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Evaluating the health benefits of transitions in household energy technologies in Kenya

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Abstract

Acute respiratory infections (ARI) are the leading cause of the burden of disease worldwide and have been causally linked with exposure to pollutants from domestic biomass fuels in developing countries. We used longitudinal health data coupled with detailed monitoring of personal exposure from more than two years of field measurements in rural Kenya to examine the reductions in disease from a range of interventions, including changes in energy technology (stove or fuel) and cooking location. Our estimates show that the suite of interventions considered here, on average reduce the fraction of times that infants and children below 5 yr are diagnosed with disease by 24–64% for ARI and 21–44% for acute lower respiratory infections (ALRI). The range of reductions is larger for those above 5 yr, and is highly dependent on the time-activity budget of individuals. These reductions due to environmental management in infant and child ALRI are of similar magnitude to those achieved by medical interventions. © 2002 Published by Elsevier Science Ltd.

Keywords: Acute respiratory infections; Biomass combustion; Household energy; Indoor air pollution; Intervention assessment; Kenya

1. Introduction

Acute respiratory infections (ARI) are the leading cause of the global burden of disease and account for more than 6% of the global burden of disease (World Health Organization, 1999b, 2000). Between 1997 and 1999, acute lower respiratory infections (ALRI) were the leading cause of mortality from infectious diseases, with an estimated 3.5–4.0 million annual deaths worldwide, mostly in developing countries (World Health Organization, 1998, 1999b, 2000). Exposure to indoor air pollution, especially to particulate matter, from the combustion of biofuels (wood, charcoal, agricultural residues, and dung) has been implicated as a causal agent of respiratory diseases in developing countries (Chen et al., 1990; de Francisco et al., 1993; Ellegard, 1996; Ezzati and Kammen, 2001a,b; Pandey, 1984; Pandey et al., 1989a; Smith et al., 2000). This association, coupled with the fact that globally more than 2 billion people rely on biomass as the primary source of domestic energy, has put preventive measures to reduce exposure to indoor air pollution high on the agenda of international development and public health organizations (Smith, 1996; World Bank, 1993; World Health Organization, 1999a). For efficient and successful design and dissemination of preventive measures and policies, the following fundamental questions must be answered:

1. What are the factors that determine human exposure and what are the relative contributions of each factor to personal exposure? These factors include emission source and energy technology (stove–fuel combination), ventilation and housing characteristics such as the size and material of the house and the number of windows, and behavioural factors such as the amount of time spent indoors or near the cooking area.
2. What is the quantitative relationship between exposure to indoor air pollution and the incidence of disease (i.e. the exposure–response relationship)?
3. Which of the determinants of human exposure (source, ventilation, or behaviour) will be influenced,

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and to what extent, through any given intervention strategy?
4. What are the resulting impacts of any intervention on human exposure and on health outcomes?

In a recent series of papers, we addressed the first three of these questions (Ezzati and Kammen, 2001a,b; Ezzati et al., 2000a,b) with a focus on improved (high efficiency and low emission) cookstoves and cleaner biofuels. In this paper, we turn to the fourth question and estimate exposure reduction and the resulting health benefits as a result of changes in energy technology as well as changes in the location of cooking. This work provides a quantitative basis for evaluating the efficacy of interventions and policies to reduce the burden of disease from ARI by environmental management, thereby providing an input for estimating the cost-effectiveness of different interventions in international public health policy (Bang et al., 1990; Kirkwood et al., 1995; Lye et al., 1996; Mtango and Neuvians 1986; Murray et al., 2000; Pandey et al., 1989b; van Ginneken et al., 1996).

2. Research location

The study took place at Mpala Ranch/Research Centre, in Laikipia District, central Kenya (0°20′N 36°50′E). The altitude of Mpala Ranch, located on semi-arid land, is approximately 2000 m and the average monthly temperature varies between 17°C and 23°C. Cattle herding and domestic labour are the primary occupations of most of the 80–100 households residing on the ranch, with the remaining households employed as maintenance staff. The households have similar tribal backgrounds (Turkana and Samburu), economic status, and diet. The houses in both cattle-herding and maintenance villages are cylindrical with conic straw roofs. Detailed information on housing is provided in Ezzati et al. (2000b). The stoves used by the households in the study group use firewood or charcoal (and kerosene in the case of three households) as their fuel. The stove–fuel combinations considered in this paper (Table 1) include the traditional open fire as well as a set of improved cookstoves, and are used extensively by Kenyan households. Improved cookstoves were introduced in the study area after approximately 6 months of baseline data collection. Workshops were held for the household members in each village on the proper use and maintenance of the stoves.

3. Methods and data

Characterizing exposure, exposure–response relationship, and stove performance were based on data collected as a part of a long-term study of the relationship between energy technology, indoor air pollution, and health in rural Kenya. Field research at Mpala Ranch began in 1996 and continued until late 1999. The first 6 – 8 months of field research were spent on the collection of background data, including detailed demographic data for all the households residing on the ranch and surveys of energy use, energy technology, and related characteristics.

3.1. Exposure assessment

We conducted continuous real-time monitoring of PM_{10} (particles below 10 μm diameter) in 55 households—randomly selected among different villages and fuel types—for more than 200 days, and for the duration of 14–15 hours per day. All measurements took place under actual conditions of use (see Ezzati et al., (2000b) for details of procedures). During this time we also recorded the location and activities of all the household members, with emphasis on energy and exposure related variables. We also monitored the spatial dispersion of pollution inside the house. We complemented these data with extensive interviews with household members and local extension workers on household energy technology and time-activity budget. Demographic information for the individuals in the 55 households in the study group are given in Table 2. Table 3 provides summary statistics for

Table 1
Stove–fuel combinations in the study group

Stove name	Material		Fuel	Price (US$)	Number in use[a]
	Body	Liner		equiv.	
3stone	N/A	N/A	Firewood	$0	50
Kuni Mbili	Metal	Ceramic	Firewood	$4–6	26
Upesi	Metal	Ceramic	Firewood	$4–6	5
Lira	Metal	Ceramic	Firewood	$4–6	1
Metal Jiko	Metal	N/A	Charcoal	$1.5–2	1
Kenya Ceramic Jiko (KCJ)	Metal	Ceramic	Charcoal	$4–6	24
Loketto	Metal	Metal	Charcoal	$4–6	4

[a] Number in use refers to the number of each stove type owned by the households in a random sample of 55 households.

emission concentrations from different stove–fuel combinations (Ezzati et al., 2000a).

Measurement and data analysis methods for determining personal exposure values are discussed in detail in Ezzati et al. (2000b). In summary, we constructed *profiles of exposure* for each individual in the monitored households based on the combination of time-activity budgets, spatial dispersion, and daily and day-to-day exposure variability. We divided the time budget of household members into the following activities: cooking, non-cooking household tasks, warming around the stove, playing, resting and eating, and sleeping. We also considered the set of potential microenvironments where each activity takes place (a total of seven microenvironments outside plus six microenvironments inside the house). For example, playing or resting may take place inside the house or outside, cooking activities directly above the fire or slightly farther away, and so on. Daily exposures were then obtained using the following relationship:

$$E = \sum_{i=1}^{n} \sum_{j=1}^{7} w_j t_{ij} c_i, \tag{1}$$

where c_i is the emission concentration in the ith period of the day with each period corresponding to one type of activity and n representing the total number of activities for each individual (therefore, the two summations together represent all the activity–location pairs for each individual such as playing outside, cooking inside near fire, resting inside away from fire and so on), t_{ij} the time spent in the jth microenvironment in the ith period, and w_j the conversion (or dilution) factor for the jth microenvironment which converts the emission concentration measurements to concentration at the jth microenvironment. Table 4 provides a summary of time spent inside and near fire (defined as a distance of approximately 1 m from the fire where much of the cooking-related activities take place) for the study group.

We have shown in Ezzati et al. (2000a,b) that stove emissions exhibit large temporal variability throughout the day including intense peaks of short duration, and that some household members are consistently closest to the fire when the pollution level is the highest. These episodes typically occur when the fuel is added or moved, the stove is lit, the cooking pot is placed on or removed from the fire or food is stirred. This indicates that average daily concentration alone is not a sufficient measure of exposure. Therefore, in addition to mean daily concentration (m) we used the following two

Table 2
Demographic characteristics of the study group[a]

Age group (yr)	Number of individuals in the group	Fraction female	Mean age (yr)
0–4	93	0.56	3.0 (1.4)
5–14	109	0.56	9.7 (2.7)
15–49	120	0.54	29.4 (10)
50+	23	0.65	63.8 (9.4)
Total	345	0.56	18.3 (17.6)

[a] Numbers in brackets indicate standard deviations. Note that the mean age reflects the age at the end of the study period. The choice of age divisions was made since children under the age of 5 have additional susceptibility to ARI and at higher ages chronic conditions begin to show. For those between the ages of 5 and 49, a division was made at the age of 15 when it is common for people to enter the workforce or get married.

Table 3
Average emission concentrations ($\mu g/m^3$) for different stove fuel combinations[a]

Stove–Fuel	Number of sampling days	Mean	Median	Standard deviation
(a) *During burning phase*				
3-stone (wood)	142	3881	2394	4097
Ceramic wood stoves (wood)	21	1922	1335	1752
Metal Jiko (charcoal)	6	807	710	816
Kenya Ceramic Jiko (KCJ) (charcoal)	26	316	127	470
Loketto (charcoal)	8	275	207	237
(b) *During smouldering phase*				
3-stone (wood)	138	1523	510	3201
Ceramic wood stoves (wood)	19	507	236	690
Metal Jiko (charcoal)	3	388	111	510
Kenya Ceramic Jiko (KCJ) (charcoal)	21	89	14	231
Loketto (charcoal)	8	25	22	16

[a] In almost all houses, a low background level of combustion takes place throughout the whole day. For the purpose of this analysis, we define *burning* as the periods when the stove is used for cooking and/or it is in flame. *Smouldering*, therefore, refers to periods that the stove is neither in active use nor in flame. Mean, median, and standard deviations are calculated from the multiple sampling days for each stove–fuel combination (for details see Ezzati et al., 2000a). Note that the emission values are relative to factory calibration of the measurement instrument which is based on light scattering properties of a standard mixture (dry Arizona road dust) with an uncertainty of 20% for wood smoke. Therefore, although mean and median emission values are calculated to 3–4 digits, the accuracy of measurement is limited to the first 2 digits.

Table 4
Time-activity budget for demographic sub-groups[a]

Age group (yr)	Fraction of time inside[b]		Fraction of time near fire[c]		Probability of cooking[d]	
	Female	Male	Female	Male	Female	Male
0–4	0.43	0.44	0.20	0.20	0	0
5–14	0.40[e]	0.26[e]	0.23[e]	0.13[e]	0.39[e]	0.02[e]
15–49	0.54[e]	0.24[e]	0.38[e]	0.06[e]	0.98[e]	0.11[e]
50+	0.39	0.30	0.24	0.13	0.27	0.19
Total	0.45[e]	0.30[e]	0.27[e]	0.13[e]	0.48[e]	0.06[e]

[a] The results are averages among different days. In practice, the amount of time spent inside on different days is from a distribution around this value.
[b] Fraction of time is based on a 14-h day from 6:30 to 20:30.
[c] Fraction of time is based on a 14-h day from 6:30 to 20:30. Near fire refers to areas within a radius of approximately 1 m from the stove.
[d] Average within the group, with a probability of 1 assigned to those who cook regularly, 0.5 to those who cook or look after fire sometimes, and 0 to those who do not perform cooking and energy-related tasks.
[e] Difference between male and female rates is significant with $p<0.0001$.

Table 5
The impacts of age, gender, and PM10 concentration[a]

	0–4 yr	5–14 yr	15–49 yr	50+ yr
(a) *On time spent inside the house*				
Female	0.002	0.14	0.33	0.11
	($p=0.94$)	($p<0.001$)	($p<0.001$)	($p=0.12$)
Age	−0.07	0.0008	0.0008	0.005
	($p<0.001$)	($p=0.84$)	($p=0.55$)	($p=0.18$)
PM_{10} (μg/m^3)	-6×10^{-6}	-4×10^{-6}	−0.00001	-9×10^{-6}
	($p=0.36$)	($p=0.50$)	($p=0.13$)	($p=0.51$)
Constant	0.67	0.26	0.23	0.03
	($p<0.001$)	($p<0.001$)	($p<0.001$)	($p=0.92$)
R^2	0.43	0.31	0.69	0.23
(b) *On time spent near fire (defined as within a distance of approximately 1 m from the fire)*				
Female	−0.03	0.12	0.36	0.12
	($p=0.37$)	($p<0.001$)	($p<$ 0.001)	($p=0.09$)
Age	−0.03	0.008	0.0001	0.005
	(p = 0.009)	(p = 0.02)	(p = 0.94)	(p = 0.17)
PM_{10} (μg/m^3)	-9×10^{-6}	−0.00001	−0.00001	−0.00001
	($p=0.14$)	($p=0.04$)	($p=0.12$)	($p=0.45$)
Constant	0.39	0.09	0.11	−0.16
	($p<0.001$)	($p=0.03$)	($p=0.04$)	($p=0.55$)
R^2	0.15	0.36	0.76	0.25

[a] *Female* is a variable that takes the value of 1 if the individual is female and 0 if male. Constant refers to the regression constant in a linear model.

descriptive statistics for characterizing human exposure (i.e. to characterize c_i in Eq. (1)):

- Mean above the 75th percentile ($m_{>75}$): to account for the fact that some household members are closest to the stove during high-pollution episodes caused by cooking activities.
- Mean below the 95th percentile ($m_{<95}$): to eliminate the effect of large instantaneous peaks that especially occurs when lighting or extinguishing the fire, or when fuel is added.

Therefore, the value of concentration, c_i, in Eq. (1) was chosen from $m_{>75}, m$, and $m_{<95}$ based on the criteria in Table 5 in Ezzati et al. (2000b). For example, for cooking very close to the stove when emissions are highest, c_i was $m_{>75}$ of the burning period. On the other hand, for sleeping at night, when the stove is smouldering and not disturbed, c_i was $m_{<95}$ of the smouldering period.

In addition to the above daily variations, one may expect day-to-day variability in exposure to indoor smoke as a result of variation in both emissions and time-activity budget. Emissions in a single household can vary from day-to-day because of fuel characteristics such as moisture content or density, air flow, type of food cooked, or if the household uses multiple stoves or fuels. Activity patterns can also vary due to seasonal nature of work and school, illness, market days, and so on. Therefore in addition to the use of multiple descriptive statistics for characterizing daily exposure, we constructed measures of exposure which are not solely based on measurements from a single day.

Specifically, rather than using measurements of emission concentration directly, we assigned households to pollution concentration categories. This categorization was performed for the three descriptive statistics defined above ($m, m_{<95}, m_{>75}$) for both burning and smouldering phases. A similar grouping was done for time budgets (including time spent inside, near fire, and inside during cooking) and activity (whether the person cooks regularly/sometimes/never and whether the person performs non-cooking household tasks regularly/sometimes/never) using the data from the 210 days of direct observation as well as the supplemental interviews.

3.2. Exposure-response relationship

The health data and the methodology used in deriving the exposure–response relationships for ARI and ALRI are provided in Ezzati and Kammen (2001a,b). In summary, two community nurses from Nanyuki District Hospital visited all the households in the study group on a regular basis. The nurses underwent the training provided by the National Acute Respiratory Infection (ARI) Programme (designed in consultation with the World Health Organization) on the WHO protocols for clinical diagnosis of ARI as described in World Health Organization (WHO) (1990). In the initial months of the programme, each village was visited once in 2 weeks. The visits then increased to approximately one per week. In each visit, at least one adult member from each household reported to the nurse on the health status of the household members, with specific emphasis on the presence of cough and other respiratory ailments. The responses were collected in the language of choice of the respondent and recorded in English by the nurse, who spoke Swahili and Turkana.

The nurse then clinically examined all those who were reported as having symptoms and recorded the relevant clinical information, including symptoms and diagnosis. The reporting process also included information on visits to any other health facility since the nurse's last visit. Therefore, the health data include a 2-yr longitudinal array of weekly health records for each individual in the study group. Depending on the severity, the cases were treated with the standardized treatment of the National ARI Programme, which also resulted in standardization of treatment in the study group. Treatments included drugs that are readily available in the nearest town (Nanyuki), dispensed by the nurse for more severe cases as well as providing assurance or recommending home remedies for minor cases. The extreme, and potentially fatal, cases were referred to one of the hospitals in Nanyuki. No information was recorded for those households from which no adult member was present or for household members who were away from home during the day of visit.

The health outcomes considered in the analysis were ARI and ALRI rates—defined as the fraction of weeks that an individual is diagnosed with ARI and ALRI. Note that for a disease such as ARI whose episodes have a limited and short duration, disease episode and case have interchangeable definitions. As a result, all episodes in a time interval count towards disease incidence and the fraction of weeks diagnosed with disease are an aggregate measure of both incidence and duration.

Using linear and logistic risk models and controlling for a number of covariates including age, gender, the type of village that an individual resided in (maintenance or cattle-herding), smoking, and number of people in the household, we demonstrated that both ARI and ALRI are increasing functions of average daily exposure to PM_{10} but the rate of increase declines for exposures above approximately 1000–2000 $\mu g/m^3$ (Ezzati and Kammen, 2001a,b) especially for ARI. Although this concave shape is within the uncertainty range of the parameters of the exposure–response relationship, it was also confirmed in the analysis with a continuous exposure variable. For ALRI, the rate of increase rises again at the highest exposure levels, above 3500 $\mu g/m^3$ for infants and children (age $\leqslant$ 5 yr) and 7000 $\mu g/m^3$ for young and adult individuals.

Health status of the individuals in the study group was likely to have been affected by the treatment provided during the collection of health data. In addition to ethical considerations, this provision standardized treatment in the study group and prevented confounding due to factors such as differing participant access to health care facilities. At the same time, if treatment affected the cases differently in a way that was correlated with severity or exposure, then the shape of the exposure–response curve would be modified. Therefore, the relationships obtained in this analysis are based on the use of a small level of health care.

4. Exposure reduction as a result of environmental intervention

We considered four environmental interventions for reduction of exposure to indoor smoke: (1) change in fuel from wood to charcoal, (2) change in stove technology from traditional open fire to improved (ceramic) woodstoves, (3) change in location of cooking from inside the house to outside, and (4) the combination of the last two interventions: cooking outside with improved woodstoves. The last intervention was included because many Kenyan improved stoves are portable and can be used outside. Technology transfer efforts can, therefore, encourage a shift not only in stove technology but also in the location of cooking to achieve further reductions in exposure.

In the case of outside cooking, we assumed that some inside heating or cooking, using a smaller charcoal stove, is done early in the morning or at night to reflect the reality of household energy use in our research area, where weather and other environmental factors do necessitate some source of energy inside the house. We compared the impacts of the four intervention strategies to the baseline of cooking indoors with traditional open fire.

In considering the impacts of interventions we first calculated how concentrations in each of the exposed microenvironments (characterized by m, $m_{>75}$, and $m_{<95}$ as described above) changed as a result of each intervention (Ezzati et al. 2000a). For example, moving the location of cooking outside will not affect the exposure during the moments that the cook is very close to the fire but will eliminate exposure completely for those resting or playing inside the house. A shift to charcoal, on the other hand, would lower exposure for all the people in the house without eliminating it and so on.

4.1. Behavioural change and confounding

Before considering the impacts of the interventions, we address the issue of confounding due to behavioural change in intervention analysis. It has been hypothesized that with reduction in emissions, people may spend more time indoors or close to the fire, thereby limiting the benefits of intervention. We tested this hypothesis for our study group. We considered only one class of villages (cattle-herding villages) to avoid any unobservable factors which may introduce systematic differences in the time spent inside the two village types.[1]

Table 5 contains the coefficients for regression of time spent inside and time spent near fire (as a fraction of the day) on gender, age, and PM_{10} concentration for different age groups. We estimated the coefficients separately for different age groups to allow for heterogeneous behaviour and activities and in different demographic sub-groups.

The coefficients in Tables 5(a) and (b) show that the effect of pollution on time spent inside or near fire is either statistically not significant, or when statistically significant, it is physically negligible, in the order of 0.00001 of the day for each $\mu g/m^3$ increase in PM_{10} concentration. In other words, for a $4000\,\mu g/m^3$ change in emission concentration—approximately equal to the standard deviation (and also inter-quartile range) of the emission concentrations of the three-stone fire and larger than the difference between average for this technology and Loketto charcoal stove which has the lowest emissions—the time spent near fire would change by 0.04 of the day, which is a relatively small fraction of the total time spent inside.

Qualitative analysis of time-activity budgets in the study group also confirms this finding. The time spent on cooking, especially in rural areas, is determined by the type of food cooked and/or the price and availability of energy. Given the small number of food items in the diet of most rural areas, we expect limited variation in the time of cooking. Work hours and other household tasks, which are exogenous to the time–pollution relationship, are also important determinants of how much time is spent inside the house or near fire. Once again, this is especially the case in rural areas where agriculture or cattle-herding, and collection of wood and water consume a large fraction of household members' time.

Finally, environmental conditions (such as climate and lack of outside activities at night) are another important determinant of time budget. In brief, in our area of study social, economic, and environmental determinants of time-activity budget seem too important to be modified by pollution level significantly. This is likely to be true for most rural regions as also illustrated by research on household economics in developing countries.

4.2. Exposure reduction

The panels of Fig. 1 show the average (over 24 h) daily exposure for different demographic sub-groups under the base scenario as well as after the four intervention mechanisms described above. The values in Fig. 1 were obtained using the median for each stove–fuel category (i.e. column 4 in Table 3 as well the corresponding values for $m_{>75}$ and $m_{<95}$).[2]

Fig. 1 shows that after the age of 15, the first two interventions, change in fuel or stove technology, result

[1] For example, people in the maintenance villages cook outside more often than cattle-herding villages, therefore resulting in a different choice of location for some household members compared to those who cook inside. A child playing near her/his mother, for instance, would be outside when she is cooking, a choice determined less by pollution level than by other factors, particularly the location of the mother. Other inter-village heterogeneity includes different work hours, proximity of wild animals, and the physical layout of the village. Note that in this case most of these environmental effects would cause people in maintenance villages, where pollution is generally lower, to spend *less* time inside, therefore weakening the above hypothesis if considered in the analysis.

[2] We repeated the analysis using the mean emissions for each stove–fuel category (i.e. column 3 in Table 3 as well as the corresponding values for $m_{>75}$ and $m_{<95}$). The absolute values of exposures are higher than those in Fig. 1 since for all stove–fuel categories, the median is smaller than the mean (Ezzati et al., 2000). The *relative* reduction in exposure for the different demographic sub-groups are nonetheless very similar to those using the median.

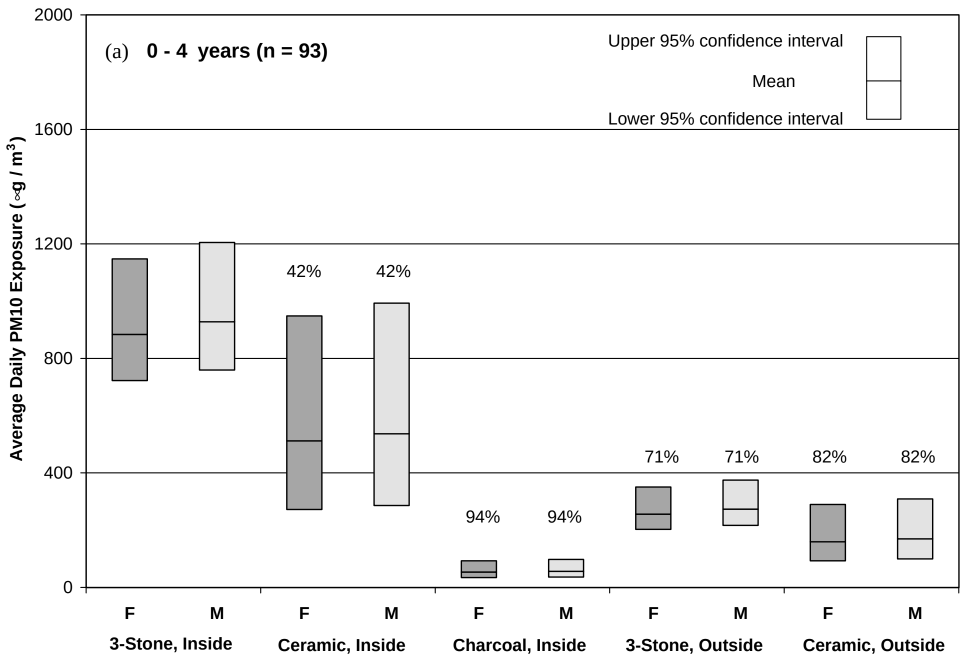

Fig. 1. Reduction in daily exposure to PM_{10} as a result of environmental intervention for: (a) 0–4 yr, (b) 5–14 yr, (c) 15–49 yr, (d) 50 + yr. For each demographic group, the number in brackets indicates the average reduction with respect to the baseline of cooking inside with three-stone fire. For emission concentrations, the median for each stove–fuel category was used. For time budget of each individual we used the mid-values of time spent inside and near fire, as described in Ezzati et al. (2000b). Therefore, only variations in time-activity budget between individuals and variations between stove types (but not within individual stoves) are considered. Confidence intervals for each group were obtained using the confidence interval of the emission concentrations. The confidence interval for the median was obtained using a binomial method that makes no assumptions as to the underlying distribution of the variable. Three of the men in the last two age groups work as cattle guards during night and use a three-stone fire through the night for warmth and deterring wild animals. We assumed that this group will continue to use the open fire under all scenarios both because of the cost of using charcoal for the whole night and because the large size of the fire is important for its purpose of deterring wild animals.

in a slightly larger *relative* exposure reductions for females (46–47% for females versus 35–38% for males for ceramic stoves and 94–95% for females versus 75–83% for males for charcoal stoves). The higher relative reduction for women is because cleaner fuels and stoves not only lower average emission concentrations, but also provide significant reductions in high-intensity emission episodes which are a large contributor to the exposure of women during cooking (Ezzati et al., 2000a,b). Further, since young and adult women have the highest baseline exposure, larger relative reductions imply that in absolute terms the exposure of women is reduced by a much larger amount with change to a cleaner fuel or stove. Finally, the results in Fig. 1 illustrate that transition to charcoal is the only intervention scheme that lowers the exposure of most household members to the range of a few hundred $\mu g/m^3$, which is in the same order of magnitude as international standards.[3]

With relocating the stove outside, on the other hand, young and adult women who perform the cooking and related tasks observe smaller *relative* reductions than men (although the reductions are still large in absolute terms). Their exposure pattern during cooking is mostly transferred elsewhere and the reductions are from those times when they perform other household tasks or rest slightly farther from the stove or inside the house. Household members who do not use the stove regularly (except for occasional warming), such as young and adult men and infants, on the other hand, benefit the most from moving the source of pollution outdoors (65–85% reduction). For this group, but not for young and adult women, cooking outside also lowers exposure to the levels that have the same order of magnitude as international standards.

5. Disease reduction as a result of environmental intervention

To estimate the impacts of the above interventions on ARI and ALRI, we considered the scenarios of exposure reduction in Fig. 1 along with the exposure–response relationships estimated in Ezzati and Kammen

[3] The latest US-EPA National Ambient Air Quality Standards, for instance, required the concentration of PM_{10} (particles below the diameter of 10 µm) to achieve a 24-h average below 150 $\mu g/m^3$. The standards have recently been reviewed and are now based on $PM_{2.5}$ concentration.

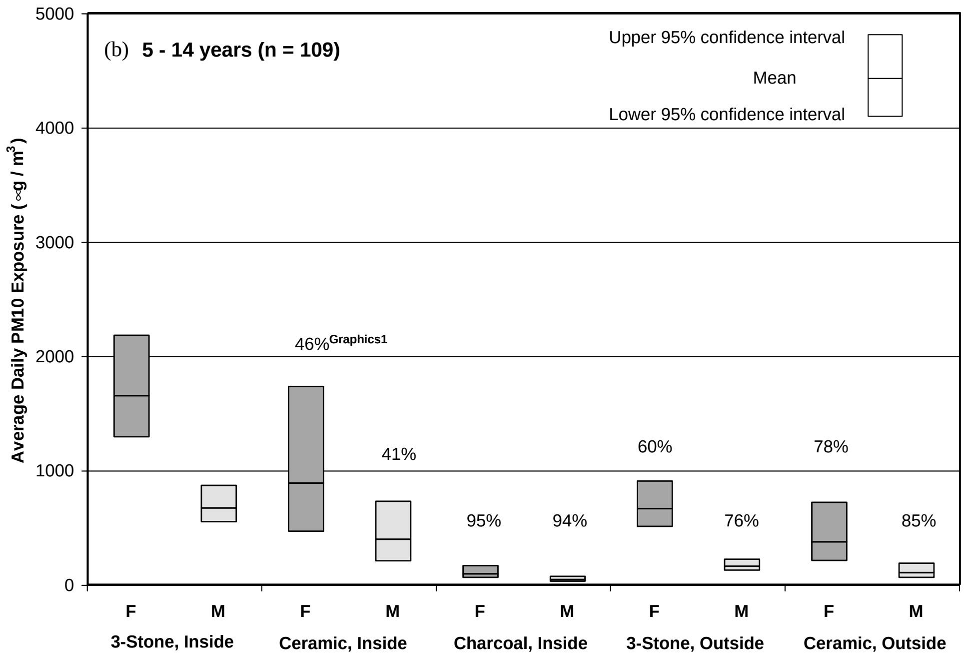

Figure 1. (*Continued*).

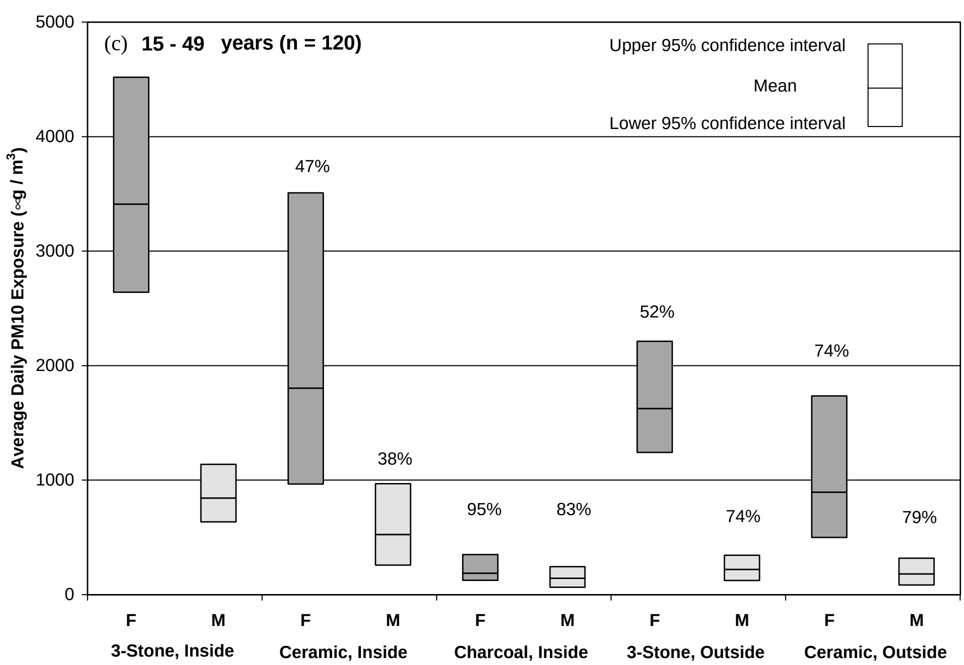

Figure 1. (*Continued*).

(2001a,b). The corresponding disease rates were calculated using the post-estimation *predict* command in *Stata*[4] for each individual and are reported in Table 6.

Table 6 and Fig. 1 together demonstrate an important characteristic of different exposure reduction strategies. Fig. 1 shows that exposure reduction as a result of transition to charcoal is slightly more than twice that of using ceramic woodstoves for all demographic subgroups. In Table 6, a similar ratio is seen in disease reduction for infants and children below 6 yr. For most of those older than 5 yr, on the other hand, disease reduction as a result of transition to charcoal is 3–6

[4]The predict command calculates the value of the dependent variable (disease rate in this case) for each individual from the values of the independent variables for the person (exposure, age, gender, the type of village that an individual resided in (maintenance or cattle-herding), smoking, and number of people in the household) as well as the estimated regression model.

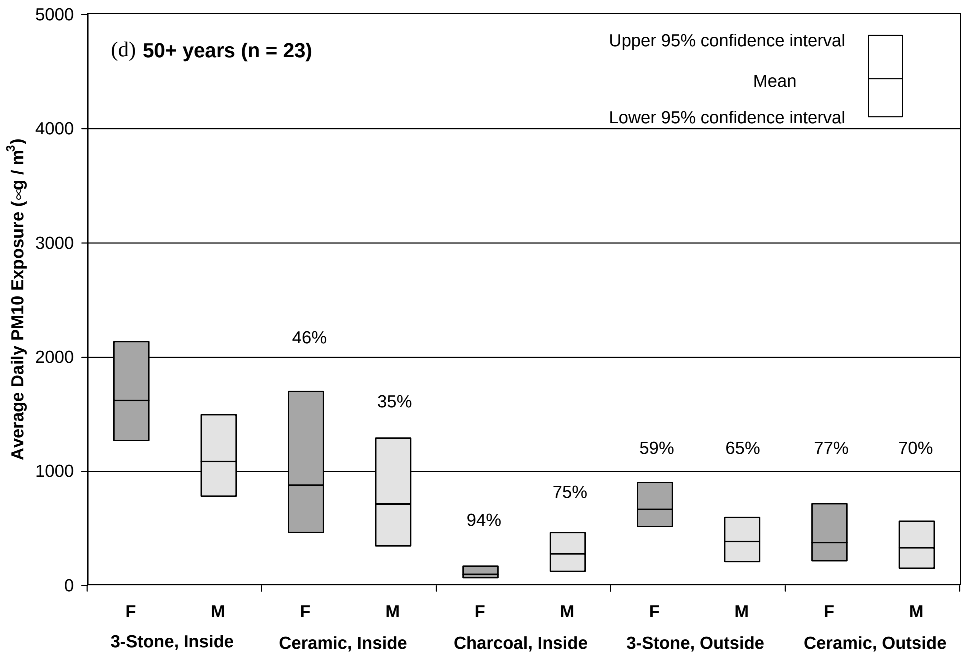

Figure 1. (*Continued*).

times that of using improved (ceramic) woodstoves (the ratio is as high as 30 for ARI among adult men but this is because of the small reduction as a result of ceramic woodstoves for this group in the denominator). Similar relationships can be seen for the small versus large exposure reductions from other intervention mechanisms. The analysis in Ezzati and Kammen (2001a,b) showed a concave exposure–response relationship for ARI and ALRI as a result of exposure to indoor PM_{10} especially among adults. One implication of a concave exposure–response relationship is that there are increasing marginal benefits to exposure reduction. Therefore, the additional exposure reductions as a result of transition to charcoal (or outside cooking for some demographic groups) provide more health benefits than the initial decrease that occurs with a shift to ceramic woodstoves. Finally, the larger ratios of charcoal-to-ceramic stove disease reduction for those older than 5 yr, are a result of the more pronounced concave behaviour of the exposure–response relationship for this group which was seen in Ezzati and Kammen (2001a,b).

In Table 6, the *distribution* of benefits among different demographic groups shows a pattern that is similar to exposure reduction scenarios in Fig. 1. For infants and children below 5 yr there is no gender-based difference in disease reduction. For young and adult household members (age$\geqslant$5 yr), relocating the stove to an outside cooking location biases the distribution of benefits towards male household members who do not cook. For this intervention, the relative reductions in illness for adult men are up to 4 times those of women, who continue to cook using polluting stoves in a different location. Substituting the three-stone fire with a cleaner stove (ceramic stoves) or fuel (charcoal) eliminates the disease reduction gap between male and female adults and further results in a slightly larger *relative* disease reduction for females. The *absolute* benefits to women are then considerably larger than men because of the larger initial (baseline) disease rates among women.

Finally, it is important to emphasize that the reductions in exposure, and therefore disease, are dependent on the spatial and behavioural determinants of exposure as discussed in Ezzati et al. (2000). For example, in our research area, infants are usually not carried on their mothers' back while cooking. In highlands of Guatemala, on the other hand, where infant exposure is firmly connected to a maternal one (Bruce et al., 1998; McCracken and Smith, 1998) a different distribution of benefits may exist.

6. Discussion

We have used continuous monitoring of PM_{10} concentration, data on spatial dispersion of indoor smoke, and detailed quantitative and qualitative data on time-activity budget to compare the emissions of various biomass fuels and stoves, and to construct detailed measures of individual exposure to indoor particulate matter (Ezzati et al., 2000a,b). We have also used data from more than 2 yr of monitoring of health status to derive an exposure–response relationship for ARI and ALRI as a result to exposure to indoor PM_{10} (Ezzati and Kammen 2001a,b). In this work, we used these

Table 6
Reduction in (a) ARI and (b) ALRI as a result of environmental intervention for different demographic groups in the study area[a]

Age group (yr)		Open fire inside	Ceramic woodstove inside	Charcoal stove inside	Open fire outside	Ceramic woodstove outside
(a) *ARI*						
0–4	F	0.11 (0.09–0.14)	0.09 (24%) (0.09–0.12)	0.04 (64%) (0.04–0.04)	0.07 (35%) (0.07–0.08)	0.05 (42%) (0.04–0.08)
	M	0.12 (0.09–0.14)	0.09 (24%) (0.09–0.13)	0.04 (64%) (0.04–0.04)	0.07 (35%) (0.06–0.08)	0.06 (49%) (0.04–0.08)
5–14	F	0.06 (0.06–0.07)	0.05 (12%) (0.05–0.06)	0.02 (71%) (0.02–0.03)	0.05 (17%) (0.04–0.06)	0.04 (38%) (0.03–0.05)
	M	0.04 (0.04–0.04)	0.04 (7%) (0.03–0.04)	0.01 (64%) (0.01–0.02)	0.03 (32%) (0.01–0.03)	0.01 (63%) (0.01–0.03)
15–49	F	0.07 (0.06–0.08)	0.06 (14%) (0.04–0.07)	0.02 (68%) (0.01–0.05)	0.06 (15%) (0.05–0.07)	0.04 (37%) (0.04–0.06)
	M	0.04 (0.04–0.05)	0.04 (2%) (0.03–0.04)	0.02 (62%) (0.01–0.02)	0.02 (50%) (0.02–0.02)	0.02 (58%) (0.01–0.02)
(b) *ALRI*						
0–4	F	0.05 (0.04–0.06)	0.04 (21%) (0.04–0.05)	0.03 (44%) (0.03–0.03)	0.04 (27%) (0.03–0.04)	0.03 (36%) (0.03–0.04)
	M	0.06 (0.04–0.07)	0.05 (21%) (0.04–0.06)	0.03 (44%) (0.03–0.04)	0.04 (28%) (0.04–0.05)	0.03 (35%) (0.04–0.05)
5–14	F	0.01 (0.01–0.01)	0.01 (19%) (0.01–0.01)	0.00 (61%) (0.00–0.01)	0.01 (26%) (0.01–0.01)	0.01 (44%) (0.00–0.01)
	M	0.01 (0.01–0.01)	0.01 (15%) (0.00–0.01)	0.00 (46%) (0.00–0.01)	0.00 (30%) (0.00–0.01)	0.00 (45%) (0.00–0.01)
15–49	F	0.02 (0.02–0.02)	0.02 (15%) (0.01–0.02)	0.01 (65%) (0.00–0.01)	0.02 (17%) (0.01–0.02)	0.01 (43%) (0.01–0.02)
	M	0.01 (0.01–0.01)	0.01 (10%) (0.01–0.01)	0.01 (45%) (0.00–0.01)	0.01 (38%) (0.00–0.01)	0.01 (42%) (0.00–0.01)

[a]The results are not calculated for the 50+ age group, since the exposure–response relationship was not estimated for this group in Ezzati and Kammen (2001a) due to a small sample size. For each entry, the first number indicates disease rate (defined as the fraction of weekly examinations diagnosed with the corresponding illness) resulting from the implementation of the respective intervention scheme. Exposures are from Fig. 1, calculated using the median emission concentration for each stove–fuel category. The first brackets contain average reduction relative to the baseline of cooking inside with three-stove fire. Numbers in the second brackets indicate the uncertainty range. The uncertainty range was obtained using the 95% confidence interval of stove emissions and the 95% confidence interval of exposure–response parameters. The lower (or upper) confidence limit was obtained by *simultaneous* use of the lower (or upper) confidence limit for both stove emissions and exposure–response parameters. Therefore, these are lower and upper *bounds* on the confidence limits of the estimated disease rates, and the actual 95% confidence interval is smaller than those reported. Note that the uncertainty intervals are not symmetrically distributed around the mean. This is because in estimating the exposure–response relationship, we divided exposure into categories (Ezzati and Kammen, 2001a). Therefore, the effects of a decrease or increase in exposure on health depends on whether an individual shifts to a lower or upper exposure category. The exposure–response relationship was estimated as a logistic function, using *blogit* estimation as described in (Ezzati and Kammen 2001a). The results using a linear probability model and OLS estimation are similar.

results to examine the impacts of various technology transfer programmes on exposure and disease reduction.

These results should be verified in further observational studies with larger samples as well as randomized controlled trials in different settings. At the same time, these first estimates indicate that significant reductions in ARI and ALRI can be obtained using inexpensive environmental interventions. Table 6 illustrates that *a median*[5] ceramic woodstove, which does not require a shift in fuel, can reduce ARI by approximately 25% and ALRI by approximately 20% among infants and young children compared to *a median* three-stone fire. With a larger transition in energy technology and by using charcoal, the reductions are in the order of 65% for ARI and 45% for ALRI. Older household members also benefit from these interventions, especially from using charcoal. At the same time, since ALRI is the largest cause of mortality and the burden of disease among developing country infants, most benefits (in terms of life years gained) will be concentrated in this group. The reductions in under-5 ALRI cases as a result of transitions in stove and fuel are similar to reductions in incidence of ARI or reductions in mortality due to the provision of antibiotics through primary health care systems (Bang et al., 1990; Kirkwood et al., 1995; Lye et al., 1996; Mtango and Neuvians, 1986; Pandey et al., 1989b; van Ginneken et al., 1996). Given the additional

[5]These results were obtained using median emissions for each stove category. The relative reductions in health benefits (but not in exposure) would be slightly larger if mean emissions were used because of the non–linear exposure–response relationship.

benefits of transitions in energy technology—including reductions in long-term adult morbidity or mortality (due to COPD), reductions in burns, and increased fuel efficiency—and their low costs, such environmental management methods should receive increased attention in the public health and energy sectors.

The results also show that the benefits from transition to charcoal are larger than those of ceramic woodstoves, in a manner disproportionate to their emission reductions for adult household members. Therefore, they quantitatively confirm that public health programmes aiming to reduce the adverse impacts of indoor air pollution in developing countries should focus on measures that result in large reductions in pollution, since the marginal benefits of reduction are higher at lower emissions levels. This finding raises an important policy question: although from an environmental conservation perspective, current charcoal production methods are more damaging than fuelwood (Ahuja, 1990; Dutt and Ravindranath, 1993), benefits to public health are likely to be considerable. This tension is a reminder of the need for integrated approaches to technology, environment, and health in designing successful intervention strategies.

Technology transfer programmes and public health initiatives provide a variety of benefits in developing nations. With more than 2 billion people worldwide relying on biomass as their primary source of energy, efforts to introduce new energy technologies should also pay detailed attention to health outcomes. A long record of national, multilateral, and private donor efforts to promote improved (high-efficiency and low-emissions) stoves exists (Barnes et al., 1994). We have illustrated that transitions through the "energy ladder", from wood to charcoal, or to kerosene, gas, and electricity require a detailed evaluation of public health and environmental trade-offs (such as impacts on vegetation and greenhouse gas emissions) of various energy technologies. In particular, with a richer quantitative understanding of health impacts of particulate matter, public health and energy R&D efforts that aim to reduce disease burden can effectively address acute respiratory infections.

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