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Urban and rural exposure to indoor air pollution from domestic biomass and coal burning across China

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Abstract

Although indoor air pollution (IAP) from solid fuel use in the households of the developing countries is estimated to be one of the main health risks worldwide, there is little knowledge of the actual exposure experienced by large populations. We have developed a method to estimate exposure to PM_{10} from IAP for large populations, applied to different demographic groups in China. On a national basis we find that 80%–90% of exposure in the rural population results from IAP. For the urban population the contribution is somewhat lower, about 50%–60%. Average exposure is estimated at 340 $\mu g/m^3$ (SD 55) in southern cities, and 440 $\mu g/m^3$ (SD 40) in northern cities. For the rural population we find average exposure to be 750 $\mu g/m^3$ (SD 100) and 680 $\mu g/m^3$ (SD 65) in the south and north respectively. Quite surprisingly our results indicate that the heavily polluted northern provinces, largely dependent on coal and believed to have the population with the largest exposure burden, turn out to have medium exposure when IAP is included. We find that the largest exposure burden is in counties relying heavily on biomass, and that there are only small gender differences in exposure.

Keywords: Indoor air pollution; Rural; Urban; Exposure; China; Solid fuels

1. Introduction

Indoor air pollution (IAP) from solid fuel use in developing countries is estimated by the World Health Organization (WHO, 2002a) to be the eighth leading health risk worldwide. Although there is general consensus that IAP is a major risk factor, there is very little knowledge of actual exposure experienced by the population subject to indoor air pollution.

The WHO estimates of disease burden from IAP are based on binary measures of exposure: exposed or not exposed. The WHO chose this approach because the bulk of epidemiological research looking at the impact of solid fuels on population health is given in that form, and because of the current paucity of reliable exposure data. While useful for providing a general overview of exposure, binary exposure estimates are not suitable for answering more complex questions, such as who is at risk, how large the exposure is, and how efficient interventions are. Answering questions of this complexity requires estimating more detailed exposure patterns.

In this paper we demonstrate a method for making detailed estimates of exposure for multiple demographic

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groups in a large population. The method is an extension of a formerly published exposure assessment for the Shanxi population in China (Mestl et al., 2006). The exposure estimates are Monte Carlo based and make use of previously published IAP data in conjunction with time activity patterns for different population groups, and demographic data for the population being studied.

We apply this method to investigate exposure patterns in the Chinese population.

The Chinese government is one of the first in the world to define a national health based indoor air quality (IAQ) standard for residences (Edwards et al., in press). The standard is set at 150 μg PM_{10}/m^3, a level which still represents substantial health risks. China has also undertaken several large-scale programs to promote improved household stoves, primarily improved efficiency in biomass stoves in response to a biomass shortage in the 1980s. A total of 786 counties took part in the first program, and most households in these counties had improved stoves installed, i.e. stoves with a chimney and grate. Coal-using households were not targeted in this effort, and some of the 'improved' coal stoves cannot be considered as improved at all because they lack a chimney. In a recent study assessing the effect of the programs, the indoor air did not meet the Chinese standard for IAQ, even after installing improved stoves (Sinton et al., 2004a; Edwards et al., in press). The exposure estimates presented here provide a far more detailed picture of who is at risk, where they live, the fuel they use, and the level of particulates to which they are exposed, and thus provide a basis for more precise targeting of intervention policies.

2. Materials and methods

The exposure assessment method described below makes use of published IAP data and time activity patterns. The exposure estimates are made for demographic groups based on age, sex, household fuel, and geographic location based on climate zone and urban or rural classification. The IAP data are grouped according to geographical location, and the time activity patterns are estimated for all demographic groups.

2.1. Population data for China

Comprehensive demographic data from the China census in 2000 is assembled by All China Marketing Research Co. Ltd. (ACMR, 2004). We use data for the population, disaggregated for age and sex, and the reported household cooking fuel. For the exposure modeling, we split the population into several groups. The classification is based on the assumption that different population groups are subject to different levels of exposure, as discussed below. The classification criteria are related to geographic location (north/south and urban/rural), age and sex, and the reported household cooking fuel.

2.1.1. North and south

China can be divided into five climate zones: (1) severe cold; (2) cold; (3) warm summer, cold winter; (4) hot summer, warm winter, and (5) warm (Ogawa et al., 2005). Traditionally, heating in winter was required by law in the two coldest zones with average temperatures in the coldest month around and below −10 °C. In zones 4 and 5, no heating in winter is required by law. These are all provinces south of the Yangze River. Zone 3 comprises the provinces surrounding the Yangze River. Here, heating may be necessary in many areas. We divide the population into north and south along the Yangze River, with a 'heating zone' in the north, and the 'non-heating zone' in the south. Thus zones 1 and 2, and parts of zone 3 fall into the 'heating zone'. The remaining part of zone 3, and zones 4 and 5 fall into the 'non-heating zone'. Some counties south of the Yangze River have a relatively cold climate in winter, but many people cannot afford heating, and we assume that heating in winter occurs predominantly in the north. We also assume that the stoves used within each of the two zones are of similar quality and technology. Most households use more than one stove, typically three to four, of varying design and quality. The assumption of similar technology across various stoves and regions within each zone is a very crude approximation with potentially large effects on the exposure estimates.

2.1.2. Urban and rural populations

China is divided into several administrative levels. Below the state level, there are 23 provinces, five autonomous regions, and four centrally administered municipalities (corresponding to province level). These entities are typically divided into prefectures, containing a core urban area surrounded by counties. The counties are either rural (which includes townships and villages), or so-called county level cities, which are administrative units with an urban centre and rural surrounding. The China Census 2000 (ACMR, 2004) includes data for 2871 counties and districts in mainland China. Of these, 793 are urban districts of prefecture level cities, and 26% of the Chinese population lives in these urban areas. There are 401 county level cities, home to 21% of the Chinese population, where the population is defined as partially urban and partially rural. Fifty-three percent of the population lives in the 1677 rural counties. Here, we assume that the population living in urban districts and 60% of the population in county level cities are urban citizens and classify them as such, while the remaining population is classified as rural. This procedure results in 40% of the population being classified as urban citizens, in agreement with the National Bureau of Statistics (NBS, 2004).

2.1.3. Household fuels

In this paper, we apply the method developed in Mestl et al. (2006), which assumes that indoor exposure is first and foremost related to the main household cooking fuel. Although a simplification, there is evidence that it is a reasonable assumption. The assumption seems, however, to be more reasonable for southern China than for northern China. Data from National Research Center for Science and Technology for Development (NRCSTD), Beijing and Fafo, Institute for Applied International Studies, Oslo (NRCSTD and Fafo A/S, 2006) for the western provinces of China show that there is a high correlation between the usage of a specific solid cooking fuel (coal or biomass) and the usage of a specific solid heating fuel in households in the south. In the north there is a high correlation between the usage of coal as a cooking fuel and coal as a heating fuel, whereas the correlation between the usage of biomass as a cooking fuel and biomass as a heating fuel is lower (in the north about as many use coal for heating as those using biomass for heating among those using biomass for cooking). The data also shows a higher degree of fuel mix in rural areas compared to urban, and the highest frequency of fuel mix is found in rural north. Edwards et al. (in press) measured IAP for 28 different household stove/fuel combinations in three provinces. They observed no large differences in IAP between provinces for specific fuel combinations, but found rather large differences in patterns of fuel use between the provinces resulting in different levels of IAP.

The fuels used in Chinese households are of very varying quality. Coal ranges from honeycomb briquettes with relatively high combustion efficiency and clean handling to 'smoky' coal with high emission rates and dirty handling. The same is true for biomass, with quality ranging from wood to different kinds of crop residue and cow dung. In addition, the housing in the different provinces varies. We have taken these considerations into account to a certain degree by dividing the exposure estimates in northern and southern provinces as described above, assuming that the differences within these two subpopulations regarding stove technology, fuel mix, housing and climate can be ignored — again a very crude approximation.

From the China 2000 Census (ACMR, 2004) we have data on number of households reporting on their use of gas, electricity, coal, wood and other fuels for cooking. Using these data, we have categorized households as 'coal users', 'biomass users', and 'gas users'. The households reporting use of electricity for cooking represent only 1% of the Chinese households. They have been included in the 'gas users' category.

While the main household cooking fuel is used here to classify the population according to fuel use, the indoor air pollution measurements that we draw upon to estimate indoor air pollution levels are taken from a variety of households, in which there may potentially have been a mix of fuels in use. These households were classified according to the main fuel in use, and we assume that the measurement households are representative for households in the given region and urban/rural setting, and also for the common mix of fuel in use.

Household cooking fuel use is shown in Fig. 1. Biomass is the dominant cooking fuel in rural areas, especially in the south. Most of the coal use takes place in the north, and some southern counties, whereas gas is predominantly used in the coastal area, in the large metropolitan areas and in the northwest where natural gas reserves are located.

The distribution of households by fuel category for north/south and urban/rural areas is shown in Table 1. In the county level cities, 50% of the population has access to clean fuels (i.e. gas and electricity). We assume that the clean fuels are predominantly used in the urban areas of these counties, whereas the rural population uses solid fuels (coal and biomass).

2.2. Exposure estimates

The annual exposure to PM_{10} is estimated as the proportion of time spent in the different microenvironments multiplied by the PM_{10} concentration in the given microenvironment using the equation

$$\mathrm{EXP}_{j,f} = \sum_k t_{j,k,f} \cdot q_{k,f} \qquad (1)$$

where $t_{j,k,f}$ is the fraction of time spent by population group j belonging to fuel-use category f in each microenvironment k. The term $q_{k,f}$ is the PM_{10} concentration in μg/m^3 by fuel category f in each microenvironment k. The microenvironments are kitchen, bedroom, living room, indoors away from home (typically school and work) and outdoors. The time activity tables and pollution levels are gathered from the literature as described below. In Mestl et al. (2006) we

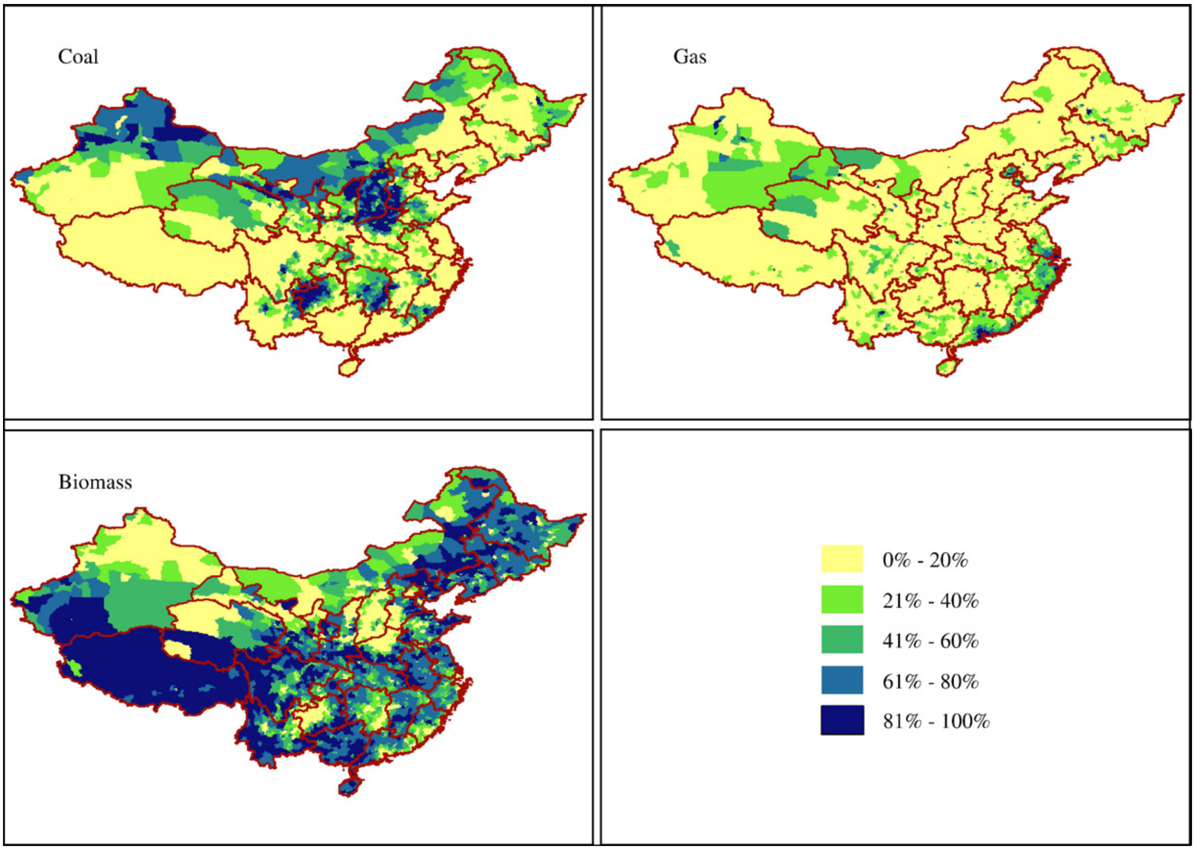

Fig. 1. Percentage of households per county reporting to use various fuels for cooking in mainland China.

developed a method to estimate typical exposure for different demographic groups in Taiyuan based on Eq. (1). We applied a two-dimensional Monte Carlo simulation (2D-MC). 2D-MC is a two-loop method to account for both variability and uncertainty in the data. The inner loop estimates the mean and variability standard deviation, in our case using the Bootstrap method. In the Bootstrap method the data is resampled several times, and the mean of each sampled series is calculated. These means are normally distributed and used to calculate the mean and standard deviation, which reflects the variability of the data. This method virtually increases the size of the dataset, and reduces the influence of outliers, thus the estimated mean is different from the mean of the raw data. The method also differs from conventional MC simulations in that no distribution of the original data is assumed. The mean and standard deviation from the bootstrapping are then given an uncertainty inversely proportional ($3/(2n)$) to the size (n) of the original dataset in the outer loop MC simulation. By applying this method we assume that much of the uncertainty and variability of the data is accounted for.

Table 1
Portion (in %) of households reporting to use various fuel categories for cooking

	Urban		Rural	
	North	South	North	South
Gas	47	65	7	16
Coal	30	16	31	25
Biomass	23	19	62	59

2.2.1. *Estimating indoor pollution levels*

Sinton et al. (1995) cite more than 110 English and Chinese papers on IAP published between 1980 and 1994. The database is organized according to pollutant (particulates, SO_2, CO, NO_x and BaP), fuel type (coal, gas and biomass) geographic location (urban or rural and province/city).

The selection criteria were that the papers had measurements in relevant indoor microenvironments, that fuel type was stated, and that particulate air pollution was measured. Conversion factors of 0.7 for PM_{10}/TSP and 1.4 for PM_{10}/PM_4 were used as discussed in Mestl et al. (2006). An additional criterion for measurements made in the north was that the time of year for measurement was stated, since here the climatic differences between the seasons are so large that separate estimates for winter and summer exposure are necessary.

There are 63 publications on particulates in the database, of which 39 met these criteria and were used in this work. Twenty five of these reported IAP in the south and fifteen in the north.

In addition to the papers cited in Sinton et al. (1995), we draw from some newer reports: Xu and Wang (1993), Zhao (2003), and Jin et al. (2005) for the north, and Lee et al. (1999, 2002) and Chau et al. (2002) for the south (Hong Kong). In total, we draw from 45 different studies. The selected publications are summarized in Table 2.

Measurements made in the south often lack information on when the measurements were made. We therefore chose to pool the data into one all-year indoor pollution value. Data on the rural households lack information about in which room the measurement was made. For the urban households, separate measurements in the kitchen, bedroom and living room are given.

The papers used are of varying quality and character. Four studies report that no smoking took place during sampling; one reported that smoking did take place during sampling; six reported some smoking during sampling; and the remaining 34 omit commenting upon smoking. Some report standard deviation or other measures of uncertainty, but not all. Some report mean, others median, and the number of data points is often not reported. We use the median and mean as centre points in our Monte Carlo simulations under the assumption that the researchers writing the report have chosen the best central estimate for their measurement series.

The majority of the reports selected from Sinton et al. (1995) are from the late 1980s and early 1990s, well into the period of the first improved stove program. The reports do not identify the state of the household stoves in the measured residences, and most probably the measurements are made in homes having both 'improved' and 'unimproved' stoves. Edwards et al. (in press) found that households reporting the use of improved stoves to a large extent still also used unimproved stoves. In some households even open fires were used in the kitchen in addition to stoves. Reported IAP levels generally refer to the main fuel, although many households use several fuel/stove combinations.

There has been a general improvement in urban outdoor pollution level since the late 1980s, which influences the IAP levels (Sinton et al., 2004b). Of the 45 publications used here, 20 report concurrent outdoor levels. For rural China and the northern urban areas, the reported outdoor pollution levels are on average on the same level as the outdoor pollution levels used in the exposure assessment below. However, the outdoor levels reported in studies in the southern urban areas are on average twice the outdoor level found in more recent observations. Since the outdoor air has an influence on the IAP level, we adjust the IAP levels in the southern urban areas to reflect the general improvement in air quality that has taken place. This is done by subtracting the outdoor level given in the publications from the indoor level and adding the more recent average outdoor level used in this study. In studies with no reported outdoor level, we assume an outdoor level for the city and year in question from Sinton et al. (2004b).

Outliers, i.e. those measurements higher than the average by a factor of 10, are removed from the calculations. These samples largely correspond to the publications where it is stated that the measurements were made during cooking. Some people, especially women, are exposed to such high values for periods of the day. We seek to avoid overestimating the concentrations by excluding the outliers in the estimates. This will, however, lead to underestimation of the exposure for some people as discussed in the Results section. We found no IAP measurements reported for urban residences that use biomass, and thus used the indoor levels measured for rural biomass users also for this group. Neither did we find any reports on IAP for rural households using gas. Mestl et al. (2006) report that the gas-using households in urban Taiyuan probably have negligible extra exposure from IAP. We therefore set the IAP level in the rural gas-using households equal to the outdoor pollution level.

For schools/work places, we use the same pollution levels for urban and rural populations because there are few publications to draw from. The measurements reported are mainly from urban areas. We pool together measurements from schools, office buildings, restaurants etc. to estimate the concentration indoors away from home.

2.2.2. Estimating outdoor pollution levels

To estimate urban outdoor pollution levels, we use the average urban ambient level reported in Sinton et al. (2004b). These are averages for northern and southern cities based on monitoring in 53 cities in 2002 as reported by the State Environmental Protection Administration (SEPA). The averages from 2000 and 2001 are

Table 2
Summary of the publications used for estimating indoor air pollution levels

Reference	Fuel[&]	Pollutant	Region[§]	Season	Sampling location[#]	Measurement notes
Yunnan prov. health stat., 1984*	C	TSP	RS		I, O	2 times a day for 5 days during meal preparation; low vol. samplers 10–15 m^3/h
Zhou et al. (1984)*	C	TSP	UN	W	K, B	Heating and cooking
Zhou, Yang and Chen (1984)*	G, C	TSP	US		K, B	
Yu et al. (1985)*	C	TSP	UN	S, W	I, O	24 h sampling, 5 days; PC-I 10 mm fibreglass filters
He et al. (1986)*	C, B	TSP	RS	S	I, O	4 times a day for 10 days. 2 h mean
Meng (1986)*	C	TSP	RS		I	
Zhao et al. (1986)*	C	TSP	RS		I	Anderson 2000 high vol. sampler; 16 h samples
Xu (1986)*	G, C	TSP	US	W	K, B	Sampling according to Chinese standard
Cai (1987)*	C	PM_{10}	RS	S	I	
Chen et al. (1987)*	G, C, B	TSP	RS		K, O	
Mumford et al. (1987)*	C, B	PM_{10}	RS		I, O	3 times a day during cooking. 1.5 m from fire; high and medium volume samplers
Shi, Gao and Hu (1987)*	C	TSP	RN	W	K, B, O	
Qiu and Chen (1988)*	C	TSP	RS	S, W	L	3 times a day for 3 days; centre of room 1.5 m above floor; kitchen in separate building
Yang et al. (1988)*	C, B	TSP	RS		I	2 h mean 6× day; high flow sampler
Hu and Liu (1989)*	C	PM_{10}	RN	S, W	I, O	3 times a day, 2 h means; KC-8301 sampler
Zhou, Chen et al. (1989)*	G, C	PM_{10}	US	W	I, O	Sampled daytime every 2–4 h, 1.2 m above floor; PC-I sampler (piezoelectric)
Zhou et al. (1989)*	C	PM_{10}	US		K, B, O	12 h mean; sampled middle of room; all cooking periods. XC-8301 IP sampler; no smoking during sampling
Wang et al. (1989)*	C	PM_{10}	UN	W	B	3 days cont. sampling; KC-8301 inhalable PM sampler; model 49 filter, 13 l/min
Chang and Zhi (1990)*	C, B	PM_{10}	RN	S, W	I	Samples morning and afternoon
Yen et al. (1990)*	C, B	TSP	RS	W	I, O	3 times a day, 1.5 h average; no door between kitchen and bedroom; some smokers
Zhang et al. (1990)*	C	TSP	RN	W	B, L, K	6 times a day for 3 days; 1.5 m above floor; TSP filter gravimetric method
Du and Ou (1990)*	C	TSP	US		I, O	Once per day over 5 days
Qiu and Chen (1990)*	C	TSP	US	W	B, O	
Cai (1990)*	G, C	Dust	US		K, O	Dust used as TSP
Qin et al. (1990)*	G, C	PM_4	UN, US	S, W	K, B	2 days each household, P-2500 sampler with nylon cyclone sampling head, 2 l/min; no smoking during measurement
Yu, Zhang and Zhou (1990)*	G, C	TSP	US	W	I	Every 2 h over 2 days
Wang and Zhang (1990)*	G	PM_{10}	UN		L, K, O	2 times a day in kitchen for 2 days; living room 4 day sampling; some smoking
Zhang et al. (1991)*	C	TSP	RN	W	B, K, L	Lab simulated dwellings; samples 3× day; 1.5 m above floor
Zhang, Tao and Liu (1991)*	G	TSP	UN	S	I, B, K	“Conventional” sampling methods, TSP-model KB-250 sampler, gravimetric method; no smoking
Cai (1991)*	B	TSP	RS	S	I	
Ren (1992)*	G, C	PM_{10}	UN	W	K, B, O	Sampling at 1.5 m, IP-model P-5 L2 digital particulate monitor; some smoking
Zhang et al. (1992)*	G, C	TSP	UN	S, W	K, B	Monitoring four times a day for three consecutive days
Ou and Huang (1993)*	G, C	TSP	US		K	Five consecutive days in each season
Yu et al. (1993)*	C	TSP	RS		I	Andersen 5-stage sampler with fibreglass filter
Gao et al. (1993)*	G, C, B	PM_{10}	US, RS	S	K	Sampled during cooking, am, noon, 7 pm, 2–3 consecutive days
Li et al. (1993)*	C	TSP	UN	S, W	I, O	Sampling 3 times a day for 3 days; procedure outlined in GB3095-82 Ambient Air Quality Standards
Mao et al. (1993)*	G	TSP	US		Power plant	Daily average; used as school/work environment
Wu, Zhang and Li (1994)*	G	TSP	UN	W	Office	HL-15 particulate sampler; smoking
Guo et al. (1994)*	G, C	TSP	UN	W	K, B	Monitoring 7 times a day for 3 consecutive days; no smoking during sampling
Zhao (2003)	G, C	PM_{10}	UN	S, W	I, S, O	

(continued on next page)

Table 2 (*continued*)

Reference	Fuel[&]	Pollutant	Region[§]	Season	Sampling location[#]	Measurement notes
Xu and Wang (1993)	G	TSP	UN	S	I, O	KC 8301 particulate monitor; 8h means
Chau et al. (2002)	G	PM_{10}	US		I, S	Dust Trak 8520 laser scattering and Q-Trak 8551 (TSI) average pollutant concentration; some smoking
Lee et al. (1999)	G	PM_{10}	US	W	K, L, B, I, O	Sampling at 1.5 m, 24 h mean; Dust Trak 8520 (TSI); some smoking
Lee et al. (2002)	G	PM_{10}	US	S	K, L, O	Dust Trak 8520 (TSI); some smoking
Jin et al. (2005)	C, B	PM_4	RN, RS	W	K, B, L	24 h mean; 10mm nylon cyclone with 37 mm diameter PVC filter; flow rate 2.5 l/min

*From Sinton et al. (1995).
[&]C: Coal, G: Gas, B: Biomass.
[§]U: Urban, R: Rural, N: North, S: South.
S: Summer, W: Winter.
[#]K: Kitchen, B: Bedroom, L: Living room, I: Indoors, S: School, O: Outdoors.

similar to the 2002 averages, and are based on 93 and 78 cities respectively. For rural areas we use as a starting point the estimated ambient level in rural Shanxi (Mestl et al., 2006). The rural PM_{10} level is estimated based on an emissions inventory in a rural county and the ambient background level. We assume that this value is representative for Shanxi. Papineau et al. (submitted for publication) estimate ambient levels of PM_1 on a 1 degree scale across China based on emissions inventory and using a detailed chemical tracer model. We use the PM_1 levels to estimate a ratio of the ambient PM_1 between Shanxi and all other provinces. The ratio varies between 0.2 and 1.2. We assume that the ambient PM_{10} levels in China vary in a similar way. For each of the provinces we estimate the rural outdoor PM_{10} concentration by multiplying our estimated Shanxi PM_{10} value with this ratio.

2.2.3. Time activity patterns

The time activity pattern of a population depends on age, sex, rural/urban location and climate. For instance, the time spent outdoors for the rural population in the north or the high mountain regions in the west is probably short compared with the sub-tropical regions in the south.

We draw from a recent survey conducted in Chongqing close to the Yangze River (Wang et al., submitted for publication) along with a Bangladesh study (Dasgupta et al., 2004), supported by a Hong Kong study (Chau et al., 2002). The latter two were used in our previous study in Shanxi (Mestl et al., 2006). In the Chongqing survey, 770 persons (525 in urban areas and 249 rural) were asked to record the time they spent in different microenvironments within a seven-day period in January and in March 2006. The questionnaire was sent primarily to families with a schoolchild and two parents, thus the age groups chosen were children under 15, adults 15–64 and elderly older than 65. The microenvironments used in the survey were "kitchen," "bedroom," "living room," "school/work," "other indoors away from home," "transit" and "outdoors." The air pollution data are divided into "kitchen," "bedroom," "living room," "indoors away from home" and "outdoors." We modify the Chongqing study by defining "school/office," "other indoors away from home" and half the time spent in transit as the "indoors away from home" microenvironment corresponding with the concentration data. "Outdoors" is expanded to include the time reported to be spent outside plus half the time in transit.

The time activity patterns for the rural population are based on the Chongqing and Bangladesh studies. Chongqing lies at 29° north and 260 m above sea level. The survey was conducted when the average maximum day temperature lies between 12 °C and 16 °C. Thus it is relatively cold, limiting the time spent outdoors (between 1.5 and 6 h reported in the study), and we used this survey for the winter time activity in the south. For the northern rural population we use the same data. However, the climate in the north is colder and we assume less outdoor activity. Hence for winter we base the time activity patterns on the Chongqing study, but limit the time spent outdoors for all groups to 1 h a day. Winter is modeled as November–March. Many farmers, mainly men, seek seasonal work in the cities in winter, but the effect of that is not included in our estimates.

For summer, we use the Bangladesh study in both the north and the south, modified by the Chongqing data. There are, of course, cultural differences between China and Bangladesh, leading to differing time use. However, according to the China 2000 census, the majority of the rural population in China is (at least part time) farmers, which probably holds true for the rural Bangladeshi population as well. We therefore believe that the error of this assumption is not too large. Moreover, except for the time spent outdoors, the Chongqing and the Bangladesh time activity results show similar age and gender patterns, which supports the validity of using the Bangladesh results. In the Bangladesh study the microenvironments are “cooking area,” “living area” and “outdoors.” We add the time that children attend school from the Chongqing study, and subtract those hours partly from the time they spend indoors at home, and partly from the time they spend outdoors. In both the Chinese studies, elderly women constitute the group spending the most time in the kitchen, almost twice the time spent by the younger women (15–64). In the Bangladesh study, the elderly seem to have been freed from the cooking task, spending less time in the kitchen than the younger women. To adjust the Bangladesh study to the Chinese context, we modify the time spent in the kitchen by the elderly to twice the time spent by the younger women, and subtract that time from the time spent in the living room.

The Bangladesh survey is divided into the following age-groups: 0–1, 2–5, 6–8, 9–12, 13–19, 20–60 and older than 60. Infants are often found to be at risk for acute respiratory infection (ARI) and acute lower respiratory infections (ALRI); we therefore want to estimate exposure for this age group. In the Bangladesh study we find that the time activity patterns for the two youngest groups (both sexes) and for the elderly women are quite similar, probably implying that childcare is a task for the elderly. In order to have the same age groups in summer and winter, we modify the Bangladesh age groups to be 0–5, 6–14, 15–64, and above 65. For the Chongqing study we add an age group 0–5 by setting that time activity equal to the female elderly in accordance with the findings in Bangladesh.

For the urban population we use the Chongqing time activity patterns supported by comparison of the Hong Kong study. The Chongqing survey gives separate results for men and women. Because the gender differences in time activity for the urban population were small, we save computing time by not taking gender into account in estimating time activity patterns for the urban group. The results indicate that people in Chongqing spend more time outdoors than those in Hong Kong, even though the survey was made in winter and Hong Kong has a warmer climate. However, Hong Kong is a highly developed metropolitan area, and urban Chongqing might be more representative for the general Chinese urban population. Therefore we chose to use the Chongqing results on an annual basis for the southern population.

To estimate exposure for young children, we include a time activity pattern for infants equal to the elderly as we did for the rural population. However, in urban China it is becoming increasingly common to send children to kindergarten at the age of three. Because these children are away from home in a similar pattern as the schoolchildren, we divide the groups as follows: infants (0–2), children (3–14), adults (15–64) and elderly (above 65). The same time activity patterns are used for the northern urban population in summer, and modified in winter, limiting the time spent outdoors to 1 h a day.

2.2.4. Population Weighted Exposure (PWE)

The exposure experienced by individuals belonging to a demographic group is given by Eq. (1). To determine the population weighted exposure (PWE), i.e. the average exposure experienced by the population in a particular county c, we use the equation:

$$\mathrm{PWE}_c = \frac{1}{P_c} \sum_{j,k} (\mathrm{EXP}_{j,k} \cdot p_{c,j} \cdot f_{c,k}) \tag{2}$$

where $\mathrm{EXP}_{j,k}$ is the exposure for age/sex group j and fuel-use group k, $p_{c,j}$ is the population in county c that belongs to age/sex group j; and $f_{c,k}$ is the fraction of households in county c using cooking fuel k. The sum is made for each county and divided by the county's population P_c.

3. Results

3.1. Estimated air pollution levels in the microenvironments

The pollution levels and their standard deviations estimated for the different microenvironments using the 2D-MC method are shown in Table 3. Due to data limitations, we could generally not distinguish between the various rooms in the households in rural areas, but had to estimate only one value (Indoors at home). The IAP values in southern rural households were found to generally be higher than the values found in northern rural households for the same fuel type. The outdoor pollution levels for the rural areas shown in the table are the averages of the provincially varying ambient levels estimated using Shanxi data and a provincial ratio as described in Section 2.2.2. For the northern rural biomass users, the data supply was somewhat scarce, and we could not estimate separate indoor pollution

Table 3
Estimated PM_{10} concentrations (μg/m^3) in the different modeled micro-environments (S.D.)

Fuel category	Region	Season[2]	Kitchen	Bedroom	Living room	Indoors at home[3]	Indoors away from home[4]	Outdoors[5]
Gas	South, rural					84 (22)		84 (22)
	North, rural	Summer				84 (22)		84 (22)
		Winter				160 (41)		160 (41)
	South, urban		201 (31)	131 (40)	136 (15)			131 (32)
	North, urban	Summer	282 (84)	160 (76)	231 (87)			237 (58)
		Winter	347 (96)	177 (54)	451 (166)			
Coal	South, rural					837 (145)		
	North, rural	Summer				258 (104)		
		Winter	901 (254)	654 (185)	827 (120)			
	South, urban		832 (173)	251 (42)	314 (72)			
	North, urban	Summer	111 (57)	98 (50)	451 (117)			
		Winter	790 (158)	477 (88)	580 (131)			
Biomass[1]	South					1496 (513)	252 (142)	
	North	Summer[1]	1056 (527)	1198 (327)	1198 (327)		318 (171)	
		Winter					640 (173)	

[1]There was no data for the biomass using urban population, thus the same indoor values are used both for the urban and rural biomass users. There were not enough data to estimate seasonal variation in the north.
[2]In the south no seasonal variation in indoor air pollution estimates was made.
[3]Where there were too few data for indoor air pollution estimates in different indoor microenvironments the data were pooled to one 'indoors at home' value. For rural gas users there was no data, and we assumed equal indoor and outdoor values for this category.
[4]The 'indoors away from home' values are independent of fuel user classification. For this microenvironment we had not enough data to make different urban and rural estimates.
[5]The outdoor values are independent of fuel user classification. The rural outdoor values given here are the averages for south and north China respectively. In the exposure estimates, different rural values for all provinces according to a ratio as described in Section 2.2.2 were used. The urban outdoor values are annual averages measured in northern and southern cities (Sinton et al., 2004b).

levels in summer and winter. This probably leads to an underestimation of the northern rural exposure, since people spend more time indoors in winter when the pollution levels probably are higher than estimated here.

For the urban households the data availability was generally better than for the rural households, and we were able to estimate different indoor pollution levels in different indoor microenvironments. For the urban gas users the IAP values for the southern households are lower than for the northern households, probably reflecting that the urban ambient air in southern cities is better than the ambient air in northern cities. For the urban coal users we find that the southern households have higher IAP levels than their northern counterparts in summer, except in the living room. This reflects the same trend as for the rural coal users, and might imply that the stove technology and fuels are better in the north than in the south. The IAP levels in the kitchen and bedroom of northern urban coal users in summer are found to be lower than for the northern urban gas users. This might indicate that the coal user levels are too low. However, within one standard deviation the IAP levels overlap. At the same time, the living room IAP level for northern urban coal users in summer is found to be high. In winter the northern urban coal users have higher bedroom and living room concentrations than their southern counterparts, which probably is a result of seasonal heating. For urban biomass users there was, as mentioned, no data to draw from, and we use the same estimates as for the rural households. The 'indoors away from home' values are the same for all fuel categories and are only divided in north and south. In this environment it is probable that smoking has a large influence on the IAP level. The measurements were made in urban schools, offices and restaurants with gas/central heating. These levels exceed the urban gas user levels and thus we conclude that the elevated levels must be ascribed to other sources than cooking and heating fuels, probably smoking and in the case of the restaurant also cooking oil fumes. Rural schools and offices might use solid fuels for heating, and thus the representativeness of these measurements for the rural population is questionable. However, the levels found are high, at the level of the solid fuel users in the rural areas. It is hard to say whether this simplification leads to an over- or underestimation of exposure.

The IAP levels are generally also influenced by other sources like cooking oil fumes, incense burning, candles, oil lamps and smoking. Smoking is a big health issue in China, with smokers comprising 67% of the male adult population and 4% of the female (WHO, 2002b). We have no indications that there are large socio-economic differences in smoking habits, and the effect is likely to

Table 4
Median estimated time spent (hours) in different microenvironments by the different age/gender groups of the rural population

Age				Kitchen	Bedroom	Living room	Indoors away from home	Outdoors
0–4	South	All year	Male	3.4 [0.7–6.6]	9.6 [6.3–13.0]	4.5 [1.7–4.5]	3.2 [1.7–4.5]	3.2 [0.5–6.2]
			Female	3.4 [1.4–5.3]	9.6 [7.6–11.6]	4.7 [2.0–7.3]	3.3 [2.2–4.4]	3.0 [0.6–5.6]
	North	Summer	Male	1.4 [0.1–4.2]	9.5 [6.3–12.7]	5.8 [3.4–8.4]	3.1 [1.7–4.4]	4.0 [1.2–7.2]
			Female	1.2 [0.0–3.1]	9.5 [7.6–11.5]	6.3 [3.7–9.1]	3.2 [2.1–4.3]	3.7 [1.3–6.2]
		Winter	Male	6.6 [3.1–9.5]	9.6 [6.2–12.4]	3.4 [0.9–5.9]	3.1 [1.7–4.4]	1.3 [0.0–4.1]
			Female	6.4 [4.5–8.3]	9.5 [7.7–11.4]	3.4 [0.9–6.1]	3.1 [2.2–4.1]	1.3 [0.1–3.7]
5–14	South	All year	Male	0.8 [0.0–2.3]	9.7 [8.0–11.4]	1.6 [0.1–4.0]	7.8 [5.1–10.7]	3.9 [1.4–6.5]
			Female	1.3 [0.0–3.3]	9.9 [7.9–12.0]	1.4 [0.1–3.8]	8.2 [5.1–11.1]	3.0 [0.6–5.3]
	North	Summer	Male	0.6 [0.0–2.2]	8.9 [7.0–10.6]	1.2 [0.0–3.4]	7.8 [5.0–10.5]	5.4 [2.8–7.9]
			Female	1.3 [0.1–3.3]	9.4 [7.9–11.4]	1.0 [0.0–3.2]	8.3 [5.0–11.1]	4.0 [1.6–6.6]
		Winter	Male	0.9 [0.0–2.6]	10.6 [8.9–12.6]	3.3 [1.1–5.6]	7.8 [4.7–10.7]	1.1 [0.0–3.4]
			Female	1.1 [0.0–3.1]	10.6 [8.5–12.7]	2.7 [0.5–5.3]	8.1 [5.2–11.1]	1.2 [0.1–3.6]
15–64	South	All year	Male	1.3 [0.0–3.9]	9.6 [6.9–12.4]	2.0 [0.1–5.5]	2.3 [0.5–4.0]	8.5 [3.4–13.2]
			Female	3.2 [0.2–7.1]	10.7 [7.2–14.6]	2.3 [0.1–5.5]	2.5 [0.5–4.5]	4.8 [0.9–9.8]
	North	Summer	Male	1.0 [0.0–3.3]	8.9 [5.8–11.9]	1.7 [0.1–4.9]	2.2 [0.2–3.8]	10.0 [5.0–15.4]
			Female	3.3 [0.4–6.9]	10.9 [7.4–14.5]	2.4 [0.1–5.8]	2.6 [0.5–4.4]	4.5 [0.7–9.1]
		Winter	Male	1.7 [0.1–4.4]	10.4 [7.7–13.0]	7.2 [3.8–10.2]	2.2 [0.4–3.7]	2.0 [0.1–6.5]
			Female	2.8 [0.2–6.6]	10.6 [7.0–13.9]	6.0 [2.6–9.6]	2.3 [0.6–3.9]	1.9 [0.1–5.9]
Over 65	South	All year	Male	1.5 [0.1–4.4]	12.9 [9.5–16.3]	2.0 [0.1–4.5]	1.2 [0.1–2.4]	6.2 [3.2–9.2]
			Female	6.3 [4.2–8.3]	9.5 [7.6–11.6]	2.2 [0.3–4.8]	3.2 [2.3–4.2]	2.5 [0.4–5.1]
	North	Summer	Male	1.1 [0.0–3.8]	12.7 [9.6–15.8]	1.7 [0.1–4.1]	1.1 [0.1–2.3]	7.1 [4.2–10.1]
			Female	6.2 [4.3–8.2]	9.5 [7.6–11.5]	2.0 [0.2–4.8]	3.2 [2.1–4.2]	3.0 [0.6–5.7]
		Winter	Male	2.0 [0.1–5.2]	12.9 [9.5–16.4]	6.2 [3.9–8.8]	1.3 [0.1–2.5]	1.3 [0.0–3.8]
			Female	6.5 [4.6–8.4]	9.4 [7.4–11.3]	3.5 [1.0–6.3]	3.1 [2.0–4.1]	1.3 [0.1–3.7]

[95% of simulations are within the range in the brackets]. These distributions are used in the exposure estimates.

be similar for all population groups in this paper. The impact of cooking oil fumes is likely to vary regionally due to different cooking styles in the country. The use of incense burning, candles and oil lamps may also have a regional pattern. With the available data we cannot quantify these effects on the estimated IAP levels.

3.2. Time activity patterns

The resulting time activity patterns for the rural and urban populations respectively are given in Tables 4 and 5. The values within the brackets show the interval comprising 95% of the simulated values. The mean 95% time range is 5.1 h. These ranges simulate the variability in the time activity patterns of the population, and the use of these varying patterns gives more confidence in the exposure estimates, as they simulate the true population variability better than simply using a point estimate.

3.3. Exposure estimates

The estimated exposures for the rural north and south and urban populations are shown in Figs. 2, 3 and 4, respectively. Not surprisingly, we find that the biomass-using population experiences the highest exposure. The

Table 5
Median estimated time spent (hours) in different microenvironments by the different age groups of the urban population, no gender differentiation

Age		Kitchen	Bedroom	Living room	Indoors away from home	Outdoors
0–2	Summer*	2.0 [0.1–4.5]	10.9 [5.4–16.1]	6.4 [3.4–9.6]	1.4 [0.0–3.7]	2.8 [0.2–7.3]
	Winter	1.7 [0.0–4.2]	10.9 [5.3–15.9]	8.1 [5.3–10.9]	1.1 [0.0–3.6]	1.7 [0.0–5.7]
3–14	Summer*	0.5 [0.0–2.0]	9.3 [6.4–12.2]	2.1 [0.0–5.1]	9.0 [4.0–13.9]	2.6 [0.1–6.9]
	Winter	0.4 [0.0–1.8]	9.0 [5.8–12.1]	3.2 [0.2–6.4]	9.1 [4.2–14.0]	1.7 [0.0–5.4]
14–64	Summer*	1.2 [0.0–4.0]	9.7 [6.0–13.4]	2.9 [0.1–6.9]	5.5 [0.7–12.0]	3.9 [0.3–9.9]
	Winter	1.0 [0.0–3.6]	9.5 [5.5–13.2]	5.2 [1.6–9.2]	5.3 [0.7–10.6]	2.4 [0.0–7.3]
Over 65	Summer*	2.0 [0.1–4.6]	11.1 [5.5–16.5]	6.5 [3.6–9.4]	1.4 [0.0–3.7]	2.8 [0.1–7.1]
	Winter	1.8 [0.0–4.2]	10.7 [5.7–15.9]	8.0 [5.2–10.9]	1.2 [0.0–3.5]	1.7 [0.1–5.6]

[95% of simulations are within the range in the brackets]. These distributions are used in the exposure estimates.
*The summer values are used as annual values in the south and summer values in the north. The winter values only apply to the northern population.

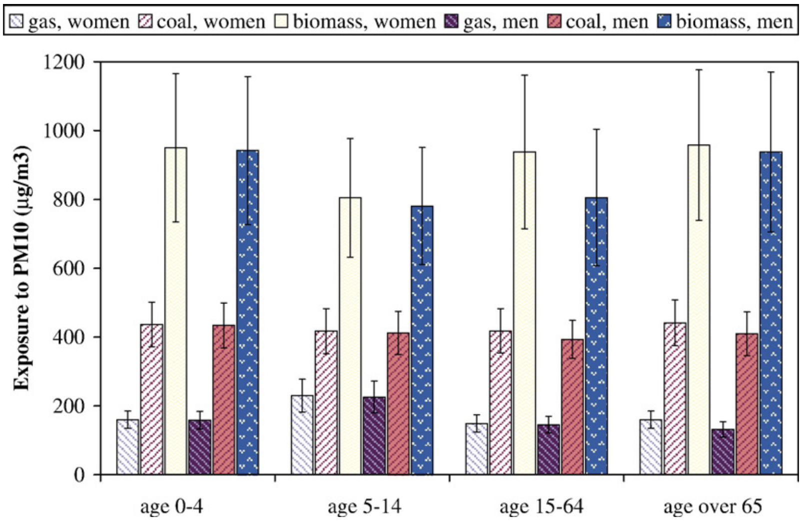

Fig. 2. Estimated exposure levels (µg/m^3) for different demographic groups in rural north China. The exposure is estimated based on indoor and outdoor pollution levels and time activity patterns for the different groups. The error bars show one standard deviation.

southern biomass-using population is found to have the highest exposure. The gender differences are found to be small, even for the southern population. There are differences between male and female adults, especially in the south, but not as large as could be expected based on the literature. This is probably because in the rural south all indoor microenvironments are modeled with the same IAP level, and thus the gender difference depends only on how much time is spent outside the home. The removal of outliers, probably representing levels experienced during cooking, may lead to the exposure for females being underestimated. All groups, both urban and rural, have exposure levels representing a health hazard.

3.4. Population Weighted Exposure (PWE)

The exposure estimates discussed above show the average pollution burden for each of the modeled demographic groups. In Fig. 5, the population weighted exposure (PWE) is shown for each county. Comparing Figs. 1 and 5 we see that the counties with the highest share of biomass users also are the counties with the highest PWE. Heavy coal-using counties have a

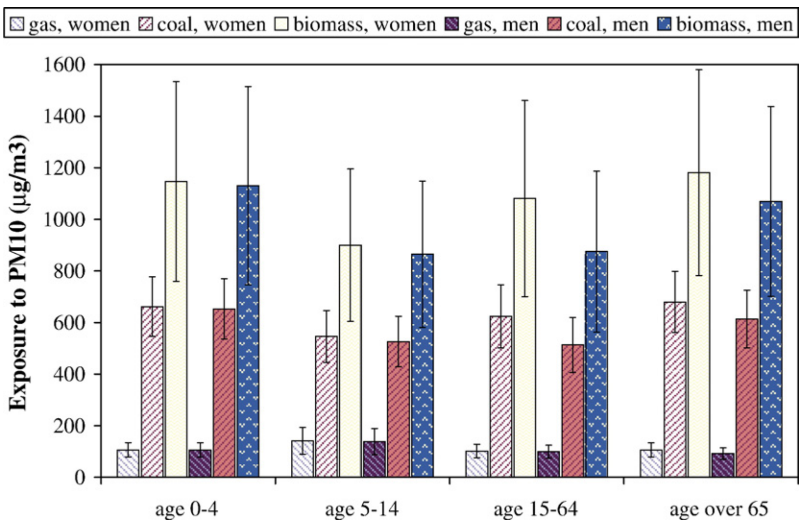

Fig. 3. Estimated exposure levels (µg/m^3) for different demographic groups in rural south China. The exposure is estimated based on indoor and outdoor pollution levels and time activity patterns for the different groups. The error bars show one standard deviation.

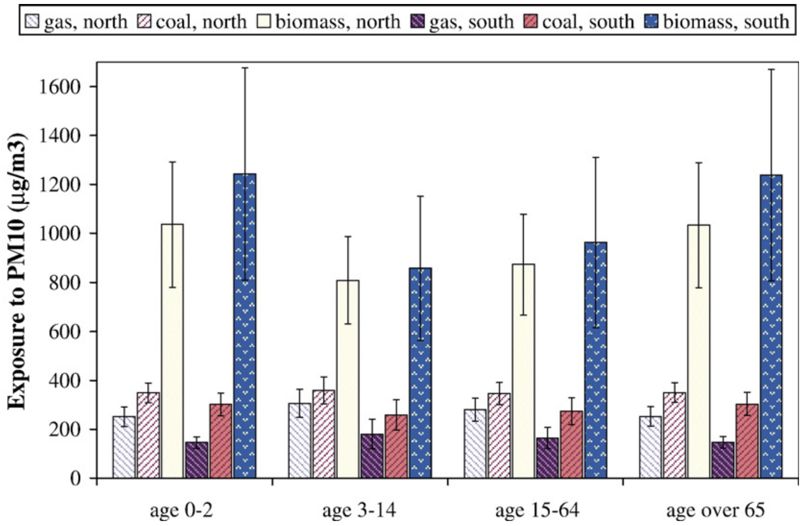

Fig. 4. Estimated exposure levels (μg/m^3) for different demographic groups in urban China. The exposure is estimated based on indoor and outdoor pollution levels and time activity patterns for the different groups. The error bars show one standard deviation.

somewhat lower PWE, and counties with high gas usage have the lowest PWE. Although biomass stoves to a large extent have been targeted through the improved stove programs, our estimates show that the biomass-using households still experience the highest indoor pollution levels. We find that there is no significant exposure difference between northern and southern China, even though people in the north have higher fuel consumption due to winter heating. Main household fuel seems to be more crucial than whether the households need heating in winter. However, the exception to this is the gas-using urban areas in the south. People in these areas seem to have lower exposure than their northern counterparts, probably due to cleaner outdoor air, especially in winter.

We find that all counties have an average PWE that fails to meet the Chinese IAQ standard, although the level in some of the coastal cities comes relatively close. Table 6 shows the PWE for each fuel category along with the share of exposure explained by IAP, and population belonging to the different groups. Standard deviation is shown in parentheses. Again, the table clearly shows that the highest exposure is experienced by the biomass-using population, where 73–92% of exposure is explained by IAP, followed by the coal users, and with the lowest exposure for the gas users. It also shows that the highest exposure is in the rural areas, except for gas users. The gas users are found to have a 17–29% increase in exposure from IAP compared to the outdoor pollution level. The enhanced PWE found for

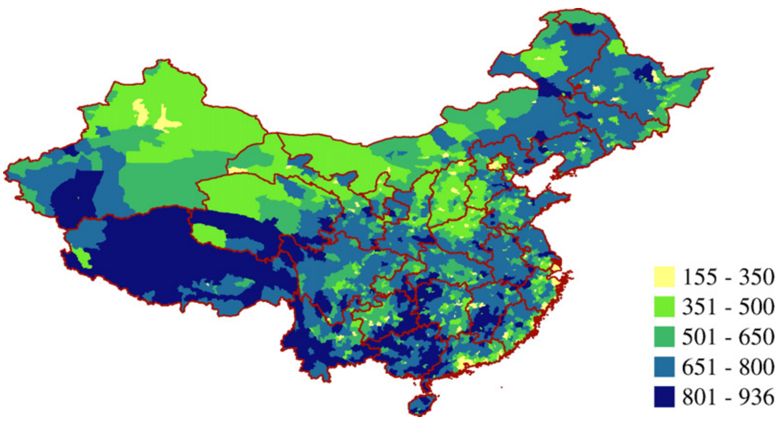

Fig. 5. PWE (μg/m^3) for each county in mainland China.

Table 6
Population Weighted Exposure (PWE μg/m^3) for urban and rural population according to cooking fuel use classification (S.D.)

		North			South		
		PWE	% Indoor	Pop	PWE	% Indoor	Pop
Gas	Urban	284 (36)	17	135	168 (36)	22	132
	Rural	163 (14)	29	31	109 (14)	23	42
Coal	Urban	348 (35)	32	97	274 (43)	52	37
	Rural	411 (30)	72	135	571 (55)	85	66
Biomass	Urban	879 (154)	73	55	969 (263)	87	27
	Rural	865 (103)	87	304	992 (167)	92	180
Total	Urban	441 (40)	47	287	336 (55)	61	196
	Rural	676 (65)	83	471	746 (99)	89	289

"% Indoor" is the excess exposure due to Indoor Air Pollution (IAP) experienced by the group relative to total exposure. Population in million.

gas users in the rural areas is an effect of using the same "indoors away from home" value in both rural and urban estimates. The enhanced PWE for gas users is probably due to smoking and other sources mentioned in Section 3.1 during measurements. A similar share of the estimated PWE for other fuel user categories due to smoking and other sources is probable.

4. Discussion

We find that, despite programs to improve household stoves in China, the population still suffers from high exposure to indoor air pollution. Surprisingly, we find that the population in Shanxi is on the lower end of the exposure scale, even though Shanxi is known as a heavily polluted province (Mestl et al., 2005). In Shanxi we estimate PWE between 300 and 700 μg/m^3, with median PWE at 415 μg/m^3. For China as a whole we estimate values between 150 and 930 μg/m^3, with median PWE at 620 μg/m^3. This relatively low exposure in Shanxi is probably because the Shanxi population mainly uses coal in the households, which leads to lower PM_{10} levels indoors compared to biomass. This again stresses the importance of using IAP in the exposure estimates. Excluding IAP, the Shanxi population is assessed among the most heavily exposed populations in China. When we include IAP, however, we find that their exposure is modest compared to other regions, though still high, impairing population health.

We also find that the rural population generally experience higher exposure than the urban even though the outdoor air particulate level in rural areas is much lower than in the urban areas. Biomass users are found to have the highest exposure levels, followed by coal users while the lowest levels are estimated for gas users. We find quite surprisingly that the southern population are exposed to higher particulate levels than the northern population. We would have expected it to be the other way around, since they have a colder climate in the north with more need for heating in winter, and people spending more time indoors.

It is often assumed that women are most at risk for household particulate exposure since they do the cooking. We found only small gender differences in exposure. This may, however, be an artifact of the data since we rely on measurements of the average levels of indoor air pollution to estimate population exposure, and not measurements of levels experienced during cooking. Thus the female exposure might be underestimated, or at least women may experience a different exposure pattern, with intermittent peaks. By using average levels however, we reduce the risk of overestimating exposure for population groups that are not doing the cooking. Still, however, we find was that the exposure experienced by men is high and thus represents a health hazard. This is an important result because in the health impacts estimates by WHO (2002a) different exposure patterns and odds ratios are used for men and women, implying that men are less exposed than the women. Our results indicate that this may not be the case, which suggests that WHO may be underestimating the health impact of IAP in China. This issue is discussed further in a complementary paper (Mestl et al., submitted for publication) where we estimate health effects of indoor air pollution using the method for exposure assessment described here.

The model to estimate exposure described here can be a powerful tool to assess population exposure based on multiple sources and environments. A point estimate will most probably not be representative for the population exposure, whereas this method allows for including the variability within the population. It may well be that the central estimate is not the "true" center, but measured population exposure would probably fall within our estimated distribution. In order to improve the exposure estimates further, more IAP measurements are needed. Most of the IAP measurements used in this paper are made during the period of the improved stove program. Newer measurements could provide evidence that the IAP levels have improved since the 1990s, and thus potentially result in lower exposure estimates. The paucity of measurements in some microenvironments also forced us to lump the data reducing the accuracy of the estimates. Maybe more measurements would show that schools e.g. have lower IAP levels than offices which in turn may have lower IAP levels than restaurants due to other indoor activities like smoking, candles and cooking oil fumes. With the current data availability we have no way of correcting for these confounders. Using the model on a provincial level with more specific time activity data, housing characteristics and data on fuel mix could provide useful further insight in population exposure in China.

Better knowledge of exposure patterns and determining who is at risk is also useful in providing targeted interventions in the households. In a recent paper by Jin et al. (2006) the importance of housing characteristics, infrastructure, usage of multiple fuels and behavioral patterns in identifying useful interventions is discussed. This exposure analysis supports those findings, and can be a useful tool when targeting interventions in the future. There are efforts in China to introduce more improved stoves, this time with a focus on population exposure and health. A national competition is being held in 2005–2006 by the Chinese Association of Rural Energy Industries funded by Shell Foundation to promote the development of low emission gasifier biomass stoves. Projects on bio-digestors for converting biomass to dimethyl ether (DME) and research on processes for converting coal to DME are also in progress (Zhang and Smith, 2005). Renewed and more intensive efforts to improve the indoor air quality could result in large exposure reductions and health benefits for the population. Thorough intervention studies, including monitoring of indoor air pollution levels, health impact, and cost–benefit analysis, constitute future research needs.

5. Conclusions

In our view the presented method provides an improved tool for characterization of exposure compared to classifying the population as exposed/not exposed which is the method previously used for estimating the burden of disease due to IAP in the developing world. Using measured IAP and time activity tables in the exposure estimates gives a quite different picture of who is at risk than when only prevalence of stove/technology is accounted for. We found that men also are exposed to high IAP levels representing a serious health risk, contrary to what is often assumed in IAP health assessments in developing countries. However, further work is necessary to reduce probable biases in the exposure estimates due to confounders like smoking and cooking style and uncertainties related to, for instance, the fact that households tend to use a mix of fuels.

The model should also be useful in other developing countries provided sufficient data.

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References

ACMR. "2000 China County Population Census Data with county maps (Version III)", All China Marketing Research Co. Ltd.; 2004. http://chinadatacenter.org/newcdc/.

Chau CK, Tu EY, Burnett DWT, Burnett CJ. Estimating the total exposure to air pollutants for different population age groups in Hong Kong. Environ Int 2002;27(8):617–30.

Dasgupta S, Huq M, Khaliquzzaman M, Pandey K, Wheeler D. Who Suffers from Indoor Air Pollution? Evidence from Bangladesh. World Bank Policy Research Working Paper 3428. Development research Group World Bank; 2004. http://wdsbeta.worldbank.org/external/default/WDSContentServer/IW3P/IB/2004/10/22/000012009_20041022102225/Rendered/PDF/wps3428.pdf.

Edwards RD, Liu Y, He G, Yin Z, Sinton J, Peabody J, Smith KR. "Household CO and PM measured as part of a review of China's National Improved Stove Program", Indoor Air. in press.

Jin YL, Zhou Z, He GL, Wei HZ, Liu J, Liu F, et al. Geographical, spatial, and temporal distributions of multiple indoor air pollutants in four Chinese provinces. Environ Sci Technol 2005;39(24):9431–9.

Jin Y, Ma X, Chen X, Cheng Y, Baris E, Ezzati M. Exposure to indoor air pollution from household energy use in rural China: the interactions of technology, behavior, and knowledge in health risk management. Soc Sci Med 2006;62(12):3161–76.

Lee SC, Chang M, Chan KY. Indoor and outdoor air quality investigation at six residential buildings in Hong Kong. Environ Int 1999;25(4):489–96.

Lee SC, Li WM, Ao CH. Investigation of indoor air quality at residential homes in Hong Kong — case study. Atmos Environ 2002;36(2):225–37.

Mestl HES, Aunan K, Fang J, Seip HM, Skjelvik JM, Vennemo H. Cleaner production as climate investment — integrated assessment in Taiyuan City, China. J Clean Prod 2005;13:57–70.

Mestl HES, Aunan K, Seip HM. Potential health benefit of reducing household solid fuel use in Shanxi province, China. Sci Total Environ 2006;372:120–32.

Mestl HES, Aunan K, Seip HM. "Health benefits from reducing indoor air pollution from household solid fuel use in China — three abatement scenarios". submitted for publication.

NBS. China Statistical Yearbook 2004. Beijing: National Bureau of Statistics; 2004.

NRCSTD and Fafo A/S. Life in Western China: Tabulation Report of Monitoring Social and Economic Development in Western China. Beijing: China Statistics Press; 2006.

Ogawa Y, Weijun G, Zhou N, Watanabe T, Yoshino H, Ojima T. Investigation on the standard for energy and environmental design of residential house in China. J Asian Archit Build Eng 2005;4(1):1–6.

Papineau M, Aunan K, Berntsen T. "Distributional determinants of household air pollution in China: is pollution inequality rising?" submitted for publication.

Sinton JE, Smith KR, Peabody JW, Yaping L, Xiliang Z, Edwards R, et al. An assessment of programs to promote improved household stoves in China. Energy Sustain Dev 2004a;VIII(3).

Sinton JE, Fridley DG, Lewis JI, Lin J, Chen Y, Zhou N. China Energy Databook. Environmental Energy Technologies Division. Lawrence Berkeley National Laboratory; 2004b. http://china.lbl.gov.

Sinton JE, Smith KR, Smith HH, Liu JZ. "Indoor Air Pollution Database for China", Office of Global and Integrated Environmental health. World Health Organization; 1995 [http://whqlibdoc.who.int/hq/1995/WHO_EHG_95.8.pdf].

Wang SX, Zhao Y, Chen G, Wang F, Aunan K, Hao J. Assessment of population exposure to particulate matter air pollution in Chongqing, China. submitted for publication.

WHO. The World Health Report 2002. World Health Organization; 2002a. http://www.who.int/whr/2002/en/.

WHO. "Smoking Statistics" Fact Sheet World Health Organization; 2002b. http://www.wpro.who.int/media_centre/fact_sheets/fs_20020528.htm.

Xu XP, Wang LH. Association of indoor and outdoor particulate level with chronic respiratory illness. Am Rev Respir Dis 1993;148(6):1516–22.

Zhang J, Smith KR. Indoor air pollution from household fuel combustion in China: a review. The 10th International Conference on Indoor Air Quality and Climate; 2005. http://ehs.sph.berkeley.edu/krsmith/page.asp?id=1.

Zhao BX. Study on the effect of PM_{10} and SO_2 air pollution on children's pulmonary function in Taiyuan city, China. J Environ Occup Med 2003;20(3):203.