Estimating the burden of disease attributable to household air pollution from cooking with solid fuels in South Africa for 2000, 2006 and 2012

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Background. Household air pollution (HAP) due to the use of solid fuels for cooking is a global problem with significant impacts on human health, especially in low- and middle-income countries. HAP remains problematic in South Africa (SA). While electrification rates have improved over the past two decades, many people still use solid fuels for cooking owing to energy poverty.
Objectives. To estimate the disease burden attributable to HAP for cooking in SA over three time points: 2000, 2006 and 2012.
Methods. Comparative risk assessment methodology was used. The proportion of South Africans exposed to HAP was assessed and assigned the estimated concentration of particulate matter with a diameter <2.5 μg/m^3 ($PM_{2.5}$) associated with HAP exposure. Health outcomes and relative risks associated with HAP exposure were identified. Population-attributable fractions and the attributable burden of disease due to HAP exposure (deaths, years of life lost, years lived with disability and disability-adjusted life years (DALYs)) for SA were calculated. Attributable burden was estimated for 2000, 2006 and 2012. For the year 2012, we estimated the attributable burden at provincial level.
Results. An estimated 17.6% of the SA population was exposed to HAP in 2012. In 2012, HAP exposure was estimated to have caused 8 862 deaths (95% uncertainty interval (UI) 8 413 - 9 251) and 1.7% (95% UI 1.6% - 1.8%) of all deaths in SA, respectively. Loss of healthy life years comprised 208 816 DALYs (95% UI 195 648 - 221 007) and 1.0% of all DALYs (95% UI 0.95% - 1.0%) in 2012, respectively. Lower respiratory infections and cardiovascular disease contributed to the largest proportion of deaths and DALYs. HAP exposure due to cooking varied across provinces, and was highest in Limpopo (50.0%), Mpumalanga (27.4%) and KwaZulu-Natal (26.4%) Provinces in 2012. Age-standardised burden measures showed that these three provinces had the highest rates of death and DALY burden attributable to HAP.
Conclusion. The burden of disease from HAP due to cooking in SA is of significant concern. Effective interventions supported by legislation and policy, together with awareness campaigns, are needed to ensure access to clean household fuels and improved cook stoves. Continued and enhanced efforts in this regard are required to ensure the burden of disease from HAP is curbed in SA.

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The article in context

Evidence before this study. In 2000, the first South African (SA) Comparative Risk Assessment Study 2000 (SACRA1) assessed the attributable burden from three health-related disease outcomes for indoor air pollution due to solid fuel use. Solid fuel use prevalence was estimated to be 20% among SA households, with significant variation by population group. Approximately 2 489 deaths (95% uncertainty interval (UI) 1 672 - 3 324) were attributed to indoor air pollution, with a total of 60 934 DALYs (95% UI 41 170 - 81 246) or 0.4% of all disability-adjusted life years (DALYs) (95% UI 0.3 - 0.5%) in SA in 2000.
Added value of this study. Our study used updated methods to estimate the attributable burden due to cooking with solid fuels from seven health-related outcomes for three time points: 2000, 2006 and 2012. We used national survey data to estimate the proportion of people exposed to household air pollution (HAP), and extrapolated this figure to account for the burden in males and females by age group and, in 2012, by province. We estimated a reduction in the prevalence of exposure to HAP between 2000 and 2012; however, 9 million people were still exposed to HAP in 2012. There was a decrease in deaths and DALYs owing to the risk factor over time. The high number of deaths due to lower respiratory infections (LRIs), particularly in children <10 years of age and in certain areas (e.g. Limpopo Province), remains a cause for concern.
Implications of the available evidence. While the prevalence of HAP due to cooking and the disease burden due to the risk factor has decreased, more work is needed to lower and eventually eradicate the use of polluting fuels for cooking. A multipronged approach must be taken that involves legislation and interventions to reduce the use of solid fuels for cooking in SA. Large studies should be conducted to quantify the concentration of pollutants generated when using polluting fuels (including paraffin) for cooking in SA.

In 2017, air pollution was ranked the leading environmental cause of death globally, and was responsible for an estimated 4.9 million deaths worldwide.[1] A third of these deaths were attributed to household air pollution (HAP) due to cooking with solid fuels.[1] The use of solid, polluting fuels for cooking remains an environmental health problem, disproportionately affecting low- and middle-income countries (LMICs).[2-5] HAP arises from the combustion of solid fuels (namely coal, wood, charcoal, dung and agricultural residues) in inefficient stoves and often in poorly ventilated homes,[6,7] resulting in the generation of a complex mixture of carbon-based particles, inorganic particles and irritant gases.[6] Particulate matter with a diameter <2.5 μg/m^3 ($PM_{2.5}$) is a harmful product of this combustion, and is implicated in many acute and chronic health conditions,[8] such as lower respiratory infections (LRIs),[9-11] chronic obstructive pulmonary disease (COPD),[6,12] trachea, bronchus and lung cancers,[12] ischaemic heart disease (IHD),[13] stroke,[13] type 2 diabetes[14,15] and adverse birth outcomes.[16,17] Especially within LMICs, women and young children tend to bear the brunt of exposure to HAP, as traditional gender roles determine that women and girls spend a lot more of their time cooking compared with men/boys.[18] This finding is borne out by women's increased risk of cataracts due to HAP.[14] The burden of disease due to HAP can be reduced through the adoption of clean household fuels.[19] In fact, there have been substantial reductions in HAP exposure in regions such as Europe and India,[20] while more modest reductions have been experienced in the African region.[5]

The use of solid fuels for cooking is inextricably linked to poverty and an associated lack of electricity.[21] The post-1994 SA government adopted policies to redress apartheid inequalities by improving access to basic services through the provision of free basic electricity for low-income South Africans.[22] Several programmes have been implemented, such as the National Electrification Programme (1994 - 2001), the Integrated National Electrification Programme (focused on rural electrification) and the Integrated Resource Plan (2010 - present), which emphasised the use of renewable energy sources, specifically in areas that were not grid-accessible.[23] Despite some issues with implementation, electrification programmes have been successful in raising overall access to electricity, although rural areas[23] and informal settlements[24] tend to lag behind. In the late 1980s, only 35% of the population had access to electricity,[22,25] and by 2013, 85% of households were connected to the grid.[26] However, electrification does not necessarily translate into electricity use. For example, households may not be able to afford electricity despite being connected to the grid,[27] and while electrification plays a role in the type of fuel used by households to cook, households may still demonstrate energy poverty.[28] Many households use a mixture of fuels specific to their end use.[29,30] Factors such as household income,[31] education level, employment status, cultural norms and values influence fuel use.[29] Energy switching and energy stacking describe fluid energy use patterns where household members either change which energy source they prefer to use for specific energy needs, or use various energy sources simultaneously for different needs depending on fuel availability, income or household size and even season.[29,32] In winter months, when HAP exposure levels are at their highest, for example, households may make use of traditional coal stoves for heating and cooking purposes when money is limited, and may then revert to gas or electricity stoves and/or heaters when finances allow.[33] Households may also use a range of fuel sources simultaneously: electricity for lighting and refrigeration, gas or electricity for cooking and coal or wood for heating activities.[33] The concept of the energy ladder sees households moving from cheap and dirty fuels to more expensive, cleaner fuels (or vice versa) as their income or economic status changes.[34]

In the SA context, with some households off the grid, high costs of electricity and rolling blackouts,[35] multiple fuel use is common.[24,36-38] Since the mid-2000s, SA has experienced energy shortages resulting in rolling blackouts.[39] The energy crisis led to a sharp increase in real electricity tariffs between 2008 and 2011, which is thought to have forced poorer households into using solid fuels to fulfil their energy needs.[39] The cost of electricity continues to increase. As the use of solid fuels is correlated with decreasing per capita income, it is expected that poorer households would be forced to use solid fuels.

Relatively small, local studies showed that most households use electricity and gas for cooking,[38,40-45] although a few studies indicated a heavy reliance on solid fuels in the areas they studied.[46-48] A recent cohort study in a rural area in Eastern Cape Province showed that only 23% of households used electricity for cooking; the majority used paraffin and outside fires.[49] Several studies have reported measuring pollutants within homes. Particulate matter with a diameter <10 μg/m^3 (PM_{10}) was the most frequently reported size of particulate matter,[42,44-46,50,51] while a few studies reported on personal PM_4[52,53] and others measured $PM_{2.5}$.[54,55] Where PM_{10} was measured, it was difficult to compare the median levels of indoor air pollution because of differing study methodologies. However, unelectrified houses or households using dirty fuels had a two- to threefold increase in median PM_{10} compared with households using clean fuels.[44,46] A study that measured $PM_{2.5}$ in 23 households in KwaZulu-Natal Province found a median concentration of 63 μg/m^3,[54] while a more recent study found a median of 35 μg/m^3 (range 2 - 303 μg/m^3) in the cold season and 22 μg/m^3 (range 3 - 179 μg/m^3) in the warm season.[55] These studies were limited by their small sample sizes. However, small sample sizes are to be expected as the measurement of particulate matter within homes is often constrained owing to the high instrument costs and intensive nature of monitoring. While SA has no indoor air quality standards for domestic use, both studies reported concentrations of $PM_{2.5}$ >10 μg/m^3, which is known to be harmful to health.[56]

Several SA studies have examined the impact of HAP on health. Respiratory health outcomes were identified as a health effect of HAP exposure by a quasi-systematic review.[57] The use of non-electrical fuel sources was associated with upper and lower respiratory tract infections.[36] Even though electricity was the main fuel source, fuel switching or fuel stacking may have been responsible for a higher prevalence of LRIs in households. A large multi-country study that included SA showed that HAP exposure increased the risk of all-cause mortality, cardiovascular disease and cardiorespiratory disease.[58] These studies collectively indicate a large burden of disease due to HAP in SA.

SACRA1[59] quantified the contribution of indoor air pollution to deaths and DALYs in SA for the year 2000. Limited data exist on the current burden of disease due to HAP in SA. The present study aimed to estimate the disease burden attributable to HAP in the country, as well as the trends over time for three time points: 2000, 2006 and 2012, using improved methods. In doing so, the study aimed to estimate the burden of disease from household use of solid fuels in SA to inform legislation and policy development for clean energy, as well as guide interventions for the reduction of HAP and prevention of diseases associated with HAP exposure. Results presented here supersede all previously published SACRA estimates.

Methods

Overview

Comparative risk assessment (CRA) methodology was used.[60] We estimated the proportion of deaths and DALYs that could be attributed to HAP due to cooking, using the counterfactual scenario of theoretical minimum risk exposure level (TMREL). We used a modified version of the methodology established by the Global Burden of Disease (GBD) study,[8] where people exposed to HAP through cooking are assigned an individual $PM_{2.5}$ concentration level of exposure, as outlined in Fig. 1.

Exposure estimation

The exposure definition used was based on the GBD 2017's[8] twofold definition, and was defined as: (*i*) 'the proportion of households using solid cooking fuels … [which] includes coal, wood, charcoal, dung, and agricultural residues'; and (*ii*) 'individual exposure to $PM_{2.5}$ due to use of solid cooking fuel'.[8]

Survey data closest to each time point of interest were used (Census 2001,[61] Community Survey 2007[62] and Census 2011[63]) for 2000, 2006 and 2012 estimates, respectively. These surveys were determined to be the most complete and accurate datasets for SA, and were obtained from Statistics SA. Each survey contained the question, 'What type of energy/fuel does the household mainly use for cooking?' The responses for wood, coal and animal dung were combined to estimate the proportion of households using solid fuels for cooking. Household survey datasets were then extrapolated to individuals by age group (5-year age bands) and sex. For Census 2011, data were also stratified by province. Census 2011 was projected to the year 2012 using a growth factor estimated by age, sex and province. For each dataset, the population was divided into exposed (uses solid fuels for cooking) and unexposed (does not use solid fuel for cooking).

Only the proportion of the population using solid fuels for cooking is included in this analysis. The proportion of people exposed to solid fuels was assigned an estimated annual average concentration value of $PM_{2.5}$ to calculate appropriate relative risks for concentrations of $PM_{2.5}$ exposure. A literature review revealed inconsistent findings from seven community studies that sampled $PM_{2.5}$ in solid fuel using households in SA (appendix: https://www.samedical.org/file/1931). Therefore, here we used the findings from a global model to estimate HAP-$PM_{2.5}$ exposure values for SA. This global model was based on studies from the World Health Organization (WHO)'s Global Household Air Pollution Database, and modelled HAP-$PM_{2.5}$ exposure for each country, with explanatory variables including fuel types, season, urban/rural and country-level sociodemographic index.[64] The model produced concentrations for the average HAP-$PM_{2.5}$ kitchen concentration and average female HAP-$PM_{2.5}$ concentration. A previously cited ratio was applied to calculate male and child HAP-$PM_{2.5}$ concentrations to account for males, females and children being differentially exposed to HAP.[64]

The global model estimated the annual average HAP-$PM_{2.5}$ concentrations for SA by fuel source. Using data from Census 2011, the proportion of the population using each type of solid cooking fuel was calculated, and a fuel-weighted, average country-level HAP-$PM_{2.5}$ exposure was generated for adult females (personal communication: M Shupler, 2019). The fuel-weighted average HAP-$PM_{2.5}$ was very similar using Census 2001 and the Community Survey 2007, hence the Census 2011 estimate was applied to all three time points. The adult male and child HAP-$PM_{2.5}$ concentrations were estimated using a ratio method (namely 0.72 for males and 0.87 for children).[64] For males and females aged 5 - 24 years, the lowest level of exposure was assumed (Table 1). These estimates were used to calculate relative risks for each $PM_{2.5}$ concentration level.

Disease outcomes and associated relative risks related to HAP and PM2.5 exposure

GBD 2017[8] was referenced for appropriate disease outcomes and relative risks, as the

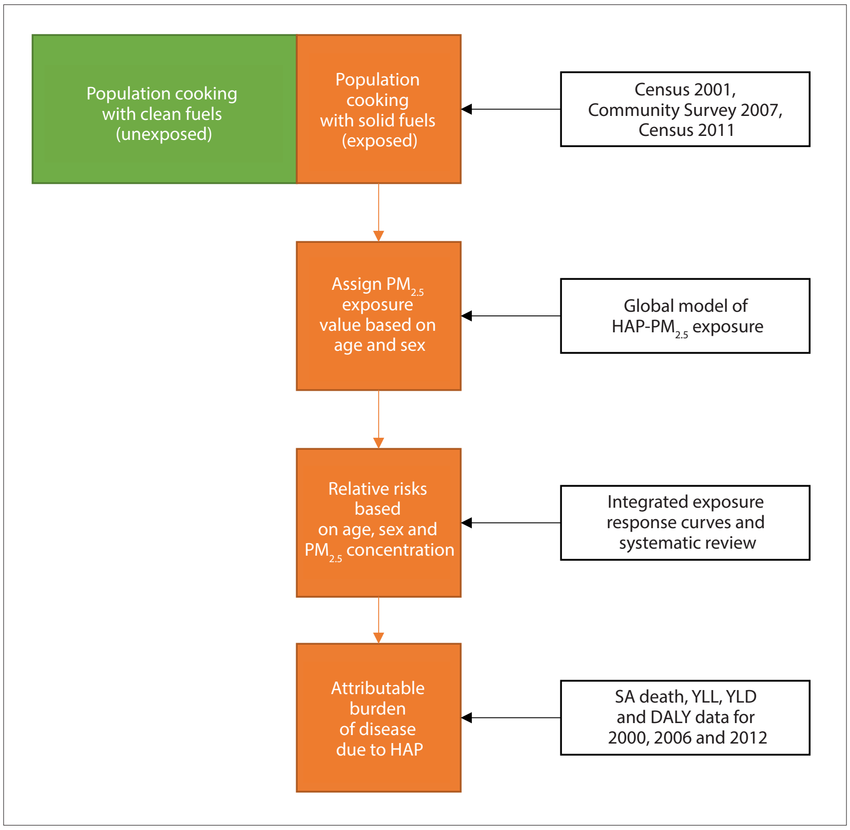

Fig. 1. Schematic overview of risk factor, household air pollution exposure and the datasets that were applied at each stage of the study. ($PM_{2.5}$ = particulate matter <2.5 μg/m^3; HAP = household air pollution; YLL = years of life lost; YLD = years lived with disability; DALY = disability-adjusted life year.)[62-64]

Table 1. Fuel-weighted annual average HAP-PM2.5 in SA in 2000, 2006 and 2012

	Fuel-weighted annual average HAP-$PM_{2.5}$ (μg/m^3)	
Age group, years	**Female estimate (LCL - UCL)**	**Male estimate (LCL - UCL)**
0 - 4	117.4 (83.4 - 166.7)	117.4 (83.4 - 166.7)
5 - 24	97.2 (69.0 - 138.0)	97.2 (69.0 - 138.0)
≥25	134.9 (95.8 - 191.6)	97.2 (69.0 - 138.0)

SA = South Africa; HAP-$PM_{2.5}$ = household air pollution particulate matter with diameter <2.5 μg/m^3;
LCL = lower confidence level; UCL = upper confidence level.

Table 2. Health outcomes and relative risks associated with HAP and $PM_{2.5}$

Health outcome	ICD-10 code	Age group affected	Relative risk
Lower respiratory infections	J09 - J18, J20 - J22, P23 >6 years, J86	All ages	IER curves
Ischaemic heart disease	I20 - I25	>25 years	IER curves
Stroke	I60 - I69, G81	>25 years	IER curves
Type 2 diabetes	E11	>25 years	IER curves
Chronic obstructive pulmonary disease	J40 - J44, J47	>25 years	IER curves
Trachea, bronchus and lung cancers	C33 - C34	>25 years	IER curves
Cataracts	H25 - H26	>15 years (women only)	2.47 (95% CI 1.61 - 3.73)[67]

HAP = household air pollution; $PM_{2.5}$ = particulate matter with diameter <2.5 µg/m³; IER = integrated exposure response; CI = confidence interval.

group have conducted a comprehensive review to identify outcomes associated with HAP. Based on GBD studies, two methods were used to obtain relative risk information for HAP and $PM_{2.5}$ disease outcomes: (*i*) integrated exposure response (IER) curves; and (*ii*) results of a published systematic review (Table 2). IER curves were used to ascertain the shape of the dose-response curve for various health outcomes.[8] These curves integrate relative risk information from outdoor air pollution, second-hand tobacco smoke, HAP-$PM_{2.5}$ and active smoking studies to estimate risks across the global range of $PM_{2.5}$ exposure.[65,66] The statistical programming language R (R Foundation for Statistical Computing, Austria) was used to generate GBD 2017 IER curves for concentrations of $PM_{2.5}$ according to age group and $PM_{2.5}$ concentration (see appendix Table S2: https://www.samedical.org/file/1931). The relative risks for age band 80 - 84 years were used for the >80 years age group. At the time, it was not possible to use the IER curves to estimate the relative risks of cataracts due to HAP. The relative risk used for cataract was 2.47 (95% confidence interval (CI) 1.61 - 3.73), based on a published systematic review.[67]

Theoretical minimum risk exposure level

The TMREL is defined as 'the level of risk exposure that minimises the risk at the population level, or the level of risk that captures the maximum attributable burden.'[8] For disease outcomes based on the IER curves, the TMREL was defined as a uniform distribution between 2.4 µg/m³ and 5.9 µg/m³.[8] For cataracts, the theoretical minimum was defined as no households using solid fuels for cooking.[59]

Computation of population-attributable fraction

Customised Excel (Microsoft, USA) spreadsheets based on templates developed in a previous CRA were used for each year of interest. The population-attributable fraction (PAF) is the proportion by which the related health outcomes would be reduced in the SA population in a given year if exposure to the HAP risk factor were reduced to the counterfactual level of the TMREL.

For outcomes based on the IER curves, the population exposed was broken down by age and sex, and assigned the relevant HAP-$PM_{2.5}$ concentration. The relative risk was calculated, using corresponding GBD 2017 IER curves, for that $PM_{2.5}$ concentration. The attributable fraction was calculated by multiplying the proportion exposed by the relative risk.

Attributable fractions were calculated by disease condition, age group and sex for 2000, 2006 and 2012, and by province (in the 2012 estimation only).

The PAF was estimated using the formula:

$$PAF = \frac{P(RR(x) - RR(TMREL))}{P(RR(x) - 1) + 1}$$

where *P* represents the proportion of the population exposed to HAP and *RR* is the relative risk of disease at a given exposure.

Computation of attributable burden

Attributable fractions were calculated for males and females by age group and disease condition. These were multiplied by disease burden estimates (including deaths, YLLs, YLDs and DALYs) for SA for the respective year using SA national burden of disease estimates.[68,69] Age-standardised attributable death, YLL, YLD and DALY rates were calculated using alternative mid-year estimates[70] for each respective year and the WHO population standard.[71]

Uncertainty

Monte Carlo simulation techniques, using Ersatz software version 1.35 (Epigear, Australia), were used to present uncertainty ranges around the attributable burden estimates. Separately for each year, sex, age group and health outcome, we drew 2 000 random samples from the distributions of the parameters of the exposure and the relative risks functions, and we repeated the calculation of the PAF. We used the 2.5th and 97.5th percentiles of the replicated results as the bounds of the 95% UI. In drawing the samples, we assumed a normal uncertainty distribution for the exposure and a lognormal distribution for the relative risks. The uncertainty of the fuel-weighted HAP-$PM_{2.5}$ estimates was modelled as a uniform distribution with limits of 29% and 42%, based on the study by Balakrishnan *et al.*[72]

Results

Prevalence of household air pollution exposure

In 2012, approximately 9 million people (17.6% of the SA population) were exposed to HAP as a result of cooking with solid fuels. Between 2000 and 2006, the proportion of people exposed decreased by 26.0%, and a more modest decrease (18.5%) was observed between 2006 and 2012 (Fig. 2).

Burden of disease attributable to household air pollution in SA

The total number of deaths attributable to HAP decreased over time (Table 3). In 2000, HAP caused an estimated 6 646 deaths in females and 5 825 deaths in males. By 2012, this had decreased to 4 879 deaths in females and 3 982 in males. There were more deaths and DALYs attributable to HAP in females than in males. While DALYs decreased in total from 280 676 to 208 816 between 2000 and 2012, this still represents a significant burden of disease due to HAP exposure. In 2000, HAP was responsible for 2.5% of all deaths in SA, and this decreased to 1.7% by 2012. The DALYs followed a similar trend.

The age-standardised death and DALY rates decreased in females and males over time. The age-standardised death rate decreased by 41.8% between 2000 and 2012, while the age-standardised DALY rate decreased by a similar amount (39.4%) during the same period (Figs 3A and B). While there were more attributable deaths in females than in males, the age-standardised death rates were higher in males than

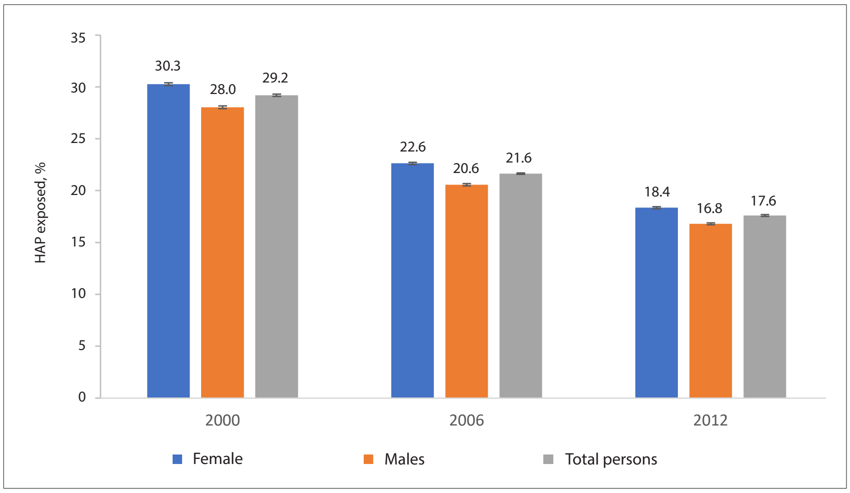

Fig. 2. Proportion of people exposed to household air pollution (HAP) from cooking with solid fuels by year and sex in South Africa.

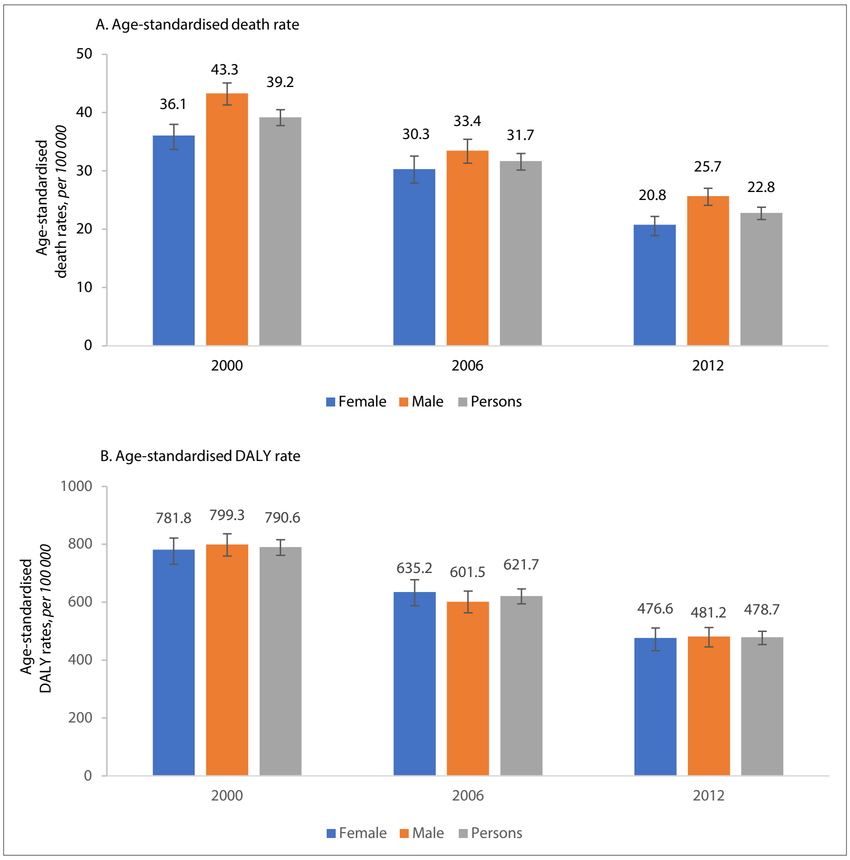

Fig. 3. (A) Age-standardised death rate attributable to household air pollution by year; (B) age-standardised disability-adjusted life year (DALY) rate attributable to household air pollution by year.

in females. This is due to the underlying population structure in SA where there are more females than males, especially in the older age groups.

Contribution of disease conditions to burden

LRIs and cardiovascular disease accounted for the majority of the disease burden attributable to HAP (Figs 4A - H). Deaths and DALY patterns were similar between females and males, as well as in the years 2000 and 2012. The contribution of LRIs and diabetes increased (deaths and DALYs) between 2000 and 2012.

The age distribution of deaths attributable to HAP differed by sex (Figs 5A and B). The attributable death age pattern remained the same for males across 2000 and 2012. Deaths peaked in 60 - 79-year-olds, and there was a high burden of LRIs in 0 - 9-year-olds. The female age pattern differed from males in that deaths peaked in the oldest age group (>80 years).

Burden of disease due to household air pollution by province in 2012

In 2012, HAP exposure varied substantially by province (Table 4). It was highest in Limpopo (50.0%), Mpumalanga (27.4%) and KwaZulu-Natal (26.4%) Provinces. More than half of the people exposed nationally resided in Limpopo and KwaZulu-Natal.

When applying the age-standardised death and DALY rates, Limpopo had the highest rates in the country (Figs 6A and B). This could be due to their high burden of LRI deaths (see appendix S2: https://www.samedical.org/file/1808).

Discussion

An estimated 17.6% of the SA population was exposed to HAP through cooking in 2012. This percentage was slightly lower than that found in the previous assessment.[59] SACRA1 estimated the burden of respiratory ill health in SA due to exposure to indoor air pollution through the use of solid fuels for cooking and heating.[59] Census 2001 data were used to estimate the proportion of households using solid fuels, and the exposure estimates were adjusted through a ventilation factor. SACRA1 estimated that 2 489 deaths and 60 934 DALYs occurred in SA for the year 2000 as a result of exposure to indoor air pollution.[59] Our study used an updated method to estimate the burden of disease whereby the proportion of households using solid fuels for cooking (heating was excluded) were assigned a $PM_{2.5}$ concentration value to calculate appropriate relative risks using the IERs. Our study also included updated disease outcomes, as evidence has emerged to support the causality of HAP in other diseases (e.g. diabetes, cerebrovascular disease, IHD, cataracts). Hence we report a much higher number of deaths and DALYs attributable to HAP in 2000 (12 471 deaths and 280 676 DALYs) compared with the same year in the previous study.

The number of people using solid fuels for cooking decreased between 2000 and 2012, from approximately 13 million to 9 million. The proportion using solid fuels decreased from 29.2% to 17.6% (a 40% decrease) between 2000 and 2012. Although the total population increased during this period (45.0 million to 52.4 million), the number of people exposed to HAP decreased by 4 million. The main factor driving this decrease appears to be the increased access to electricity, which increased

Table 3. Burden of disease due to household air pollution in 2000, 2006 and 2012 by health outcome and gender

	Female			Male			All		
Disease	AF (%)	Deaths, *n*	DALYs, *n*	AF (%)	Deaths, *n*	DALYs, *n*	AF (%)	Deaths, *n*	DALYs, *n*
2000									
LRI*	23	2 404	63 625	18	2 150	59 377	20	4 554	123 001
Trachea, bronchi and lung cancers	16	250	4 400	11	439	7 331	12	689	11 731
Diabetes mellitus	13	934	19 169	10	481	9 730	12	1 415	28 899
IHD	9	1 053	18 538	8	950	16 894	8	2 003	35 432
Cerebrovascular disease	6	1 233	21 429	5	760	13 447	5	1 993	34 876
COPD	19	771	23 834	14	1 045	21 411	16	1 816	45 245
Cataract[†]	0	0	1 492	NA	NA	NA	0	0	1 492
Total attributable burden[‡]	-	**6 646**	**152 486**	-	**5 825**	**128 190**	-	**12 471**	**280 676**
Uncertainty interval	-	6 187 - 7 007	141 241 - 161 637	-	5 505 - 6 133	118 272 - 137 163	-	11 835 - 12 966	260 854 - 297 344
% total burden	-	**2.8**	**1.6**	-	**2.2**	**1.3**	-	**2.5**	**1.5**
Uncertainty interval, %	-	2.6 - 2.9	1.5 - 1.7	-	2.1 - 2.3	1.2 - 1.4	-	2.3 - 2.6	1.4 - 1.6
2006									
LRI*	19	2 302	55 955	14	1 778	47 850	16	4 080	103 805
Trachea, bronchi and lung cancers	13	237	3 928	8	315	5 064	10	552	8 993
Diabetes mellitus	10	1 027	20 811	8	484	9 388	9	1 511	30 199
IHD	7	940	16 387	5	790	13 869	6	1 730	30 257
Cerebrovascular disease	4	1 087	18 305	4	589	10 058	4	1 677	28 362
COPD	15	610	19 642	10	761	16 462	12	1 372	36 104
Cataract[†]	0	0	1 299	NA	NA	NA	0	0	1 299
Total attributable burden[‡]	-	**6 202**	**136 327**	-	**4 719**	**102 692**	-	**10 921**	**239 018**
Uncertainty interval	-	5 800 - 6 579	126 903 - 145 089	-	4 429 - 4 988	94 716 -110 984	-	10 352 - 11 421	22 207 - 254 248
% total burden	-	**1.9**	**1.1**	-	**1.4**	**0.8**	-	**1.6**	**1.0**
Uncertainty interval, %	-	1.7 - 2.0	1.0 - 1.1	-	1.3 - 1.5	0.8 - 0.9	-	1.5 - 1.7	0.9 - 1.0
2012									
LRI*	16	2 057	49 856	13	1 764	47 102	15	3 821	96 958
Trachea, bronchi and lung cancers	6	121	2 097	5	218	3 596	5	339	5 693
Diabetes mellitus	9	991	24 016	7	540	11 606	8	1 532	3 5622
IHD	4	511	9 324	4	489	9 217	4	1 000	18 541
Cerebrovascular disease	4	864	14 258	3	505	8 467	3	1 369	22 725
COPD	9	335	16 286	7	466	11 847	8	801	28 132
Cataract[†]	0	0	1 144	NA	NA	NA	0	0	1 144
Total attributable burden[‡]	-	**4 879**	**116 981**	-	**3 982**	**91 835**	-	**8 862**	**208 816**
Uncertainty interval	-	4 546 - 5 190	109 149 - 123 950	-	3 764 - 4 179	85 216 - 97 794	-	8 413 - 9 251	195 648 - 221 007
% total burden	-	**1.9**	**1.1**	-	**1.4**	**0.9**	-	**1.7**	**1.0**
Uncertainty interval, %	-	1.8 - 2.1	1.0 - 1.2	-	1.4 - 1.5	0.8 - 1.0	-	1.6 - 1.8	1.0 - 1.0

AF = attributable fraction based on the numbers of attributable deaths; DALY = disability-adjusted life year; LRI = lower respiratory infection; IHD = ischaemic heart disease; COPD = chronic obstructive pulmonary disease.
*LRI was a disease outcome for people of all ages.
[†]Cataract is only a disease outcome in females >15 years old. There were no deaths due to cataracts.
[‡]The denominator refers to the total burden of disease in South Africa.

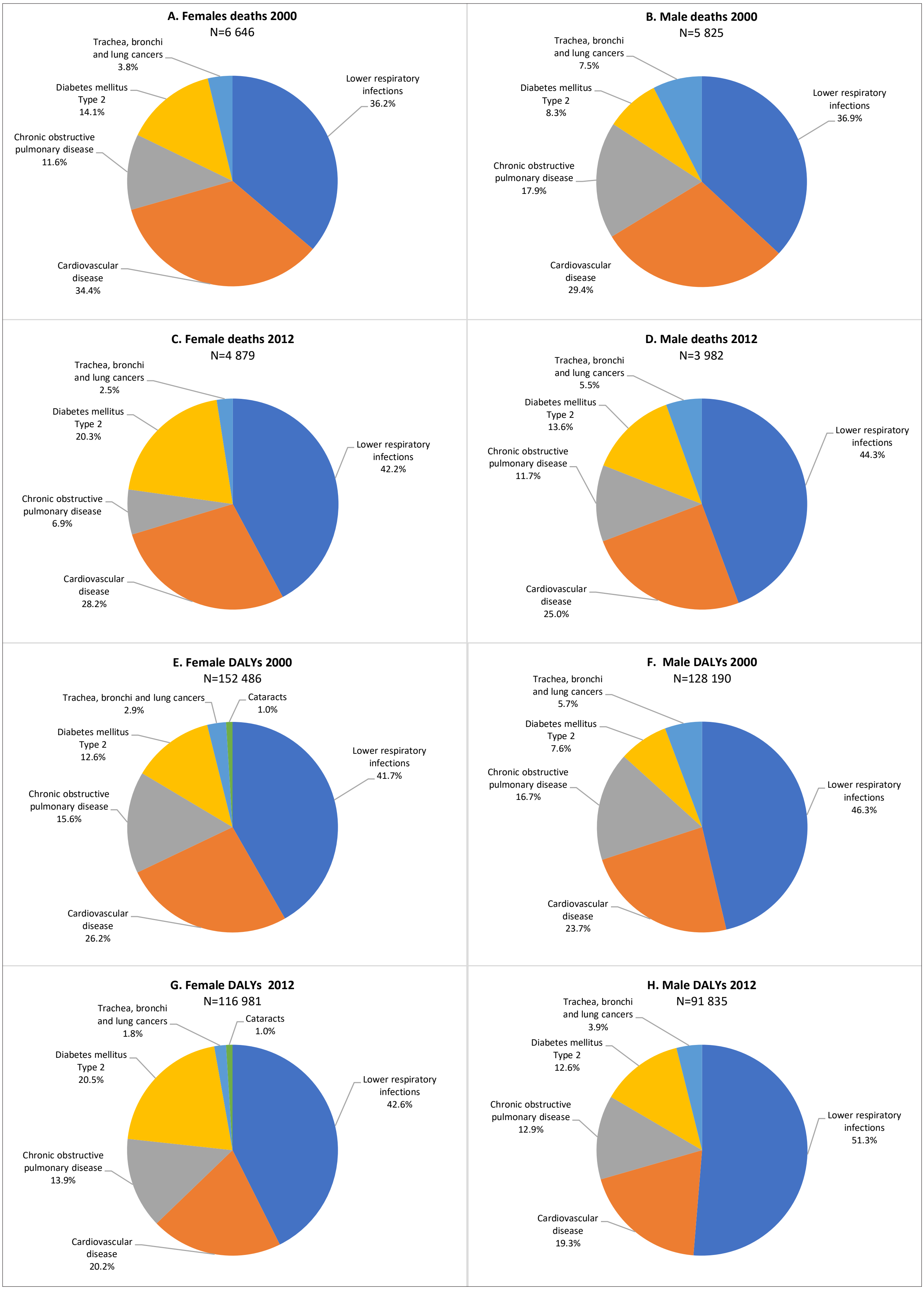

Fig. 4. Deaths attributable to household air pollution (HAP) by disease condition in 2000 in (A) females and (B) males. Deaths attributable to HAP by disease condition in 2012 in (C) females and (D) males. Disability-adjusted life years (DALYs) attributable to HAP by disease condition in 2000 in (E) females and (F) males. DALYs attributable to HAP by disease condition in 2012 in (G) females and (H) males. (LRIs = lower respiratory infections; COPD = chronic obstructive pulmonary disease; lung cancers = trachea, bronchus and lung cancers; cardiovascular disease is the addition of ischaemic heart disease and stroke. LRIs were a disease outcome for all ages.)

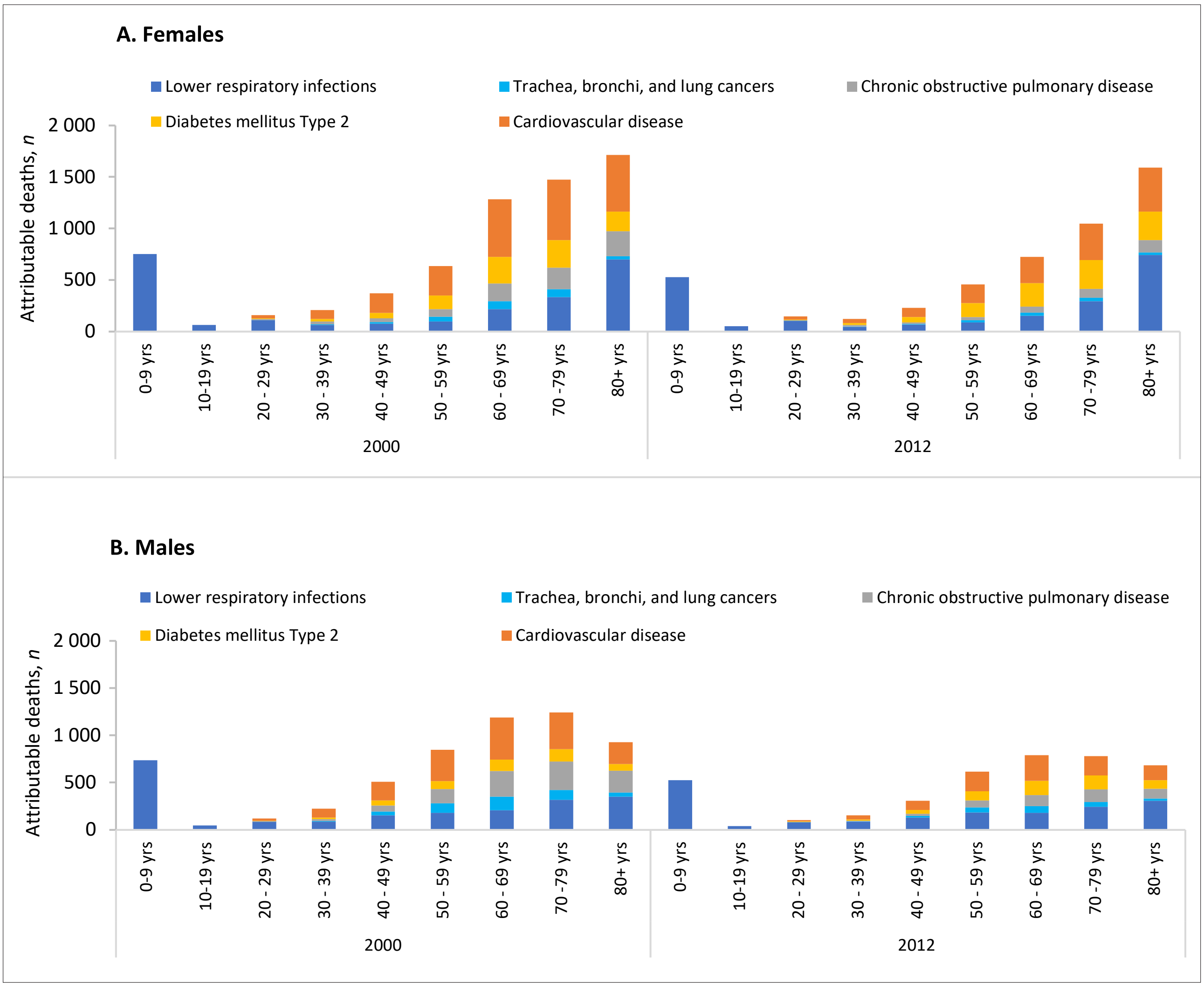

Fig. 5. Deaths attributable to household air pollution (HAP) by year in 2000 and 2012 in (A) females and (B) males. (In younger age groups (<25 years), lower respiratory infections were the only disease condition investigated that was attributable to HAP.) (Cardiovascular disease = ischaemic heart disease plus stroke.)

from 57.5% of households in 2002 to 75.2% in 2012.[26] The decrease in the use of solid fuels may have arisen from increased use of clean fuels, such as electricity and solar energy. The latter have become relatively more affordable in recent years, although solar energy tends to be used more by wealthy households than poorer households.[73] However, government commitment to renewable energy may see future improvements in HAP exposure.[74] Meanwhile, coal-fired power stations have continued to provide electricity to households in SA, where access to electricity increased from 35% of households in 1990 to 91% in 2018.[75] It is important to note that the emissions from coal-fired power stations also negatively impact human health and the environment.

While access to electricity may have increased, its affordability and reliability may restrict its use, especially in rural and informal dwellings.[76,77] Energy switching or stacking is common in SA, where different fuels on the energy ladder are used for cooking.[28] A continued transition to cleaner fuels, such as electricity or gas, for cooking would lead to a decrease in HAP exposure.

According to the latest GBD estimates for 2012, HAP was responsible for 7 983 deaths in SA.[78] We estimated a higher number of deaths (8 862), which may be due to differences in population and mortality data used. The top two causes of deaths attributable to HAP exposure identified by the GBD were LRIs and cardiovascular disease (specifically IHD).[79] Each of these diseases accounted for 27% of the deaths attributable to HAP, followed by COPD (20%), stroke (18%) and lung cancer (8%). Our findings were similar: LRIs were of particular concern, especially among children 0 - 9 years of age and the elderly (60 - 79 years). HAP exposure almost doubles the risk of childhood pneumonia, and is responsible for 45% of all pneumonia deaths in children under 5 years.[80] In response to this problem, the WHO's 'Guidelines for indoor air quality: Household fuel combustion' provides health-based recommendations on fuel type and technologies to protect health, as well as strategies for effective dissemination and sustainable adoption of clean home energy technologies and behaviours.[81]

Diabetes and COPD also contributed to the disease burden attributable to HAP exposure in SA. Several studies report an association between exposure to air pollution and diabetes,[82-84] some even reporting associations with air pollution levels below guideline values.[84] About 4.5 million adults suffer from diabetes (prevalence is estimated at 12.8%) in SA.[85] While smoking is the major cause of COPD, exposure to solid fuels is an important additional factor.[86] In Cape Town, the prevalence of COPD was reportedly 19%,[87] compared with 13% on the African continent,[88] possibly due to a high incidence of smoking, occupational dust exposure, HAP and prior tuberculosis. Diabetes and COPD morbidity place a significant burden on the healthcare system, hence the need for interventions to reduce HAP exposure.

Study limitations

Our study followed the GBD method and excluded HAP due to heating. However, household burning of solid fuels for heating would likely have a higher burden of disease estimate with cumulative risks from cooking and heating with solid fuels. We also followed the GBD method and excluded paraffin as a solid fuel. A recent multi-country study that included SA (the Prospective Urban and Rural Epidemiology Study) looked at the health impacts of cooking with paraffin[89] and found that its use was associated with increased risk of mortality and cardiorespiratory outcomes. If parrafin had been included in our analysis, our burden estimates would undoubtedly have been higher, especially given that paraffin is still commonly used in SA.[74] Including solid fuel use for heating and the use of paraffin would likely result in a change in our provincial estimates. Future assessments should take this into account.

The HAP-$PM_{2.5}$ exposure assigned to people exposed to HAP that we used was a crude estimate. The actual concentration of $PM_{2.5}$ generated when burning HAP could be higher or lower. However, because of the limited SA data available, we used the results of a global model.[64] Future studies may better inform the quantification of the concentration of pollutants generated when using solid fuels for cooking in SA. We used disease-outcome pairs based on GBD 2017. The disease-outcome pairs were systematically interrogated by GBD; however, there may still be residual confounding factors present.

The analyses presented here considered the burden attributable to HAP. HAP exposure as a risk factor may work synergistically with other risk factors, such as undernutrition, ambient air pollution exposure, etc., to increase the effects of HAP-related diseases. While these relationships are important, they are difficult to quantify and were not assessed here. Similarly, impacts of time and effort spent collecting or gathering solid fuels for household use on the socioeconomics of the household and the health of those responsible for doing so, especially women, were also not assessed.

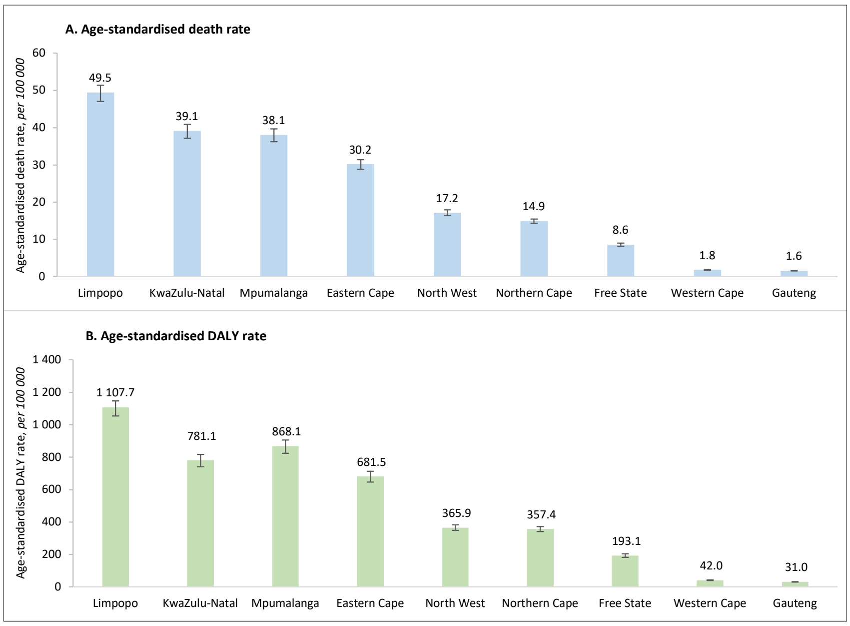

Fig. 6. (A) Age-standardised death rates due to household air pollution in 2012 by province; (B) age-standardised disability-adjusted life year (DALY) rates due to household air pollution in 2012 by province.

Conclusion

While the prevalence of HAP exposure decreased during the study period, approximately 9 million people were still exposed to HAP in 2012. Despite the reported decrease in the prevalence of HAP exposure and the decreased disease burden over the years of the study, the number

Table 4. Household air pollution exposure prevalence by sex and province in 2012

Province	Females exposed, % (95% UI)	Total female population, *n*	Males exposed, % (95% UI)	Total male population, *n*	Persons exposed, % (95% UI)	Total population exposed, *n* (95% UI)
Limpopo	51.5 (51.2 - 51.9)	2 948 206	48.1 (47.8 - 48.5)	2 587 080	50.0 (49.6 - 50.3)	2 764 875 (2 746 609 - 2 782 588)
Mpumalanga	28.2 (27.8 - 28.6)	2 052 156	26.5 (26.1 - 26.9)	1 962 411	27.4 (27.0 - 27.8)	1 099 188 (1 084 334 - 1 114 444)
KwaZulu-Natal	27.2 (26.9 - 27.5)	5 421 309	25.5 (25.2-25.8)	4 909 453	26.4 (26.2 - 26.6)	2 726 288 (2 701 494 - 2 752 115)
Eastern Cape	24.6 (24.3 - 24.9)	3 491 545	23.9 (23.6 - 24.2)	3 104 210	24.2 (24.0 - 24.5)	1 598 811 (1 580 343 - 1 617 279)
North West	12.7 (12.4 - 13.1)	1 780 728	12.9 (12.6 - 13.3)	1 823 208	12.8 (12.5 - 13.2)	462 025 (450 492 - 473 918)
Northern Cape	8.9 (8.4 - 9.3)	569 468	9.3 (8.9 - 9.8)	555 275	9.1 (8.7 - 9.5)	102 127 (97 403 - 107 076)
Free State	5.0 (4.8 - 5.2)	1 418 377	5.3 (5.1 - 5.5)	1 319 699	5.1 (4.9 - 5.4)	140 463 (134 987 - 146 487)
Western Cape	1.3 (1.3 - 1.4)	2 997 750	1.6 (1.5 - 1.7)	2 895 423	1.5 (1.4 - 1.5)	85 451 (80 147 - 90 755)
Gauteng	1.1 (1.1 - 1.2)	6 236 363	1.16 (1.11-1.22)	6 352 663	1.1 (1.1 - 1.2)	143 515 (137 220 - 149 809)
South Africa	18.4 (18.3 - 18.5)	26 915 902	16.8 (16.7 - 16.9)	25 509 422	17.6 (17.5 - 17.7)	9 232 100 (9 184 917 - 9 274 040)

UI = uncertainty interval.

of deaths and DALYs due to HAP exposure is still substantial, placing strain on households and the healthcare system. Globally, significant progress has been made for interventions to reduce HAP exposure,[2,90,91] including access to electricity, clean cook stoves, behavioural change[92-94] and housing with improved ventilation.[92,96,97] Evidence exists in the SA context of the potential for reducing HAP exposure.[50,57] Such interventions need to be sustainable, and inequalities that lead to energy poverty must be eliminated. Appropriate interventions should be targeted among vulnerable groups, especially infants, children and the elderly.

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Author contributions. Conceived and designed the study: RAR, CYW, EC, RP, DB, VPvW. Analysed and prepared the data: all. Interrogated and interpreted results: all. Drafted manuscript: RAR, CYW, EC, AC, ET, OA, IN, BN, RP, DB, VPvW. Critical review of manuscript for important intellectual content: all. Senior authors: VPvW, DB, RP. Agreed to final version: all.

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Conflicts of interest. None.

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