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Boiled or Bottled: Regional and Seasonal Exposures to Drinking Water Contamination and Household Air Pollution in Rural China

Alasdair Cohen,[1] Ajay Pillarisetti,[2] Qing Luo,[3] Qi Zhang,[3] Hongxing Li,[3] Gemei Zhong,[4] Gang Zhu,[5] John M. Colford Jr.,[6] Kirk R. Smith,[6]* Isha Ray,[7,8] and Yong Tao[3]

[1]Public Health Program, Department of Population Health Sciences, Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, Virginia, USA
[2]Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, Georgia, USA
[3]National Center for Rural Water Supply Technical Guidance, Chinese Center for Disease Control and Prevention (CDC), Beijing, China
[4]Guangxi CDC, Nanning, Guangxi Autonomous Region, China
[5]Henan CDC, Zhengzhou, Henan Province, China
[6]School of Public Health, University of California, Berkeley, Berkeley, California, USA
[7]Energy and Resources Group, University of California, Berkeley, Berkeley, California, USA
[8]Berkeley Water Center, University of California, Berkeley, Berkeley, California, USA

BACKGROUND: Inadequate access to safe drinking water remains a global health problem, particularly in rural areas. Boiling is the most commonly used form of point-of-use household water treatment (HWT) globally, although the use of bottled water in low- and middle-income countries (LMICs) is increasing rapidly.

OBJECTIVES: We assessed the regional and seasonal prevalence of HWT practices (including bottled water use) in low-income rural areas in two Chinese provinces, evaluated the microbiological safety of drinking water and associated health outcomes, and estimated the air pollution burden associated with the use of solid fuels for boiling.

METHODS: We conducted cross-sectional surveys and collected drinking water samples from 1,033 rural households in Guangxi and Henan provinces. Temperature sensors affixed to pots and electric kettles were used to corroborate self-reported boiling frequencies and durations, which were used to model household air pollution (HAP) in terms of estimated particulate matter $\leq 2.5\ \mu\mathrm{m}$ in aerodynamic diameter ($PM_{2.5}$) concentrations.

RESULTS: Based on summer data collection in both provinces, after controlling for covariates, boiling with electric kettles was associated with the largest log reduction in thermotolerant coliforms (TTCs) ($-0.66\ \log_{10}$ TTC most probable number/100 mL), followed by boiling with pots (-0.58), and bottled water use (-0.39); all were statistically significant ($p < 0.001$). Boiling with electric kettles was associated with a reduced risk of TTC contamination [risk ratio (RR) $= 0.25$, $p < 0.001$] and reported diarrhea (RR $= 0.80$, $p = 0.672$). TTCs were detected in 51% ($n = 136$) of bottled water samples. For households boiling with biomass, modeled $PM_{2.5}$ concentrations averaged $79\ \mu g/m^3$ (standard deviation $= 21$).

DISCUSSION: Our findings suggest that where boiling is already common and electricity access is widespread, the promotion of electricity-based boiling may represent a pragmatic stop-gap means of expanding safe water access until centralized, or decentralized, treated drinking water is available; displacing biomass use for water boiling could also reduce HAP concentrations and exposures. Our results also highlight the risks of increasing bottled water use in rural areas, and its potential to displace other sources of safe drinking water, which could in turn hamper efforts in China and other LMICs toward universal and affordable safe water access. https://doi.org/10.1289/EHP7124

Introduction

Safe, affordable, and accessible water is necessary for health, development, and dignity. It is enshrined in the United Nations' Sustainable Development Goal 6 (SDG6) (UN 2019). There have been significant gains in the global water, sanitation, and hygiene (WASH) sector over the last few decades; however, as of 2017, an estimated 2.2 billion people still lacked access to safely managed drinking water services (WHO/UNICEF 2019). With regard to the associated burden of disease, a recent analysis concluded that of the estimated 1.4 million diarrhea-attributed deaths in 2016, inadequate safe water access accounted for close to half a million (485,000) deaths, and another half million deaths were attributed to inadequate sanitation and hygiene (432,000 and 165,000, respectively) (Prüss-Ustün et al. 2019).

The lack of reliable access to safe drinking water in low- and middle-income countries (LMICs)—and in high-income countries—disproportionately affects those living in rural areas (Bain et al. 2014b; WHO/UNICEF 2019). Indeed, most of the ~785 million people who rely on limited water services (i.e., improved sources, but with collection times exceeding 30 min), unimproved sources (i.e., unprotected wells or springs), or surface water, live in rural areas of LMICs (WHO/UNICEF 2017, 2019).

The first target of SDG6 aims to "achieve universal and equitable access to safe and affordable drinking water for all" by 2030 (UN 2019). At present, however, in most rural LMIC settings without reliable and affordable centralized or decentralized safe water supply, the burden of providing safe water falls to the household. Point-of-use household water treatment (HWT) is often considered a stop-gap measure, yet in many low-income rural areas, the household will remain responsible for treating drinking water for the foreseeable future. This is particularly the case in much of sub-Saharan Africa and Asia, where rural–urban gaps in safe water access are acute (WHO/UNICEF 2019). In China too, the rural–urban WASH gap remains pronounced (Li et al. 2015, 2019a).

With respect to global gains in WASH, China's contribution has been substantial. Over the last few decades, China has invested heavily in drinking water treatment and supply infrastructure, and rates of WASH-associated diarrheal disease have fallen (Li et al. 2016). From 1990 to 2012, an estimated 488 million Chinese gained access to improved water sources (WHO/UNICEF 2014), and, in roughly the same period (1990 to 2013),

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Address correspondence to Alasdair Cohen, Public Health Program, Department of Population Health Sciences, Virginia Polytechnic Institute and State University, 205 Duck Pond Dr., Blacksburg, VA 24061 USA. Email: alasdair.cohen@linacre.oxon.org

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*Deceased.

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the age-standardized death rate associated with diarrheal disease decreased by 95.2% (Zhou et al. 2016). Although industrial, agricultural, and other chemical contaminants in drinking water are a growing problem in China and elsewhere, with respect to reducing acute drinking water-associated health risks in rural China, the control of pathogens in drinking water remains a government priority (Li et al. 2019b, 2020).

Compared with other large LMICs, data on HWT and storage practices in China are relatively sparse. Publicly available data from a 2006–2007 national survey revealed that, at the time, ~85% of rural Chinese households regularly boiled their drinking water (Tao 2008; Zhang et al. 2009). At a global level too, the best available estimates show that boiling is the most commonly used HWT method (Rosa and Clasen 2010; Tao 2009; Yang et al. 2012). Boiling is a straightforward and highly effective method for pathogen inactivation (WHO 2015; Cohen and Colford 2017). However, in LMIC settings, fuel can be relatively expensive to purchase or time consuming to collect (Psutka et al. 2011), and boiling with solid fuels is often a time-consuming endeavor. Boiled water is also susceptible to secondary contamination (Wright et al. 2004), and boiling with solid fuels increases household air pollution (HAP) exposure and its associated health risks (GBD 2017 Risk Factor Collaborators 2018). In addition, hot water presents a burn or scalding risk and boiling alone does not mitigate exposure to heavy metal and chemical contamination.

In recent years, rural Chinese households have increasingly adopted cleaner fuels, such as electricity and various forms of gas for water boiling (Du et al. 2018a). However, it is often the case that, even as incomes in rural areas rise, many households continue to use a variety of fuels at different times or for different purposes—a practice termed fuel stacking (Masera et al. 2000). This is also the case in China, where many rural households that can afford higher quality fuels still opt to use biomass for certain cooking or heating applications (Peng et al. 2010; Tao et al. 2018), including the boiling of drinking water (Du et al. 2018a).

Previous electrification campaigns in China have resulted in near-universal rural electricity access (Luo and Guo 2013), a phenomenon not typical of LMICs. In spite of the general shift to cleaner fuels, as much as one-third of China's outdoor air pollution burden still stems from residential biomass combustion for cooking, heating, and—in many households—the boiling of drinking water (Tao et al. 2018; Shen et al. 2019). Exposure to HAP has been linked to a number of cardiorespiratory outcomes—including chronic obstructive pulmonary disease, lower respiratory infection, stroke, heart disease, and lung cancer—and type-2 diabetes mellitus (Chafe et al. 2014; Smith et al. 2014; HEI 2019). Particulate air pollution is now the fourth leading health risk factor in China (IHME 2018). The burden of disease attributable to HAP has decreased over the past two decades; however, it is estimated that ~30% of households across China continue to use solid fuels (HEI 2019). Owing to the size of China's rural population, there are also substantial environmental impacts associated with residential solid fuel combustion, which is estimated to be responsible for the majority of black carbon emissions in China (Chafe et al. 2014; Shen et al. 2019).

In this article, we present comprehensive results from a multistage study that assessed and evaluated HWT practices in low-income rural communities in two Chinese provinces: Guangxi and Henan. Previous research on seasonal impacts has indicated that associations between indicators of fecal contamination and diarrheal outcomes in rural areas tend to be more strongly associated during warmer and wetter periods of the year (Kostyla et al. 2015; Mertens et al. 2019). Thus, in addition to a regional comparison, we also evaluated potential seasonal differences in the prevalence, and estimated effectiveness, of different HWT methods. At the onset, we anticipated that most households would boil their drinking water; therefore, we designed our studies so that we could disaggregate and evaluate different methods of boiling and also estimate the air pollution burden associated with the use of solid fuels for boiling. In our previous publications on the first phase of this study (Cohen et al. 2015, 2017), we reported results from summer data collection in Guangxi. In this article, we report the comprehensive results from Henan as well as the winter data from Guangxi and provide comparative analyses of HWT use, drinking water safety, HAP exposure estimation, and health-related associations in and across both provinces and seasons. Our overall objective was to assess whether the HWT and health-related exposures in Henan were similar to those observed in Guangxi and to assess the extent to which seasonal differences may or may not impact HWT use, drinking water safety, and boiling-specific HAP exposures.

Methods

Study Sites, Samples, and Data Collection

Data collection efforts for these studies were managed by the National Center for Rural Water Supply Technical Guidance (NCRWSTG), an agency of the Chinese Center for Disease Control and Prevention (China CDC), the Guangxi Zhuang Autonomous Region (Guangxi Province) CDC, and the Henan Province CDC. Given our collective research objectives, we designed the studies to target low-income rural households and powered them to estimate the population prevalence of drinking water boiling and water quality outcomes in the study counties. For our sample size calculations in Guangxi, based on unpublished data provided by the township- and county-level China CDC, we assumed 68% of households in our study area regularly boiled their drinking water, and we used data from a small pilot study we had conducted in Guangxi (in June 2013, in villages outside of our target study area) to help inform the estimation of an intracluster correlation coefficient of rho = 0.01. Based on a constant of 30 households/village and a desired precision of 5% for our primary outcome (boiling proportion), our design effect was 1.29. To retain a constant of 30 households/village, we used an actual design effect of 1.35, for a total sample size of 450 households. Our previously published work provides some additional details on sample size and power calculations for our study in Guangxi Province (Cohen et al. 2015), which was used as the model for the Henan Province phase of the study, which also used a target sample size of 450 households (and the same constant of 30 households/village).

In Guangxi Province, survey data and drinking water samples were collected from a random representative cross-sectional sample of 30 households/village (i.e., per cluster) in 15 randomly selected villages in two counties during the 2013 summer/rainy season (village codes 1–15). To assess seasonal differences in key outcomes of interest, during the 2013–2014 winter/dry season, we returned to four Guangxi villages (selecting two in each study county, with relatively high and low proportions of summer boiling and untreated water consumption) and then collected data from a new random sample of 30 households in each village (village codes 3, 6, 9, 10). The Guangxi summer study protocol was subsequently replicated in Henan Province during the summer of 2014, using the same methods to collect data from a random sample of 30 rural households in 15 randomly selected villages (village codes 16–30). The total number of households sampled in Henan Province was 466, due to intentional oversampling.

Household Surveys and Drinking water Samples

Because this was the first HWT-focused research study we were aware of in rural China, we opted to use the Multidimensional

Poverty Assessment Tool (MPAT), a topically expansive, open-source, survey tool that had already been translated, used, and evaluated in rural China (Cohen 2009; Saisana and Saltelli 2010). The MPAT is a thematic indicator based primarily on a household survey instrument designed to collect a mix of data around 10 components central to rural regions, such as water, sanitation, health, rural assets, and gender equity (Cohen 2010; Cohen and Saisana 2014). Additional questions specific to our research objectives were also piloted, double-blind translated, and added to the end of the MPAT household survey. Among these additional survey items, we included a question asking whether the respondent recalled having diarrhea any time in the previous 2 wk. Completed household surveys were subjected to a three-stage quality control process involving overlapping personnel to check, double-check, and enter survey data into spreadsheets, which were then subjected to additional quality control and data cleaning via the examination of potential outliers as well as logical consistency checks (e.g., a head of household age of 120 y; responses to survey items about school-aged children in a household not reporting to have children). The standardized MPAT household survey, as well as enumerator training protocols and other details, are available in the "MPAT User's Guide" (IFAD 2014).

In addition to survey data, we collected drinking water samples from all households after respondents were asked to provide drinking water as if they themselves would drink it (i.e., not water procured for a guest). According to our China CDC collaborators, small-scale utility chlorination was rare in these areas, so we did not control for chlorine residuals. Five hundred–milliliter samples were collected aseptically and transported on ice to China CDC county-level laboratories for analysis within 6 h (in nearly all cases) of collection. As per China CDC (MoH 2006b) and World Health Organization WHO (2011) water quality guidelines and standards, China CDC laboratory staff followed a standard protocol for multiple tube fermentation (MoH 2006a) to estimate the most probable number (MPN) of thermotolerant coliforms (TTCs)—an indicator of fecal contamination—as well as total coliforms (TCs) and total bacteria (TB) per 100 mL of water. To facilitate some of our analyses and modeling, the resulting TTC data, as well as TC and TB data, were Log_{10} transformed after assigning a value of 1 to all cases where TTC were below the detection limit (lower detection limit = 2 MPN). Additional details on data collection methods and water testing protocols are available in our research team's previous publications (Cohen et al. 2015, 2017).

Temperature Sensor Data and Household Ventilation Assessment

During the winter data collection in the subsample of four villages in Guangxi, we measured the temperature of pots and electric kettles among households that reported primarily boiling their drinking water. Specifically, we used data-logging thermistors as stove use monitors (SUMs) (iButton Model DS1922T; Maxim Integrated) to measure instantaneous temperature every minute for 72 h (Ruiz-Mercado et al. 2012). In eligible households, SUMs were affixed to water kettles or pots using heat-resistant tape (Figure S1). Data were collected one village at a time, such that the same, overlapping, minimum duration of 72 h of temperature data was recorded for all subsample households, from 0001 hours on Day 1 until 2359 hours on Day 3. SUMs iButton temperature data was also compared with publicly available average low and high temperatures for the study area over the same time period (WK 2019).

Once the SUMs were collected, all of the data recorded were saved into individual files and the units were then reset for use in the next village. Minute-by-minute temperature measurements for each boiling event in a given household were highlighted (from the initiation of a heating curve until its inflection point), and these delineated intervals were used to calculate the frequency with which the household heated their water (i.e., total boiling events divided by three, to provide a daily mean), the mean duration of individual heating events per household, the standard deviation (SD) of these heating event durations, the minimum temperature recorded (i.e., during the early morning hours), the maximum temperature recorded (at the peak of a heating/boiling curve), and the median temperature (which was also used to help triangulate responses on whether water was usually heated inside or outside the home). Examples of the heating curves for an electric kettle and a pot are shown in Figure S2. If multiple boiling events were observed in the course of one boiling session, the durations were recorded separately to calculate the average duration of boiling, but the event was treated as one boiling event (e.g., as shown in the far right of the temperature curve at the top of Figure S2, for one household using an electric kettle, an initial boiling event took 13 min and was followed quickly by a boiling event that lasted 9 min).

In order to model estimated boiling-induced HAP concentrations (described in the next section), we calculated a ventilation index value for each household that reported primarily boiling their drinking water. This index was based on two survey items: *a*) self-reported response on the location of the cooking area and its proximity to the home's primary living areas, and *b*) an enumerator observation–based survey item on how the cooking area was or was not ventilated. A 1–3 scale was used to categorize responses to each item, such that 1 was the most optimal value and 3 the least optimal (e.g., no separation between the cooking and living area). The index was then calculated by multiplying these two subcomponents, resulting in a 1–9 index score for all households.

Statistical Analyses and Models for Water Quality and HAP Concentrations

For unadjusted comparative analyses of survey data, we used chi-square and two-sided t-tests for statistical significance testing, using a standard significance level (alpha = 0.05) and variance estimates that accounted for the clustered study design. SDs are reported with descriptive summary statistics and cluster-robust standard errors (SEs) are reported for significance testing as appropriate. To calculate risk ratios (RRs), binary variables were created for TTCs and reported diarrhea such that all TTC results below the detection limit were assigned a value of 0, and all TTC results ≥2 MPN were assigned a value of 1, and likewise for reported cases of diarrhea (with p-values based on chi-square tests unless noted otherwise). Given the relatively widespread use of bottled water (typically large, 19 L, bottles on dispensers with optional built-in heating elements) in many areas of rural China, for our analyses we considered bottled water to be a form of HWT.

To control for and assess covariates of interest and between- and within-village variance, as well as differences between the two study regions, we used multilevel mixed-effects linear regression models to evaluate the associative impacts of HWT and other covariates on our primary water quality outcome, $\mathrm{Log}_{10}\mathrm{TTC}$ (using summer data from both provinces). Because our data were balanced (i.e., an approximately constant number of households per village), we used restricted maximum likelihood estimation to derive less-biased variance component estimates (Rabe-Hesketh and Skrondal 2012). The null (unadjusted) model is provided in Equation 1 (null water quality model).

$$yLog_{10}TTC_{ij} = \beta_1 + \beta_2 Province_j + \zeta_j + \varepsilon_{ij}. \tag{1}$$

Assuming $\epsilon_{ij} \sim N(0,\theta)$; with ζ_j as the village-level error term, and $\zeta_j \sim N(0,\psi)$ for village j, $j = 1,2,3\ldots 30$; with each household denoted by i, each village denoted by j, village-level residuals denoted with ζ, and household-level residuals (within villages) denoted with ϵ (between-cluster variance is denoted with ψ, and within-cluster variance denoted with θ).

In order to assess outcomes across our study areas in Guangxi and Henan, and to facilitate comparison between the provinces, we based construction of our adjusted model, Equation 2 (adjusted water quality model), on the final model covariates and structure employed in our previous analysis of the Guangxi summer data in isolation (Cohen et al. 2015). This includes covariates routinely controlled for in WASH-related analyses (e.g., whether stored water was covered, use of soap, handwashing practices) as well as demographic and socioeconomic indicators [e.g., head of the household's age, literacy level, television (TV) ownership]. We were unable to include a variable for mean bottled water cost per village because in Henan there was insufficient data for some villages and no bottled water cost data for other villages (we did use available bottled water cost data from Henan for sensitivity analyses).

$$\begin{aligned} yLog_{10}TTC_{ij} &= \beta_1 + \beta_2 BoilElecKettle_{ij} + \beta_3 BoilPot_{ij} + \beta_4 BottledWater_{ij} \\ &+ \beta_5 ImprovedSource_{ij} + \beta_6 SafeStorage_{ij} + \beta_7 HeadHHLiteracy_{ij} \\ &+ \beta_8 HeadHHage_{ij} + \beta_9 TVperCap_{ij} + \beta_{10} HandwashPD_{ij} + \beta_{11} SoapUsed_{ij} \\ &+ \beta_{12} HandwashBM_{ij} + \beta_{13} Province_j + \zeta_j + \epsilon_{ij}. \end{aligned} \tag{2}$$

Assuming, $\epsilon_{ij}|\zeta_j, \boldsymbol{x}_{ij} \sim N(0, \theta)$ and $\zeta_j|\boldsymbol{x}_{ij} \sim N(0, \psi)$, where the zero mean and variance assumptions are conditional on the model covariates, denoted by vector $\boldsymbol{x}_{ij}$.

We also evaluated the potential impact of water boiling using biomass fuels on indoor concentrations of particulate matter $\leq 2.5\ \mu m$ in aerodynamic diameter ($PM_{2.5}$). We used a Monte Carlo single-compartment box model (Johnson et al. 2011; Johnson and Chiang 2015) to estimate indoor concentrations. The box model requires several inputs, including duration of stove use, air changes per hour (a measure of ventilation), emission rates (in milligrams of pollutant per unit time), kitchen volumes, and the fraction of emissions mixing in the room.

To determine stove use time for boiling, we used linear models to estimate the relationship between reported and sensor-measured boiling duration and frequency. We then predicted daily biomass usage for water boiling for all households in the study by multiplying the estimated mean frequencies of boiling by the estimated mean durations of boiling events.

We used China-specific air exchange rate (AER) estimates (per hour) from the literature (Carter et al. 2016). We scaled AER values by a qualitative ventilation index, which was created based on survey questions related to cooking location and enumerator-based observations of household ventilation status. Ventilation index results (1–9 scale) were binned into three categories to represent good (1–3), average (4–6), and poor (7–9) ventilation. Houses were assigned to these three categories, with Category 1 being the most ventilated and Category 3 being the least ventilated. For the least ventilated houses, AERs were decreased by a half SD of literature values; for the most ventilated houses, AERs were increased by a half SD.

We derived emissions-related parameters from published Chinese data (Shen 2016) for wood logs, wood twigs, and crop residues. The fuel-specific emission rate is related to the specific power, thermal efficiency, and pollutant emission factors for a fuel–stove combination, as well as the energy required, in this case, to boil a specific volume of water. The energy (Q) required to boil 1 L of water is equal to the product of the mass of water, the specific heat of water, and the change in temperature required (Equation 3; the energy required to boil 1 L of water).

$$Q = \mathrm{MC}(T_f - T_i),$$

$$Q = 1\ \mathrm{kg} \times 4.184\ \mathrm{kJ/kgC} \times (100 - 20) = 0.335\ \mathrm{MJ}. \tag{3}$$

Emissions rate were derived as shown in Equation 4 (fuel-specific estimated emissions rates).

$$\frac{\frac{\mathrm{mg}_{PM2.5}}{\mathrm{kg}_{fuel}}}{\frac{\mathrm{MJ}}{\mathrm{kg}_{fuel}}} \times \frac{\frac{0.335\ \mathrm{MJ}}{\mathrm{L}} \times \mathrm{L}}{boiling\ time_{sums} \times thermal\ efficiency}. \tag{4}$$

Kitchen volumes were derived from previous work in China (Fischer and Koshland 2007). We assumed all emissions released entered the room. $PM_{2.5}$ concentrations were estimated by taking 5,000 random draws of these parameters for each household and using them as inputs to the box model. The box model was coded and run in R and based on the WHO Household Multiple Emission Sources Model tool (WHO 2019b, 2019a).

Ethics and Reporting

The study was approved by the committee for the protection of human subjects at the University of California Berkeley (protocol identification no. 2012-05-4368) and by the ethics review board at the NCRWSTG, China CDC. All participants provided informed written consent. For our statistical analyses, we used Stata (version 15.1; StataCorp) and R (version 3.5.1; R Development Core Team). This manuscript was prepared using the Strengthening the Reporting of Observational Studies in Epidemiology reporting guidelines (Vandenbroucke et al. 2007).

Results

Household and Village-Level Characteristics

As shown in Table 1, results for demographic data and indicators of socioeconomic status were mixed across the two provinces. The mean number of adults living at home most of the year was approximately equal for Henan, with 2.84 adults, and Guangxi, with 2.89 adults ($SE = 0.14$ and $SE = 0.14$, respectively; $p = 0.787$). Households in Henan also had approximately the same mean number of children living in the home as households in Guangxi (1.81, $SE = 0.08$, and 1.83, $SE = 0.09$, children, respectively; $p = 0.895$).

Mean time to travel to the nearest health clinic (in minutes) was almost twice as long in Guangxi compared with Henan (12.1, $SE = 1.79$, vs. 6.5, $SE = 0.63$), a statistically significant difference ($p = 0.008$) potentially indicative of worse access to health care. However, average TV ownership was higher in Guangxi than in Henan (1.4 TVs/household, $SE = 0.07$ vs. 1.2, $SE = 0.05$, respectively; $p = 0.007$). Approximately 76% ($n = 344$) of households in Guangxi reported that they could afford to pay for professional health care services if needed, compared with ~62% ($n = 286$) in Henan ($p = 0.036$). Results from another indicator of socioeconomic status, home construction materials/quality, were similar, with ~87% ($n = 372$) of households in Guangxi and ~93% ($n = 379$) in Henan reporting that their home could withstand severe weather events ($p = 0.150$). Among the households required to pay for water provision or access, in Guangxi ~98% ($n = 379$) reported that they could often or always afford to do so, compared with ~90% ($n = 195$) in Henan ($p = 0.012$).

Across both provinces (summer data), close to half of the households who boiled their water reported having tap water access in their homes (47.8%, $n = 267$). Of these 267 households, 65.3% ($n = 173$) had water piped from a small-scale drinking water utility, whereas the other 35% had water that was piped (often via rubber hosing) from nearby wells, springs, and rainwater

Table 1. Summary of key household characteristics by province (summer data).

	Guangxi	Henan	Totals
HoH gender [*n* (%)]			
Male	373 (83.3)	352 (75.5)	725 (79.3)
Female	54 (12.1)	94 (20.2)	148 (16.2)
Jointly headed (male and female)	21 (4.7)	20 (4.3)	41 (4.5)
Total	448 (100.0)	466 (100.0)	914 (100.0)
HoH age (y) [mean (SD)]			
HoH age (y)	52.4 (12.5)	53.3 (12.4)	52.9 (12.4)
Persons living in household >9 months/y [age (y)] [mean (SD)]			
Adults (≥18)	2.89 (1.4)	2.84 (1.2)	2.86 (1.34)
Children (<18)	1.83 (1.3)	1.81 (0.9)	1.82 (1.1)
HoH marital status [*n* (%)]			
Married	395 (90.8)	381 (90.9)	776 (90.9)
Single	9 (2.1)	12 (2.9)	21 (2.5)
Divorced	1 (0.2)	7 (1.7)	8 (0.9)
Widowed	30 (6.9)	19 (4.5)	49 (5.7)
Total	435 (100.0)	419 (100.0)	854 (100.0)
HoH is literate or semiliterate [*n* (%)]			
No	51 (11.5)	125 (27.4)	176 (19.6)
Yes	392 (88.5)	331 (72.6)	723 (80.4)
Total	443 (100.0)	456 (100.0)	899 (100.0)
HH can afford professional health care services [*n* (%)]			
No	106 (23.6)	179 (38.5)	285 (31.1)
Yes	344 (76.4)	286 (61.5)	630 (68.9)
Total	450 (100.0)	465 (100.0)	915 (100.0)
TV ownership [mean (SD)]			
TVs per HH	1.41 (0.8)	1.16 (0.5)	1.28 (0.7)
TVs per capita (by HH population)	0.51 (0.4)	0.40 (0.3)	0.45 (0.4)
Travel time to nearest health clinic (min) [mean (SD)]			
Reported travel time	12.08 (13.9)	6.51 (7.6)	9.25 (11.5)
Home can withstand severe weather/storms [*n* (%)]			
No	55 (12.9)	30 (7.3)	85 (10.2)
Yes	372 (87.1)	379 (92.7)	751 (89.8)
Total	427 (100.0)	409 (100.0)	836 (100.0)
Fuel type/classification used for boiling water [*n* (%)]			
Clean fuels (electricity and gas)	144 (65.5)	132 (38.9)	276 (49.4)
Coals	0 (0.0)	13 (3.8)	13 (2.3)
Wood	72 (32.7)	177 (52.2)	249 (44.5)
Crop residue	4 (1.8)	17 (5.0)	21 (3.8)
Total	220 (100.0)	339 (100.0)	559 (100.0)
Adults often or always wash hands post-defecation [*n* (%)]			
No	46 (10.3)	119 (25.6)	165 (18.1)
Yes	402 (89.7)	346 (74.4)	748 (81.9)
Total	448 (100.0)	465 (100.0)	913 (100.0)
Enumerator-observed soap likely used for handwashing [*n* (%)]			
No	258 (57.7)	178 (38.8)	436 (48.1)
Yes	189 (42.3)	281 (61.2)	470 (51.9)
Total	447 (100.0)	459 (100.0)	906 (100.0)
Primary drinking water source is an improved source [*n* (%)][a]			
No	234 (52.3)	177 (38.1)	411 (45.1)
Yes	213 (47.7)	288 (61.9)	501 (54.9)
Total	447 (100.0)	465 (100.0)	912 (100.0)
HH can afford to pay for water provision or access [*n* (%)]			
No, rarely, or sometimes	9 (2.3)	22 (10.1)	31 (5.1)
Often or always	379 (97.7)	195 (89.9)	574 (94.9)
Total	388 (100.0)	217 (100.0)	605 (100.0)

Note: HH, household; HoH, head of household; SD, standard deviation; TV, television.
[a] The Joint Monitoring Program defined improved sources as public taps or standpipes, tube wells or boreholes, protected dug wells, protected springs, rainwater collection, and piped household water connections (WHO/UNICEF 2014).

harvesting cisterns. Of the households that boiled their drinking water, in ∼47% ($n = 257$) water was typically boiled by female members of the household who were ≥15 years of age (Table S1). Reported handwashing post-defecation was relatively high in both provinces, with ∼90% ($n = 402$) of households in Guangxi and ∼74% ($n = 346$) in Henan reporting that adults always or often did so ($p = 0.006$). Overall, across both provinces a slim majority (∼55%; $n = 501$) of study households reported having a drinking water source classified as improved by the WHO/United Nations International Children's Fund (UNICEF) Joint Monitoring Program (WHO/UNICEF 2014) (Table 1). However, TTC counts and concentrations were not significantly lower for improved sources compared with unimproved sources (Figure S3), a phenomenon observed elsewhere as well (Bain et al. 2014a).

With regard to HWT, on average (excluding winter subsample data) 61.4% ($n = 559$) of households boiled their water, with the majority using pots to do so, 29.7% ($n = 270$) consumed bottled water, and 8.9% ($n = 81$) drank untreated water (Table 2). Across a number of variables, there was a considerable degree of variation both within and between villages, as well as between provinces; this was the case with HWT use generally, and with bottled water use especially (Figure 1). We also observed differences in HWT use trends as they related to the head of the household's age (Figure 2) and by household size (Figure S4). (Source data for figures presented in the main text and supplemental material are provided in Supplemental Material, "Source Data for Figures Presented in the Main Text and Supplemental Material").

HWT, Drinking Water Quality, and Reported Diarrhea

Compared with untreated samples, geometric mean TTC concentrations were 83% lower for water boiled with electric kettles and pots, and 63% lower for bottled water samples (details and comparison with arithmetic means and with Guangxi winter data included in Table S2). Unadjusted associations between HWT methods and TTC from the summer data in both provinces (Figure 3) show that households boiling their water (with either electric kettles or pots) had lower TTC concentrations than those households using bottled or untreated water (for results with Guangxi winter data included, see Figure S5). Self-reported data on the costs for bottled water (19 L bottles) revealed that bottled water cost significantly less (on average) in Guangxi than in Henan [renminbi (RMB) 7.6, SE = 0.45, vs. RMB 3.7, SE = 0.17, respectively; $p < 0.0001$], although we observed no association between the cost and quality ($\text{Log}_{10}\text{TTCMPN}/100\ \text{mL}$) of bottled water in either province (Figure 4).

The null model results (Table 3) show that before controlling for covariates known to be associated with drinking water quality, compared with those using untreated water (the reference group) water samples from households using electric kettles and boiling with pots were associated with more than a half-log reduction in TTC concentrations. After controlling for key WASH-related and other covariates in the adjusted model, the log reductions in TTC observed for both boiling methods and bottled water remained statistically significant and similar to those in the unadjusted (null) model (for a comparison with adjusted model results with bottled water cost included, and with maximum likelihood estimation, see Tables S3 and S4, respectively). As shown in Figure 5, we observed notable regional and seasonal differences in trends for TTC concentrations by HWT method, such that observed TTC contamination was lower, overall, in Henan Province.

In Guangxi Province, the mean median temperature in the home cooking areas of households in the four villages during the winter data collection period (December 2013 to January 2014) was 14.2°C ($n = 47$) as measured by the SUMs iButtons (see

Table 2. Summary of household water treatment (HWT) use by province and season.

	Guangxi		Henan	Guangxi and Henan
	Summer data [*n* (%)]	Winter data [*n* (%)]	Summer data only [*n* (%)]	Summer data only [*n* (%)]
HWT method				
Boil	217 (48.7%)	86 (73.5%)	342 (73.7%)	559 (61.4%)
Bottled	154 (34.5%)	11 (9.4%)	116 (25.0%)	270 (29.7%)
Untreated	75 (16.8%)	20 (17.1%)	6 (1.3%)	81 (8.9%)
Total	446 (100)	117 (100%)	464 (100%)	910 (100%)
Boiling method				
Electric kettle	125 (28.0%)	72 (61.5%)	117 (25.2%)	242 (26.6%)
Metal pot	92 (20.6%)	14 (12.0%)	225 (48.5%)	317 (34.8%)

Table S5 for additional detail). In the four Guangxi villages for which data were collected in both the summer and winter, bottled water use remained similar across seasons ($n = 10$ and $n = 11$ households, respectively), but total boiling appeared to increase from 62.4% ($n = 73$) in the summer to 73.5% ($n = 86$) in the winter, with most of the winter boiling done with electric kettles [61.5% ($n = 72$), vs. 36.8% ($n = 43$) in the summer; Figure S6].

As TTC counts increase, generally speaking, so too does the expected risk of pathogenic infection (WHO 1997). The WHO's standard for microbiological safety is no detectable TTC/100 mL (WHO 2011). The China CDC also considers TTC samples below the detection limit as microbiologically safe (MoH 2006b). In Figure 6, the stacked bars display TTC concentrations divided into categories based on likely health risk (WHO 1997) and the percentage of households in each risk category by HWT method (at counts of 1–9 MPN/100 mL, drinking water is often considered to be low risk for most people, excluding children <5 years of age, the elderly, and the immunocompromised).

Restricting our analysis to the Henan and Guangxi summer data, compared with boiling, households that reported consuming untreated water were more than four times as likely to have TTC detected in their drinking water samples {RR = 4.58 [95% confidence interval (CI): 3.45, 6.06]; $p < 0.001$}, and those consuming bottled water were just under four times more likely [RR = 3.93 (95% CI: 3.08, 5.03); $p < 0.001$]. Overall, based on the summer data, 14.6% ($n = 35$) of the households using electric kettles and 11.7% ($n = 37$) of those boiling with pots had some level of TTCs detected, compared with 50.9% ($n = 136$) of the households using bottled water and 59.3% ($n = 48$) of those consuming untreated water. RRs for having TTCs detected are shown in Table 4 for households boiling their water with any method, boiling with electric kettles, boiling with pots, or consuming bottled water (compared with those drinking untreated water, see Table S6 for underlying data). As can be seen, across Guangxi and Henan, boiling with electric kettles or pots was associated with substantial and statistically significant reductions in the risk of TTC detection (~75% and ~80%, respectively; ~78% overall). The reduced risk for those consuming bottled water (~14%) was not statistically significant.

The reported 2-wk diarrhea incidence based on the summer data from both provinces was 5.3% ($n = 48$) overall, with a higher reported incidence in Henan Province (6.7%, $n = 31$) than in Guangxi (3.8%, $n = 17$; $p = 0.047$). Although these studies were not powered for reported diarrhea outcomes, we note that the risk associated with using any method of HWT was lower than for those consuming untreated water, and households that reported using electric kettles had a slightly larger reduction in risk (~20%) compared with those boiling with pots or using bottled water, although none of these associations were statistically

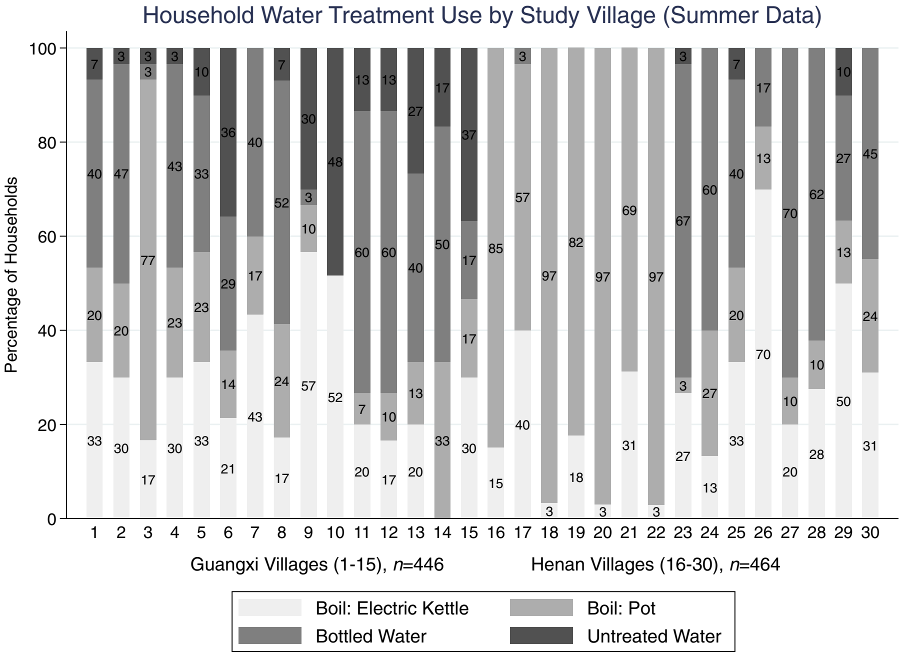

Figure 1. Proportion of households boiling drinking water and using bottled water by study village (summer data). The source data (number of households) are reported in Table S9.

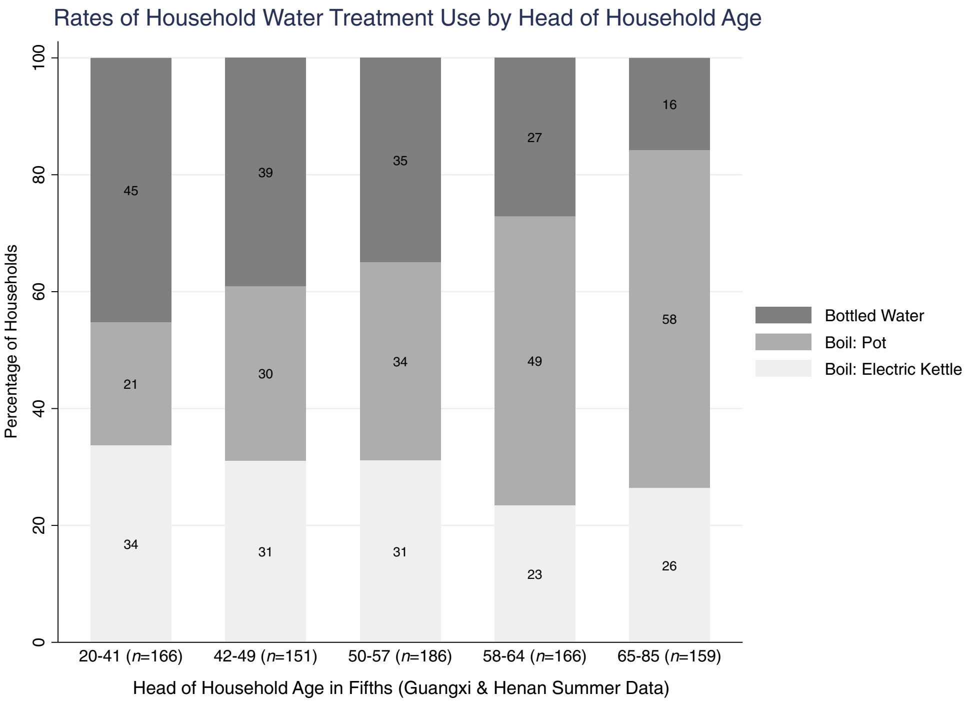

Figure 2. Household water treatment use by head of household's age: Guangxi and Henan summer data. The source data (number of households) are reported in Table S10.

significant (Table 4). There was also no significant association between TTC detection in drinking water samples and reported diarrhea among survey respondents, with 12 cases out of the 255 households with TTCs detected, and 36 cases out of the 651 households with no TTC detected [RR = 0.85 (95% CI: 0.45, 1.61); $p = 0.619$].

Temperature Sensor Data and Boiling-Associated Air Pollution Concentrations

Self-reported boiling durations and frequencies from the Guangxi winter data were largely corroborated by the SUMs iButtons data (Bland-Altman and Passing-Bablok plots provided in Figure S7).

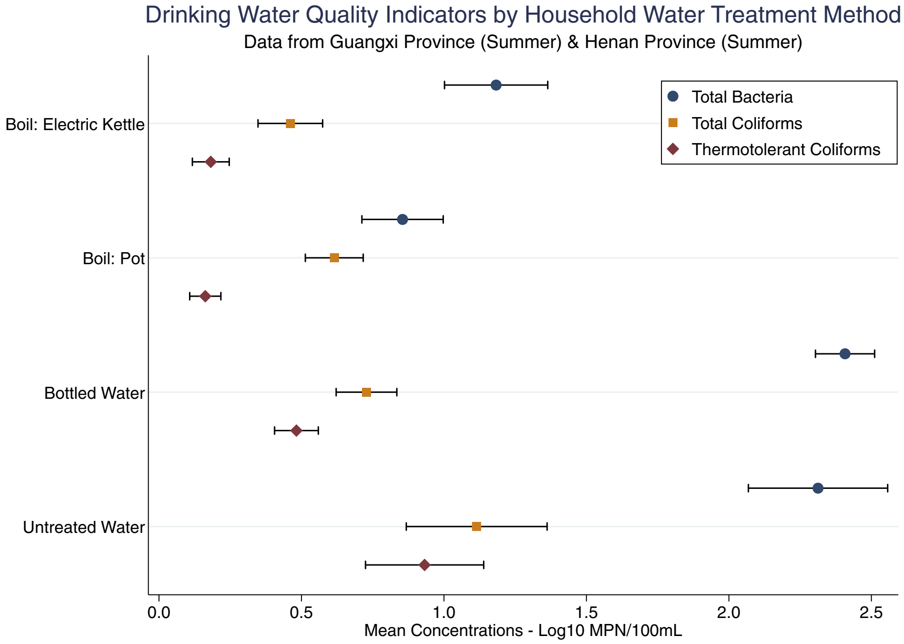

Figure 3. Geometric mean of Log_{10} concentrations for total bacteria, total coliforms, and thermotolerant coliforms by household water treatment method (combined summer data from Guangxi and Henan Provinces). Bars represent 95% confidence intervals (CIs). Total bacteria: boil in electric kettles $n = 240$; boil in pots $n = 316$; bottled water $n = 268$; untreated water $n = 81$. Total coliforms: boil in electric kettles $n = 242$; boil in pots $n = 317$; bottled water $n = 269$; untreated water $n = 81$. Thermotolerant coliforms: boil in electric kettles $n = 240$; boil in pots $n = 316$; bottled water $n = 267$; untreated water $n = 81$. The source data are reported in Table S11.

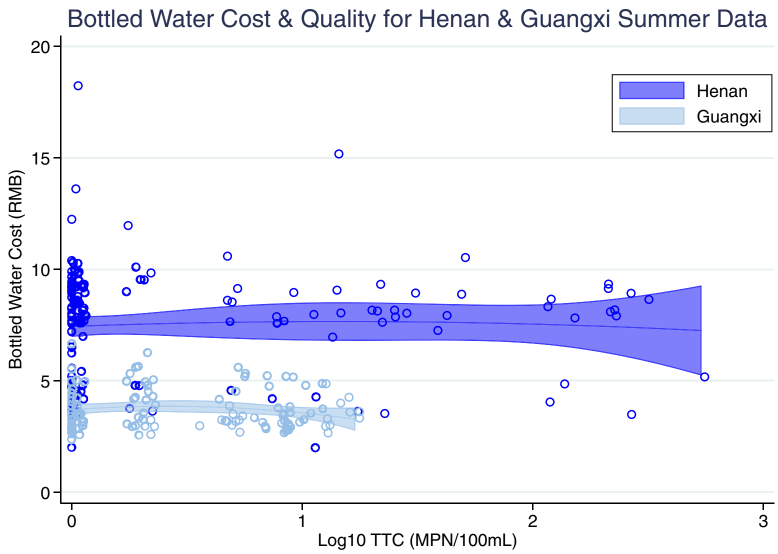

Figure 4. Bottled water cost (19 L bottles) and quality [thermotolerant coliforms (TTCs)]: Guangxi and Henan summer data. Observations overlaid with polynomial smoothers and 95% confidence intervals. Jitter = 5. Note: RMB, renminbi.

For the 34 households with nonmissing paired data, the mean SUMs-based boiling duration was 11.2 min [SD = 7.6) compared with the survey-based reported mean duration of 8.9 min (SD = 8.1). For boiling frequency (boiling events per day), the SUMs-based mean estimate was 2.7/d (SD = 2.3) compared with the mean estimate from reported frequencies of 1.8/d (SD = 1.3). This latter comparison, however, was arguably hindered by the relatively short (72 h) duration used to calculate mean boiling events/day, particularly for households with relatively infrequent boiling. Associations between observed and reported boiling duration and frequency data are shown in Figure 7.

SUMs-recorded boiling durations were significantly longer for households boiling with pots vs. those using electric kettles, at 16.3 and 8.7 min, respectively (SE = 2.6 and SE = 0.90, without adjustment for clustering, respectively; $p = 0.016$). Self-reported boiling durations in Guangxi and Henan during the summer largely reflected the subsample of paired Guangxi winter survey and SUMs iButtons data in that the mean boiling duration for electric kettle users of 7.6 min was significantly smaller than the mean of 18.8 min for those households boiling water with pots (SE = 0.38 and SE = 0.88, respectively; $p < 0.001$).

Reported mean daily boiling frequency from the combined summer data was higher for households using electric kettles, at 1.76/d, than for those using pots, at 1.52/d, although the difference was not statistically significant (SE = 0.20 and SE = 0.11, respectively; $p = 0.236$). The estimated mean total time used for boiling per day in both provinces during the summer (i.e., reported daily boiling frequency multiplied by reported boiling duration) was significantly longer for households boiling with pots, at an average of 30.1 min per day, compared with those using electric kettles, at an average of 12.6 min per day (SE = 3.32 and SE = 1.00, respectively; $p < 0.001$). Of the

Table 3. Log_{10} thermotolerant coliform coefficients (TTCs) from the null and adjusted models for Guangxi and Henan summer data.

	Null model	Adjusted model
Fixed part		
Boil with electric kettle (vs. no)	−0.63 (0.08)***	−0.66 (0.08)***
Boil with pot (vs. no)	−0.57 (0.08)***	−0.58 (0.09)***
Drink bottled water (vs. no)	−0.36 (0.08)***	−0.39 (0.08)***
Improved water source (vs. no)	—	0.01 (0.05)
Safe water storage (vs. no)	—	0.03 (0.07)
HH head is literate (vs. no)	—	−0.03 (0.06)
HH head's age (10-y steps)	—	0.00 (0.00)
TVs by HH population	—	−0.02 (0.06)
Handwashing post-defecation (vs. no)	—	−0.05 (0.10)
Soap likely used (vs. no)	—	−0.06 (0.04)
Handwashing before meals (vs. no)	—	−0.10 (0.10)
Province (Guangxi = 0 Henan = 1)	−0.31 (0.05)***	−0.29 (0.07)***
Intercept	0.97 (0.07)***	1.07 (0.17)***
Random part		
Between-level square root of ψ	0.09 (0.03)	0.14 (0.03)
Within-level square root of θ	0.57 (0.01)	0.55 (0.01)
Model comparison		
Log-likelihood	−790.1	−638.2
n	904	732

Note: Values are Log_{10}TTC β coefficients with standard errors (SEs) in parentheses. The square root of ψ and the square root of θ are the between-cluster and within-cluster standard deviation, with SE in parentheses. As the model fit improves, the log-likelihood tends to decrease. Improved water source classifications were based on Joint Monitoring Program definitions at the time of the study (WHO/UNICEF 2014). —, not applicable; HH, household; TV, television. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

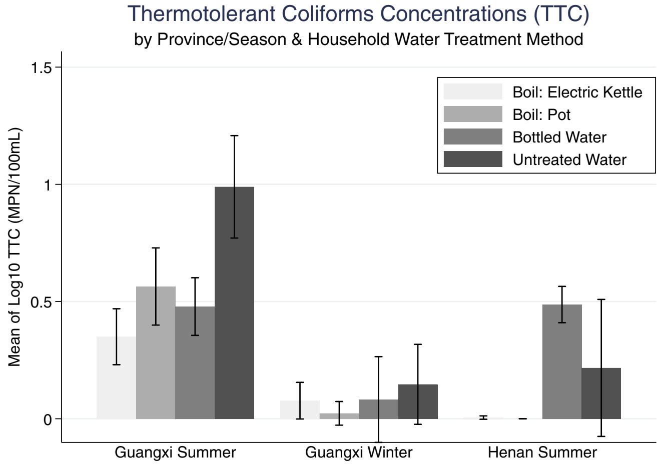

Figure 5. Geometric mean of thermotolerant coliforms (TTCs) concentrations by household water treatment method, province, and season. Bars represent 95% confidence intervals. Boil in electric kettles: Guangxi summer $n = 123$, winter $n = 69$; Henan $n = 117$. Boil in pots: Guangxi summer $n = 91$, winter $n = 13$; Henan $n = 225$. Bottled water: Guangxi summer $n = 151$, winter $n = 11$; Henan $n = 116$. Untreated water: Guangxi summer $n = 75$, winter $n = 18$; Henan $n = 6$. The summary data are reported in Table S12.

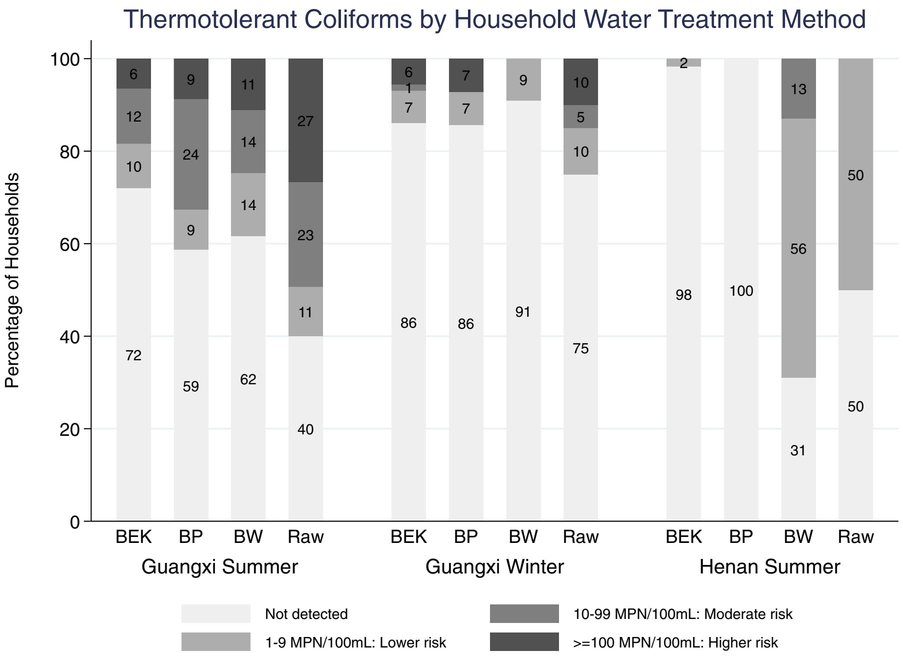

Figure 6. Thermotolerant coliforms (TTCs) and generalized risk levels by household water treatment method, province, and season. Boil in electric kettles: Guangxi summer $n = 123$, winter $n = 69$; Henan $n = 117$. Boil in pots: Guangxi summer $n = 91$, winter $n = 13$; Henan $n = 225$. Bottled water: Guangxi summer $n = 151$, winter $n = 11$; Henan $n = 116$. Untreated water: Guangxi summer $n = 75$, winter $n = 18$; Henan $n = 6$). Note: BEK, boil in electric kettles; BP, boil in pots; BW, bottled water; MPN, most probable number; Raw, untreated water.

households that boiled, a larger proportion of females ≥ 15 years of age boiled water using different classes of solid fuels as compared with clean fuels (Figure S8).

The air pollution box model was run for $\sim 80\%$ of the 276 households that reported using twigs, logs, or crop residues as their primary fuel for heating water. Details on model inputs and data sources are provided in Table 5. The $\sim 20\%$ for which it was not run were missing survey-reported frequencies. An example histogram of output concentrations from the box model ($n = 5{,}000$) from a randomly selected household is shown in Figure S9. Across both provinces, the estimated household $PM_{2.5}$ concentration arising from boiling water with biomass was $79\ \mu g/m^3$ ($SD = 21$). Modeled summer concentrations due to boiling were significantly higher in Henan ($84\ \mu g/m^3$, $SD = 24$) than in Guangxi ($66\ \mu g/m^3$, $SD = 95$; $p < 0.001$). Winter concentrations in Guangxi ($87\ \mu g/m^3$, $SD = 12$) were significantly higher than the mean summer concentrations. Concentration estimates by province and season are shown in Figure 8 and Table S7 (and by fuel type and ventilation category in Table S8).

Discussion

Overall, our results for both regions of rural China suggest that households who boiled their drinking water had significantly lower risks of exposure to waterborne pathogens compared with those consuming bottled or untreated water. Households boiling with electric kettles would also be expected to have lower HAP concentration exposures compared with those using solid fuels to boil water in pots. The post-boiling reductions in fecal indicator organisms (i.e., TTC) observed in our study are similar to those found in rural LMIC settings outside of China (Clasen et al. 2008a, 2008b; Rosa et al. 2010, 2014). These results are also in line with previously published findings (Cohen et al. 2015, 2017), and offer additional evidence of the advantages of boiling with electric kettles as opposed to solid fuels.

Table 4. Risk ratios for thermotolerant coliform coefficient (TTC) detection and reported diarrhea by household water treatment (HWT) method (Guangxi and Henan summer data).

	TTC detected		Diarrhea reported	
HWT method	RR (95% CI)	*p*-Value	RR (95% CI)	*p*-Value
Untreated water	Ref[a]	—	Ref[a]	—
Bottled water	0.86 (0.69, 1.07)	0.189	0.85 (0.32, 2.30)	0.753
Boil	0.22 (0.16, 0.29)	<0.001	0.84 (0.33, 2.11)	0.712
Boil: EK	0.25 (0.17, 0.35)	<0.001	0.80 (0.29, 2.21)	0.672
Boil: pot	0.20 (0.14, 0.28)	<0.001	0.87 (0.33, 2.28)	0.776

Note: —, not applicable; CI, confidence interval; EK, electric kettle; Ref, reference; RR, risk ratio.

[a] Reference for unadjusted risk ratios (no TTC detected = 0; no diarrhea reported = 0). See Table S6 for source data.

Our findings also shed light on the likely impacts of shifting demographics in rural China. Across both provinces, for those households drinking treated water during the summer, younger heads of household appear more likely to use bottled water and older heads of household more likely to boil with pots (Figure 2). There also appears to be a less pronounced trend that, for households boiling their water, younger heads of household are more likely to do so with electric kettles. In addition, looking at the Guangxi and Henan data, we see that as total household size increases (largely due to the presence of children) so too does the use of bottled water and, for those that boil, the use of electric kettles (Figure S4).

The relatively high degree of bottled water contamination we observed in both provinces is noteworthy. Our previous analysis in Guangxi showed that for those who boiled their water, income was a strong predictor of boiling with electric kettles rather than pots, and that income was also a strong predictor of bottled water use overall (Cohen et al. 2017). Analysis of data from a national survey of $\sim 34{,}000$ rural households in China also found that income was a strong predictor of boiling with cleaner fuels, and that as family size increased, rates of electric kettle use also increased (Du et al. 2018a). These data, in the context of China's rising per capita income trajectory, and habit-formation in children, strongly suggest that bottled water use in rural China will continue to increase. This is problematic from a number of perspectives: In addition to drinking water, safe water is also needed for food preparation, cooking, and hygiene; there are safety concerns associated with the

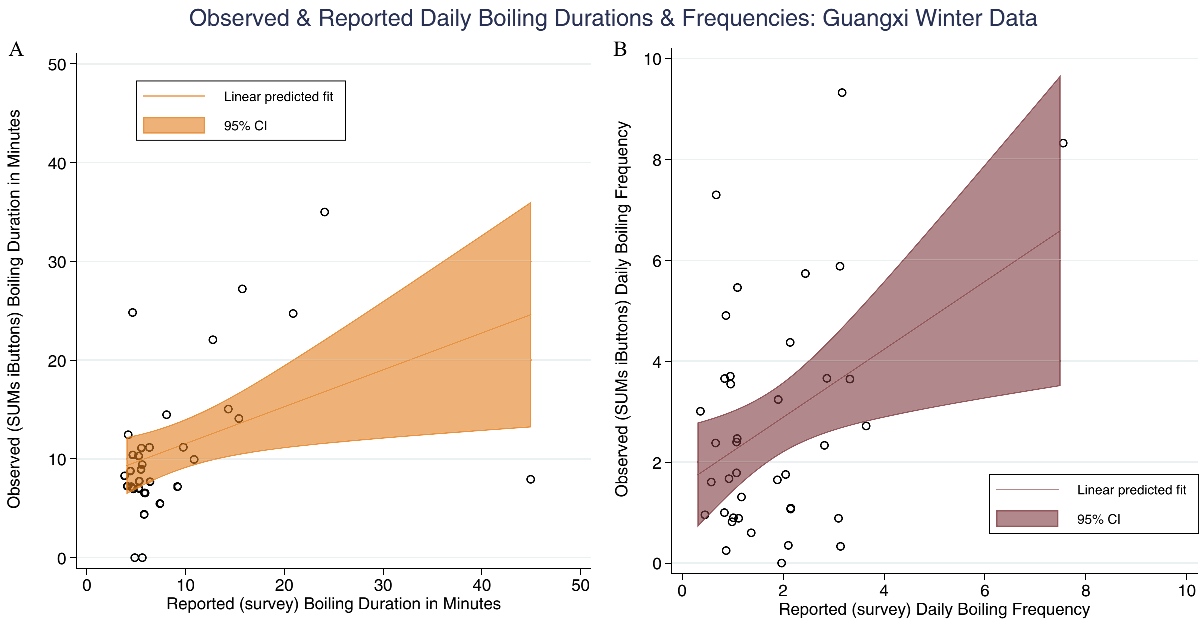

Figure 7. Associations between measured/observed and reported/survey data for (A) average boiling durations and (B) daily frequencies of boiling (Guangxi winter data). Jitter = 2. The summary data are reported in Tables S13 and S14. Note: CI, confidence interval; SUM, stove use monitor.

consumption of contaminated bottled water; and the recurring costs of bottled water comprise a relatively large share of lower-income household expenditures. The environmental health impacts of bottled water production, consumption, and associated plastic pollution are considerable (Laville and Taylor 2017), and increasing reliance on bottled water in LMICs could potentially depress efforts to expand and improve piped water provision more broadly (Cohen and Ray 2018).

The magnitude of the seasonal differences in TTC counts and concentrations indicates that the overall TTC concentrations were substantially lower during the cold and dry winter months compared with the hotter and wetter summer months, an observation supported by other research (Kostyla et al. 2015). Temperature differences between the warmer and wetter summer months and the colder and drier winter months in Guangxi would be expected to impact both water boiling practices and levels of microbiological contamination in drinking water sources. Although the winter subsample ($n = 120$) was insufficiently powered for HWT use and TTC associations, the results suggest that the comparative effectiveness of electric kettles may be more difficult to detect in the winter, when baseline contamination exposure appears to be relatively low.

Table 5. Parameters used in the single-compartment Monte Carlo box model to estimate indoor $PM_{2.5}$ concentrations related to boiling water with biomass fuels.

Parameter	Category	Unit	Mean	Min	Max	COV
AER[a]	—	h^{-1}	18.1	3	60	0.5
Kitchen volume[b]	—	m^3	32.3	12	61.2	0.5
Emissions entering room	—	—	1	1	1	—
Cooking energy required	—	MJ-delivered	0.46	0.11	1.1	0.7
Stove power	—	$KJ\ s^{-1}$	—	—	—	—
Thermal efficiency[c]	Wood (log)	%	18	—	—	0.3
	Wood (twigs)	%	14	—	—	0.1
	Crop residues	%	16	—	—	0.3
PM emission factor[c]	Wood (log)	$g\ kg^{-1}$	1.8	—	—	0.7
	Wood (twigs)	$g\ kg^{-1}$	2.6	—	—	0.3
	Crop residues	$g\ kg^{-1}$	5.6	—	—	0.6
Fuel energy content[c]	Wood (log)	$g\ MJ^{-1}$	18	—	—	0.1
	Wood (twigs)	$g\ MJ^{-1}$	17	—	—	0.1
	Crop residues	$g\ MJ^{-1}$	16	—	—	0.1

Note: Default values used as described by Johnson et al. (2011). —, not applicable; AER, air exchange rate; COV, coefficient of variation (the ratio of the standard deviation to the mean); max, maximum; min, minimum; $PM_{2.5}$, particulate matter $\leq 2.5\ \mu m$ in aerodynamic diameter.

[a] Carter et al. (2016).

[b] Fischer and Koshland (2007).

[c] Shen (2016).

As far as we are aware, this study represents the first use of temperature sensors for the analysis and verification of self-reported boiling data. Our modeled household $PM_{2.5}$ concentrations (averaging $79\ \mu g/m^3$) suggest that boiling water with biomass contributes substantially to HAP in these areas of Guangxi and Henan. By way of comparison, a recent review of HAP measurements across China found an overall daily mean kitchen concentration of $338\ \mu g/m^3$ across all fuel types (with a range of $62–1{,}944\ \mu g/m^3$ for households using solid fuels) (Du et al. 2018b). A study in rural Henan Province found mean winter kitchen concentrations of $307\ \mu g/m^3$ for households using crop residues (with a maximum of $507\ \mu g/m^3$) (Wu et al. 2015). However, the fraction of these concentrations attributable to boiling is unclear.

With regard to whom in the household most often boiled the drinking water, females ≥15 years of age usually boiled the water in 47% ($n = 101$) of the households in Guangxi and 47% ($n = 156$) in Henan, and males ≥15 years of age did so in 12% ($n = 26$) and 12% ($n = 41$) of the households in Guangxi and Henan, respectively (Table S1). Our observations with regard to gender and fuel use suggest that females may have higher overall HAP exposure from boiling with solid fuels (Figure S8), but due to limitations inherent in our data, as well as the model-derived $PM_{2.5}$ estimates, our findings are only suggestive and warrant further investigation. To better understand boiling-based HAP exposure, future work could include more precise time–activity reconstruction and personal exposure assessment to better evaluate gender-based differences in HAP exposure due to boiling activities and to more precisely quantify and contextualize the relative impacts of boiling when it occurs before, after, or completely separate from cooking with solid fuels. More broadly, in China and other LMIC settings where boiling drinking water is a

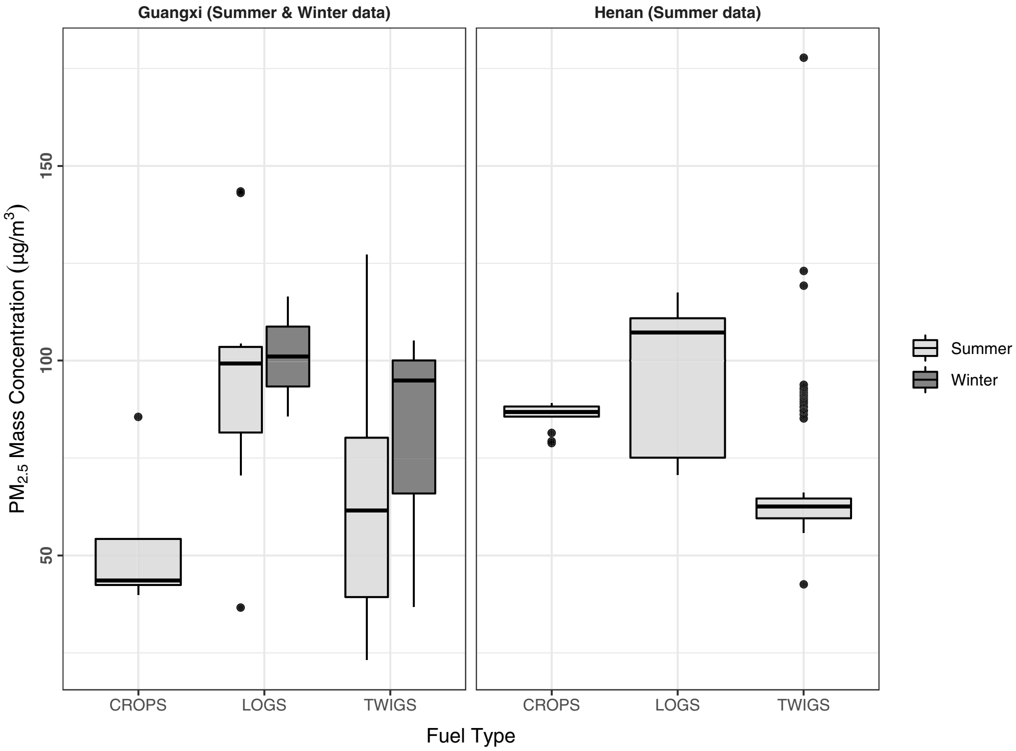

Figure 8. Model-estimated boiling-induced mean air pollution concentrations ($PM_{2.5}$) by fuel type for Guangxi (summer and winter) and Henan (summer) Provinces. The lower and upper box limits are the first and third quartiles. The upper and lower whiskers extend to the values 1.5 times the interquartile range from their respective limit. Data beyond the whiskers are plotted as individual points. Winter data were only available in Guangxi and only for log and twig fuel types. The summary data are reported in Excel Table S1. Note: $PM_{2.5}$, particulate matter ≤ 2.5 μm in aerodynamic diameter.

common practice, more effort should be made to incorporate boiling into interventions promoting the use of cleaner fuels (Clasen and Smith 2019).

Our study had a few limitations that moderated our conclusions. In both Guangxi and Henan the studies were powered to measure HWT and water quality outcomes but were underpowered to measure diarrhea-related outcomes; in addition, because our diarrhea incidence estimates were based on a 14-d recall period, they were subject to recall bias. In households that used large metal pots to heat their water, we placed the SUMs toward the top of the pot to reduce the risk of it falling off into cooking fires (see Figure S1); although we would still have sufficient data to identify heating curves, the maximum recorded temperatures might have been higher had the sensors been placed lower on the pots. Relatedly, most households using large pots to boil their water do not fill the pots completely before boiling, which could have impacted our estimates given the relatively small sample size for the SUMs data. With respect to our HAP estimates, we note that these concentrations, although relatively high, should be validated with direct measurements in homes [box model estimates of kitchen HAP in India, for example, were found to be higher than measured concentrations (Johnson et al. 2011)]. Our models do not sufficiently represent HAP exposures given that we did not have data on whether those responsible for boiling water remained in close proximity to the pot during boiling or (more likely) had varying levels of HAP exposure over different boiling events. In addition, we did not control for tobacco smoking, a common habit among adult males in these regions.

Conclusions

The community of nations, China included, is committed to SDG6, which calls for safe and affordable drinking water for all (UN 2019). As the largely null results from recent, rural-focused, large-scale WASH (using household-level chlorination) and nutrition intervention trials call into doubt some of the conventional wisdom with regard to household-based interventions (Pickering et al. 2019; Levy and Eisenberg 2019) and as numerous previous studies have highlighted the challenges of achieving HWT product adoption and consistent use (Waddington et al. 2009; Figueroa and Kincaid 2010; Amrose et al. 2015; Rosa et al. 2014), the question of what works in rural regions without safe piped water remains an urgent one.

Although boiling is the only form of HWT widely used in LMICs, compared with other HWT methods such as chlorine or filters, safer methods of boiling remain relatively understudied and underpromoted in the safe water literature. Boiling has been shown to be associated with reductions in protozoal and viral infections as well as some bacterial infections and nonspecified diarrheal disease (Cohen and Colford 2017). Our findings suggest that in regions where boiling is already common and electricity access is widespread, the promotion of safer, electricity-based, boiling methods may represent a suboptimal but pragmatic means of expanding affordable safe water access—and partially reducing HAP—until centralized, or decentralized, safe and affordable drinking water is reliably available.

At a global level, rates of bottled water use in LMICs are increasing rapidly and, in recent years, have come to outpace bottled water consumption in high-income countries (Cohen and Ray 2018). In a recent publication, the WHO/UNICEF Joint Monitoring Program acknowledged that more work is needed to assess the microbiological safety of bottled water in areas where it is relied upon as a primary source for drinking (WHO/UNICEF 2019). Our findings here support these objectives but also highlight the extent to which bottled water has the potential to displace existing and potential sources of safe drinking water in many regions, especially as per capita incomes increase.

In conclusion, these findings contribute to the relatively limited boiling-focused HWT research literature generally—and to the few such studies focused on boiling, fuel use, and HAP in particular—and contribute substantially to the scarce literature on HWT in rural China. The results from Henan substantiate our previous findings as to the comparative advantages of boiling with electric kettles in Guangxi. Taken together, these results indicate that in low-income regions where access to electricity is widespread, safer and more effective methods of boiling may offer an imperfect, but comparatively advantageous, stop-gap option for improving safe water access. More broadly, findings from both provinces highlight the growing reliance on bottled water (of questionable safety and high unit costs) in rural areas of China, and the attendant need for the global WASH community to engage with this issue more directly in order to safeguard and support efforts to achieve affordable safe water access for all.

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A.C. led the design of the study protocols, assisted with data collection in Guangxi Province, wrote the first draft of the manuscript, analyzed the data, created the tables and figures, conducted the water quality–related modeling, and incorporated coauthor feedback into the final manuscript. A.P. conducted the air pollution modeling, created the associated figures, and contributed to writing the manuscript. Q.L. assisted A.C. with managing the Guangxi study, and led the data collection, data quality control, data entry, and study management in Henan Province; Q.L. also contributed to the final draft. Q.Z. helped manage study logistics, data entry, and management in Beijing, and contributed to results interpretation. H.L. reviewed the analysis methods and models and contributed to the final draft. G. Zhong organized and oversaw data collection in Guangxi and provided feedback on analysis results. G. Zhu organized and oversaw data collection in Henan and provided feedback on analysis results. J.M.C. advised on the study design and analyses and contributed to the final draft. K.R.S. advised on the air pollution–related protocols and associated analysis and models and contributed to the final draft. I.R. advised on the study design and analyses, framing of the study and manuscript, and contributed to writing the manuscript. Y.T. advised on the study design, was responsible for and oversaw the management of both studies in Guangxi and Henan, and contributed to results interpretation.

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Due to legal restrictions, the National Center for Rural Water Supply Technical Guidance (NCRWSTG) and the China CDC do not allow raw data related to water quality to be made available in publicly accessible repositories. However, at the discretion of the NCRWSTG and China CDC, data may be made available on a case-by-case basis. Requests for data used in this study should be emailed to yewuban@crwstc.org with this article's title in the email subject line.

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