid fuels was calculated by summing the duration of residence (in years) in consecutive residences where solids fuels were used as the primary fuel. For example, if participant X lived in the three most-recent residences for 15, 18, and 21 years and cooked regularly primarily using wood, coal and coal in the three residences, respectively, the duration of continuous exposure to solid fuels for cooking would be 15+18+21 = 54 years. In contrast, if X reported cooking regularly using solid fuels in the two most recent residences but did not cook in the earliest one, the duration of continuous exposure would be 18+21 = 39 years.

For prospective analyses, those who had always used solid fuels were categorised into three groups based on their estimated duration of continuous exposure to solid fuels for cooking (<20 years, 20-39 years, ≥ 40 years), and their cardiorespiratory disease risks were compared with participants who had switched from solid to clean fuels and those who had always used clean fuels primarily during the recall period (reference category). In order to take into account of the potential confounding due to differential length of recall period across the comparison groups, all analyses were adjusted for total length of recall period. Furthermore, sensitivity analyse were conducted to exclude participants with a short recall duration (<20 years) to assess the relevant risk of bias.

## Appendix D. Concept of age-at-risk in the context of prospective analysis

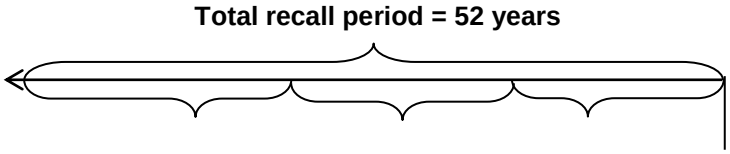
Age-at-risk refers to the attained age of individuals during the follow-up period. It is one of the most important determinants of an individual's instantaneous risk (or hazard) and it is considered to be more appropriate to adjust for age-at-risk in prospective analysis rather than baseline age. Age-at-risk is by definition a time-varying factor, and its relationships with disease and mortality risks tend to violate the proportional hazard assumption of Cox regression, because the risks in older age-at-risk groups increase at higher rate over time. To address this, all prospective analyses described in this thesis were stratified by adequately narrow age-at-risk bands (5-year intervals) within which the proportional hazard assumption is likely to be be satisfied. The derivation of these age-at-risk bands was done using the "Lexis expansion" method, which separates the observation of each participant into multiple observations.[163] For example, a participant who entered the study at the age of 40 in 2005 would have two observations across the 40-44 years and 45-49 years age-at-risk bands at the end of a 9-year follow-up period.

## Appendix E. Supplementary methods and results to Chapter 5

### Appendix E1. Example illustration of estimation of person-time of exposure to household air pollution

#### a) Scenario:

A participant aged 72 at baseline survey recalled 27 years of residence in the baseline residence, 14 years in the penultimate residence, 11 years in the antepenultimate residence (i.e. total recall period = 52 years). For cooking fuel, the participant reported using gas (i.e. clean fuels) in baseline residence, coal in penultimate residence and wood in the antepenultimate residence.




| | Antepenultimate residence | Penultimate residence | Baseline residence | Baseline survey |
|---|---|---|---|---|
| **Age started living in each house** | 21 | 32 | 45 | 72 |
| **Calendar year** | 1955 | 1966 | 1979 | 2006 |
| **Cooking fuel** | Wood | Coal | Clean fuels | |

#### b) Summary of age lived through and exposure to cooking fuel in the three most-recent houses:

| Residence | Age lived through each residence (year-old) | Primary cooking fuel in each residence* | | |
|---|---|---|---|---|
| | | Wood | Coal | Clean fuels |
| **Antepenultimate residence** | 21-31 | 1 | 0 | 0 |
| **Penultimate residence** | 32-44 | 0 | 1 | 0 |
| **Baseline residence** | 45-72 | 0 | 0 | 1 |

*For primary cooking fuel, 1 and 0 indicate EXPOSED and UNEXPOSED, respectively.

**c) Proportion of age band that was informative:**

A series of 5-year age bands was created from birth to 74 year-old. For the hypothetical scenario, the recall period covered 52/72 years of the participant's lifetime (i.e. 21-72 years old). The age bands where information of HAP exposure is available are the 'informative age bands'. The proportion of age band that was informative was calculated as illustrated below.

| | **Non-informative age bands** | | | | **Informative age bands** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-4 | 5-9 | 10-14 | 15-19 | 20-24 | 25-29 | 30-34 | 35-39 | 40-44 | 45-49 | 50-54 | 55-59 | 60-64 | 65-69 | 70-74 |
| Proportion of age band that was informative | 0 | 0 | 0 | 0 | 0.8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.6 |

There was no information provided for 0-19 year-old; With recall information from 21-72 year-old, 80% of the age band 20-24 and 60% of the age band 70-74, and all the age bands in between were considered informative.

**d) Estimating duration of exposure using informative age bands and exposure recall data:**

Then, the crude proportion of informative age band exposed to each category of cooking fuel was estimated. For example, from 21 to 31 year-old, the hypothetical participant exposed to wood as primary cooking fuel and therefore the crude proportion of exposure to wood in age band 20-24 was 0.8 (4 out of 5 years).

| | **Non-informative age bands** | | | | **Informative age bands** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-4 | 5-9 | 10-14 | 15-19 | 20-24 | 25-29 | 30-34 | 35-39 | 40-44 | 45-49 | 50-54 | 55-59 | 60-64 | 65-69 | 70-74 |
| Proportion of age band that was informative | 0 | 0 | 0 | 0 | 0.8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.6 |
| Exposure to wood | 0 | 0 | 0 | 0 | 0.8 | 1 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Exposure to coal | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Exposure to clean fuels | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

**e) Calculating percentage of length of informative age band being exposed to each HAP category:**

The length of the first and last informative age band varied and ranged from 1-5 years (as shown in (d)). To allow valid comparison across individuals, a method of standardisation of the period of exposure to each HAP category was used to calculate the percentage of length of informative age band being exposed to each HAP category with the formula below.

$$\text{Percentage of length of informative age band exposed to each HAP category} = \frac{\text{Crude proportion exposed}}{\text{Proportion of age band that was informative}} \times 100\%$$

For the hypothetical participant, the percentage of length of age band 20-24 year-old exposed to wood = 0.8/0.8 x 100% = 100%; whereas that of age band 30-34 = 0.4/1 x 100% = 40% (the remaining 60% of this complete age band was exposed to coal).

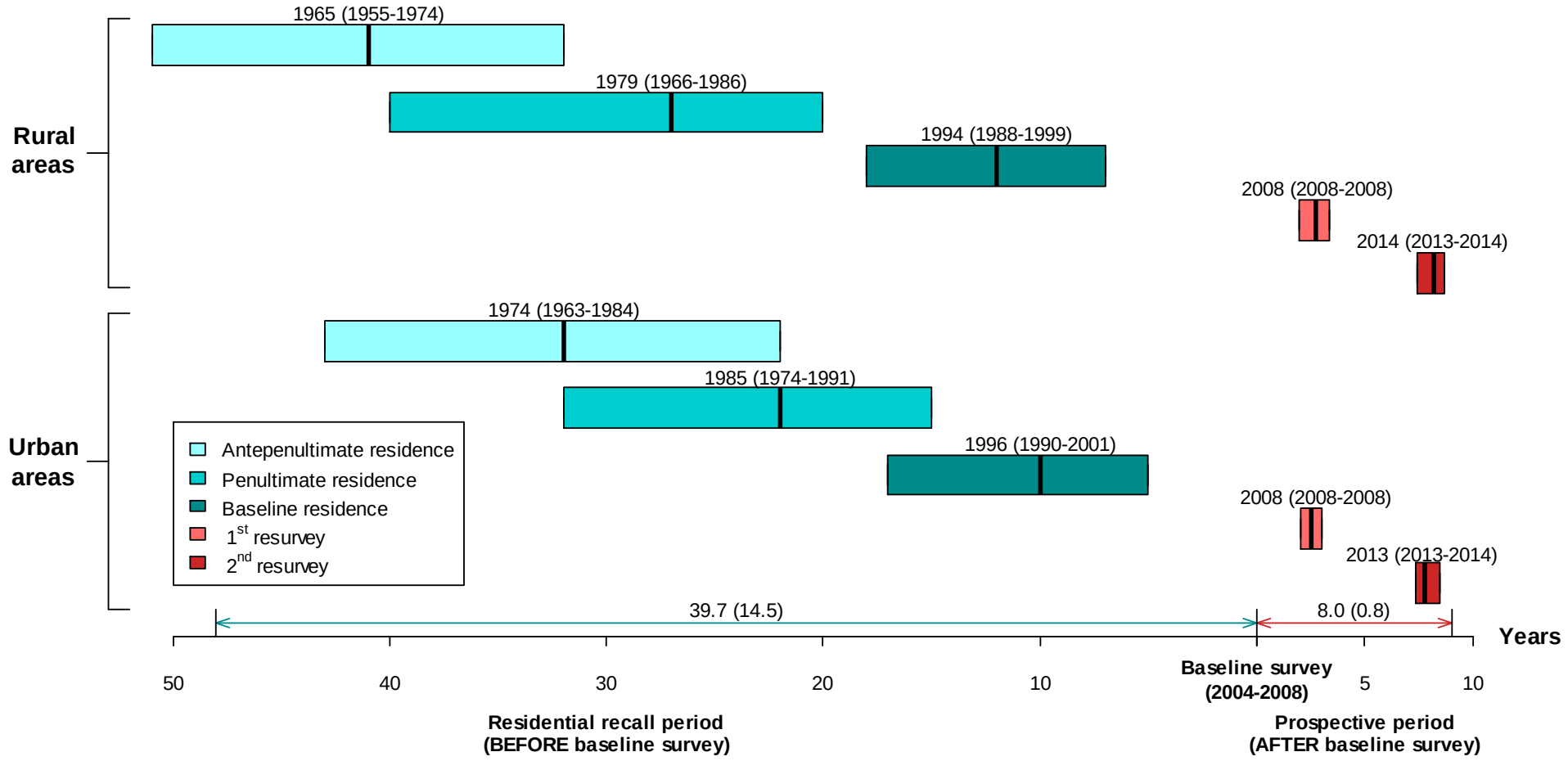
| | Non-informative age bands | | | | Informative age bands | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-4 | 5-9 | 10-14 | 15-19 | 20-24 | 25-29 | 30-34 | 35-39 | 40-44 | 45-49 | 50-54 | 55-59 | 60-64 | 65-69 | 70-74 |
| Proportion of age band that was informative | 0 | 0 | 0 | 0 | 0.8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.6 |
| Percentage of time exposed to wood | 0 | 0 | 0 | 0 | 100% | 100% | 40% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Percentage of time exposed to coal | 0 | 0 | 0 | 0 | 0 | 0 | 60% | 100% | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Percentage of time exposed to clean fuels | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

### f) Summary

Procedures c) to e) were applied to all participants for each HAP exposure indicator (primary cooking fuel, primary heating fuel and cookstove ventilation). The rural and urban participants were then divided into five birth cohorts according to year of birth: before 1940, 1940-49, 1950-59, 1960-69 and after 1969 to depict the overall historical development of HAP exposure across multiple generations in rural and urban areas.

## Appendix E2. Distribution of time started living in each residence (blue) and time of resurvey interview (red) in rural and urban participants

Box plots displaying hinges at 75th and 25th percentiles and vertical bold-line at median; four-digit numbers above median lines are equivalent calendar years of median (interquartile range); numbers of two-headed arrows are overall mean (standard deviation) of total recall and prospective periods in years counted from the date of the baseline survey (conducted in 2004-08).



## Appendix F. Supplementary results to Chapter 6

**Table F1. Comparison of conventional standard error and robust standard error estimates for the association of long-term fuel use for cooking with respiratory disease**

| | | Main analysis | | Robust estimation* | |
|---|---|---|---|---|---|
| | Hazard ratio | Standard error | 95% CI | Standard error | 95% CI |
| **Major respiratory disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.15 | 0.02678 | (1.09-1.21) | 0.02691 | (1.09-1.22) |
| Always solid | 1.37 | 0.02826 | (1.30-1.45) | 0.02905 | (1.30-1.45) |
| **Chronic lower respiratory disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.21 | 0.03918 | (1.12-1.31) | 0.03948 | (1.12-1.31) |
| Always solid | 1.47 | 0.03929 | (1.36-1.59) | 0.04054 | (1.36-1.59) |
| **Chronic obstructive pulmonary disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.95 | 0.06825 | (0.83-1.09) | 0.06831 | (0.93-1.09) |
| Always solid | 1.10 | 0.06990 | (0.96-1.26) | 0.06999 | (0.96-1.26) |
| **Acute lower respiratory infection** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.10 | 0.04326 | (1.01-1.20) | 0.04354 | (1.01-1.20) |
| Always solid | 1.18 | 0.04951 | (1.07-1.30) | 0.05103 | (1.07-1.30) |
| **Acute upper respiratory infection** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.14 | 0.06598 | (1.00-1.29) | 0.06572 | (1.00-1.29) |
| Always solid | 1.59 | 0.06484 | (1.40-1.81) | 0.06694 | (1.40-1.82) |
| **Other upper respiratory disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.10 | 0.07950 | (0.94-1.29) | 0.08075 | (0.94-1.29) |
| Always solid | 1.56 | 0.08568 | (1.32-1.84) | 0.09031 | (1.31-1.86) |
| **Respiratory death** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.93 | 0.17891 | (0.65-1.32) | 0.18133 | (0.65-1.33) |
| Always solid | 1.53 | 0.18387 | (1.07-2.19) | 0.18640 | (1.06-2.20) |

*Estimated using marginal Cox regression based on robust sandwich covariance matrix.

**Table F2. Comparison of conventional standard error and robust standard error estimates for the association of long-term fuel use for heating with respiratory disease**

| | | Main analysis | | Robust estimation* | |
|---|---|---|---|---|---|
| | Hazard ratio | Standard error | 95% CI | Standard error | 95% CI |
| **Major respiratory disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.92 | 0.04460 | (0.84-1.00) | 0.04486 | (0.84-1.00) |
| Always solid | 1.04 | 0.04729 | (0.95-1.14) | 0.04724 | (0.95-1.14) |
| **Chronic lower respiratory disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.98 | 0.07835 | (0.84-1.15) | 0.07982 | (0.84-1.15) |
| Always solid | 1.20 | 0.07690 | (1.03-1.40) | 0.07778 | (1.03-1.40) |
| **Chronic obstructive pulmonary disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.02 | 0.09983 | (0.84-1.24) | 0.10203 | (0.84-1.25) |
| Always solid | 1.27 | 0.09291 | (1.06-1.53) | 0.09302 | (1.06-1.53) |
| **Acute lower respiratory infection** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.88 | 0.05788 | (0.78-0.98) | 0.05811 | (0.78-0.98) |
| Always solid | 0.93 | 0.06392 | (0.82-1.05) | 0.06344 | (0.82-1.05) |
| **Acute upper respiratory infection** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.99 | 0.15476 | (0.63-1.18) | 0.15280 | (0.74-1.34) |
| Always solid | 0.97 | 0.17283 | (0.78-1.48) | 0.17226 | (0.69-1.36) |
| **Other upper respiratory disease** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 0.86 | 0.15875 | (0.73-1.35) | 0.15690 | (0.63-1.17) |
| Always solid | 1.07 | 0.16341 | (0.69-1.36) | 0.15835 | (0.79-1.47) |
| **Respiratory death** | | | | | |
| Always clean | Reference | - | - | - | - |
| Solid to clean | 1.18 | 0.23381 | (0.75-1.87) | 0.23622 | (0.74-1.87) |
| Always solid | 0.99 | 0.24520 | (0.62-1.61) | 0.23818 | (0.62-1.59) |

*Estimated using marginal Cox regression based on robust sandwich covariance matrix.

**Table F3. Baseline characteristics of participants with and without selected respiratory disease event during follow-up***

| Characteristics | No respiratory disease event | Chronic lower respiratory disease event | | Other respiratory disease event | Total |
|---|---|---|---|---|---|
| | | Unspecified bronchitis | COPD | | |
| **Total participants, N** | 266,867 | 6,830 | 4,452 | 11,155 | 289,305 |
| **Age (SD), years** | 50.0 (10.3) | 53.7 (9.9) | 60.9 (10.2) | 52.2 (10.4) | 50.3 (10.3) |
| **Women, %** | 90.7 | 92.8 | 89.3 | 91.8 | 90.8 |
| **Urban residency, %** | 46.2 | 25.8 | 15.2 | 34.1 | 44.7 |
| **Education level, %** | | | | | |
| No formal education | 23.2 | 25.9 | 27.8 | 23.8 | 23.4 |
| Primary | 30.4 | 32.0 | 31.5 | 32.0 | 30.5 |
| Secondary or above | 46.4 | 42.1 | 40.7 | 44.2 | 46.1 |
| **Annual household income, %** | | | | | |
| < 10,000 Yuan | 28.1 | 30.1 | 29.6 | 28.5 | 28.3 |
| 10,000-19,999 Yuan | 29.3 | 30.0 | 29.6 | 29.9 | 29.4 |
| ≥ 20,000 Yuan | 42.5 | 39.8 | 40.8 | 41.6 | 42.4 |
| **Occupation, %** | | | | | |
| Farmer | 40.5 | 46.7 | 41.3 | 42.1 | 40.8 |
| Factory worker | 12.2 | 9.7 | 7.3 | 12.3 | 12.1 |
| Non-manual labour | 10.1 | 8.1 | 11.2 | 9.4 | 10.1 |
| Others† | 37.2 | 35.5 | 40.1 | 36.2 | 37.0 |
| **Environmental tobacco smoke, %** | | | | | |
| <1 day/ week | 40.6 | 37.4 | 38.7 | 39.9 | 40.5 |
| 1-5 days/ week | 19.0 | 18.6 | 19.2 | 18.7 | 19.0 |
| 6-7 days/ week | 40.3 | 44.0 | 42.1 | 41.4 | 40.4 |
| **Leg length (SD), cm** | 71.6 (4.1) | 71.4 (3.8) | 71.5 (3.8) | 71.6 (4.0) | 71.6 (4.1) |
| **Body mass index (SD), kg/m$^2$** | 23.8 (3.4) | 23.8 (3.4) | 23.9 (3.8) | 23.8 (3.4) | 23.8 (3.4) |
| **Self-reported health conditions,%** | | | | | |
| **Poor health** | 8.9 | 13.5 | 13.5 | 11.6 | 9.2 |
| **Shortness of breath** | 4.8 | 7.4 | 9.9 | 6.6 | 5.0 |
| **Cough ≥3 months** | 1.6 | 2.2 | 4.8 | 2.4 | 1.8 |
| **Chronic phlegm** | 1.6 | 2.6 | 3.8 | 2.1 | 1.7 |
| **Lung function measures** | | | | | |
| **$FEV_1$‡ (SD), Litre** | 2.09 (0.51) | 2.05 (0.47) | 1.85 (0.56) | 2.06 (0.50) | 2.08 (0.52) |
| **FVC§ (SD), Litre** | 2.45 (0.59) | 2.41 (0.53) | 2.22 (0.60) | 2.42 (0.56) | 2.45 (0.59) |
| **$FEV_1$:FVC (SD)** | 0.85 (0.08) | 0.85 (0.08) | 0.83 (0.11) | 0.85 (0.08) | 0.85 (0.08) |
| **$FEV_1$:FVC <LLN¶, %** | 5.2 | 6.4 | 12.1 | 5.8 | 5.5 |

* Means and percentages were standardised to the age, gender and study area structure of the overall study sample, where appropriate. Participants who had both COPD and unspecified bronchitis were excluded (n = 641).

† Others: home-maker, retired, self-employed, other no stated or unemployed.

‡ $FEV_1$: forced expiratory volume in 1 second.

§ FVC: forced vital capacity.

¶ LLN: lower limit of normal.

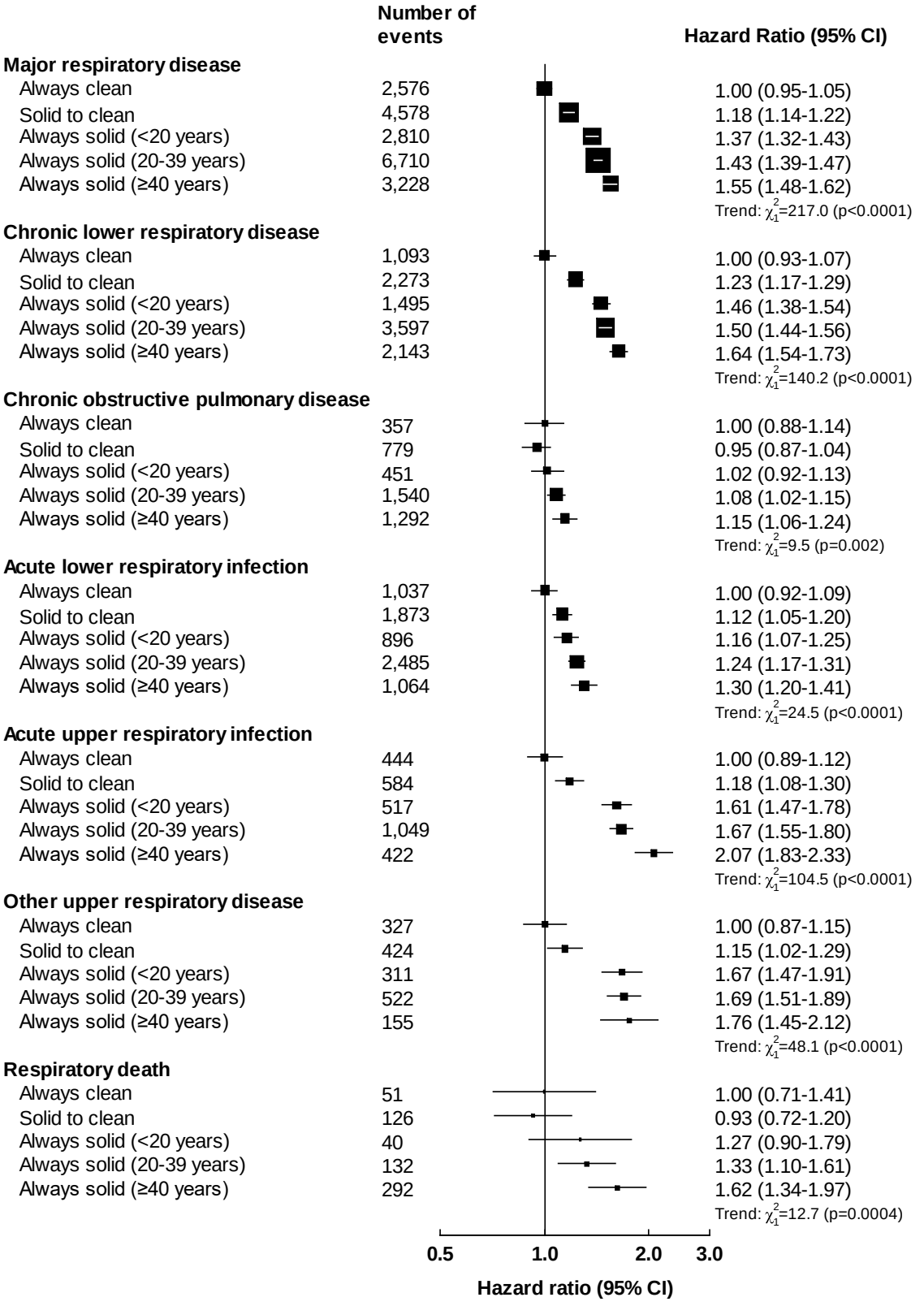
**Table F4. Association of unspecified bronchitis (J40) with subsequent risk of respiratory, cardiovascular and external causes of morbidity**

| | Number of events | | |
|---|---|---|---|
| | **No J40** | **J40** | **OR (95% CI)*** |
| **Disease event** | | | |
| Chronic obstructive pulmonary disease | 4,452 | 437 | 3.56 (3.17-3.99) |
| Acute lower respiratory infection | 7,515 | 535 | 3.30 (2.99-3.65) |
| Acute upper respiratory infection | 2,844 | 487 | 3.12 (2.80-3.48) |
| External causes of morbidity† | 986 | 43 | 1.05 (0.76-1.45) |

* Odds ratios were adjusted for age, gender, study area, education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke.
† External causes of morbidity: ICD-10 codes V00-Y99.

**Figure F1. Adjusted hazard ratios for major respiratory diseases by cooking frequency-weighted duration of continuous exposure to solid cooking fuel in never-smokers**

Hazard ratios were stratified by age-at-risk (in 5 year groups), gender and study area and adjusted for education, household income, occupation, alcohol consumption, body mass index, environmental tobacco smoke, cookstove ventilation, primary heating fuel exposure and length of recall period. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).



## Appendix G. Supplementary results to Chapter 7

**Table G1. Comparison of conventional standard error and robust standard error estimates for the association of long-term fuel use for cooking with cardiovascular death**

| | | Main analysis | | Robust estimation* | |
|---|---|---|---|---|---|
| | **Hazard ratio** | **Standard error** | **95% CI** | **Standard error** | **95% CI** |
| **All cardiovascular disease** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.99 | 0.04696 | (0.91-1.09) | 0.04679 | (0.91-1.09) |
| Always solid | 1.14 | 0.04790 | (1.04-1.25) | 0.04736 | (1.04-1.25) |
| **Ischaemic heart disease** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.95 | 0.07352 | (0.82-1.10) | 0.07337 | (0.83-1.10) |
| Always solid | 0.95 | 0.08090 | (0.81-1.11) | 0.07944 | (0.81-1.11) |
| **Stroke** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 1.06 | 0.07899 | (0.90-1.23) | 0.07885 | (0.90-1.23) |
| Always solid | 1.27 | 0.07628 | (1.09-1.47) | 0.07573 | (1.09-1.47) |
| **Intracerebral haemorrhage** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 1.12 | 0.10442 | (0.91-1.38) | 0.10505 | (0.91-1.38) |
| Always solid | 1.27 | 0.09866 | (1.05-1.54) | 0.09902 | (1.05-1.54) |
| **Ischaemic stroke** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.94 | 0.14081 | (0.72-1.24) | 0.13876 | (0.72-1.24) |
| Always solid | 1.41 | 0.14001 | (1.07-1.86) | 0.13545 | (1.08-1.84) |
| **Other cardiovascular disease** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 1.01 | 0.09802 | (0.83-1.22) | 0.09699 | (0.83-1.22) |
| Always solid | 1.25 | 0.10170 | (1.02-1.51) | 0.10131 | (1.02-1.51) |

*Estimated using marginal Cox regression based on robust sandwich covariance matrix.

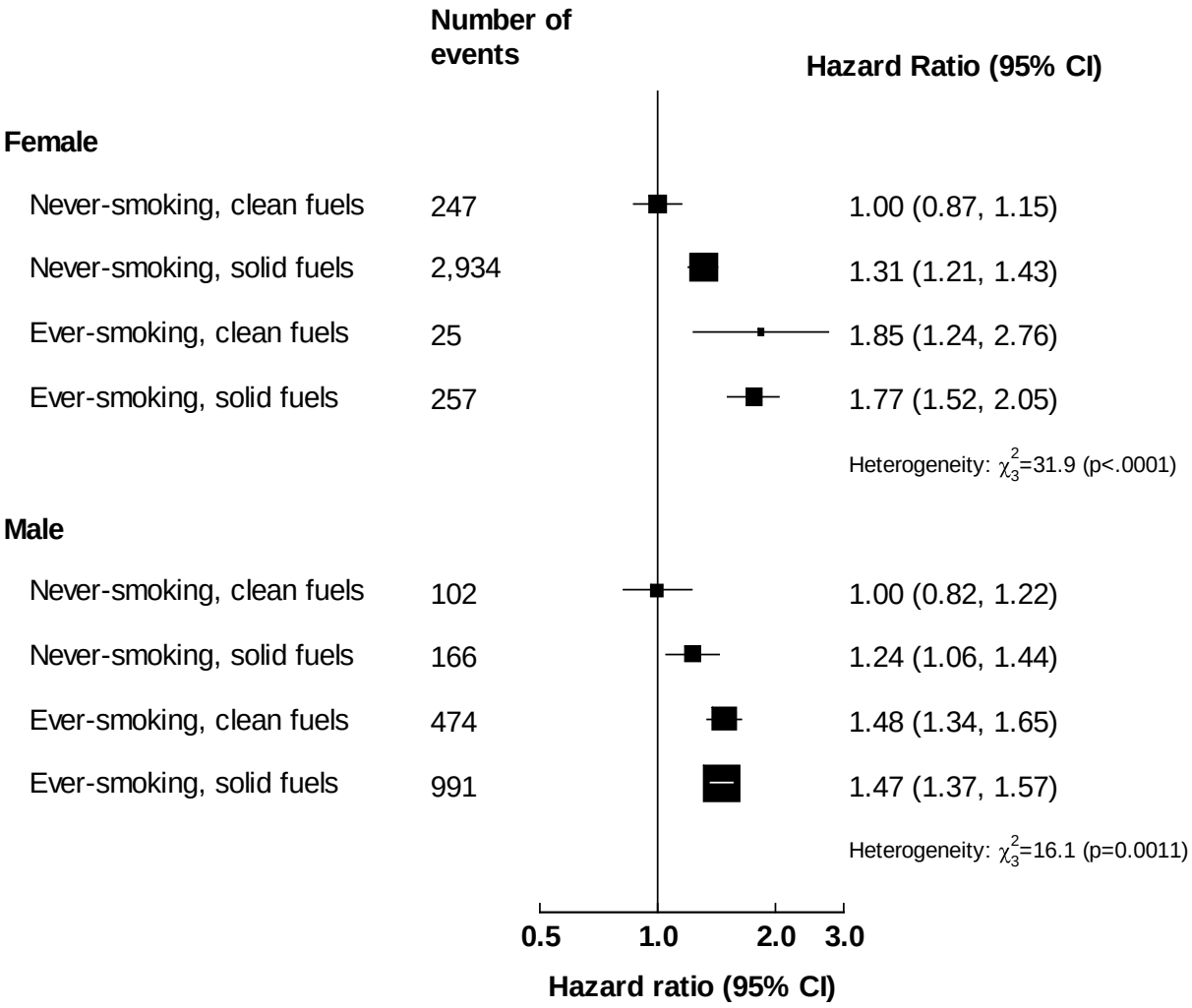
**Table G2. Comparison of conventional standard error and robust standard error estimates for the association of long-term fuel use for heating with cardiovascular death**

| | | Main analysis | | Robust estimation* | |
|---|---|---|---|---|---|
| | **Hazard ratio** | **Standard error** | **95% CI** | **Standard error** | **95% CI** |
| **All cardiovascular disease** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.98 | 0.06069 | (0.87-1.11) | 0.06075 | (0.87-1.11) |
| Always solid | 1.21 | 0.06481 | (1.07-1.38) | 0.06555 | (1.07-1.38) |
| **Ischaemic heart disease** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.97 | 0.08842 | (0.81-1.15) | 0.08913 | (0.81-1.15) |
| Always solid | 1.16 | 0.1032 | (0.95-1.42) | 0.10488 | (0.95-1.43) |
| **Stroke** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.98 | 0.10442 | (0.80-1.20) | 0.10429 | (0.80-1.20) |
| Always solid | 1.28 | 0.10382 | (1.04-1.56) | 0.10494 | (1.04-1.57) |
| **Intracerebral haemorrhage** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.99 | 0.13648 | (0.75-1.29) | 0.13611 | (0.75-1.29) |
| Always solid | 1.46 | 0.12977 | (1.13-1.88) | 0.13105 | (1.13-1.88) |
| **Ischaemic stroke** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 0.87 | 0.18328 | (0.61-1.25) | 0.18242 | (0.61-1.25) |
| Always solid | 0.91 | 0.20561 | (0.61-1.37) | 0.20767 | (0.61-1.37) |
| **Other cardiovascular disease** | | | | | |
| Always clean | Reference | | | | |
| Solid to clean | 1.03 | 0.14212 | (0.78-1.36) | 0.14126 | (0.78-1.36) |
| Always solid | 1.18 | 0.14182 | (0.90-1.56) | 0.14491 | (0.89-1.57) |

*Estimated using marginal Cox regression based on robust sandwich covariance matrix.

**Figure G1. Adjusted hazard ratios for overall cardiovascular death by composite exposure of cooking fuel use and smoking habit in female and male participants**

Hazard ratios were stratified by age-at-risk (in 5 year groups) and study area and adjusted for education, household income, occupation, alcohol consumption, diet (fresh fruit, preserved vegetables, meat), total physical activity, body mass index, environmental tobacco smoke, cookstove ventilation, heating fuel exposure, length of recall period and antihypertensive treatment, where appropriate. The black boxes represent hazard ratios, with the size inversely proportional to the variance of the logarithm of the hazard ratio, and the horizontal lines represent 95% confidence intervals (CI).



## Appendix H. Supplementary materials for Chapter 8

## Appendix H1. Household visit materials checklist

| Materials | Function/ content | Quantity per team per week |
|---|---|---|
| **Every visit** | | |
| This checklist | | 1 |
| Participant list | Contact details of invited participants each week | 1 |
| Barcode scanner | Scan participant ID and device ID | 1 |
| Staff badge | Staff identity proof | |
| Laptop computer and accessories | Obtain informed consent, deploy and collect monitors, conduct questionnaire interviews | 2 |
| Backup USB drive | Data backup | 1 |
| Clip folder | Keep consent form and other paper documents | 1 |
| Ball pen | Singing consent form | 2 |
| Fieldwork error report | Record problems encountered during fieldwork | 1 |
| **First visit (Thursday)** | | |
| Consent form | | 13 |
| Consent record | Record number of participants who had provided informed consent | 1 *(shared by 3 teams)* |
| Invitation letter | Copy of invitation letter sent to participant, for identity verification | 13 |
| Household survey kit (per pack):<br>PATS+CO x3<br>Li battery (small) and cable x1<br>Li battery (large) and cable x2<br>Harness x1<br>SUMS x1<br>Heat resistant tape x 30cm<br>Safety pin x2 | Record personal and household PM2.5 and CO levels.<br>One kit for each household. | 13 |
| Calibration set:<br>MicroPEM x1<br>EL-USB-CO x1<br>EL-USC-2-LCD x1<br>Li battery (large) x1 | Collect data to calibrate PATS+CO.<br>Only used in one household per week (per team). | 1 |
| Zeroing box and hand pump | PATS+CO zeroing | 1 |
| Sport tape | Stabilise air quality monitors and batteries | 1 roll |
| Alcohol wipe | Remove grease from cookstove (for SUMS) or clean air quality monitors when necessary | 1 pack |
| GPS locator | | |
| Trolley with carrier bag | Carry fieldwork materials | 2 |
| **Second and third visits (Monday, Friday)** | | |
| MicroCO meter | Measure exhaled carbon monoxide level | 1 |
| MicroCO disposable mouthpiece | Used with MicroCO meter | 15 |
| Ninon Oximeter | Measure blood oxygen saturation and heart rate | 1 |
| Masking tape | Stabilise air quality monitors when necessary | 1 roll |
| Safety pin | Stabilise harness or waist belt when necessary | 5 |
| Alcohol wipe | Clean air quality monitors | 1 pack |
| **Fourth visit (Tuesday)** | | |
| Trolley with carrier bag | Carry fieldwork materials | 2 |

## Appendix H2. Household questionnaire for the feasibility study (paper representation)

*(Note: the format of this document has been modified to suit the purpose of this thesis)*

**1.1 Special Survey Study ID: K _ _ _ _ _ _ _ Baseline Study ID: K _ _ _ _ _ _ _,**
**Date of survey: _____;**

**Section 1: Background information (This section is for ParticipantsDetails : Grey is not collected in SINPUT)**

**1.3 Name: _____, Sex:** Male ☐ Female ☐

**1.4 Date of birth:** ☐☐☐☐ Year ☐☐ Month ☐☐ Day

**1.5 National ID:** ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

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**1.6 What is your current occupation?**

☐ Agriculture & related workers
☐ Factory worker
☐ Administrator / manager
☐ Professional / technical
☐ Sales & service workers
☐ Retired
☐ House wife / husband
☐ Self-employed
☐ Unemployed
☐ Other or not stated

**1.7 How many people live together as a family in the household?** _____persons (same as RS2 Q1.8)

**1.8 Type of dwelling:** ☐ Apartment ☐ House

**1.9 What is the total income last year in your household?** (same as RS2 Q1.10)

☐ <2,500 yuan
☐ 2,500-4,999 yuan
☐ 5,000-9,999 yuan
☐ 10,000-19,999 yuan
☐ 20,000-34,999 yuan
☐ 35,000-49,999 yuan
☐ 50,000-74,999 yuan
☐ 75,000-99,999 yuan
☐ ≥100,000 yuan

**Section 2: Active and passive smoking**

**2.1 How often do you smoke tobacco now?** (Comparable to RS2 4.2)

☐ Do not smoke now
☐ Only occasionally
☐ Yes, on most days
☐ Yes, daily or almost every day

**2.2 During the past 12 months, how frequently have you been exposed to tobacco smoke from a <u>family member at home</u>?** (i.e. a minimum of 5 consecutive minutes each time) (Modified from 6.2 & 6.2.1)

☐ Never
☐ <1 day/week
} if ticked, go to Q2.3
☐ 1-2 day/week
☐ 3-5 day/week
☐ 6-7 day/week

**2.2.1 What is the usual duration of your exposure per week?** | | | Hours

**2.3 During the past 12 months, how frequently have you been exposed to other people's tobacco smoke in <u>workplace or public place</u>?** (i.e. a minimum of 5 consecutive minutes each time) (Modified from 6.3 & 6.3.1)

☐ Never
☐ <1 day/week
} if ticked, go to Q3.1
☐ 1-2 day/week
☐ 3-5 day/week
☐ 6-7 day/week

**2.3.1 What is the usual duration of your exposure per week?** | | | Hours

**Section 3: Cooking related exposure**

**3.1 During the past 12 months, how often was cooking done (by anyone) at your home?**

☐ Daily or almost every day
☐ A few times a week
☐ A few times a month
☐ Never or rarely →if ticked, go to Section 4 Q4.1

**3.2 During the past 12 months, how often did you cook at home?**

☐ Daily or almost every day
☐ A few times a week
} if ticked, go to Q3.3.1
☐ A few times a month
☐ Never or rarely

**3.3 Have you ever cooked regularly at home (at least few times a week)?**

☐ Yes ☐ No → if ticked, go to Q3.5

**3.3.1 At about what age did you start cooking regularly at home?** | | | Years
→ If ticked 1st or 2nd box in Q3.2, go to Q3.4

**3.3.2 At about what age did you stop cooking regularly at home?**

☐Since _____(year old) → if answered "Daily or almost every day" or "A few times a week" for **Q3.2**, this question should be skipped.

**3.4 During the time period that you were cooking regularly at home, how much time do you spend in front of the fire/ cookstove/ in the kitchen while cooking per day?**
_____ Hours

**3.5 In your household, which cooking fuels are used now, how frequently and how long have they been used (during your lifetime)?** *(Excluding boiling water for drinking or the use of electric rice cooker; tick multiple type of fuel if applicable)*

| | **Used** | | **Frequency of use** | | **Duration used (years)** |
|---|---|---|---|---|---|
| | **Yes** | **No** | **Most meals** | **Sometimes** | *(If < 1 year, enter 0)* |
| Electricity (hob/oven) | ☐ | ☐ | ☐ | ☐ | _____ |
| Natural gas/ town gas/ LPG | ☐ | ☐ | ☐ | ☐ | _____ |
| Biogas | ☐ | ☐ | ☐ | ☐ | _____ |
| Smokeless coal | ☐ | ☐ | ☐ | ☐ | _____ |
| Smoky coal | ☐ | ☐ | ☐ | ☐ | _____ |
| Coalite/ coal brick | ☐ | ☐ | ☐ | ☐ | _____ |
| Charcoal | ☐ | ☐ | ☐ | ☐ | _____ |
| Wood | ☐ | ☐ | ☐ | ☐ | _____ |
| Crop residue | ☐ | ☐ | ☐ | ☐ | _____ |
| Kerosene | ☐ | ☐ | ☐ | ☐ | _____ |
| Solar | ☐ | ☐ | ☐ | ☐ | _____ |
| Other | ☐ | ☐ | ☐ | ☐ | _____ |

**3.6 Have the cooking fuel in your home now (cool season) changed compared to that was used during the warm period (warm season)?**

☐ Yes ☐ No → if ticked, go to Q3.8

**3.7 Which cooking fuels were used in your home back then and for how long?**
*(Excluding boiling water for drinking or the use of electric rice cooker; tick multiple type of fuel if applicable)*

| | **Used** | | **Frequency of use** | | **Duration used (years)** |
|---|---|---|---|---|---|
| | **Yes** | **No** | **Most meals** | **Sometimes** | *(If < 1 year, enter 0)* |
| Electricity (hob/oven) | ☐ | ☐ | ☐ | ☐ | _____ |
| Natural gas/ town gas/ LPG | ☐ | ☐ | ☐ | ☐ | _____ |
| Biogas | ☐ | ☐ | ☐ | ☐ | _____ |
| Smokeless coal | ☐ | ☐ | ☐ | ☐ | _____ |
| Smoky coal | ☐ | ☐ | ☐ | ☐ | _____ |
| Coalite/ coal brick | ☐ | ☐ | ☐ | ☐ | _____ |
| Charcoal | ☐ | ☐ | ☐ | ☐ | _____ |
| Wood | ☐ | ☐ | ☐ | ☐ | _____ |
| Crop residue | ☐ | ☐ | ☐ | ☐ | _____ |
| Kerosene | ☐ | ☐ | ☐ | ☐ | _____ |

| | | | | | |
|---|---|---|---|---|---|
| Solar | ☐ | ☐ | ☐ | ☐ | |
| Other | ☐ | ☐ | ☐ | ☐ | |

**3.8 Where is cooking in your home usually done?**

☐ Indoors ☐ Outdoors → if ticked, go to Q4.1

**3.9 How often is the kitchen window(s) opened when cooking is done in your home?**

☐ Always ☐ Sometimes ☐ Rarely/ never/no window in the kitchen

**3.10 Does your kitchen have a chimney / extractor fan/hood?**

☐ Yes ☐ No

**3.11 Does the inside of your kitchen tend to be smoky when cooking?**

☐ Always ☐ Sometimes ☐ Rarely/ never

## Section 4: Heating related exposure

**4.1 In winter, how frequently do you normally heat your home?**

☐ Daily or almost every day

☐ A few times a week

☐ A few times a month

☐ Never/No heating →if ticked, go to Q4.7

**4.2 How long do you usually use heating on a typical day in winter? (***consider < 1 hour as 1 hour*) _____Hours

**4.3 Is your residence heated mainly by central heating in winter?** ☐ Yes ☐ No

**4.4 What heating fuels do you use in winter and for how long on a typical day, and how long have you been using them (during your lifetime)?** *(tick multiple type of fuel if applicable)*

| | **Used** | | **Duration of use (hour) in a typical day** *(to the nearest 0.5 hr)* | **Duration used (years)** *(If < 1 year, enter 0)* |
|---|---|---|---|---|
| | **Yes** | **No** | | |
| Electricity | ☐ | ☐ | | |
| Natural gas/ town gas/ LPG | ☐ | ☐ | | |
| Biogas | ☐ | ☐ | | |
| Smokeless coal | ☐ | ☐ | | |
| Smoky coal | ☐ | ☐ | | |
| Coalite/ coal brick | ☐ | ☐ | | |
| Charcoal | ☐ | ☐ | | |
| Wood | ☐ | ☐ | | |
| Crop residue | ☐ | ☐ | | |
| Kerosene | ☐ | ☐ | | |

| | | | | |
|---|---|---|---|---|
| Solar | ☐ | ☐ | _____ | _____ |
| Other | ☐ | ☐ | _____ | _____ |

**4.5 Do your (non-electric) heat stoves have a chimney / extractor?**

☐ Yes, all ☐ Yes, but not all ☐ None

**4.6 Does the inside of your home tend to be smoky when you use heating?**

☐ Always ☐ Sometimes ☐ Rarely/ never

**4.7 What is the primary reason of not using heating?** (only for those who answered "No heating" to Q4.1)

☐ No such need ☐ Cannot afford ☐ Inconvenience

## Section 5: Other sources of air pollution

**5.1 Do you keep a stove under slow burning indoors throughout the day (not for heating)?**

☐ Yes, always ☐ Yes, sometimes ☐ No

**5.2 How frequently did you use mosquito coils in summer?**

☐ Daily or almost every day

☐ A few times a week

☐ A few times a month

☐ Never or rarely

**5.3 During the past 12 months, how frequently did you burn incense indoors?**

☐ Daily or almost every day

☐ A few times a week

☐ A few times a month

☐ Never or rarely

## Appendix H3. Procedures to measure exhaled carbon monoxide using a MicroCO meter

Details of the procedures to take exhaled carbon monoxide measurements have been published elsewhere.[207] Briefly, participants were instructed to fully inhale and hold their breath for 20 seconds (or, among elderly, at least 15 seconds if longer time was not achievable) then gradually and fully exhale out to the mouthpiece of the MicroCO meter while making sure there was no sideways air leakage out of the mouthpiece. Participants were allowed to take several practice blows until they were familiar with the technique, but each actual blow had to be made only after at least three minutes of resting (to allow the carboxyhaemoglobin level in the alveoli to reach equilibrium).

**Appendix H4 Technical details of air quality monitors used**

(a) PATS+CO

The “Particle and Temperature Sensor plus Carbon Monoxide Sensor” (PATS+CO) was developed by the Berkeley Air Monitoring Group, California, USA specifically to monitor household air pollution in solid fuel-reliant communities. The logging of $PM_{2.5}$ was based on an infrared nephelometer with a modified detection range of 10 to 30,000 $\mu g/m^3$ designed for measurement of HAP from solid fuels. The CO measurement was based on an electrochemical CO sensor (Alphasense, Essex, UK), with a detection range of 0 to 500 ppm and a resolution of 1 ppm.

(b) Established monitors for cross-validation of static environment monitoring

EL-USB-CO is based on an electrochemical sensor with detection limit of 3 to 1,000 ppm and a resolution of 0.5 ppm (NAP-505, Nemoto Sensor Engineering Company Ltd., Tokyo, Japan). EL-USB-2-LCD utilises an integrated, improved band gap temperature and capacitive RH sensor with detection ranges of -35 to +80°C (resolution: 0.5°C) and 0 to 100% RH (resolution: 0.5%) (SHT21, Sensirion AG, Staefa ZH, Switzerland). Both EL-USB-CO and EL-USB-2-LCD had been shown to give highly reliable data when benchmarking against gold standard instruments and have been widely used in similar studies.[253] MicroPEM is an infrared nephelometer that could record real-time $PM_{2.5}$ concentration and collect gravimetric sample on a 25 mm Teflon filter (Zefon International, Ocala, FL, USA). Before deployment, the devices were cleaned and the rubber o-ring and sintered stainless steel impactor were lubricated with silicone oil. Filters were placed in the MicroPEM filter cassette and inserted into the filter slot in a clean environment with low air pollution levels. The device was then zeroed using a HEPA filter and calibrated for 0.50 litre/ minute flowrate using a TSI 4140 Flowmeter (TSI, Inc., Shoreview, MN, USA) and a logging channel for $PM_{2.5}$ with a 10 seconds

logging interval selected using the MicroPEM Docking Station software (RTI International, Research Triangle Park, NC, USA).

(c) Ambient environment monitoring

DustTrak$^{TM}$ measures different sizes of PM ($PM_1$, $PM_{2.5}$, $PM_{10}$) with a light scattering laser photometer, whereas CAS-A1 measures 1) PM ($PM_1$, $PM_{2.5}$, $PM_{10}$) based on similar technology, 2) gaseous pollutants (CO, $O_3$, NO and $NO_2$) using commercial electrochemical sensors, 3) temperature and 4) RH. Gravimetric sampling was done to validate the data collected using these devices. Briefly, a mini-vol portable sampler with $PM_{2.5}$ impactor (Airmetrics, Eugeene, OR, USA) was co-located with the ambient monitors to measure 24 hour average mass concentration, with $PM_{2.5}$ samples collected on 47 mm quartz micro-fibre filters (Whatman, Maidstone, Kent, UK).

**Appendix H5. Protocol for CO sensor calibration**

1. Go to “Launch” page, check the “CO Cal Enable” button and then click “CO Cal” button.
2. Calibration box will pop up.
3. To calibrate, expose the device to 0 zero gas and press “CO Zero” button.
4. The zeroing will take 3 minutes. After 3 minutes, the “CO Zero” label will turn completely red and the values will be updated in the Mean and Standard Dev boxes.
5. Check the box next to the Mean CO value and this will update the “CO Offset” on Launch page.
6. Now expose the device to CO gas ranging from 50-400 ppm and update the “CO Concentration” box with the concentration (PPM) of gas you are using.
7. Then click the “CO Span” button to start the calibration.

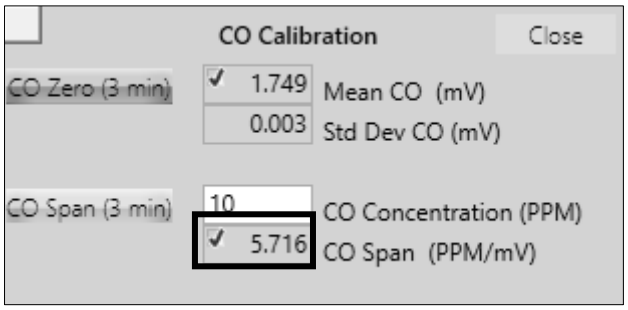



**Figure (a): Co calibration window**

8. The “CO Span” button will turn completely blue after 3 minutes and the CO Span box will be updated with the new value.
9. Check the box next to the CO Span value and this will update the “CO Coef” on Launch page
10. To program/update the CO calibration variables to the device, launch the device by pressing the “Sync launch” button.

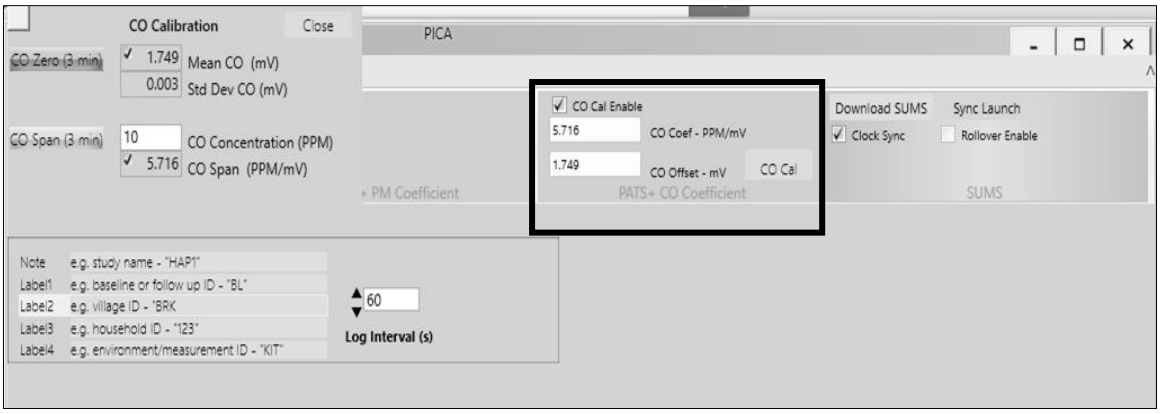



**Figure (b): Launch Page with CO calibration window**

*(Note: this was adopted and modified from the PATS+ and PICA User Manual from the Berkeley Air Monitoring Group, CA, USA)*

## Appendix H6. Procedures of gravimetric sampling

For gravimetric sampling, Teflon filters were pre-weighed using a microbalance with accuracy up to 0.1 μg and stored in labelled air-tight filter keepers before the measurement campaign. After sampling, the MicroPEMs were checked for the post-assessment flowrate to determine whether the filter was overloaded. Only those with a pre- and post-assessment flowrate difference ≤ 5% were accepted for gravimetric analysis. About 5% of the weighed filters were kept in the laboratory where weighing was carried out and another 5% were brought to the field as field-blanks. These blank filters were weighed again together with those with gravimetric samples collected, and any weight changes in these filters would be incorporated into the gravimetric analysis. Of note, it was recognised that gravimetric sampling was too complex to be carried out in the warm season campaign, so fieldworkers were asked to practice the procedures but the filters were not sent for gravimetric analysis. In the cool season, the gravimetric sampling was implemented under the supervision of collaborators at CUHK.