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Review

The state of scientific evidence on air pollution and human health in Nepal

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ABSTRACT

Air pollution has been linked to acute and chronic health effects. However, the majority of evidence is based in North America and Europe, with a growing number of studies in Asia and Latin America. Nepal is one of the many South Asian countries where little such research has been conducted. We summarized the state of scientific evidence and identify research gaps based on the existing literature on air pollution and human health in Nepal. We performed a systematic literature search to identify relevant studies. Studies were categorized as those that estimate: (1) health impacts of indoor air pollution, (2) health impacts of outdoor air pollution, (3) health burdens from outdoor air pollution in Nepal based on existing concentration-response relationships from elsewhere, or (4) exposure and air quality but do not link to health. We identified 89 studies, of which 23 linked air pollution to health impacts. The remainder focused on exposure and air quality, demonstrating high pollution levels. The few health studies focused mainly on indoor air ($n=15$), especially in rural areas and during cooking. Direct exposure measurements were for short time periods; most studies used indirect exposure methods (e.g., questionnaire). Most health studies had small sample sizes with almost all focusing on respiratory health. Although few studies have examined air pollution and health in Nepal, the existing studies indicate high pollution levels and suggest large health impacts. Nepal's dearth of scientific research on air pollution and health is not unique and likely is similar to that of many other developing regions. Future research with larger studies and more health outcomes is needed. Key challenges include data availability.

1. Introduction

Large populations exposed to high levels of air pollution have been observed in Asia, Africa, and Latin America (HEI, 2010, 2012; WHO, 2006). In Asia, urban air pollution in many cities rivals the levels that existed during the first decades of the 20th century in Europe and North America (HEI, 2010). Additionally, rural areas and urban slums face indoor air pollution mainly from burning of solid fuels (HEI, 2010). Higher indoor air pollution has been observed in the developing world in comparison to developed world primarily due to use of unprocessed solid fuels and unflued stoves (Smith, 2002).

Air pollution impacts respiratory, cardiovascular, reproductive, and other systems (Curtis et al., 2006) with health outcomes from respiratory symptoms to mortality (Brunekreef and Holgate, 2002). Most of the evidence linking air pollution and health are based on studies in North America and Western Europe, while studies are lacking in regions with comparatively higher air pollution levels (Cohen et al., 2005; HEI, 2010). For example, in Asia from 1980 to 2007 over 400 studies have been conducted on health effects of air pollution with almost all studies conducted in more developed countries in East Asia (China, South Korea, Japan) while many population centers in South and Southeast Asia are largely underrepresented (HEI , 2010). This may bias the understanding of air pollution effects towards the conditions of more Westernized and economically developed Asian countries, which include only a small proportion of the total Asian population (0.3 of 3 billion persons in this region) (Su et al., 2011). Similarly a review of studies conducted in 25 Sub African countries showed that impacts of air pollution on human health are rarely assessed (Schwela, 2012).

The Global Burden of Disease Study estimated that household air pollution from solid fuels and ambient particulate matter (PM) with aerodynamic diameter $\leq 2.5\,\mu m$ ($PM_{2.5}$) each cause over 3 million deaths annually worldwide. Household air pollution from burning of solid fuels was determined to be the leading mortality risk in 2010 for South Asia, with ambient particulate matter pollution ranked sixth (Lim et al., 2012).

Lack of research on exposure to air pollution and human health burden, despite poor air quality, is a situation common in

Abbreviations: CI, Confidence Interval; CO, Carbon Monoxide; NO_2, Nitrogen Dioxide; OR, Odds Ratio; PAHs, Polyaromatic Hydrocarbons; PM, Particulate Matter; $PM_{2.5}$, PM withAerodynamic Diameter $\geq 2.5\mu m$; PM_{10}, PM with Aerodynamic Diameter $\geq 10\mu m$; SO_2, Sulfur Dioxide; TSP, Total Suspended Particle.

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many countries. Nepal is one of the many South Asian countries where such conditions exist. Although scientific evidence on air pollution and health in Nepal is sparse, some studies have been performed. We reviewed existing literature on air pollution's human health impacts for Nepal in order to summarize the state of the scientific evidence. The review also aims to serve as an example to showcase research gaps and data needs present in developing countries like Nepal.

2. Materials and methods

We performed systematic searches (PubMed, 2008: title and abstract; Scopus, 2012: title, abstract, keywords) to identify studies of air pollution and health, and additional studies of exposure and air quality, in Nepal for articles indexed through May 30, 2012, using the following search terms:

(1) Kathmandu or Nepal; *and*
(2) air pollution, air quality, smoke pollution, domestic smoke, particulate matter, PM, PM_{10}, $PM_{2.5}$, ozone, nitrogen dioxide, carbon monoxide, traffic or urban environment.

We also reviewed available online archives of Nepalese journals (Supplementary Table 1). Reference lists of identified papers that link to health outcomes (i.e., categories 1–3 above) were reviewed for additional studies. Given the paucity of scientific study of air pollution and health in Nepal, we included relevant non-peer reviewed reports identified in reference lists and accessible online, and distinguish them from peer-reviewed publications. Conference proceedings and theses referred from reference lists were omitted. All identified articles were in English. Further, given the low number of studies and variation in study designs, a quantitative meta-analysis is not appropriate. Therefore, we instead summarize the state of scientific evidence and themes of the existing research.

Studies were categorized as those that estimate: (1) health impacts of indoor air pollution, (2) health impacts of outdoor air pollution, (3) health burdens from outdoor air pollution in Nepal based on existing concentration-response relationships from other regions, or (4) exposure and air quality without assessing associations between pollution and health. Other studies that met our search criteria but did not provide information on air pollution in Nepal, were excluded.

3. Results

The search identified 383 unique articles (Fig. 1). Of these, we identified 89 studies meeting our inclusion criteria (Fig. 2), of which 23 estimated air pollution's health impacts (19 peer-reviewed articles, 4 agency reports). Indoor air pollution's health impacts were examined by 5 studies using air quality measurements and 10 assessing exposures through surveys or assumed changes in air quality after an intervention. For studies linking outdoor air pollution to health, 2 studies used pollution measurements and 2 considered proximity to brick kilns. Four other studies estimated health burdens from outdoor air in Nepal using concentration–response relationships from elsewhere. Sixty-six additional studies examined air quality or exposure without linking to health.

3.1. Associations between indoor air pollution and health

3.1.1. Direct assessment (measurements) of indoor air quality and links to health

Five studies assessed health impacts from measured indoor air pollution (Table 1). All studies concentrated on understanding exposure and respiratory health burden mainly for women in rural areas. Only one study, written by a non-governmental organization, looked into impacts on children (ENPHO, 2008). Direct assessment of air pollution exposure was performed in the kitchen for all studies: exposure in kitchen during cooking with biomass fuel (Kurmi et al., 2011; Reid et al., 1986), comparison of exposure in kitchen after replacing traditional stoves with improved stoves (ENPHO, 2008; Reid et al., 1986) and comparison of exposure in kitchen using processed vs. unprocessed fuel (Shrestha and Shrestha, 2005; Shrestha, 2006). All 5 studies made use of questionnaires for health assessment. Use was also made of peak flow meter (Shrestha and Shrestha, 2005; Shrestha, 2006) and spirometer (Kurmi et al., 2011).

High exposure of $PM_{2.5}$ averaging 4741 $\mu g/m^3$ (range: 291–15280 $\mu g/m^3$) was observed in kitchens during cooking with biomass fuel (Kurmi et al., 2011). For 24 life-long non-smoking women, the authors concluded that acute exposure to biomass smoke for women with restrictive lung disease may increase exacerbation of pre-existing lung disease (Kurmi et al., 2011). Replacing traditional stoves with improved stoves in rural households led to decrease in total suspended particles (TSP), carbon monoxide (CO), and $PM_{2.5}$ (ENPHO, 2008; Reid et al., 1986). More users of traditional stoves complained of eye problems and coughing compared to improved stoves users (Reid et al., 1986). Additionally, reduced coughing, headache, and eye irritation was observed for women and children less than 5 years of age after stove replacement (ENPHO, 2008). During fuel burning, high particulate matter with aerodynamic diameter $\leq$10 μm (PM_{10}) (average 2418 $\mu g/m^3$) and CO (15,656 $\mu g/m^3$) levels were measured in kitchens using unprocessed fuels (e.g., dung, crop residue, wood). Levels in kitchens using processed fuels (kerosene, liquefied petroleum gas and biogas) were much lower (PM_{10}: average 793 $\mu g/m^3$; CO: 2345 $\mu g/m^3$) (Shrestha and Shrestha, 2005). PM_{10} and CO kitchen levels were observed to be associated with respiratory illness (Shrestha, 2006) with respiratory illness significantly more prevalent for users of unprocessed fuel relative to processed fuel (Shrestha and Shrestha, 2005).

3.1.2. Indirect assessment of indoor air quality and links to health

Ten studies assessed health impacts from indoor air pollution, as estimated through surveys or by an assumption that an intervention changed air quality (Table 2). Seven studies were located exclusively in rural areas (Dhimal et al., 2010; Hahn et al., 2011; Joshi et al., 2009; Pandey, 1984b; Pandey et al., 1985, 1989; Pant, 2007) and 3 studies were located in both rural and urban areas (Melsom et al., 2001; Pokhrel et al., 2005, 2010). These studies focused on understanding exposure and health impact mainly for children (Dhimal et al., 2010; Hahn et al., 2011; Joshi et al., 2009; Melsom et al., 2001; Pandey et al., 1989) and women (Joshi et al., 2009; Pandey, 1984a; Pandey et al., 1985; Pokhrel et al., 2005, 2010). Indirect exposure assessment was performed using surveys of average time/day exposed to domestic smoke (Joshi et al., 2009; Pandey 1984b; Pandey et al., 1985, 1989), fuel used (Dhimal et al., 2010; Pokhrel et al., 2005, 2010; Pant, 2007), stove used (Dhimal et al., 2010; Pokhrel et al., 2005, 2010; Pant, 2007), kitchen ventilation present (Pokhrel et al., 2005, 2010) and by stove intervention (Hahn et al., 2011). Only one study had questions related to traffic exposure (Melsom et al., 2001). All studies focused on respiratory health except for one focusing on

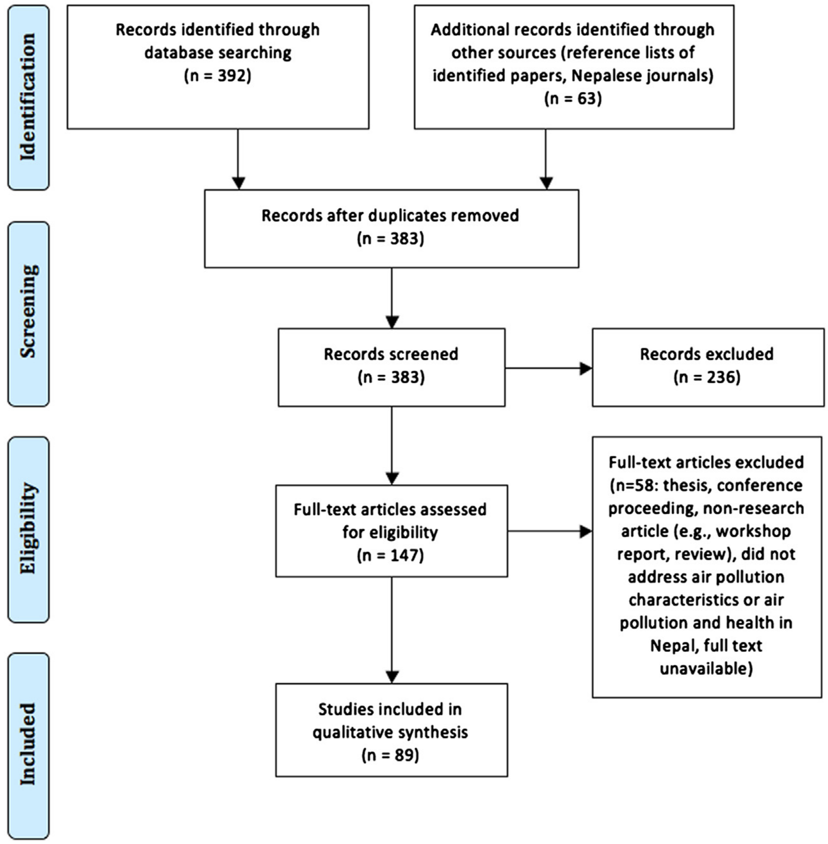

Fig. 1. PRISMA flow diagram of search.

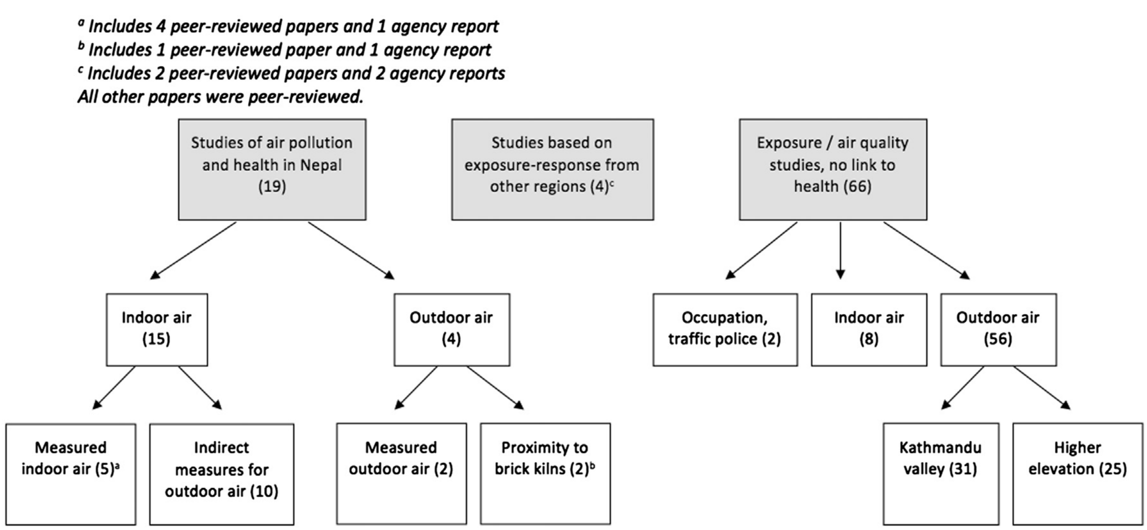

Fig. 2. Summary of study types for identified studies. (a) Includes 4 peer-reviewed papers and 1 agency report. (b) Includes 1 peer-reviewed paper and 1 agency report. (c) Includes 2 peer-reviewed papers and 2 agency reports. All other papers were peer-reviewed.

cataracts (Pokhrel et al., 2005). Health assessment was performed using questionnaire (Dhimal et al., 2010) Joshi et al., 2009; Melsom et al., 2001; Pandey, 1984b; Pant et al., 2007), spirometer (Pandey et al., 1985), peak flow meter (Joshi et al., 2009), visit by community health workers (Hahn et al., 2011; Pandey et al., 1989), hospital records (Joshi et al., 2009; Pokhrel et al., 2005; Pokhrel et al., 2010), and community registry for childhood illness (Dhimal et al., 2010).

In rural areas of Nepal, increase in respiratory health burden (e.g., chronic bronchitis, acute respiratory illness) was observed with increase in time spent near domestic smoke (Joshi et al., 2009; Pandey, 1984b; Pandey et al., 1985, 1989). More time spent near stoves was associated with higher prevalence of cough, phlegm, breathlessness, wheezing, chronic obstructive pulmonary disease, and bronchial asthma ($p < 0.05$) in adults. Peak expiratory flow rate declined with more time near stoves for men and women ($p < 0.01$). For children, acute respiratory illness episodes increased with time near stoves ($p < 0.05$) (Joshi et al., 2009).

Indoor air pollution was observed to influence respiratory health of children mainly in rural areas of Nepal. For children

Table 1
Direct assessment (measurements) of indoor air quality and links to health.

Study, location, and time period	Population	Timeframe of pollutant measure: pollutant (Number of measurements)	Health outcome: assessment method	Additional measures	Method	General result
Reid et al., 1986 ***rural*** *(Gorkha, Beni and Mustang)*: Autumn 1984	women from 60 rural households (number of subjects not provided)	***In kitchen during cooking with biomass fuel***: TSP, CO (n=22–27 kitchens); ***In kitchen and sleeping area for 1–2 weeks***: NO_2, formaldehyde in subsample of households (n=4 bedrooms, 5 kitchens)	***General symptoms***: interview using questionnaire (e.g. coughing, difficulty breathing, eye problem)	***Interview using questionnaire***: stove condition, fuel use, women's workload, cook's location, activity every 5 minutes during cooking period	t-test to compare pollutant measured in kitchen using traditional vs. improved stoves, comparison to standards and effect of time of the day on mean exposure, comparison of respiratory symptoms among cooks using traditional vs. improved stove.	Improved stoves reduced TSP 66% and CO 75% during cooking in kitchens using biomass fuel. Twice as many traditional stove users (72%) complained of eye problems and coughing compared to improved stove users (36%).
Shrestha and Shrestha, 2005 ***rural and urban*** *(Kathmandu Valley, Chitwan, Nawalparasi)*: 11/03–02/04	168 residents (94% women) who cooked daily meals from 98 households	***In kitchen during fuel use with processed vs. unprocessed fuel***: PM_{10}, CO (n=26–62)	***Respiratory health***: questionnaire (British Medical Research Council questionnaire for respiratory disease identification), peak flow meter, general physical examination	***Household survey***: household construction material (mud, brick, concrete, mixed), smoking, age	Cross sectional assessment; chi-square statistic and contingency coefficient by health and fuel type, OR for health risk associated with unprocessed fuel vs. processed fuel, smoking and age as confounders, association between health and fuel type using Mantel–Haenszel method.	About 3 times higher PM_{10} and 6.67 times higher CO levels measured in kitchens using unprocessed fuels than processed fuels. Respiratory disorders more prevalent for users of unprocessed fuel than processed fuel.
Shrestha, 2006 ***rural and urban***: *(Kathmandu Valley, Chitwan, Nawalparasi)*: 11/03–02/04	168 residents (94% women) who cooked daily meals from 98 households	***In kitchen during fuel use with processed vs. unprocessed fuel***: PM_{10}, CO (n=26–62)	***Respiratory health***: questionnaire (British Medical Research Council questionnaire for respiratory disease identification), peak flow meter, general physical examination	***Household survey***: household construction material (mud, brick, concrete, mixed), smoking, age	Principal component analysis and binary logistic regression to quantify respiratory health based on indoor air pollution, age, smoking and house type.	PM_{10} and CO kitchen levels associated with higher risk of respiratory diseases and symptoms.
*ENPHO, 2008 ***rural*** *(Boch, Dolakha, Laxmipur, Dang, Mabu VDC Ilam)*: 10/1/07–12/28/07 (before installation of improved stoves) and 02/25/08–03/30/08 (after installation of improved stoves)	36 women (principal cook) and 26 children < 5 yr from 36 households	***In kitchen with tradition stoves***: $PM_{2.5}$, CO (n=36); ***In same kitchen after improved stoves installed***: $PM_{2.5}$, CO (n=36)	***Upper respiratory problems (cough, phlegm, wheezing in chest), headache, eye irritation***: questionnaire (based on format developed by WHO, Practical Action/DFI and SANDEE)	***Questionnaire***: pre-monitoring (kitchen location and size, windows and doors present, type and design of stove, general cooking patterns); post-monitoring (stove use, number of people cooked for, fuel type, cooking frequency, smoking, burning of incense, meteorology)	Comparison of $PM_{2.5}$ and CO before and after installation of improved stoves; analysis of $PM_{2.5}$ and CO temporal patterns.	Replacement of traditional stoves with improved stoves reduced $PM_{2.5}$ 65.73% and CO 62.43%. Stove replacement reduced coughing, headache, and eye irritation.
Kurmi et al., 2011 *Exact location and time period not provided*	24 women, life-long non-smokers	***In kitchen during cooking with biomass fuel***: $PM_{2.5}$ (n=24)	***Respiratory health***: spirometry, oxygen saturation, heart rate	N/A	Calculation of mean and standard deviation; test of significance for spirometry measures, SaO_2 and heart rate before and after cooking, morning before and after cooking, evening before and after cooking.	Acute exposure to biomass smoke in women with restrictive lung disease is associated with blood deoxygenation, such that continued exposure may increase risk of exacerbation of pre-existing lung disease.

Note: Study time periods are approximate (e.g., "1990" does not indicate measurements for each day in that timeframe).

* Nonpeer-reviewed report.

Table 2
Indirect assessment of indoor air quality and links to health.

Study, location, and time period	Population	Exposure type and assessment method	Health outcome: assessment method	Additional measure	Method	General result
Pandey, 1984b ***rural*** *(Sundarijal and Bhadrabas 16 km outside Kathmandu city)*: 01/79–03/79 (Sundarijal); 01/80–03/80 (Bhadrabas)	1375 subjects; 91% and 95% female in Sundarijal and Bhadrabas, respectively	***Exposure to domestic smoke***: biomass fuel for cooking and heating; ***Interview with questionnaire***: average time/day near fireplace, kitchen location, cooking fuel, heating fuel	***Chronic bronchitis***: questionnaire, further referral of identified cases to a field clinic and hospital	***Interview with questionnaire***: smoking (current, former, never)	Exposure level (4 categories) based time near fireplace. Statistical comparison χ^2 test.	Prevalence of chronic bronchitis increased with time spent near fireplaces for men and women for each smoking category where cases were identified.
Pandey et al., 1985 ***rural*** *(Sundarijal and Bhadrabas 16 km outside Kathmandu city)*: Time period not provided.	150 females (30–44 yr)	***Exposure to domestic smoke***: biomass fuel for cooking and heating; ***Interview with questionnaire***: average time/day exposed to domestic smoke	***Respiratory function***: spirometry	***Interview with questionnaire***: smoking (current, former, never)	Comparison among 6 groups (25 subjects each) based on 3 exposure levels (<1.9, 2–3.9, 4–6 h/day) and 2 smoking groups. Significance test by using *t*-test and analysis of variance.	Mean spirometer measurements decreased as exposure increased ($p<0.025$), for smokers, but not non-smokers. Similar results after adjusting for age and height.
Pandey et al., 1989 ***rural*** *(Talkhu Dubdechaur, Chhammaile, Dakshinkali, Phakhel at southwest edge of Kathmandu)*: 02/84–07/84, 11/84-01/85	infants (0–1 yr) and children (1–2 yr) permanently residing in the area; 02/84-07/84 (233 infants, 216 children); 11/84-01/85 (247 infants, 208 children)	***Exposure to domestic smoke; Interview***: mothers asked about average time/day near fireplace	***Acute respiratory illness***: visit every 2 weeks by trained community health workers to record episodes of acute respiratory illness, use of Goroka classification grading system	N/A	Calculated average acute respiratory illness episode/child for different levels of average time near fireplace (<0.9, 1–1.9, 2–3.9, >4 h/day).	Episodes of moderate and severe acute respiratory illness increased with exposure to domestic smoke.
Melsom et al., 2001 ***urban and rural*** *(within Kathmandu city and surrounding hilly area)*: 07/97–08/97	children (11–17 yr): 121 cases, 126 controls	***Exposure***: livestock, indoor smoke pollution, other environment factors; ***Interview with questionnaire***: cooking fuel, cattle kept inside house at night, traffic; ***Home inspection***: checklist with special attention to type of cooking area	***Asthma***: cases and controls confirmed using questionnaires (based on International Study on Asthma and Allergies in Childhood)	N/A	Case-control study; mutlivariate logistic regression	For urban subjects, residence in heavy traffic region was only significant risk factor for asthma (OR 3.0, 95% CI: 1.1–9.2). For rural subjects, indoor biosmoke (OR 3.3, 1.1–9.9), tobacco smoking (OR 3.5, 1.4–8.7) and cattle indoors (OR 0.2, 0.1–0.6) associated with asthma.
Pokhrel et al., 2005 ***urban and rural*** *(Nepal–India Border)*: 07/02–10/02	female (35–75 yr): 206 cases, 203 controls	***Fuel-stove type***: stoves using non-solid fuels, unflued stoves using solid-fuels, flued stoves using solid fuels; **By *kitchen ventilation type***: full and partially ventilated vs. unventilated kitchen; ***Interview with questionnaire***: history of cooking stove and fuel, kitchen type and location, ventilation	***Cataract***: confirmed cases by ophthalmologist, controls from refractive error clinic	***interview with questionnaire***: area of residence, education, house type, smoking status of interviewee and husband, alcohol consumption, vitamin use, mosquito coil use, incense use, history of severe diarrhea, food habits, household crowding, hours worked outside, protection from sunlight exposure, childhood vaccinations, socioeconomic status	Hospital based case-control study; mutlivariate unconditional logistic regression to evaluate the effect of stove-fuel type and ventilation on risk of cataracts.	Use of solid fuel in unflued indoor stoves associated with risk of cataracts. Those without kitchen ventilation 96% more likely to have cataracts than those with ventilation. Authors concluded that replacing unflued stoves with flued stoves would greatly reduce risk, although cooking with cleaner burning fuel would be the best option.

Pant, 2007 ***rural*** *(Syangja and Chitwan)*: Time period not provided.	600 households (number of subjects not provided)	***By stove type***: improved stove, biogas; ***By fuel type***: biogas, wood fuel, liquefied petroleum gas; ***Survey using questionnaire***: stove and fuel use	***Chronic bronchitis, asthma and acute respiratory illness***: survey based on questionnaire	***Survey based on questionnaire***: income, age, gender, cost of illness	Simple probit regression and instrumental variable probit with disease symptom (0 or 1) as dependent variable, pollution and individual characteristics as independent variables	Some analyses found use of improved stoves or biogas was associated with reduced chronic bronchitis, but results were not consistent across analyses. Asthma and acute respiratory illness results also differed by analyses.
Joshi et al., 2009 ***rural*** *(Malikarjun)*: 03/14/08–04/14/08	62 households with 495 residents for housing characteristics; health survey for 225 residents (107 female, 47 male who cooked at least once in a day, 71 children < 2 yr)	***Exposure to domestic smoke***: biomass burning; ***Home inspection***: kitchen location, partition, and dimension; stove type; number of rooms; number and dimension of windows, doors and ventilations; ***questionnaire***: time near stove	***Respiratory***: questionnaire (modified British Medical Council questionnaire), hospital records, peak flow meter	***Questionnaire***: smoking, housing, lifestyle	Cross-sectional study; analysis using frequency table, analysis of variance and correlation.	Significant association between time spent near stoves and prevalence of respiratory disorders in kitchen dwelling adults and children.
Dhimal et al., 2010 ***rural*** *(Dhading)*: 10/08–01/09	2011 cases (< 59 months) residing in Dhading since at least age 6 months	***Exposure to indoor smoke; Interview with questionnaire***: fuel type, stove type	***Acute respiratory illness and pneumonia***: interview with questionnaire, cross-matching to Community Based Integrated Management of Childhood Illness register	NA	Cross-sectional study; calculation of disability adjusted life years, attributable fractions.	About 50% of acute respiratory illness and pneumonia cases attributable to indoor smoke.
Pokhrel et al., 2010 ***urban and rural*** *(Pokhara)*: 07/05–11/07	female (20–65 yr): 125 cases, 250 controls	***By fuel type***: gaseous fuel stoves (liquefied pertroluem gas and biogas), kerosene fuel stoves, biomass fuel stoves; ***By kitchen ventilation type***: full and partially ventilated vs. unventilated kitchen; ***Interview with questionnaire***: history of cooking fuel and stove use, present kitchen type and location, kitchen ventilation; ***Home inspection***: 28 homes	***Tuberculosis***: confirmed cases using chest X-ray and positive active sputum, controls from outpatients and inpatients from other departments	***Interview with questionnaire***: education, area of residence, house type, smoking history of participant and family, alcohol consumption, vitamin use, mosquito coil use, incense use, household crowding, vehicle ownership, annual income	Hospital based case-control study; multivariate unconditional logistic regression model for tuberculosis risk.	Use of kerosene stoves, kerosene lamps, and biomass fuel for heating associated with tublerculosis.
Hahn et al., 2011 ***rural*** *(Dhading)*: *03/07–03/09*	children < 5 yr in 5344–5945 households	***Before and after intervention***: **s**imultaneous acute respiratory illness prevention measures, HIV/AIDS education, and promotion of family planning to address multiple goals. ***Intervention***: training on improved stoves, installation of biogas units in some homes, new stoves. Biogas units installed in some households.	**Acute respiratory illness signs and symptoms**: monthly meetings between non-governmental organization staff and female community health volunteers to track number of cases	Households using clean energy, couples with modern family planning methods, estimated tons of firewood saved	Comparison of number of cases before and after intervention.	Acute respiratory illness cases reduced from 690 to 301. Number of households using clean energy increased from 26.5% to 40.5%.

Note: Study time periods are approximate.

< 59 months and residing since age of 6 months in Dhading district (87% of households use solid biomass as primary fuel source), indoor smoke was estimated to cause 50% of acute respiratory illness and pneumonia cases (Dhimal et al., 2010). For children 11–17 years in rural areas of Kathmandu Valley, asthma was associated with indoor biosmoke, tobacco smoking and cattle indoors (Melsom et al., 2001). On the other hand, for children 11–17 years in urban areas of Kathmandu Valley, residence in heavy traffic regions was the only significant risk factor for asthma (Melsom et al., 2001). In Dhading, through interventions the percent of households using clean energy increased from 26.5% to 40.5% from Mar. 2007 to Mar. 2009, while the number of children < 5 years with acute respiratory illness signs and symptoms deceased from 690 to 301 (Hahn et al., 2011).

For women 35–75 years, those without kitchen ventilation were 96% (95% confidence interval (CI): 25–207%) more likely to have cataracts than those with ventilation (Pokhrel et al., 2005). For women 20–65 years, tuberculosis was associated with biomass fuel for heating (Odds Ratio (OR) 3.45, 95% CI 1.44–8.27) compared to no heating fuel or electricity. For the home's main light source, tuberculosis for women was associated with kerosene lamps (OR=9.43, 95% CI: 1.45–61.32) compared to electricity. In terms of stove type, tuberculosis for women 20–65 years was associated with use of kerosene stoves (OR 3.36, 95% CI: 1.01–11.22), with a non-significant association for use of biomass fuel stoves (OR 1.21, 95% CI: 0.48–3.05), compared to use of clean burning stoves (liquefied petroleum gas, biogas) (Pokhrel et al., 2010). Some analyses in 600 households from village development committees (administrative division in Nepal) in Syangja and Chitwan found that use of improved stoves or biogas was associated with reduced chronic bronchitis but results were not consistent across analyses. Similarly, for asthma and acute respiratory illness, results differed by analyses (Pant, 2007).

3.2. Associations between outdoor air pollution and health

Only 4 studies linked outdoor pollution to health in Nepal (Supplementary Table 2). Two studies were based on use of hospital admission data (Saraf, 2005; Shrestha, 2007). Health burden was observed for daily PM_{10} based on hospital admission for acute respiratory illness for children (Saraf, 2005) and respiratory ailments for all admitted patients (Shrestha, 2007). Saraf (2005) noted the lack of appropriate disease classification in hospital records as a study limitation.

Two studies, including one agency report, assessed exposure through proximity to brick kilns with areas with or close to brick kilns, defined as the "affected area" assumed to have higher exposure, and areas without brick kilns as the " control area" (Joshi and Dudani, 2008; Tuladhar and Raut, 2002). Both studies involved air pollution measure for 2–3 days during kiln operation and 2–3 days without kiln operation, household surveys and health examination of school children to compare health status of those living in affected area verses control area. Higher pollution level during kiln operation than without kiln operation was shown by Joshi and Dudani (2008) (PM_{10}: 50 μg/m^3 vs. 29 μg/m^3; TSP: 56 μg/m^3 vs. 33 μg/m^3) and Tuladhar and Raut (2002) (PM_{10}: 602.16 μg/m^3 vs. 217.95 μg/m^3; TSP: 633.78 μg/m^3 vs. 265.49 μg/m^3). Both studies identified greater health burden for communities and school children in the affected area than control area.

3.3. Assessments of health burden from outdoor air pollution based on existing concentration-response relationships from other regions

In order to estimate air pollution's health effects in Nepal, 4 studies relied on concentration–response functions from other regions (Supplementary Table 3). In other words, they combined pollution levels and baseline health rates from Nepal with numerical estimates of how pollution affects health elsewhere, assuming that the relationship between air pollution and health from other areas applies to Nepal. PM_{10} was estimated to cause 17,132 premature deaths/year in Kathmandu Valley, with 95 of 10,000 deaths attributable to airborne particles (Giri et al., 2007). With population of 1.4 million for Kathmandu Valley and target PM_{10} of 40 μg/m^3, about 60 excess deaths/year were attributed to prevailing PM_{10}. Excess mortality increased to 120 and 226 deaths/yr with target levels of 30 and 20 μg/m^3, respectively. Respiratory illnesses/year were estimated at 71, 141 and 266 cases for target levels of 20, 30 and 40 μg/m^3, respectively (Regmi et al., 2003). PM_{10} was estimated to cause 84 deaths, 506 cases of chronic bronchitis, 475,298 restricted activity days, and 1.5 million respiratory symptom days in Kathmandu Valley in 1990 in a World Bank report (Shah and Nagpal, 1997). An update of this study was summarized in a non-government report (CEN and ENPHO, 2003), where reducing annual $PM_{2.5}$ in Kathmandu Valley of 94.7 μg/m^3 and Kathmandu Municipality of 126.7 μg/m^3 by 50% was estimated to lower mortality by 7% and 10%, respectively. Lowering annual PM_{10} in Kathmandu Valley from 148 μg/m^3 to 50 μg/m^3 was estimated to avert 40,000 emergency room visits, 5.2 million restricted activity days, 0.5 million asthma attacks, and 32 million days with respiratory symptoms annually, assuming a population of 1.8 million in 2003 (CEN and ENPHO, 2003).

3.4. Additional studies of exposure and air quality, without estimated associations with health endpoints

Although few studies directly linked air pollution and health in Nepal, we identified 64 studies that did not measure health outcomes but document high exposure levels and explore air quality in the region, and 2 additional studies that measured air pollution and health, but did not examine associations between them. These studies provide evidence on pollution's levels, patterns, and sources, with implications for health.

3.4.1. Measurements of occupational air pollution exposure

Two studies examined air pollution exposures for traffic police. PM_{10} at 3 high-density traffic locations in Pokhara was measured over 7 days (8 h/day) in mid-March 2008 (Bashyal et al., 2008). Monitors were passed between traffic police at the same location as shifts changed. PM_{10} was almost 10–15 times higher than the Nepal national ambient PM_{10} standard of 120 μg/m^3.

Another study measured $PM_{2.5}$ personal exposure of traffic police ($n=18$) and indoor office workers next to main roads ($n=9$) and away from main roads ($n=9$) during working hours in urban, urban residential, and semi-urban areas in Kathmandu Valley (Gurung and Bell, 2012). Traffic police had higher personal $PM_{2.5}$ exposure (average 51.2 μg/m^3, hourly maximum > 500 μg/m^3) than office workers. Levels for traffic police were higher at the urban area than other locations. For indoor office workers, PM_{10} was higher near main roads (46.9 μg/m^3) than away from main roads (26.2 μg/m^3).

3.4.2. Measurements and modeling of indoor air quality

Eight assessments of indoor air pollution levels from biomass burning were identified, mainly for rural areas. Three studies looked into exposure to air pollution levels in kitchens based on fuel type (Davidson et al., 1981; Kurmi et al., 2008; Semple et al., 2010). Around Khumjung village (elevation 3900 m) indoor aerosols were collected over 2 days (December 1979) in a typical family living quarter next to an open fire. On the first day, pine needles and undried wood were burned for heat, and on the second day yak dung and dry wood were burned. Levels were higher on day one than day two for Pb (160 vs. 110 ng/m^3), Al (40,000 vs. 6800 ng/m^3), and Mg (15,000 vs. 2600 ng/m^3), but lower for Cu (850 vs. 1200 ng/m^3) (Davidson et al., 1981). Daily respirable dust levels in kitchens were higher in rural households ($n=245$) using wood as the predominant fuel (range: 13–2600 μg/m^3) than urban households ($n=245$) using liquefied petroleum gas (range: 3–110 μg/m^3) in Kathmandu Valley (Kurmi et al., 2008). One study found that endotoxin units were higher in rural homes burning dung than those burning wood, and that levels were orders of magnitude higher than in homes of developed countries, where this exposure has been linked to children's respiratory illness (Semple et al., 2010). Passive sampling of polyaromatic hydrocarbons (PAHs) for 11 days in 10 rural homes indicate indoor wood combustion for cooking and heating as an origin of PAHs (Rantalainen et al., 1999).

Measurements in 20 rural households in Kathmandu Valley showed high levels of respirable suspended particles (8200 μg/m^3), CO (82.5 ppm) and formaldehyde (1.4 ppm) during cooking with traditional unflued stoves with local firewood and agricultural residues. Traditional stoves were replaced by smokeless flued stoves, which lowered respirable suspended particles (3000 μg/m^3), CO (11.6 ppm), and formaldehyde (0.6 ppm) (Pandey et al., 1990). Time activity survey data, estimated fuel consumption, $PM_{2.5}$ emission factors by fuel type, room volume, air exchange frequency and removal rate, and average exposure were used to estimate indoor exposures by microenvironment for 15 Asian countries. In Nepal, estimated daily $PM_{2.5}$ was 285.2, 128.8 and 1.4 μg/m^3 in microenvironments with fuels primarily used for cooking and eating, heating, and illumination, respectively. For all countries including Nepal, $PM_{2.5}$ exposure was highest for children and unemployed women 35–64 years with time indoors greatly influencing exposure (Shimada and Matsuoka, 2011).

Two additional studies directly measured indoor air pollution and assessed health endpoints, but did not estimate how pollution affects health. TSP concentrations of 3000–42,000 μg/m^3 were measured for 1–2 h during stove operation (cooking or tending to fire) in 18 rural households using biomass fuel with no chimneys for ventilation (December 1982–January 1983), and interviews were conducted for health problems (Davidson et al., 1986). Women responsible for stove operation were interviewed regarding stove use, fuel type, attitude towards the smoke, and health (Salerno et al., 2010). Daily stove use for cooking averaged 4.6 h/day, with $>50\%$ of that time at or near the stove for all respondents. Daily stove use for other purposes (mainly heating) differed by elevation, averaging 3.4 and 9.7 h/day at low and high elevation, respectively. Almost all women reported chronic coughing and eye irritation. In 35 households in Thame and surrounding villages, indoor 8-h CO during cooking was 0.006–0.034 g/m^3 in houses with improved stoves (November–December 2008) The highest concentration (0.230 g/m^3) was observed during cooking (about 2-h average) in households using traditional stoves, and the lowest when no cooking was performed in a home with an electric heater for cooking. Respiratory health was tested in 104 individuals >14 years. Spirometry tests showed that 83% of subjects had no respiratory obstruction. However, 13% had mild and 5% had moderate respiratory obstruction. Of the 18% of subjects with pulmonary obstruction, 71% were women.

3.4.3. *Measurements and modeling of outdoor air pollution and characteristics*

We identified 56 studies of outdoor air pollution, without associations of pollution and health. Here we briefly summarize these studies' key contributions (Supplementary material, p. 5–8 for additional details and full references).

Twenty-five studies described ambient measurements and/or air quality modeling results for high elevation areas, including 10 from Nepal Climate Observatory-Pyramid at Khumbu Valley (5079 m a.s.l) where measurements have been conducted since March 2006. Primary contributions of these studies relate to understanding composition, sources, temporal patterns, and regional influences of pollution. Key modeling approaches include backward trajectory modeling, and all modeling studies included ambient measurements. Studies focused on aerosols, ozone, biological particles, black carbon, and airborne pesticides (e.g., Bonasoni et al., 2010; Decesari et al., 2010; Fiorina et al., 1998, Li et al., 2006; Moore and Semple, 2009; Sellegri et al., 2010). Analysis was performed using lichens (e.g., Bergamaschi et al., 2004) and snow samples (e.g., Marinoni et al., 2001). Major PM_{10} components were identified as organic matter, elemental carbon, inorganic ions, and mineral dust, with combustion as a key source (e.g., Decesari et al., 2010). Findings indicate stratospheric ozone as an important contributor to surface ozone at high elevation (e.g., Moore and Semple, 2009). Measurements show strong temporal patterns (e.g., peak BC during daytime) (e.g., Sellegri et al., 2010). Most pollutants (e.g., BC, $PM_{2.5}$, ozone) were higher during premonsoon than monsoon, although not all pollutants (e.g., bromine) (e.g., Bonasoni et al., 2010; Moore and Semple, 2009; Sellegri et al., 2010). Studies showed regional influence on air quality at high elevation (e.g., Bergamaschi et al., 2004; Bonasoni et al., 2010; Marinoni et al., 2001).

Ambient measurements and/or air quality modeling results in Kathmandu Valley were provided in 31 studies; all but one (e.g., Shrestha and Malla, 1996) included pollution measurements. Emissions and pollutant levels were estimated by atmospheric transport, deposition, and chemistry models (e.g., Adhikary et al., 2007). Other measurement studies examined pollutant concentrations in dust from trees (e.g., Gautam et al., 2005), PAHs in PM_{10} in an urban area (e.g., Kishida et al., 2009), and HONO in urban areas (e.g., Yu et al., 2009). Emissions from burning of waste vehicle tires during general strikes, when all vehicles and industries cease operation, were estimated in a laboratory study (e.g., sulfur dioxide (SO_2) 102–820 μg/g) (e.g., Shakya et al., 2008). Findings identify key sources as biomass burning and fossil fuels, especially from vehicles (e.g., Shrestha and Malla, 1996; Yu et al., 2008). Several studies observed high pollutant levels (e.g., nitrogen dioxide (NO_2), SO_2) and emissions (e.g., Kitada and Regmi, 2003). Kathmandu City was as polluted as Jakarta and Beijing (e.g., Sapkota and Dhaubhadel, 2002). Other studies showed spatial trends, (e.g., higher lead near roads) (e.g., Sharma et al., 2002). Pollution levels varied by land use (e.g., highest PM_{10} near industry) (e.g., Aryal et al., 2008; Sharma, 1997). Concentrations were typically higher in winter, except for ozone (e.g., Aryal et al., 2008; Giri et al., 2008). Other work showed patterns by day of week (e.g., higher ozone during weekends) (e.g., Giri et al., 2008; Pudasainee et al., 2010) or time of day (e.g., morning and evening peaks for $PM_{2.5}$) (e.g., Pudasainee et al., 2010; Sapkota and Dhaubhadel, 2002; Sharma et al., 2002; Yu et al., 2009). In Kathmandu Valley, air quality was strongly affected by wind systems generated by surrounding topography (e.g., Panday et al., 2009).

4. Discussion

Our review indicates a dearth of research on air pollution and health in Nepal, although the few existing studies indicate potentially serious health consequences. Several studies do not estimate air pollution's health impacts, but demonstrate higher levels of pollution than in other parts of the world where air pollution and health associations are well documented. Only 4 studies directly estimated outdoor air pollution's health impacts in Nepal, all focused on Kathmandu Valley, the major urban area in Nepal. Fifteen studies examined indoor air pollution and health, almost all conducted in rural areas, with a focus on cooking fuel. Of the health studies, only 2 outdoor and 5 indoor studies included air quality measurements.

Study timeframes were small (e.g., few days to a year), with many studies measuring for only a few days during that timeframe. The longest study time period for a health study with measured pollution was 16 months for outdoor air and 4 months for indoor air. For indirect indoor air exposure and health, the longest study timeframe was 29 months. Sample sizes were also small, especially for health studies with measured indoor air pollution (24–168 subjects). Studies using surveys to assess indoor air often had more participants (highest at 2011 subjects, second highest at 1375 subjects). For the 4 studies on health from outdoor air, the largest study had 7131 participants, with other studies substantially smaller. Not all studies defined time periods or sample size. Additionally, almost all health studies focused on respiratory health.

Four studies were based on extrapolation of health burden based on exposure responses from other regions. Extrapolation of health impacts from studies performed in other regions provides useful information but has limitations (Bell et al., 2002; O'Neill et al., 2003). Kathmandu Valley has substantially higher pollution levels than in the developed world where most health studies were conducted. The form of exposure–response relationships developed for lower pollution levels may not be appropriate for higher exposures. The pollution mixture (e.g., PM constituents) may differ from other regions due to sources and long-range transport. Vehicle emissions may impact health differently than in developed countries from variation in physical and chemical characteristics of fuels, design and technology, vehicle distribution (e.g., more motorcycles), driving habits, frequent congestions, and roadways (e.g., graded vs. ungraded roads) (Han and Naeher, 2006). Actual exposure may vary through differences in lifestyle and culture that affect indoor/outdoor activity patterns and housing characteristics. Finally, populations' health responses to pollution may vary due to differences in baseline health, nutrition, health care systems, socioeconomic status, etc.

A key limitation of research on how air pollution affects human health in this region is a lack of data on health and exposure. For example, hospital admissions records are not standardized across hospitals and in many cases are not computerized. Many studies conducted in other regions base exposure on ambient monitoring networks maintained by government organizations, such as the U.S. Environmental Protection Agency, and such data are not available for Nepal and many other regions. For PM, a major pollutant of Kathmandu Valley, the Nepalese government conducted routine measurements of PM_{10} until 2007 and did not routinely measure $PM_{2.5}$. Information on the current levels of particles, including different size fractions, and other pollutants are needed. Such work could involve ambient monitoring or the use of alternate exposure methods (e.g., satellite imagery, see Lee et al., 2012; Kloog et al., 2012) although some ground-based monitoring would be necessary to evaluate novel exposure techniques.

While the size of particles affect health outcomes, research is also needed on different types of particles, as toxicity is likely affected by the particles' chemical structure. Substantial temporal and spatial variation in chemical composition of particles has been shown in the U.S. (Bell et al., 2007a and b), which explained a large fraction of geographical and seasonal variation in short-term effects of PM on mortality and morbidity (Bell et al., 2009). Scientific evidence on risk based on specific sources of pollutants would help decision makers target the most harmful sources. For example, in six U.S. cities, several distinct source-related fractions of fine particles were identified and association of these fractions to daily mortality examined. Increases in daily mortality by 3.4% and 1.1% was observed for a 10 $\mu g/m^3$ increase in $PM_{2.5}$ from mobile sources and coal combustion sources, respectively (Laden et al., 2000).

Like many Asian countries, Nepal is urbanizing quickly. According to Census 2011, urban areas in Kathmandu Valley have a population density of 14,355 person/km^2 with 3.92% average annual population growth in the past 10 years (Central Bureau of Statistics, 2012). Hence, in addition to studies in rural areas, attention should be given to urban pollution and health. No studies were found examining the general population's exposure to traffic pollution, although traffic was identified as one of the major sources of pollution (Asian Development Bank and Clean Air Initiative-Asia., 2006). Specifically, studies are required to understand intraurban variation of traffic-related exposure in urban areas of Kathmandu Valley and similar regions. One option for future work is landuse regression modeling, which has been successfully applied in Windsor, Ontario for intraurban exposure assessment, explaining 77%, 69%, 73% and 46% of variability for NO_2, SO_2, benzene and toluene, respectively (Wheeler et al., 2008). In comparison to Western cities, Kathmandu and other rapidly developing cities may have different built characteristics, topography, weather, and landuse patterns influencing the spatial and temporal distribution of traffic pollutants, hence requiring studies specifically for each region.

Studies are also required for indoor air pollution with direct measure of exposure, to better estimate the health impacts suggested by the identified studies using indirect exposure measurements such as fuel type. Indirect exposure measurements may lead to incorrect estimation of exposure and mask complexities of exposure (Ezzati and Kammen, 2002) hence biasing the estimated health effects. Determination of human exposure to pollutants also requires understanding of people's location and activities, which has led to many large-scale time activity pattern studies (e.g. National Human Activity Pattern Survey in U.S.) (Klepeis et al., 2001). Activities have been shown to vary among individuals by age, ethnicity, race, socioeconomic status, health status, weather and various other factors (Leaderer et al., 1993). Studies of this type specifically for Nepal and similar regions are needed for accurate exposure modeling.

Other research gaps include the need for studies on additional types of health impacts (e.g., cardiovascular diseases, birth weight). For example, exposure to air pollution during pregnancy has been associated with outcomes such as lower birth weight and infant mortality (Geer et al., 2012; Woodruff et al., 2006). Further work is needed with larger study populations and longer time frames in order to aid more focused policies to protect public health. Research could investigate the health effects of long-term exposure to air pollution. Additional studies are required to understand how risk varies by sub-population (e.g., socioeconomic status, age, education). Different health effects by subpopulation have been demonstrated in other regions of the world. For example, in 9 Italian cities based on hospitalized subjects $\geq$65 years, women had higher risk of heart failure (1.2%–2.8%) and men were observed to have higher risk of arrhythmias (0.8%–3.0%) from exposure to PM_{10} (Colais et al., 2012).

Although this review focused on Nepal, many other rapidly developing regions also suffer high air pollution levels with sparse quantification of the subsequent health impacts, and thereby would benefit from additional scientific studies. Such regions also face many of the research challenges listed above. While many topics of research are worth investigation, research needs to be balanced within a spectrum of broader issues of competing priorities and feasibility that affect rapidly developing nations.

5. Conclusion

Our review identified large gaps in the scientific understanding of air pollution and health in Nepal. This dearth of studies in Nepal relates to lack of exposure data (e.g. ambient PM_{10} monitoring ceased after 2007), absence or poor quality of health records (e.g. absence of International Classification of Disease (ICD) codes in hospital records), limited resources, and competing policy, health, and research challenges. These challenges observed in Nepal are common for many Asian countries with limited air quality monitoring, heath data, and institutional capacity (HEI, 2010). Studies investigating air pollution and health burden in Nepal can benefit by restoring air quality monitoring stations, monitoring pollutants in addition to PM_{10} and more thorough and detailed health data collection than currently exists. The Nepalese government does collect monthly hospital admission summary data, although detailed information (e.g. cause of hospital admission) is not included and not all hospitals participate.

Like many Asian countries, Nepal is observed to have research gaps that include understanding chronic effects of air pollution exposure, risk associated with pollution mixture such as constituents of PM, and vulnerability by sub-population (HEI, 2010; Su et al., 2011). Specifically for indoor air pollution, like most developing countries studies are limited with direct exposure measures and consideration for various confounding factors (Bruce et al., 2000). There is a critical need for additional research and method development on health effects of air pollution in the developing world with poor air quality (Cohen et al., 2005). Findings from such research are essential to aid decision makers in the developing and implementing effective mitigation strategies to protect public health from air pollution in understudied places like Nepal. Despite a lack of studies on par with that of other regions, the limited number of studies that have been conducted, in conjunction with the wealth of scientific evidence on air pollution and health from elsewhere, suggest that the population of Nepal faces a substantial health burden from air pollution.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2013.03.007.

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