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The gains in life expectancy by ambient $PM_{2.5}$ pollution reductions in localities in Nigeria☆

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ABSTRACT

Global burden of disease estimates reveal that people in Nigeria are living shorter lifespan than the regional or global average life expectancy. Ambient air pollution is a top risk factor responsible for the reduced longevity. But, the magnitude of the loss or the gains in longevity accruing from the pollution reductions, which are capable of driving mitigation interventions in Nigeria, remain unknown. Thus, we estimate the loss, and the gains in longevity resulting from ambient $PM_{2.5}$ pollution reductions at the local sub-national level using life table approach. Surface average $PM_{2.5}$ concentration datasets covering Nigeria with spatial resolution of ~1 km were obtained from the global gridded concentration fields, and combined with ~1 km gridded population of the world (GPWv4), and global administrative unit layers (GAUL) for territorial boundaries classification. We estimate the loss or gains in longevity using population-weighted average pollution level and baseline mortality data for cardiopulmonary disease and lung cancer in adults ≥25 years and for respiratory infection in children under 5. As at 2015, there are six "highly polluted", thirty "polluted" and one "moderately polluted" States in Nigeria. People residing in these States lose ~3.8–4.0, 3.0–3.6 and 2.7 years of life expectancy, respectively, due to the pollution exposure. But, assuming interventions achieve global air quality guideline of 10 $\mu g/m^3$, longevity would increase by 2.6–2.9, 1.9–2.5 and 1.6 years for people in the State-categories, respectively. The longevity gains are indeed high, but to achieve them, mitigation interventions should target emission sources having the highest population exposures.

1. Introduction

Globally, remarkable gains in life expectancy have been achieved, with global average lifespan rising from 66.4 years in 2000 to 71.4 years in 2015 (WHO, 2016a). Although the gains were highest in Africa during that period – an increase from 50.6 to 60 years – the region still has the lowest life expectancy in the world (WHO, 2016a). The situation is much worse in Nigeria where people have an even shorter lifespan of 54.5 years (WHO, 2016a).

One of the top risk factors responsible for the short lifespan in Nigeria is air pollution. The toll of premature deaths attributed to air pollution in Nigeria is the largest in Africa, and among the top 5 position in the world (IHME, 2016; OECD, 2016a; WHO, 2016b). It is estimated that exposure to air pollution (ambient and household combined) currently accounts for ~114 thousand annual deaths and ~5.4 million disability adjusted-life years (DALYs) lost in Nigeria (IHME, 2016), with the attendant economic cost of ~USD 112 billion, annually (OECD, 2016a). The death toll attributed to air pollution exposure in Nigeria exceeds that due to childhood underweight,

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unsafe water or unsafe sanitation (OECD, 2016a), suggesting that sustained reductions in population exposure to air pollution should result in substantial gains in life expectancy. The magnitude of this gain however remains unknown.

Increased survival is a potential benefit of reducing air pollution. Thus, estimates of life expectancy gains are considered to be one of the best metrics in communicating the public health significance of air pollution. Because such estimates will vary from place to place within a country, and air quality improvements would also depend largely on decisions and actions taken at the local, sub-national level (Amegah and Agyei-Mensah, 2017; Etchie et al., 2017), local level estimates of the gains in life expectancy is critically important to inform policy decision-making and implementation. Indeed, such estimates may justify and drive mitigation efforts in Nigeria. In this study, we estimate the share of the deaths, DALYs, economic cost and loss in life expectancy attributable to population exposure to ambient $PM_{2.5}$ pollution at the local, sub-national level in Nigeria in 2000 and 2015, and calculated the averted burdens, cost and the gains in life expectancy accruing from attainment of the World Health Organization (WHO) air quality guideline (AQG), to inform policy decision making for mitigation.

2. Methodology

2.1. Sources of information

We obtained surface average $PM_{2.5}$ concentration datasets covering Nigeria with spatial resolution of $0.01 \times 0.01°$ (~1 km) from the global $PM_{2.5}$ gridded concentration fields (van Donkelaar et al., 2016). van Donkelaar et al. (2016) derived the global $PM_{2.5}$ concentration fields by Geographically Weighted Regression (GWR) of satellite-derived Aerosol Optical Depth (AOD) retrievals from different satellite products (MODerate resolution Imaging Spectroradiometer [MODIS], Multiangle Imaging SpectroRadiometer [MISR], Sea-viewing Wide Field-of-view Sensor [SeaWiFS], Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation [CALIPSO]), simulation from chemical transport model (GEOS-Chem) and ground-based observations from Aerosol Robotic Network (AERONET) and surface monitors for 1998 to 2014. The GWR-predicted $PM_{2.5}$ datasets showed strong correlation ($R^2 = 0.81$) with the out of sample cross-validated $PM_{2.5}$ concentrations from surface monitors.

To reduce error for each single year, we obtained 3-year moving average $PM_{2.5}$ concentrations for 2000 and 2015. Put in other words, the dataset for year 2000 is the average of $PM_{2.5}$ concentration in 1998, 1999 and 2000, while that for year 2015 is the average of $PM_{2.5}$ concentration in 2013, 2014 and 2015.

We obtained gridded population count datasets, the Gridded Population of the World version 4 (GPWv4), in TIFF format for 2000 and 2015 from the Socioeconomic Data and Applications Center (SEDAC) at the NASA's Earth Observing System Data and Information System (EOSDIS) (SEDAC, 2015). The datasets are at 30 arc seconds (~1 km) resolution and therefore could match the $PM_{2.5}$ concentration datasets for population exposure assessment at the local sub-national level. The Global Administrative Unit Layers (GAUL) of the Food and Agricultural Organization (FAO, 2016) were used for the territorial boundaries classification of States and Local Government Areas (LGAs) in Nigeria.

2.2. Estimation of population-weighted average concentration of $PM_{2.5}$

We used the gridded $PM_{2.5}$ surface concentrations and populations for 2000 or 2015 to calculate the population-weighted average concentration of $PM_{2.5}$ for the administrative units (States or LGAs) using the following algorithm (OECD, 2016b):

$$E = \frac{\sum_x (Pop_x \times C_x)}{\sum_x Pop_x} \quad (1)$$

where:

E is population-weighted average concentration of $PM_{2.5}$ for each administrative unit (State or LGA).
$x = 1, \ldots, N$, refers to the grid cells belonging to the same spatial administrative unit
Pop_x is the population of people in a given grid cell x.
C_x is the 3-year running average concentration of $PM_{2.5}$ in a grid cell x.
$\sum_x Pop_x$ is the total population of people in an administrative unit (LGA or State)

Population exposure assessment was carried out using QGIS 2.14.20. Zonal statistics were computed using the administrative unit boundary layers (FAO, 2016). $PM_{2.5}$ pollution and population data for the same time period were used for estimations of each study year.

2.3. Estimation of $PM_{2.5}$-related deaths, DALYs and the economic cost

We examined the contribution of five health outcomes linked to ambient $PM_{2.5}$ pollution exposure using the integrated exposure-response (IER) functions of Burnett et al. (2014): acute lower respiratory infections (ALRI) for children < 5 years; ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer for adult ≥ 25 years. We calculated the $PM_{2.5}$-related deaths and DALYs for each administrative unit, using relative risk values reported by Apte et al. (2015) derived age group and cause-specific relative risk values for $PM_{2.5}$ from 0 to 410 μg m^{-3} in 0.1 μg/m^3 step, using the IER parameters provided by Burnett et al. (2014), assuming a counterfactual $PM_{2.5}$ concentration of 5.8 μg/m^3.

We estimated the number of premature deaths attributable to $PM_{2.5}$ exposure for the different age group and health outcome in the 773 LGAs or 37 States in Nigeria, using standard approach (Giannadaki et al., 2016).

$$M_{ij} = \left(\frac{RR_{ij} - 1}{RR_{ij}}\right) \times B_{ij} \times \sum_x Pop_x \quad (2)$$

where:

M_{ij} is the $PM_{2.5}$-related mortality for an age group i and health outcome j, for each administrative unit in Nigeria.

RR_{ij} is the relative risk for the age group i and health outcome j at the $PM_{2.5}$ exposure level, derived from IERs (Apte et al., 2015).

B_{ij} is the baseline death rate for an age group i and health outcome j, in 2000 or 2015 in Nigeria, assuming same rate for all administrative units. The values were downloaded from the Institute for Health Metrics and Evaluation GBD country database (IHME, 2016).

The $PM_{2.5}$-related DALYs in year 2000 or 2015 was estimated using the same algorithm (Equation (2)), except that the baseline DALYs rates for the health outcomes, rather than the death rates, were used as B_{ij} in Equation (2). The baseline DALY rates, by age groups, for the health outcomes in 2000 or 2015 in Nigeria were downloaded from IHME (2016).

The economic cost was estimated using the value of statistical life (VSL) for Nigeria. The VSL is often used for cost benefit analysis, and it represents an individual's willingness to pay for marginal reduction in risk of dying (OECD, 2014). The economic cost per year of $PM_{2.5}$-related premature deaths was estimated as:

$$EC_{mort} = M \times VSLn \tag{3}$$

where:

EC_{mort} is the economic cost of $PM_{2.5}$-related deaths in each unit in 2000 or 2015
M is the number of $PM_{2.5}$-related deaths in each unit in 2000 or 2015;
VSLn is the value of statistical life for Nigeria.

Using the value transfer method, OECD (2016a) derived a VSLn value of USD 1.049 million, with an income elasticity beta of 1, while Yaduma et al. (2013) used meta regression analysis to derive a VSLn value of USD 489,000. We used the latter value in our estimation because it is a conservative value and compares reasonably with the VSL value for India or China of USD 602,000 or USD 975,000, respectively (OECD, 2014). The average (range) VSL value for the OECD countries in year 2010 is approximately USD 3.3 (1.8–6.3) million (OECD, 2014). We did not however include the economic cost for $PM_{2.5}$-related morbidity (EC_{morb}) as done in the developed countries, due to the negligible effect of YLDs on $PM_{2.5}$-related DALYs in Africa (OECD, 2016a). We did not also apply discounting or age-weighting in our estimations.

2.4. Estimation of the loss or gains in life expectancy accruing from attainment of global air quality guideline

For each health outcome j, the gain in life expectancy ($G_{(\geq 25\ year)j}$) accruing from attainment of WHO AQG of 10 μg/m^3 for people ≥ 25 years of age relates to the loss in life expectancy ($\Delta e_{(\geq 25\ year)j}$) resulting from $PM_{2.5}$ pollution exposure as follows:

$$G_{(\geq 25\ year)j} = \Delta e_{(\geq 25\ year)j} - \Delta e_{(\geq 25\ year)j}{}^{*} \tag{4}$$

$$\Delta e_{(\geq 25\ year)j} = e_{(\geq 25\ year)j} - e_{(\geq 25\ year)j}{}^{*} \tag{5}$$

$$\Delta e_{(\geq 25\ year)j}{}^{*} = e_{(\geq 25\ year)j}{}^{**} - e_{(\geq 25\ year)j}{}^{*} \tag{6}$$

where:

$G_{(\geq 25\ year)j}$ is gain in life expectancy accruing from attainment of WHO AQG
$\Delta e_{(\geq 25\ year)j}$ is loss in life expectancy at the $PM_{2.5}$ pollution exposure
$\Delta e_{(\geq 25\ year)j}{}^{*}$ is loss in life expectancy at WHO AGQ of 10 μg/m^3
$e_{(\geq 25\ year)j}$ is life expectancy at the $PM_{2.5}$ pollution exposure
$e_{(\geq 25\ year)j}{}^{*}$ is life expectancy at $PM_{2.5}$ concentration of 5.9 μg/m^3
$e_{(\geq 25\ year)j}{}^{**}$ is life expectancy at WHO AQG of 10 μg/m^3

We used a combination of hazard and survival analyses based on the abridged life-table calculation method that separates the dimensions of age and calendar time in a system of Excel spreadsheets (Mathers et al., 2001; Miller and Hurley, 2003; Etchie et al., 2017) to calculate $e_{(\geq 25\ year)j}$, $e_{(\geq 25\ year)j}{}^{*}$ and $e_{(\geq 25\ year)j}{}^{**}$. In the life table analysis method, we defined hazard as the age-specific risks of dying, conditional on having survived to that age. The hazard rate for ≥25 years of age, for a health outcome was estimated as:

$$H_{ij} = \left(\frac{RR_{ij} - 1}{RR_{ij}}\right) \times B_{ij} \tag{7}$$

where:
H_{ij} is the $PM_{2.5}$-related hazard rate for an age group $i \geq 25$ years and health outcome j for the administrative unit in Nigeria.
RR_{ij} and B_{ij} have been defined in Equation (2)
The probability of surviving ($5p_i$) and the probability of dying ($5q_i$) for each 5-year age interval and health outcome were calculated from H_{ij} using the following algorithms (Mathers et al., 2001; Etchie et al., 2017):

$$_5q_{ij} = \frac{5 \times H_{ij}}{1 + 5(0.5 \times H_{ij})} \tag{8}$$

$$_5p_{ij} = 1 - {}_5q_{ij} \tag{9}$$

Population starting the next five-year interval ($l_{(i+5)j}$) across a diagonal was estimated as:

$$l_{(i+5)j} = l_{ij} \times {}_5p_{ij} \tag{10}$$

where:
l_{ij} is the population of previous five-year interval i, for health outcome j.
The $PM_{2.5}$–related death ($_5d_{ij}$) for an age group and health outcome was estimated as:

$$_5d_{ij} = \frac{l_{ij} \times {}_5q_{ij}}{5} \tag{11}$$

We estimated the person-years lived in an age group ($_5L_{ij}$), which is the number of years contributed by the people who survived an age group and those who died in it (Mathers et al., 2001).

$$_5L_{ij} = \frac{5(l_{(i+5)j} + l_{ij})}{2} \tag{12}$$

The total number of person-years lived by an age group ($_5T_{ij}$) was estimated by cumulating the values of L_i diagonally from the bottom-up of the life table:

$$_5T_{ij} = {}_5T_{(i+1)j} + {}_5L_{ij} \tag{13}$$

where:

T_{i+1} is the total number of person-years lived for the next age group
For the last age group in the life-table (i.e. i = 100+ years), $_5T_{(100+)j} = {}_5L_{(100+)j}$.
The average life expectancy for ≥25 years, for a health outcome ($e_{(\geq 25)j}$) was estimated as:

$$e_{(\geq 25\ year)j} = \frac{_5T_{(25-29\ year)j}}{l_{(25-29\ year)j}} \tag{14}$$

These calculations, although straightforward, become very cumbersome when repeated for each of the 773 LGAs or 37 States in Nigeria, and for each health outcome. Stieb et al. (2015) made similar observation, and used the Canadian life table for the years 2007–2009 to demonstrate that $\Delta e_{(\geq 25\ year)j}$ for each health outcome j, could be accurately derived directly from the excess rate ratio (ε_j = RR − 1) by a linear or quadratic regression at lower or higher values of ε_j, respectively. Thus, we used the life table method to calculate $\Delta e_{(\geq 25\ year)j}$ values only for ε_j values that correspond to an increment of 10 percentile from 0 percentile to 100 percentile (i.e. 11 points of ε_j percentile values). $\Delta e_{(\geq 25\ year)j}$ and ε_j values corresponding to $PM_{2.5}$ concentration of 10 μg/m^3 and 5.9 μg/m^3 were also included for predictions at low pollution levels. The proportionality constants were then used to derive $\Delta e_{(\geq 25\ year)j}$ and $G_{(\geq 25\ year)j}$ for all other LGAs (or States) in Nigeria.

2.5. Estimation of the influence of demography on $PM_{2.5}$-related health burden and cost in Nigeria under a planned mitigation scenario

By using standard life-table calculations, in a system of excel spreadsheets to separate the dimension of age and calendar year, we could compare future changes in the distribution of $PM_{2.5}$-related deaths, DALYs and economic costs in Nigeria, in two scenarios: a baseline scenario that assumes that the average $PM_{2.5}$ pollution exposure level and baseline mortality rates for the health outcomes in 2015 remained unchanged; and a planned mitigation scenario that assumes gradual but purposive reductions from the 2015 pollution level of 32 μg/m^3, to 25 μg/m^3, 15 μg/m^3 and 10 μg/m^3, which are the interim targets (IT-2, IT-3) and the AQG, in the year 2025, 2035 and 2045, respectively. The interim targets are incremental steps in a progressive reduction to lower concentrations in highly polluted areas, and are intended to promote a shift from concentrations that if achieved, would result in significant reduction in risks from acute and chronic effects (WHO, 2005; Krzyzanowski and Cohen, 2008; Dockery and Pope, 2014; Etchie et al., 2017).

We calculate the attributed or averted $PM_{2.5}$-related deaths in Nigeria in 2015, 2025, 2035 and 2045, under the baseline and planned mitigation scenarios using Equations 1 and 7-11. For the $PM_{2.5}$-related DALYs, the same procedure as the $PM_{2.5}$-related deaths was used, except that the baseline DALYs rates for the health outcomes, rather than the baseline death rates, were used as B_{ij} in Equation (7). The United Nations projected population for Nigeria was used for the future years' estimations (2025, 2035 and 2045) (UN, 2015). The spreadsheets method is flexible and allows monetary values to be estimated with or without discounting. The economic costs in those years were estimated using Equation (3).

3. Results

3.1. Population-weighted average concentration of ambient $PM_{2.5}$

The population-weighted average exposure to total and combustion $PM_{2.5}$, in Nigerian States, in 2015, are shown in Fig. 1. Estimates for the 773 LGAs are available in the Supplemental Materials. We estimate that the levels of exposure to ambient $PM_{2.5}$ pollution in all administrative units (States or LGAs) in Nigeria, in 2015, exceed the global AQG of 10 μg/m^3. No administrative locality in Nigeria averaged below the IT-3 of 15 μg/m^3. If the States in Nigeria are grouped according to WHO classification of annual average $PM_{2.5}$ pollution – "highly polluted" locality (mean $PM_{2.5} > 35$ μg/m^3), "polluted" locality ($35 \geq$ mean $PM_{2.5} > 25$ μg/m^3), "moderately polluted" locality ($25 \geq$ mean $PM_{2.5} > 15$ μg/m^3) and "mildly polluted" locality ($15 \geq$ mean $PM_{2.5} > 10$ μg/m^3) – there are six "highly polluted" States, thirty "polluted" States and one "moderately polluted" State in Nigeria, as at 2015.

People residing in Nembe, Brass and Southern Ijaw LGAs of Bayelsa State have the lowest average level of exposure to $PM_{2.5}$ of 19 μg/m^3, while the inhabitants of Tarauni LGA in Kano State have the highest average level of exposure to $PM_{2.5}$ of 51 μg/m^3. Generally, the populations in the Northern States of Nigeria have higher level of exposures to $PM_{2.5}$ pollution than those in the Southern States. Specifically, people residing in Kano, Katsina and Jigawa States have the highest level of $PM_{2.5}$ exposure than elsewhere in Nigeria. However, the $PM_{2.5}$ pollution in the Northern States of Nigeria is dominated by dust from the Saharan desert. Deforestation and agricultural practices leading to desertification, coupled with low rainfalls further aggravate the pollution.

Conversely, the high rainfalls in the Southern region, over 8 months of rainy season and less than 4 months of dry season per year, appear to play a major role in reducing $PM_{2.5}$ pollution exposures, particularly in the coastal States – Bayelsa, Rivers, Delta and Lagos. Precipitation has strong influence on airborne $PM_{2.5}$ concentration, and has been reported to scavenge $PM_{2.5}$ from the atmosphere even in low to moderate amount (Singla et al., 2012; Pandey et al., 2013; Etchie et al., 2017). Furthermore, although the levels of exposure to $PM_{2.5}$ pollution in the Southern States are lower than those of the Northern States, the former is dominated by

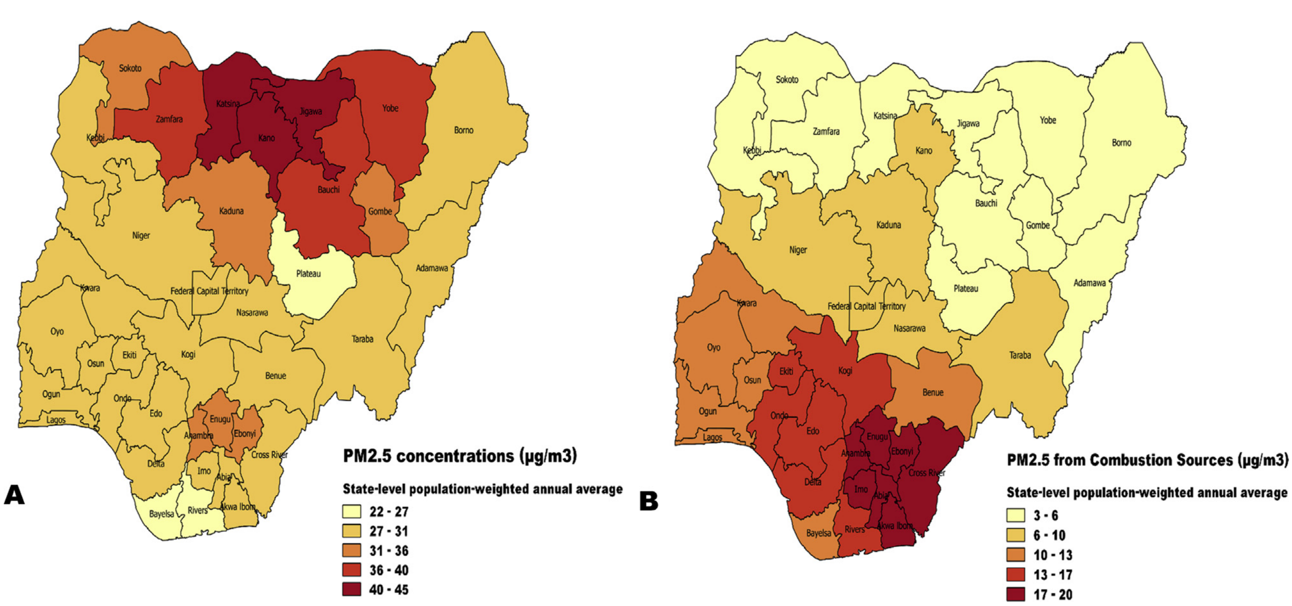

Fig. 1. Population-weighted average concentration of total $PM_{2.5}$ (A), and $PM_{2.5}$ from combustion sources (B) in Nigerian States in 2015.

combustion $PM_{2.5}$. A growing body of evidence show that exposure to combustion $PM_{2.5}$ has stronger association with mortality, and the risk of mortality is roughly five times higher for combustion $PM_{2.5}$ than for $PM_{2.5}$ mass in general, on a per μg/m^3 $PM_{2.5}$ basis (Laden et al., 2000; Lipfert et al., 2006; Beelen et al., 2015; Lelieveld et al., 2015; Ostro et al., 2015; Silva et al., 2016; Thurston et al., 2016). Combustion $PM_{2.5}$ often contains persistent organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), dioxins and furans, polychlorinated biphenyls (PCBs) and other hazardous by-products of incomplete combustion emissions (Tasdemir et al., 2004; Wu et al., 2007; Mandalakis et al., 2009; Martínez et al., 2010; Callén et al., 2013; Chakraborty et al., 2013; Qadir et al., 2013; Ni et al., 2016; Samburova et al., 2016; Chen et al., 2017). These pollutants are not only mutagenic carcinogens, capable of causing cancer at any level of exposure no matter how small; they also elicit reproductive, immunological, neonatal, and neuro-psycological impairments (US EPA, 2017).

We compared the $PM_{2.5}$ average exposure concentration across the States in 2000 and 2015. Fig. 2 shows the change in population exposure to ambient $PM_{2.5}$ pollution in Nigerian States in 2000 and 2015. There was substantial reduction in the average level of exposure to $PM_{2.5}$ between 2000 and 2015 in most of the States. However, eight Southern States (Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Rivers, Imo and Lagos) witnessed an increased level of $PM_{2.5}$ pollution exposure during this period. In early 2017, the Nigerian Federal Ministry of Environment declared air pollution emergency in Port Harcourt, Rivers State, because the locality is covered with black smog. Media report that the situation there is very severe (BBC, 2017; Theguardian, 2017). In the words of Theguardian (2017) “if you wipe surfaces indoors and outdoors with a white towel or tissue paper, you get a black smudge; perhaps more worrisome is that if you clean your nostrils with a white material, you come up with a jet black residue; if you walk bare-footed, the soles of your feet turn black”. Plate 1 shows the severity of exposure to black soot in Port Harcourt. Our 2015 exposure estimate for Rivers State or its LGAs, do not account for this recent pollution episode. Thus, the present level of pollution may represent increased exposure and risk of mortality for the inhabitants. Indeed, Port Harcourt, Warri and Kaduna are major petroleum oil exploitation hubs in Nigeria, which contain large government refineries. Gas flaring from the refineries perhaps account for Nigeria's current position as the 7th top flaring country worldwide, with an estimate of 7.7 billion cubic meters of gas flared in 2015 (World Bank, 2017a).

3.2. $PM_{2.5}$-attributed health burden and economic loss at the sub-national level

The number of premature deaths, DALYs and economic cost attributed to population exposures to $PM_{2.5}$ pollution in Nigerian States, in 2000 and 2015, are shown in Fig. 3. Estimates for the LGAs are available in the Supplemental Materials. We observed that over the 15 year period, the annual number of premature deaths attributed to $PM_{2.5}$ pollution exposure have increased rather than decrease in most States in Nigeria. This increase is noticeable even in States where substantial reductions in pollution exposures were observed during this period. The relative large increase in the number of premature deaths attributed to $PM_{2.5}$ pollution exposure in urbanized affluent Nigerian States, such as the Federal Capital Territory (FCT), Lagos, Rivers and Akwa Ibom indicates that population growth and/or rural to urban drift may be the key factor responsible for the increased mortality. The situation is somewhat different for $PM_{2.5}$-related DALYs, where population growth between 2000 and 2015 appears to be insufficient to offset the large burden due primarily to ALRI in 2000. Premature deaths of children below 5 years of age from ALRI have indeed the strongest influence on the total $PM_{2.5}$-related DALYs.

In year 2000, the burden from ALRI dominated the overall estimation, accounting for approximately 50% of the $PM_{2.5}$-related deaths and 76% of the DALYs lost, followed in decreasing order by IHD (26% of $PM_{2.5}$-related deaths and 12% of DALYs lost), stroke (21% of $PM_{2.5}$-related deaths and 11% of DALYs lost), COPD (2% of $PM_{2.5}$-related deaths and 1% of DALYs lost) and lung cancer (1% of $PM_{2.5}$-related deaths and 0% of DALYs lost). In year 2015 however, $PM_{2.5}$-related deaths from stroke dominate the estimation accounting for approximately 34% of the $PM_{2.5}$-related deaths, followed in decreasing order by IHD (32% of $PM_{2.5}$-related deaths), ALRI (30% of $PM_{2.5}$-related deaths), COPD (3% of $PM_{2.5}$-related deaths) and lung cancer (2% of $PM_{2.5}$-related deaths). In contrast, ALRI accounted for the greater share (58%) of the $PM_{2.5}$-related DALYs lost in 2015, followed in decreasing order by stroke and IHD (each 19% of $PM_{2.5}$-related DALYs lost), COPD (2% of $PM_{2.5}$-related DALYs lost) and lung cancer (1% of $PM_{2.5}$-related DALYs lost). The pattern of disease contribution to total $PM_{2.5}$-related deaths or DALYs in Nigeria contrast that of India, which is IHD > stroke > COPD > ALRI > lung cancer (Ghude et al., 2016; Etchie et al., 2017).

We estimate that approximately 3.5 thousand $PM_{2.5}$-attributed deaths, 159 thousand lost DALYs, and USD 1.7 billion in economic cost accrue in Kano State in 2015. Kano, thus ranks as the worst

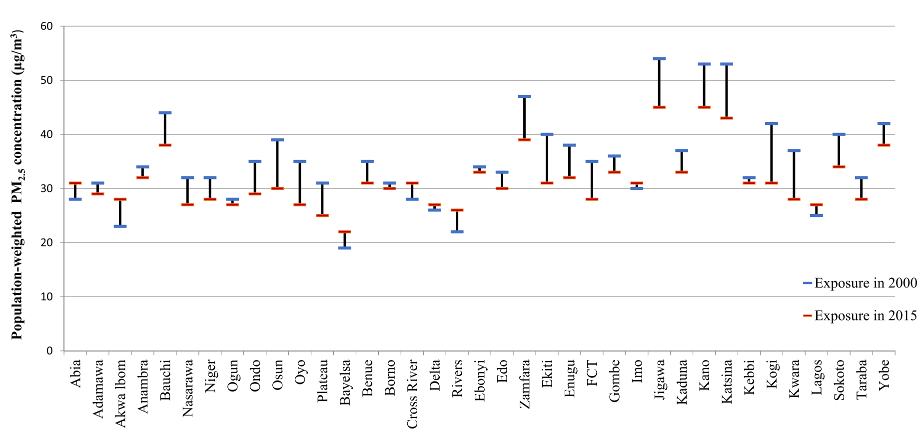

Fig. 2. The change in population exposure to ambient $PM_{2.5}$ pollution in the Nigerian States in 2000 and 2015.

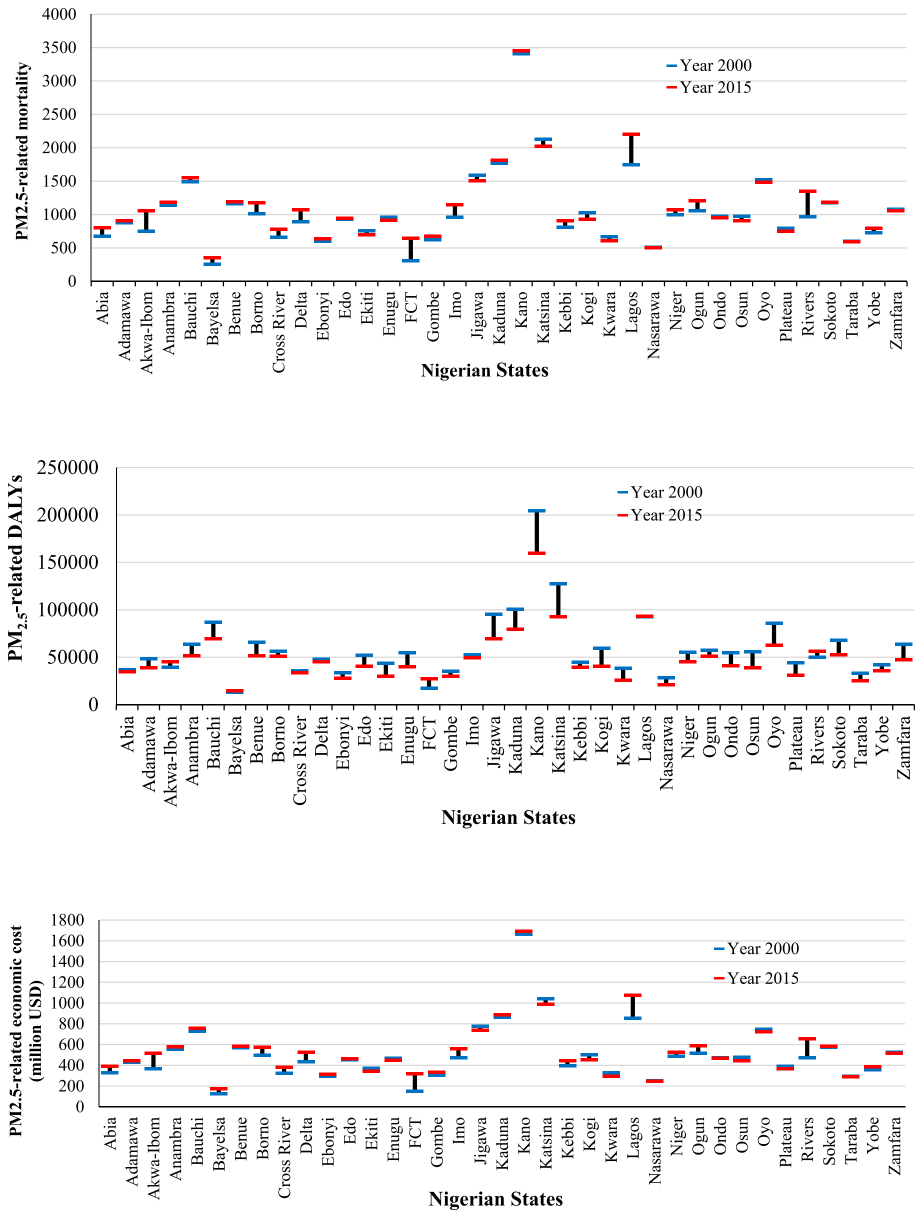

Fig. 3. The number of premature deaths, disability adjusted-life years (DALYs) and economic cost attributed to population exposures to $PM_{2.5}$ pollution in the Nigerian States, in 2000 and 2015.

affected State in Nigeria in 2015, followed in a decreasing order by Lagos State with approximately 2.2 thousand $PM_{2.5}$-attributed deaths, 93 thousand lost DALYs, and USD 1.1 billion in economic cost. Furthermore, as at 2015, Bayelsa State is the least affected State in Nigeria in terms of ambient air pollution, with approximately 350 $PM_{2.5}$-attributed premature deaths, 14 thousand lost DALYs, and USD 170 million in economic cost. Although the risk of mortality from exposure to $PM_{2.5}$ pollution is reported to be approximately five times higher for combustion $PM_{2.5}$ than for the total $PM_{2.5}$ on an equivalent concentration basis (Thurston et al., 2016), we did not however include the differential $PM_{2.5}$ toxicity in weighting exposure or risk of mortality in our estimation. This would have resulted into a larger toll of $PM_{2.5}$-related deaths, DALYs and the economic cost in the Southern States relative to the Northern States. Moreover, the IER function used to attribute the health impact from $PM_{2.5}$ pollution exposure has not included most health outcomes linked to combustion emissions, such as reproductive, immunological, neonatal, and neuropsycological impairments (Burnett et al., 2014), and to date, the Global Burden of Disease (GBD) estimates of the deaths and DALYs attributed to $PM_{2.5}$ pollution exposure have also been restricted to the health outcomes in the IER function – lung cancer, stroke, IHD and COPD (Forouzanfar et al., 2016; Cohen et al., 2017; Roy and Braathen, 2017). Therefore, there is a likelihood of a future upward revision to the toll of deaths, DALYs and economic costs from $PM_{2.5}$ pollution exposure, particularly in the Southern States of Nigeria, where combustion $PM_{2.5}$ dominates.

Our findings are consistent with similar local-level analyses reported elsewhere. A recent study in Nagpur, India reports that ambient $PM_{2.5}$ pollution caused 3.3 thousand deaths and 91 thousand DALYs with economic loss of USD 2.2 billion, yearly (Etchie et al., 2017). A state-level estimate in Kerala, India attributed 6.1 thousand annual deaths and 96 thousand DALYs to ambient $PM_{2.5}$ pollution (Tobollik et al., 2015). Other estimates includes 240 $PM_{2.5}$-

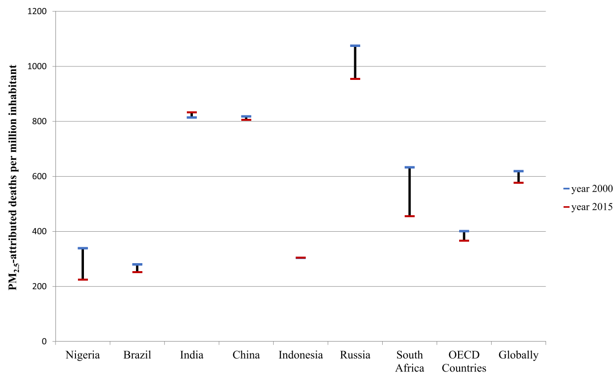

Fig. 4. Comparison of ambient $PM_{2.5}$-related death rates per one million inhabitants in Nigeria, with those in the BRIICS (Brazil, India, Indonesia, China and South Africa), OECD countries, and worldwide, between year 2000 and 2015 (OECD, 2014)

related deaths in Valladolid, Spain (Arranz et al., 2014); and 430 $PM_{2.5}$-related deaths and 5.8 thousand DALYs in Sydney, Australia (Broome et al., 2015). Higher annual estimates of 6.4 thousand deaths in Beijing's central area (Zheng et al., 2015), 13 thousand deaths in the Yangtze River Delta (Wang et al., 2015), 6.3 thousand deaths in Taiwan (Lo et al., 2016), and 12 thousand deaths in the Pearl River Delta (Jiang et al., 2015), were also attributed to ambient $PM_{2.5}$ pollution exposures.

We compare ambient $PM_{2.5}$-related death rates per one million inhabitants in Nigeria as a whole, with that in Brazil, India, Indonesia, China, and South Africa (BRIICS), and the average for countries within the Organization for Economic Cooperation and Development (OECD) and global average, between year 2000 and 2015 (Roy and Braathen, 2017) (Fig. 4). There was substantial (~34%) reduction in $PM_{2.5}$-related death rates in Nigeria over the fifteen year period due in part to the reduction in average level of $PM_{2.5}$ exposure from 36 μg/m^3 in 2000, to 32 μg/m^3 in 2015, indicating that population growth is a key factor in the observed increase in absolute number of premature deaths from air pollution. Moreover, and surprisingly, mortality rate from $PM_{2.5}$ pollution, as at 2015, is lower in Nigeria than in Brazil, India, Indonesia, China or South Africa. $PM_{2.5}$-related death rate, in 2015, is also lower in Nigeria, than in OECD countries or global average. Population age distribution may be an important factor accounting for the mortality rate from air pollution being lower in Nigeria than in the other countries. Nigeria has a higher percentage of younger people than the countries making up BRIICS, OECD or the global average population age structure (World Bank, 2017b). If so, the baseline mortality rates for age-related conditions (COPD, IHD, stroke, lung cancer) in Nigeria will be lower than in other countries, which would be propagated through the air pollution attributable mortality calculations. The mortality rate from air pollution may however worsen as Nigerian population grows old.

3.3. *The gains in life expectancy accruing from attainment of the global AQG*

Fig. 5 shows $\Delta e_{(\geq 25\ year)j}$ plotted against ε_j for an increment of 10 percentile, starting from 0 percentile to 100 percentile for COPD, IHD, stroke and lung cancer, and for $\Delta e_{(\geq 25\ year)j}$ and ε_j values corresponding to $PM_{2.5}$ concentration of 10 μg/m^3 and 5.9 μg/m^3. The relationship appears to be nonlinear for the four health outcomes, with % mean absolute error (%MAE) for out-of-sample cross validation of 0.1%, 0.4%, 0.9% and 0.1% for COPD, IHD, stroke and lung cancer, respectively. This is in agreement with an earlier report, that for highly polluted localities, the loss in life expectancy from $PM_{2.5}$-related mortality may be accurately approximated by a quadratic function of the excess rate ratio for each of the four health outcomes: COPD, IHD, stroke or lung cancer (Stieb et al., 2015).

The estimates of the loss in life expectancy attributed to ambient $PM_{2.5}$ pollution exposure, and the gains accruing from attainment of the global AQG of 10 μg/m^3, in the 37 States in Nigeria, are shown in Fig. 6. Estimates for the 773 LGAs are available in the Supplemental Material. Assuming equal toxicity of $PM_{2.5}$ emission from all sources, we estimate that long-term exposure to ambient $PM_{2.5}$ pollution reduces life expectancy of people residing in the six “highly polluted” States (Kano, Jigawa, Katsina, Zamfara, Yobe and Bauchi) by approximately 3.8–4.0 years. Similarly, people residing in the thirty “polluted” States and one “moderately polluted” State (Bayelsa), lose on average between 3.0 and 3.6 years, and 2.7 years of life expectancy due to exposure to ambient $PM_{2.5}$ pollution. Our estimates are substantially higher than the predicted loss of life expectancy of 3.1 years, 1.6 years and 0.8 years for people residing in “highly polluted”, “moderately polluted” and “mildly polluted” Chinese localities, respectively (Dockery and Pope, 2014). The Chinese estimates were however derived using age-specific death rates of US population.

We estimate that if average annual ambient $PM_{2.5}$ pollution levels in all Nigerian localities were reduced to WHO AQG of 10 μg/m^3, current life expectancy in Nigerian States could increase by approximately 2.6–2.9 years; 1.9 to 2.5 years; and 1.6 years for people residing in the highly polluted, polluted and moderately polluted States, respectively. These gains in life expectancy, particularly in the highly polluted and polluted Nigerian States exceed the estimated gain in longevity of 1.8 years or 1.7 years for similar reductions in ambient $PM_{2.5}$ pollution in highly polluted European cities (Medina, 2012; WHO, 2013) or polluted Indian district (Etchie et al., 2017), respectively, suggesting that pollution reductions in Nigeria have greater survival benefits than in these countries. This information is especially important since the absolute $PM_{2.5}$-related health burden in India is by far larger than that in Nigeria (IHME, 2016).

For Nigeria as a whole, and as at 2015, long-term exposure to ambient $PM_{2.5}$ pollution reduces life expectancy by approximately 3.5 years on the average, with a range of 2.4–4.1 years in the LGAs. But, assuming all 773 LGAs in Nigeria attain the global AQG of 10 μg/m^3, average life expectancy could increase by approximately 2.4 years with a range of 1.3–3.0 years. A study that correlates actual reductions in $PM_{2.5}$ pollution exposure over several decades in the US with changes in life expectancies found that a 10 μg/m^3 decline in $PM_{2.5}$ pollution exposure levels resulted in a gain in life expectancy of ~7.3 months (Pope et al., 2009). Further analysis using more recent dataset revealed additional gain of ~4.2 months for similar $PM_{2.5}$ reduction (Correia et al., 2014). Similar changes in life expectancy of 13.3 months in the Netherlands (Brunekreef, 1997), 16.4 months in Finland (Nevalainen and Pekkanen, 1998), 9.6 months in Canada (Coyle et al., 2003), and 9 months in India (Etchie et al., 2017), were predicted for a 10 μg/m^3 change in $PM_{2.5}$ pollution exposure level.

3.4. *The influence of demography on $PM_{2.5}$-related health burden and cost in Nigeria under a planned mitigation scenario*

We compared future changes in the distribution of the health burden and economic cost attributed to $PM_{2.5}$ pollution in Nigeria, in two scenarios – a baseline scenario that assumes that future average $PM_{2.5}$ pollution level and baseline mortality rates for the diseases in Nigeria remained unchanged, and a planned mitigation scenario that assumes sustained pollution reductions down to the AQG by 2045. But first, a look at the trend of the observed $PM_{2.5}$-related health burden and cost between 2000 and 2015 in Nigeria

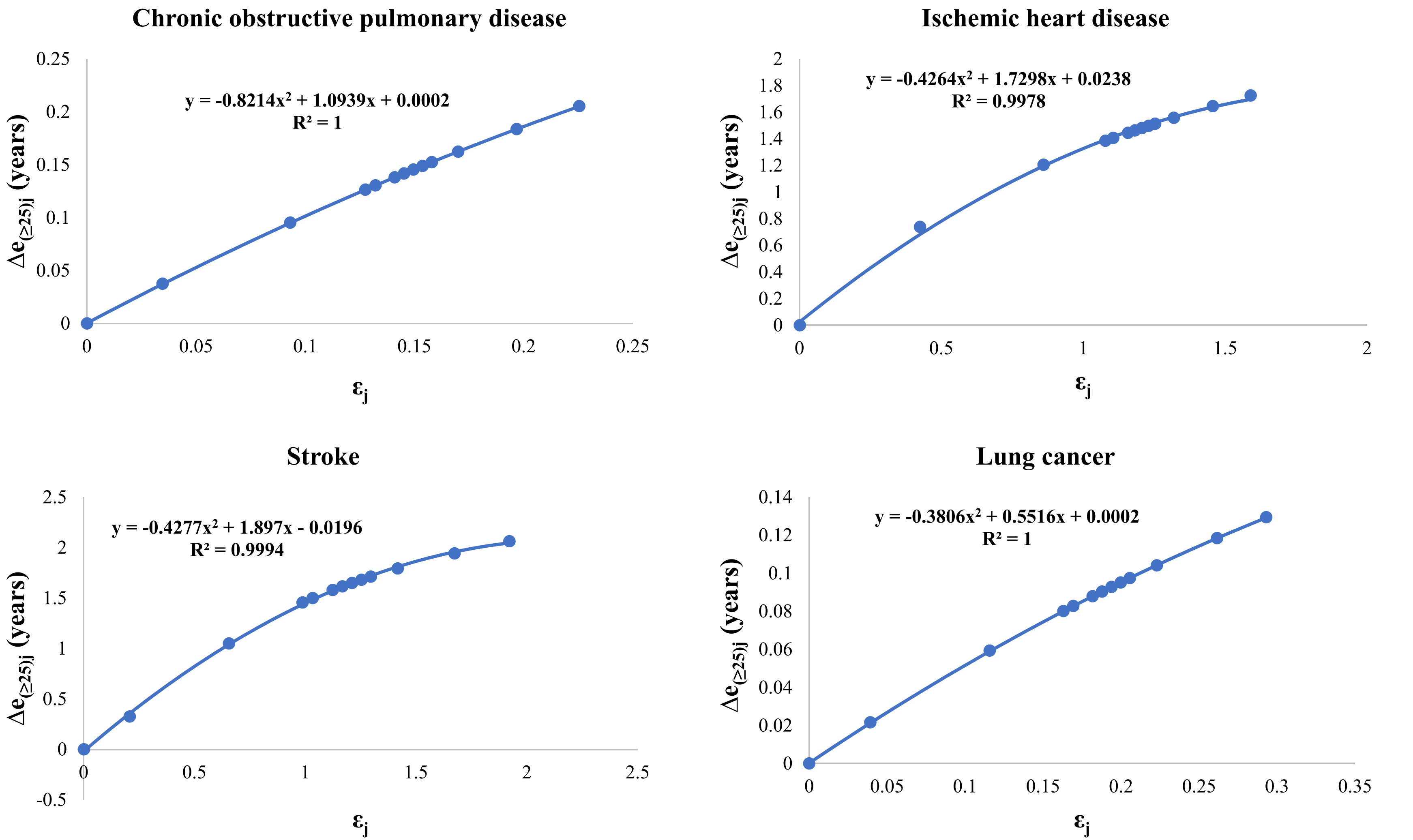

Fig. 5. Ambient $PM_{2.5}$-attributed cause-specific loss in life expectancy for the cohort ≥ 25 years old in Nigeria ($\Delta e_{(\geq 25)j}$), plotted against excess rate ratio (ε_j).

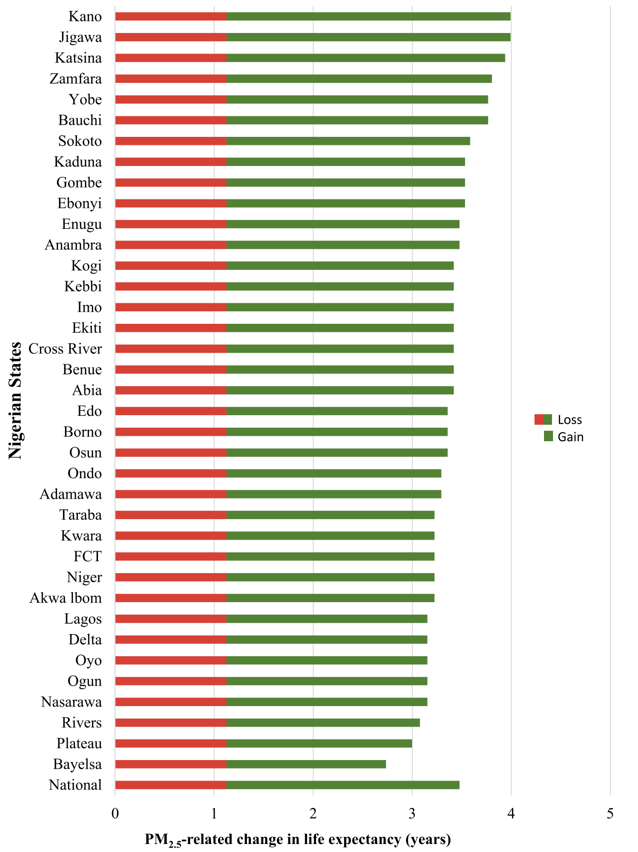

Fig. 6. Estimate of the loss in life expectancy attributed to ambient $PM_{2.5}$ pollution exposure, and the gains accruing from attainment of the global air quality guideline of 10 μg/m^3; in States and in Nigeria as a whole.

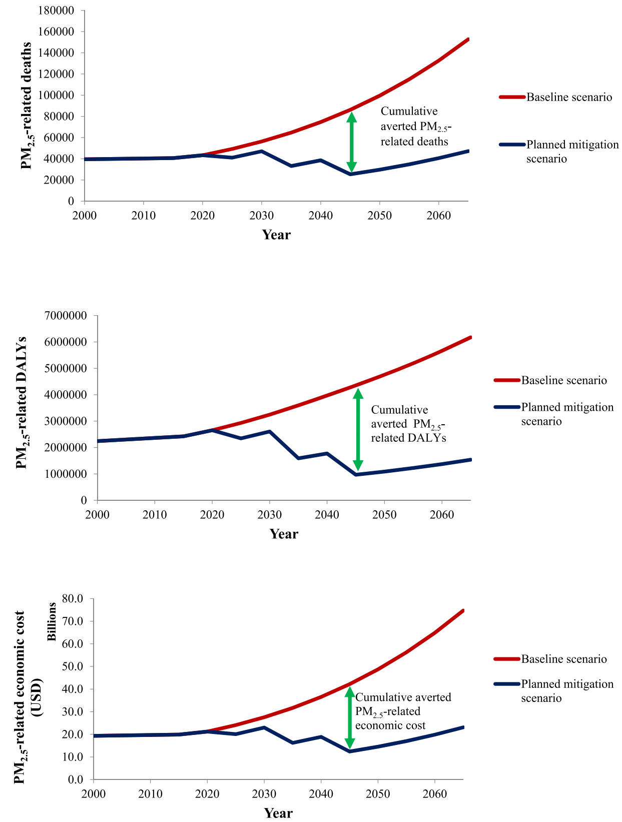

Fig. 7. Distribution of $PM_{2.5}$-related deaths, disability-adjusted life years (DALYs) and economic cost in Nigeria under baseline scenario that assumes constant average annual $PM_{2.5}$ pollution exposure and constant baseline mortality rates for the disease outcomes; and a planned mitigation scenario that attains global interim target 2 (25 μg/m^3) by 2025, global interim target 3 (15 μg/m^3) by 2035 and global air quality guideline (10 μg/m^3) by 2045.

as a whole (Fig. 7) reveals that the toll of premature deaths, DALYs and economic cost attributed to ambient $PM_{2.5}$ pollution exposure increased by approximately 3%, 8% and 3% respectively over the fifteen year period, even though average $PM_{2.5}$ pollution exposure reduced by approximately 11% during that period. Assuming that future exposure level and baseline mortality rates of the disease in Nigeria remained the same as that of 2015, the toll of premature deaths, DALYs lost and economic cost attributed to ambient $PM_{2.5}$ pollution exposure would increase each by about 21% by the year 2025, with even higher percentages in the future. Under the planned mitigation scenario, it could be seen that the residual health and economic burdens in any year vary around the value at the start of mitigation, which is 2015. This indicates that the number of premature deaths, DALYs and economic cost averted due to the mitigation intervention would largely offset increases in $PM_{2.5}$-related deaths, DALYs lost and cost arising from future changes in population demography. Specifically, we estimate that a reduction in the annual average $PM_{2.5}$ pollution exposure level from 32 μg/m^3 to 25 μg/m^3 by 2025 would be insufficient to offset the increase in $PM_{2.5}$-related mortality arising from changes in population demography in Nigeria within that period. Indeed, while the $PM_{2.5}$-related premature mortality and the economic cost would increase by approximately 1%, $PM_{2.5}$-related DALYs would decrease by about 3%. Further reduction from 25 μg/m^3 to 15 μg/m^3 by 2035 would avert on the average, approximately 19% of the $PM_{2.5}$-attributed premature deaths (7.9 thousand), 32% of DALYs (757 thousand) and 19% of the economic lost (USD 3.9 billion) in that year. Attainment of the global AQG of 10 μg/m^3 by the year 2045 would avert approximately 19% of the $PM_{2.5}$-attributed deaths (7.8 thousand), 39% of DALYs lost (620 thousand) and 19% of the economic lost (USD 3.8 billion) in 2045. Also, judging from the large residual health burden in 2055, there would be substantial gains going further below the AQG in the future. This is especially true as air pollution has no safe limit (Krzyzanowski and Cohen, 2008), indicative of the need to achieve the lowest level of exposure possible in all microenvironments both outdoor and indoor.

Our findings are consistent with similar analyses reported elsewhere. A district-level estimate in India revealed that a step-wise reduction in $PM_{2.5}$ pollution exposure from 34 μg/m^3 to 25 μg/m^3, from 25 μg/m^3 to 15 μg/m^3, and from 15 μg/m^3 to 10 μg/m^3 in every 10 years would avert approximately 15%, 30% and 36% of the $PM_{2.5}$-related premature deaths, DALYs lost and economic cost, respectively, translating into an impressively large health and economic gains in those years (Etchie et al., 2017). Also, a state-level estimate in India showed that a 10% decrease in PM exposure level in Kerala, would avert 16 thousand lost life years annually (Tobollik et al., 2015). Another study reports that a 17% reduction in average $PM_{2.5}$ pollution exposure in the Pearl River Delta region in China would avert greater than 2.9 thousand premature deaths, annually (Jiang et al., 2015). A study in Brazil reports that a reduction from the yearly average $PM_{2.5}$ level of exposure in São Paulo, by 5 μg/m^3 would avert approximately 1.7 thousand premature deaths and save USD 5.0 billion, yearly (Abe and Miraglia, 2016). The study further reports that attainment of the global AQG in São Paulo would avert greater than 5 thousand premature deaths and 266 thousand DALYs lost, and save USD 15 billion, yearly (Abe and Miraglia, 2016).

Plate 1. 2017 Plate 1: Level of exposure to black soot in Port Harcourt, Rivers State, Nigeria (BBC, 2017).

4. Discussion

We have, for the very first time in Nigeria, used a combination of hazard and survival analyses based on Nigeria life table to calculate the share of premature deaths, DALYs, economic cost and the loss in life expectancy attributed to ambient $PM_{2.5}$ pollution exposure, at the local, sub-national level in Nigeria for the year 2000, 2015, 2025, 2035 and 2045. We have also calculated the averted burdens, economic cost and the gains in longevity accruing from attainment of the global AQG. We have derived the estimates from clinical counts of the annual number of premature deaths or DALYs from ALRI, COPD, stroke, IHD and lung cancer in Nigeria (IHME, 2016) and the epidemiology that attributes the percentage of clinically diagnosed premature deaths from each of the diseases to air pollution (Burnett et al., 2014; Apte et al., 2015).

Ambient $PM_{2.5}$ pollution exposure claims several thousand premature deaths and DALYs in Nigeria as a whole, and imposes thereby an annual economic cost of several tens of billions of US dollars. It is striking to note that the toll of premature deaths, DALYs and economic cost of ambient air pollution exposure are rising very fast in Nigeria in spite of the slow or zero industrialization, and not even the 11% reduction of pollution exposure observed between year 2000 and 2015 could reverse this increasing trend. In order to reverse this negative trend, arising from changes in population demography, ambient $PM_{2.5}$ pollution exposure would need to be cut, on the average, by over 25% over the next 10 years. Achieving this magnitude of pollution reduction in Nigeria would require conscious effort coupled with radically innovative mitigation interventions that target localities having the highest level of exposure to air pollution.

For the very first time, we have detailed results of the toll of premature deaths, DALYs lost and economic cost from ambient air pollution exposure at the local sub-national official administrative levels in Nigeria (States and LGAs). So, policy decision-makers at the three levels of government in Nigeria, and all relevant stakeholders can understand and appreciate the magnitude of the burdens, and identify priority areas and suitable mitigation interventions. There is reason to suppose that future revisions to the toll of premature deaths, DALYs and economic cost from ambient air pollution exposure in Nigeria are very likely to be an upward rather than downward direction because our present estimates are conservative. We only consider the contribution from just five health outcomes listed in the IER function. But a growing body of evidence indicates that exposure to ambient air pollution could also increase the risk of mortality from diabetes mellitus, preterm and underweight births (Meo et al., 2015; Weinmayr et al., 2015; Coker et al., 2016; Dõâaz et al., 2016; Feng et al., 2016; Li et al., 2016; Nachman et al., 2016), reproductive, immunological and neuropsycological impairments (Guxens and Sunyer, 2012; Amegah and Jaakkola, 2014; García-Pérez et al., 2015; Roy and Braathen, 2017; US EPA Etchie et al., 2017) especially in Nigeria where both exposure to $PM_{2.5}$ and the baseline mortality rates from these health outcomes are very high (IHME, 2016; WHO, 2016b). Furthermore, we have not included the additional health burdens and cost arising from gaseous pollutants such as volatile organic compounds, ozone, nitrogen and sulfur oxides in our estimation, which have been shown to be independently harmful to human health (Roy and Braathen, 2017). The likelihood of such a future upward revision to the toll from ambient air pollution exposure in Nigeria should therefore underscore the importance and urgency to act now.

In order to obtain optimum health and economic gains from mitigation interventions, immediate priority should be given to localities and pollution sources having the highest level of population exposure, both outdoor and indoor. It is estimated that more than half of the population in Nigeria use “dirty” fuels like firewood and coal, kerosene, petrol and diesel for cooking and electrification purposes, causing PM exposure level within households reaching 750 $\mu g/m^3$ (Lam et al., 2012; Chafe et al., 2014). A complete changeover from these dirty fuels for cooking and electrification, to clean fuels like liquefied petroleum gas, abundant but being flared in Nigeria, and renewable energy sources, would achieve substantial pollution reductions both indoors and outdoors, resulting into disproportionately greater health and economic gains in Nigeria, and should therefore be prioritized. Furthermore, innovative thinking and green urban landscape would be required to cut down air pollution exposure from the Saharan desert and from desertification in the Northern region. A more comprehensive approach, from end-of-pipe emission control in the short run, to a more structural control strategy such as the switch from dirty to clean and renewable energy sources for power generation and changes in urban landscape would be required to tackle exposure from vehicular, industrial and construction emission in the long run. Additional recommendations suitable for addressing air pollution and its associated burdens in Nigeria have been documented (Amegah and Agyei-Mensah, 2017; Etchie et al., 2017).

5. Conclusion

Exposure to ambient $PM_{2.5}$ pollution in Nigeria as a whole reduces life expectancy by approximately 3.5 years on average, with a range of 2.4–4.1 years in the local government areas. But, assuming all localities in Nigeria attain the global air quality guideline of 10 $\mu g/m^3$, average life expectancy could increase by approximately 2.4 years with a range of 1.3–3.0 years. But, if nothing is done now to cut down on the level of exposure to air pollution in Nigeria, several tens of thousands of people in Nigeria will continue to become sick and die prematurely. This situation will become even worst in the future where ageing and population growth will cause more and more money to be spent to cure and manage air pollution related illness, which would otherwise have been averted.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2018.01.034.

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