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Development of the Low Emissions Analysis Platform – Integrated Benefits Calculator (LEAP-IBC) tool to assess air quality and climate co-benefits: Application for Bangladesh

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ABSTRACT

Low- and middle-income countries have the largest health burdens associated with air pollution exposure, and are particularly vulnerable to climate change impacts. Substantial opportunities have been identified to simultaneously improve air quality and mitigate climate change due to overlapping sources of greenhouse gas and air pollutant emissions and because a subset of pollutants, short-lived climate pollutants (SLCPs), directly contribute to both impacts. However, planners in low- and middle-income countries often lack practical tools to quantify the air pollution and climate change impacts of different policies and measures. This paper presents a modelling framework implemented in the Low Emissions Analysis Platform – Integrated Benefits Calculator (LEAP-IBC) tool to develop integrated strategies to improve air quality, human health and mitigate climate change. The framework estimates emissions of greenhouse gases, SLCPs and air pollutants for historical years, and future projections for baseline and mitigation scenarios. These emissions are then used to quantify i) population-weighted annual average ambient $PM_{2.5}$ concentrations across the target country, ii) household $PM_{2.5}$ exposure of different population groups living in households cooking using different fuels/technologies and iii) radiative forcing from all emissions. Health impacts (premature mortality) attributable to ambient and household $PM_{2.5}$ exposure and changes in global average temperature change are then estimated. This framework is applied in Bangladesh to evaluate the air quality and climate change benefits from implementation of Bangladesh's Nationally Determined Contribution (NDC) and National Action Plan to reduce SLCPs. Results show that the measures included to reduce GHGs in Bangladesh's NDC also have substantial benefits for air quality and human health. Full implementation of Bangladesh's NDC, and National SLCP Plan would reduce carbon dioxide, methane, black carbon and primary $PM_{2.5}$ emissions by 25%, 34%, 46% and 45%, respectively in 2030 compared to a baseline scenario. These emission reductions could reduce population-weighted ambient $PM_{2.5}$ concentrations in Bangladesh by 18% in 2030, and avoid approximately 12,000 and 100,000 premature deaths attributable to ambient and household $PM_{2.5}$ exposures, respectively, in 2030. As countries are simultaneously planning to achieve the climate goals in the Paris Agreement, improve air quality to reduce health impacts and achieve the Sustainable Development Goals, the LEAP-IBC tool provides a practical framework by which planners can develop integrated strategies, achieving multiple air quality and climate benefits.

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1. Introduction

Low- and middle- income countries (LMICs) are disproportionately affected by air pollution impacts on health, with millions of premature deaths attributed globally to exposure to outdoor (ambient) and household particulate matter each year (Health Effects Institute, 2018). Climate change is affecting many countries with increasingly severe and frequent heat waves, unusual levels of flooding and disruption of rainfall (Myles et al., 2018). These countries are least able to cope with the impacts of climate change, and air pollution places an additional burden on economic productivity, on the health system, and disproportionately affects the poor, women and children. Countries have outlined their contribution to mitigating climate change through their Nationally Determined Contributions (NDCs), which are currently not sufficient to achieve the global average temperature targets set out in the Paris Agreement, and additional ambition is needed (Rogelj et al., 2016). Some pollutants contribute to both poor air quality and climate change, while others share the same source (Fiore et al., 2015; von Schneidemesser et al., 2015). Therefore, in the context of the increased ambition needed to meet global temperature goals, and the substantial burden air pollution has in LMICs, there is substantial potential for the development of integrated mitigation strategies in these countries to achieve simultaneous benefits for local air pollution and global climate change.

The effectiveness of integrated air pollution and climate change strategies has been demonstrated by multiple global and regional assessments. For example, the global implementation of actions targeting the major sources of Short-Lived Climate Pollutants (SLCPs), which contribute to both air quality and climate impacts and include methane, black carbon, tropospheric ozone and hydrofluorocarbons (HFCs) could reduce global temperature increases by 0.5 °C. Simultaneously, it was estimated to also avoid 2.4 million premature deaths attributable to air pollution exposure annually by 2030 (Shindell et al. (2012); UNEP/WMO (2011)). In Asia and the Pacific, the top 25 'clean air' measures were estimated to reduce $PM_{2.5}$ concentrations below WHO guidelines for 1 billion people, and at the same time avoid 0.3 °C of global temperature increases (UNEP, 2019). Finally, increasing climate change mitigation ambition to limit global temperature increases to below 2 °C was also estimated to avoid 1 million premature deaths per year globally from the reduction in air pollution that would be simultaneously achieved (Vandyck et al., 2018).

Effective planning is needed at the national level to realise benefits of integrated air pollution and climate change mitigation strategies. However, there are few examples of such integrated planning, especially in LMICs, which have the largest health burdens from air pollution exposure and are most vulnerable to climate change. Integrated planning on air pollution and climate change at the national level can be effectively facilitated by a quantitative assessment of the potential of different mitigation measures to simultaneously reduce emissions of greenhouse gases (GHGs), SLCPs and other air pollutants, in combination with other activities such as engagement of stakeholders, evaluation of barriers and implementation pathways etc. This can allow actions to be identified and prioritised, and can inform evidence-based decision making (Sutcliffe and Court, 2005). However, LMICs are often lacking tools to allow such analysis and the capacity to use them. Running detailed atmospheric models and applying epidemiological concentration–response relationships to assess impacts is computationally and resource intensive and not widely undertaken in LMICs.

This paper describes the development and application of LEAP-IBC. The Low Emissions Analysis Platform (LEAP) system, is a scenario-based planning framework for integrated planning of energy policy and emissions abatement, developed over the last 30 years at the Stockholm Environment Institute (Heaps, 2020). LEAP has recently been updated to include a new calculation module called IBC, the Integrated Benefits Calculator. IBC is integrated within LEAP, and calculates $PM_{2.5}$-attributable health (premature mortality), and climate (global temperature change) impacts for different emissions scenarios developed within LEAP. The results are displayed within LEAP's graphical user interface (GUI). While different tools exist to assess the impact of different strategies on air pollution and climate change (Anenberg et al., 2016; Kiesewetter et al., 2015; Van Dingenen et al., 2018), the overall tool (hereafter referred to as LEAP-IBC) has been specifically designed to be accessible to planners in LMIC countries, in situations where data and institutional capacity for modelling are typically limited. This study presents the analytical methodology within LEAP-IBC that allows for the integrated assessment of the air quality and climate benefits of different mitigation measures, as well as overall strategies related to climate mitigation, air quality management, energy planning, low emission development, and sustainable development.

The application of LEAP-IBC to assess integrated air pollution and climate change strategies in LMICs is illustrated for Bangladesh, where there are significant air pollution health impacts (Goyal and Canning, 2017; Gurley et al., 2013; Khan et al., 2019; Shi et al., 1999), and vulnerabilities to climate change (Karim and Mimura, 2008; Ruane et al., 2013). Two national strategies relevant for air pollution and climate change are assessed. These are Bangladesh's Nationally Determined Contribution (NDC) that contains Bangladesh's climate change commitment and the mitigation measures to achieve it (Ministry of Environment and Forests, 2015), and Bangladesh's National Action Plan to reduce SLCPs (Bangladesh Department of Environment, 2018). Bangladesh was a founding member of the Climate and Clean Air Coalition to reduce SLCPs (http://ccacoalition.org/), a voluntary partnership of over 120 State and non-State partners. With support from the CCAC Supporting National Action & Planning initiative, the Bangladesh Department of Environment led the development of a National Action Plan to reduce SLCPs. This plan identifies priority measures in major source sectors for SLCP-relevant emissions, and recommends specific actions for their implementation. The aim of the LEAP-IBC modelling application is to evaluate both plans in terms of their collective impact on improving air quality locally in Bangladesh, while also contributing to reducing Bangladesh's contribution to global climate change.

2. Methods

2.1. LEAP-IBC modelling framework

The overall modelling framework for the assessment of air pollution and climate change benefits within LEAP-IBC is shown in Fig. 1. LEAP, the Low Emissions Analysis Platform (Heaps, 2020) is used as the basis for estimating emissions of relevant GHGs, SLCPs and air pollutants from all major source sectors. These estimates include an emission inventory for historical year(s), as well as future scenarios of how emissions might evolve into the future under a range of alternative scenarios. These scenarios typically include baseline scenarios as well as abatement scenarios specifically designed to reduce emissions of GHGs, SLCPs and air pollutants. The emissions developed in LEAP are then used as input to the Integrated Benefits Calculator (IBC) module, which converts them into the estimated population-weighted annual average ambient $PM_{2.5}$ concentration across the target country and change in radiative forcing associated with a given level of emissions. These are finally converted into changes in impacts, on premature mortality attributable to ambient $PM_{2.5}$ exposure, and global average temperature change, respectively. IBC itself has no graphical user interface. It is seamlessly integrated within LEAP. Results are returned for display using LEAP's results visualization capabilities (charts, tables, maps, energy balances, sankey diagrams, etc., an example of which is shown in Fig. 2). The overall system makes extensive use of LEAP's Application Programming Interface (API), a system that allows LEAP to be closely connected to other models and tools based on a programmable interface and a series of additional external scripts that connect LEAP and the IBC calculator. The following sub-sections describe in more detail the approach to developing emission estimates for different scenarios (Section 2.1.1), the conversion of emissions to ambient $PM_{2.5}$ concentrations (Section

2.1.2), and exposure to household air pollution (Section 2.1.3) and the health (Section 2.1.4) and climate (Section 2.1.5) impact assessment methodologies included in LEAP-IBC.

2.1.1. Emission inventory and scenario modelling

LEAP is flexible with regard to geographic scale (i.e. regional, national or sub-national models are supported), time-frame, and the emission sources that are modelled. There are then requirements for models to be compatible with modelling of air pollution and climate change impacts using IBC. Firstly, the modelling of $PM_{2.5}$ concentrations described in Section 2.1.2 is available only at the national scale, and therefore a national model must be developed. Secondly, the $PM_{2.5}$

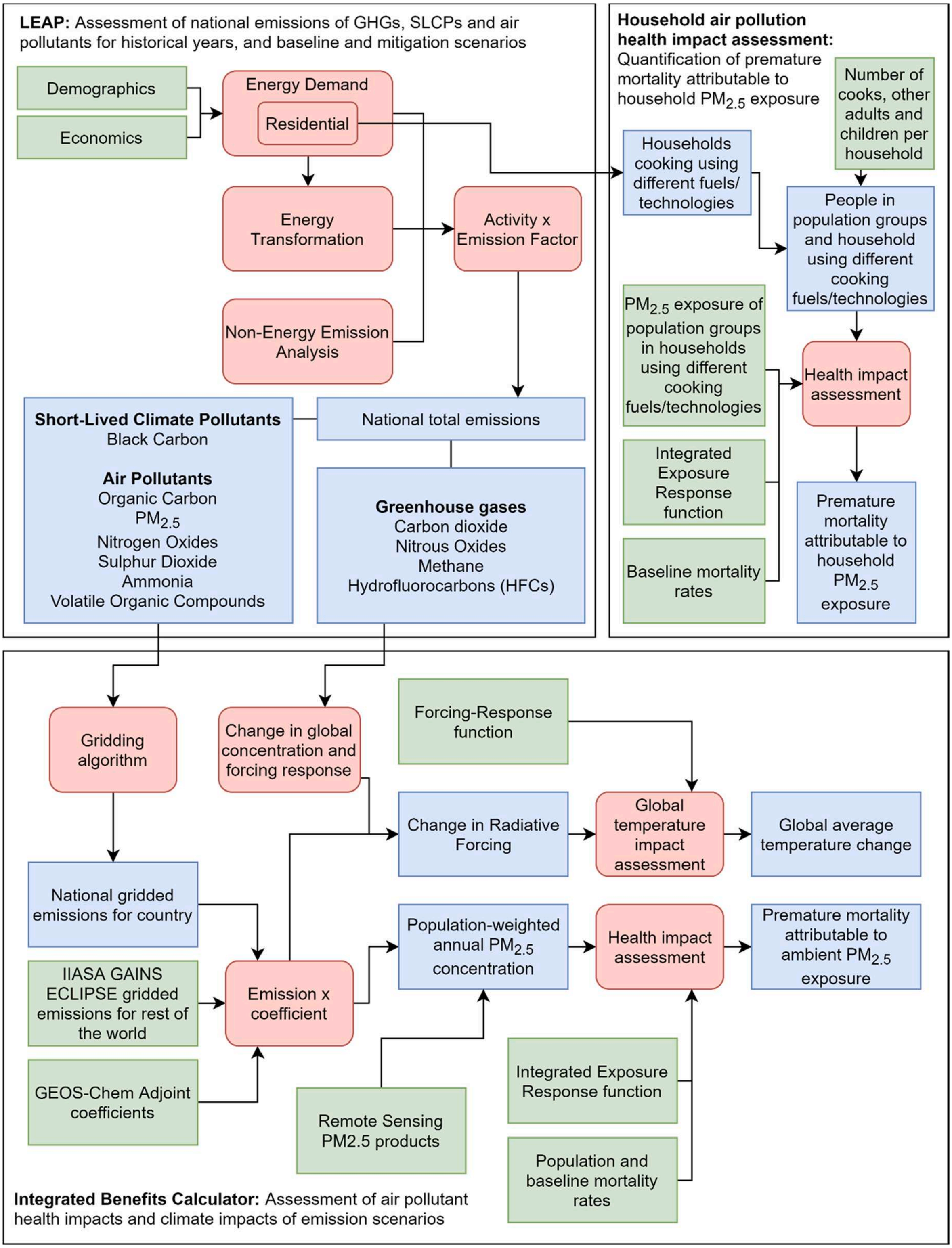

Fig. 1. Schematic of LEAP-IBC framework for estimating emissions for different scenarios and the resultant population-weighted annual average $PM_{2.5}$ concentration, health impacts, and impact on global average temperature change. Key inputs are shown in green, calculations in red, and outputs in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concentrations in the atmosphere are a result of the combination of emissions of primary $PM_{2.5}$ from multiple sources, as well as secondary formation of $PM_{2.5}$ from gaseous precursors (Heal et al., 2012). The overall impact of a country on global temperature increases depends on the balance of emissions of substances that warm the atmosphere (e.g. GHGs and black carbon) and those that cool the atmosphere (e.g. cooling aerosols like organic carbon, and secondary inorganic aerosols. Therefore, to robustly estimate $PM_{2.5}$ concentrations, attributable health impacts and impacts on global temperature change, a complete inventory of GHG, SLCP, and air pollution emissions from all major source sectors is required. For this reason, a LEAP model used in combination with IBC should quantify total national emissions of GHGs (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons), SLCPs (black carbon, methane, HFCs), and other air pollutants (nitrogen oxides, non-methane volatile organic compounds, sulphur dioxide, ammonia, primary particulate matter ($PM_{2.5}$, PM_{10}, made up of organic carbon, black carbon and mineral dust), carbon monoxide). Emissions from all major sources of these substances must be quantified, including the energy, industrial processes, waste, and agricultural sectors. A default LEAP model has been developed which meets these requirements. It was used to develop the analysis for Bangladesh and is outlined in Section 2.2. While this LEAP model contains a set of methods for estimating emissions of GHGs, SLCPs and air pollutants from all major source sectors, LEAP can accommodate a range of methods for estimating emissions from energy and non-energy sectors (e.g. higher Tier IPCC or EMEP/EEA methods could be used to estimate emissions if data was available (EMEP/EEA, 2016; IPCC, 2006)), as well as country-specific activity and emission factors if available.

2.1.2. Modelling ambient $PM_{2.5}$ exposure

Once national total emissions of GHGs, SLCPs and air pollutants have been estimated using LEAP for all major source sectors, for historical years, and future scenarios (e.g. as described in Section 2.2. for Bangladesh), the IBC module converts these emissions into national, population-weighted annual average ambient $PM_{2.5}$ concentrations (hereafter abbreviated to $PM_{2.5PW}$). The $PM_{2.5PW}$ value is used as the estimate of the average exposure of the population of the target country to $PM_{2.5}$, for use in the health impact assessment (Section 2.1.3). $PM_{2.5PW}$ is calculated for the target country for each year and for each scenario. Ambient $PM_{2.5}$ concentrations in a country depend on emissions of $PM_{2.5}$ and $PM_{2.5}$-precursors in the target country, and emissions in other countries that are transported into the country. The impact of these emissions on $PM_{2.5}$ in the target country depends on where they are emitted, and therefore gridded emission estimates of each pollutant are developed for both national and 'rest of world' emissions.

National total emissions of primary $PM_{2.5}$ (black carbon, organic carbon and other primary PM emissions), and secondary inorganic $PM_{2.5}$ precursors (NO_x, SO_2 and NH_3) derived using LEAP for the target country are spatially distributed into 2° × 2.5° grids covering the country to match the scale of the GEOS-Chem Adjoint model results (see below). The proportion of national total emissions of each pollutant assigned to the 2° × 2.5° grids covering the country was based on the spatial distribution of emissions across Bangladesh in an existing gridded emission dataset, the IIASA GAINS ECLIPSE emissions dataset (Stohl et al., 2015). The ECLIPSE estimates emissions of SLCPs and air pollutants for historical and future projections in 0.5° grids globally. For those grids that cover the target country, the ECLIPSE emissions were apportioned by population (based on Gridded Population of the World v3 dataset (CIESIN, 2005)). This ensured that the LEAP-derived emissions only replace the emissions associated with the target country. Emissions from the rest of the world are represented by the gridded ECLIPSE emissions outside of the target country, aggregated from the native 0.5° grids to 2° × 2.5°.

Next, to translate gridded emissions to $PM_{2.5PW}$, accounting for transport and chemical processing in the atmosphere, tgidded emissions are then combined with parameterized output from the adjoint of the

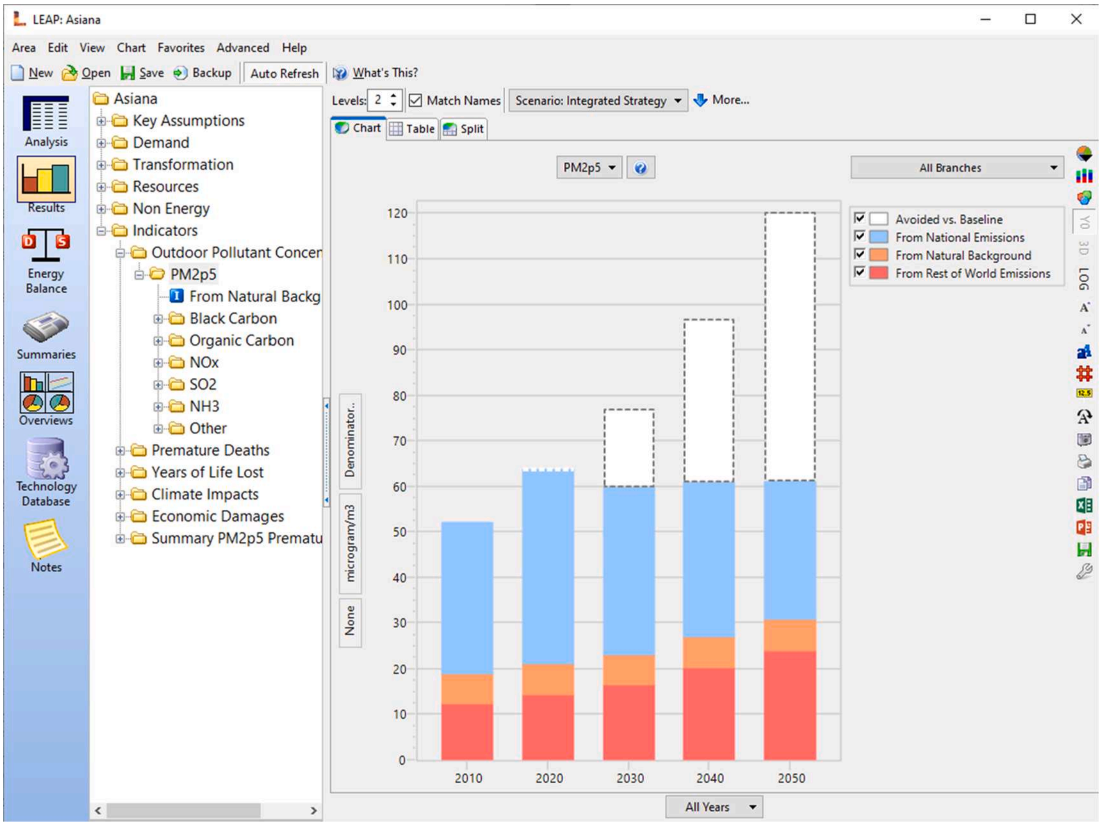
Levels: 2 ☑ Match Names Scenario: Integrated Strategy

Fig. 2. A screenshot showing health impacts results calculated in IBC being displayed within LEAP's Graphical User Interface (Sample Results).

GEOS-Chem global atmospheric chemistry transport model (Bey et al., 2001; Henze et al., 2007). The GEOS-Chem Adjoint model output quantifies the relationship between emissions of a particular pollutant that contributes directly to $PM_{2.5}$ (BC, OC or other PM), or is a precursor to $PM_{2.5}$ (NO_x, SO_2 and NH_3) in any location, and the associated change in $PM_{2.5}$ in the target country. GEOS-Chem simulates the formation and fate of pollutants globally at a grid resolution of 2° × 2.5°, with 47 vertical levels. Emissions of aerosols and aerosol precursors include both natural (i.e., ocean, volcanic, lightning, soil, biomass burning, biogenic and dust) and anthropogenic (transportation, energy, residential, agricultural, etc.) sources. The model accounts for the transport and hydrophilic aging and removal of primary carbonaceous aerosols (BC and OC) (Park et al., 2003) along with heterogeneous surface chemistry (Evans and Jacob, 2005), aerosol feedbacks on photolysis rates (Martin et al., 2003), and partitioning of secondary inorganic aerosols (sulfate, nitrate, and ammonium) (Park, 2004). The adjoint of the GEOS-Chem model calculates the sensitivity of a particular model response metric (in this case population-weighted annual average surface $PM_{2.5}$ concentration across the target country) with respect to an emission perturbation in any of the global model 2° × 2.5° grid cells (Henze et al., 2007), accounting for all of the mechanisms related to aerosol formation and fate. These sensitivities are output from the GEOS-Chem adjoint as gridded 'coefficients', which are then multiplied by emission estimates in IBC to estimate the change in $PM_{2.5PW}$ for each year and emission scenario. For more details, see previous applications of GEOS-Chem adjoint coefficients for estimating responses to spatially explicit emissions changes (e.g. Henze et al., 2012; Lacey and Henze, 2015; Lacey et al., 2017; Lapina et al., 2015; Paulot et al., 2013).

Adjoint coefficients were produced for each pollutant that contributes to $PM_{2.5PW}$ concentrations, namely, BC, OC, NO_x, SO_2, NH_3 and other PM (in this case, predominantly mineral dust), reflecting their different reactivity and formation pathways in the atmosphere. The adjoint coefficients are applied by multiplying, in each grid and for each pollutant, the coefficient by emissions, and summing across all grids to estimate the change in $PM_{2.5PW}$ for a particular year for a particular scenario.

A limitation of the application of the adjoint coefficients is that they provide a linear representation of the response of $PM_{2.5PW}$ to emissions perturbations, which leads to uncertainty when emission perturbations are large (considered to be approximately > 50% for NO_x, SO_2, and NH_3 impacts on $PM_{2.5}$ (Henze et al., 2012; Lee et al., 2015)). Another limitation of applying a model with a resolution of 2° × 2.5° is uncertainty in estimated $PM_{2.5PW}$ concentrations owing to strong gradients in population that may be up to 30–50% (Punger and West, 2013). Additionally, baseline $PM_{2.5}$ values estimated in the present day by GEOS-Chem may have biases. To overcome these limitations, the gridded GEOS-Chem values of $PM_{2.5}$ ($PM_{2.5\_GC}$) were downscaled at the 0.1° × 0.1° resolution using surface $PM_{2.5}$ concentrations from van Donkelaar et al. (2016). These are derived from a combination of satellite and modelled $PM_{2.5}$ data, calibrated to a global network on ground-based $PM_{2.5}$ measurement. The downscaling occurs through multiplication of the average ratio of the $PM_{2.5}$ from van Donkelaar et al. (2016) at the 0.1° × 0.1° resolution to the van Donkelaar et al. (2016) values averaged to the 2° × 2.5° resolution, $PM_{2.5\_vanD2016}$ / $PM_{2.5\_vanD2016\_2x25}$. Additionally, for 2010 estimates, an additional bias correction factor is applied, which is the ratio of van Donkelaar et al. (2016) estimates to the GEOS-Chem estimates, both at the 2° × 2.5° resolution, $PM_{2.5\_vanD2016\_2x25}$ / $PM_{2.5\_GC}$, which essentially reduces to using the 0.1° × 0.1° values from van Donkelaar et al. (2016). National average population weighted concentrations ($PM_{2.5PW}$) are then calculated from these, which in 2010 was calculated to be 52.1 μg m^{-3} in Bangladesh (Equation (1)).

$$\begin{aligned} PM_{2.5\_2010} &= PM_{2.5\_GC}{}^{*}\frac{PM_{2.5\_vanD2016}}{PM_{2.5\_vanD2016\_2x2.5}}{}^{*}\frac{PM_{2.5\_vanD2016\_2x2.5}}{PM_{2.5\_GC}} \\ &= PM_{2.5\_VanD2016} \end{aligned} \tag{1}$$

$$PM_{2.5PW\_2010} = \sum_i \frac{\mathrm{PM2.5\_2010}_i p_i f_i}{p_t} \tag{2}$$

where p_i is the population in each 0.1° × 0.1° grid in the target country, f_i is the fraction of the population in each 0.1° × 0.1° grid that are classified as being in the target country and p_t is the total population in the target country.

Gridded (2° × 2.5°) $PM_{2.5}$ concentrations in 2010 from natural background emissions, and from natural and anthropogenic $PM_{2.5}$ concentrations were calculated from GEOS-Chem and used to calculate population-weighted annual $PM_{2.5}$ concentrations for the target country from natural and total emissions in 2010 ($PM_{2.5PW\_GC\_nat}$, and $PM_{2.5PW\_GC\_tot}$, respectively). $PM_{2.5}$ concentrations are calculated at 35% RH and standard temperature and pressure; satellite-derived estimates of the organic matter to OC ratio from Philip et al. (2014) are applied seasonally. The anthropogenic fraction ($PM_{2.5PW\_GC\_anth}$) was calculated by subtraction (Equation (3)). The natural concentration of $PM_{2.5PW\_2010}$ ($PM_{2.5PW\_nat}$) was then calculated with Equation (4), and this was assumed to be constant for all future years and scenarios. The anthropogenic component of $PM_{2.5PW\_2010}$ ($PM_{2.5PW\_2010\_anth}$) was then estimated through subtraction (Equation (5)).

$$PM_{2.5PW\_GC\_anth} = PM_{2.5PW\_GC\_tot} - PM_{2.5PW\_GC\_nat} \tag{3}$$

$$PM_{2.5PW\_nat} = PM_{2.5PW\_2010}{}^{*}\frac{PM_{2.5PW\_GC\_nat}}{PM_{2.5PW\_GC\_tot}} \tag{4}$$

$$PM_{2.5PW\_2010\_anth} = PM_{2.5PW\_2010} - PM_{2.5PW\_nat} \tag{5}$$

The $PM_{2.5PW\_2010\_anth}$ component was further disaggregated into contributions from emissions of each primary $PM_{2.5}$ (black carbon, organic carbon, other primary PM) or $PM_{2.5}$ precursor pollutant (nitrogen oxides, sulphur dioxide, ammonia), and the contribution from emissions in the target country, and from emissions from grid squares outside of the country (rest of the world emissions). For each pollutant, for the target country and rest of the world emissions separately, the contribution to $PM_{2.5PW\_2010\_anth}$ was calculated by i) summing, across all grids globally, the product of the adjoint coefficients parameterised for that pollutant and the pollutant emissions in the grids covering the target country or rest of the world emissions, and ii) scaling these values so that the sum for all pollutants equalled $PM_{2.5PW\_2010\_anth}$.

The impact of changes in emissions for future scenarios on $PM_{2.5PW}$ are calculated by multiplying the adjoint coefficients for each grid, for each $PM_{2.5}$ and $PM_{2.5}$-precursor pollutant, by the difference in emissions between 2010 and the future year in a particular scenario. The change in emission in the grids covering the rest of the world, in the baseline scenario, is estimated from the ECLIPSE current legislation scenario (Stohl et al., 2015). The change in emissions in the grids covering the target country are calculated by subtracting the emissions of each pollutant in the future year for a given scenario (baseline or mitigation) from the values in 2010. The sum of the coefficient × change in emission for each pollutant for each grid is then scaled by the ratio of $PM_{2.5PW\_2010\_anth}$ to $PM_{2.5PW\_GC\_anth}$ to provide the estimate of the change in $PM_{2.5PW}$ in the future year due to changes in emissions of each pollutant for a particular scenario that is consistent with the $PM_{2.5PW}$ value set to the van Donkelaar et al. (2016)-derived value in 2010.

2.1.3. Household $PM_{2.5}$ exposure

In addition to modelling ambient $PM_{2.5}$ exposure and health impacts in IBC, the latest versions of LEAP also include methods for estimating the health impacts associated with exposure to $PM_{2.5}$ pollution from cooking in households, which is associated with substantial health burdens (Stanaway et al., 2018). The methods implemented in LEAP for estimating cooking-related impacts are based upon a set of methods developed and implemented in the Household Air Pollution Intervention Tool (HAPIT III) (Pillarisetti et al., 2016). These methods are consistent with those used to quantify global burdens of disease attributable to household $PM_{2.5}$ exposure (WHO, 2018). The methods used in HAPIT III were originally intended to be applied in small-scale, static assessments of the potential benefits of interventions at the village-scale to promote clean cooking. In LEAP, we have adapted those methods to make them suitable for use at the national-scale, and have made them dynamic and scenario-based so that they can show the comparative benefits of transitioning societies away from a reliance on traditional cooking and toward cleaner cooking technologies.

Modelling of indoor air pollution in LEAP accounts for six separate groups of households members: male and female primary cooks, other male and female adults and male and female children (under five years old). The number of primary cooks, other adults and children living in households cooking using different types of fuels and technologies is then calculated by multiplying the number of households cooking using a particular fuel/technology by the fraction of the average household size that are primary cooks, other adults and children. For each cooking fuel/technology combination, the 24-hour personal exposure of the primary cook is specified for each cooking technology and relative exposures are defined for other groups of household members. This provides the number of people in each population group and their personal $PM_{2.5}$ exposure which is used as input to the health impact assessment described in section 2.1.4.

Currently, the methodology accounts only for cooking technologies. Exposure to other sources of indoor $PM_{2.5}$, such as kerosene use for lighting or smoking are not included. The specific application of this method to estimate household air pollution health impacts in Bangladesh is described in Section 2.2.

2.1.4. $PM_{2.5}$ health impact assessment

In the LEAP-IBC framework, the health endpoint for which the impact of ambient and household $PM_{2.5}$ exposure is estimated is premature mortality. Premature mortality attributable to $PM_{2.5}$ exposure is estimated for children (less than 5 years) and adults (>30 years) in −5-year age groups (30–34, 35-39…75-79, >80 years) from 5 disease categories (children: acute lower respiratory infection; adults: chronic obstructive pulmonary disease, ischemic heart disease, cerebrovascular disease and lung cancer). The $PM_{2.5PW}$ estimate of exposure to ambient $PM_{2.5}$ concentrations, and the personal $PM_{2.5}$ exposure for different population groups to household $PM_{2.5}$, are combined separately with 'integrated exposure response' (IER) functions that have previously been extensively used for quantifying air pollution health burdens (Burnett et al., 2014; Cohen et al., 2017). The IER functions (Equation (6)) quantify the relative risk (RR) for mortality from specific diseases for $PM_{2.5}$ exposures up to very high levels (up to 10,000 μg m^{-3}), by integrating RRs derived from epidemiological studies between cause-specific mortality and $PM_{2.5}$ exposure from ambient air pollution, household air pollution, second hand smoke, and active smoking.

$$RR_{IER} = 1 + \alpha\left(1 - e^{-\gamma\left(z - z_{cf}\right)^{\delta}}\right) \tag{6}$$

where z_{cf} is the $PM_{2.5}$ low concentration cut-off, z is the $PM_{2.5}$ concentration that a population is exposed to, and α, δ, and γ are IER-specific parameters (Burnett et al., 2014; Cohen et al., 2017). The RR derived from the IER function for a particular disease and age group, is then used in combination with the baseline mortality rate for that disease for the population in the target country, and the exposed population in the age category in the target country to estimate the number of premature deaths attributable to ambient $PM_{2.5}$ exposure from the particular disease in that age group (Equation (7)).

$$\Delta \mathrm{Mort} = y_0\left(\frac{RR_{IER} - 1}{RR_{IER}}\right)Pop \tag{7}$$

Here y_0 is the baseline mortality rate for each disease category, and Pop is the exposed population for each child or adult age category. The ambient $PM_{2.5PW}$ estimated as described in Section 2.1.2 is used with Equations (6) and (7) to estimate the number of premature deaths attributable to ambient $PM_{2.5}$ exposure for each year in the analysis, and for each scenario, i.e. historical years, and future years for baseline and mitigation scenarios. Personal $PM_{2.5}$ exposure from household sources estimated for each population group (primary cook, other adults and children under 5 years) living in households cooking with different fuels/technologies is combined with Equation (6) and (7) to estimate the number of premature deaths attributable to household air pollution for each year/scenario.

Household and ambient air pollution and two overlapping risk factors for premature mortality. For example, residents in households cooking using solid biomass, exposed to high levels of household air pollution may also be exposed to high levels of ambient air pollution. This is particularly the case in countries such as Bangladesh where i) a high proportion of the population cooks using solid fuels, and ii) outdoor $PM_{2.5}$ concentrations are many times higher than the WHO ambient air quality guideline for the protection of human health (i.e. an annual average of 10 μg/m3). Due to uncertainties in the degree of overlap between exposures to household and ambient air pollution in Bangladesh, health impacts from both sources of exposure are reported separately in this study. Within the LEAP-IBC platform, health impacts from household and ambient $PM_{2.5}$ exposure can be combined to estimate the overall air pollution health burden using the approach outlined in Ezzati et al. (2003) for combining multiple independent risk factors.

2.1.5. Climate impact assessment

LEAP calculates Global Warming Potential (GWP) using standard factors taken from IPCC assessment reports. To allow LEAP to be useful in national GHG mitigation assessments, it supports a range of different GWP factors reflecting the revisions made in successive IPCC assessment reports (Myhre et al., 2013). In addition, in order to give more accurate assessments of likely year-on-year global warming, LEAP-IBC can also be used to estimate the contribution to global temperature change of the national-scale emissions calculated within LEAP.

To allow the impacts of different future emissions on climate change to be evaluated, transient changes in global surface temperature, in annual time steps, are calculated accounting for the climate effects of both short-lived climate forcers (SLCFs) and greenhouse gases. In this applications SLCFs include short-lived climate pollutants (SLCPs), i.e. black carbon, tropospheric ozone and methane, which are relatively short-lived in the atmosphere and have a warming impacts, but also short-lived species that have a cooling impact, i.e. organic carbon and secondary inorganic aerosol. Methane is also a greenhouse gas, and therefore the methods to quantify the impact of methane on global temperatures is described alongside other greenhouse gases, such as carbon dioxide.

The methodology included in LEAP-IBC to achieve the transient climate calculations has been described previously in Lacey and Henze (2015), and Lacey et al. (2017). For all climate forcers, the change in radiative forcing of those emissions are estimated in 4 latitudinal bands (arctic, northern mid-latitudes, tropics, and southern hemisphere extratropics), following the framework developed in Shindell and Faluvegi (2009) and Shindell (2012). The transient surface temperature change, relative to the base year of the analysis can then be estimated without additional global climate model simulations by using the absolute regional temperature potentials forcing-response relationships (Shindell and Faluvegi, 2009; Shindell, 2012). The use of this parameterization has been evaluated through comparisons to a number of fully coupled chemistry-climate models for both the global temperature response (Stohl et al., 2015) and the regional temperature responses (Sand et al., 2013). The methods for both SLCPs and long-lived GHGs are outlined in the following sections.

2.1.5.1. Short-lived climate forcers. In order to calculate the radiative forcing from aerosols, the GEOS-Chem model is combined with a radiative transfer model (RTM), LIDORT (Spurr et al., 2001). Aerosol species from GEOS-Chem are assigned species-specific optical properties (refractive index and size distribution) and the assumption of a fully external mixture of aerosols is used with Mie theory to calculate gridded aerosol optical depths, phase functions, and single scattering albedo that are input to the RTM (Henze et al., 2012). Radiative effects at the top-of-the-atmosphere (TOA) are calculated over the wavelengths of incoming solar radiation. In order to calculate radiative forcing, the radiative flux from a pre-industrial case (1850) is subtracted from the present-day TOA flux calculated using the GEOS-Chem modelled concentrations of aerosols and other trace constituents in the atmosphere (Henze et al., 2012; Lacey and Henze, 2015). LIDORT calculates the Jacobian matrix of inputs (optical properties) with respect to outputs (gridded radiative flux); these derivatives are used as inputs to the GEOS-Chem adjoint model, which is able to propagate these sensitivities of radiative forcing with respect to changes in optical properties back to sensitivities with respect to gridded global emissions of individual aerosol and aerosol precursor species. Ozone radiative forcing is calculated following Bowman and Henze (2012), which is summarized as follows. Remote sensing observations of the sensitivity of outgoing longwave radiation to the 3D distribution of tropospheric O_3 is quantified using the Instantaneous Radiative Kernels (IRK) measured by the Thermal Emission Spectrometer (TES) aboard the Aura satellite (Worden et al., 2011; 2008). The GEOS-Chem adjoint model is used to apportion this radiative effect from all tropospheric O_3 to its contributions from anthropogenic emissions to derive an O_3 radiative forcing per unit emission of NOx, NMVOCs, and CO.

The change in radiative forcing (RF) in the four latitudinal bands was calculated for emissions that contribute to aerosol formation (i.e. BC, OC, NH_3, NO_x, SO_2), and ozone precursors (i.e. NO_x, CO, VOCs). Once formed, the lifetimes of aerosols and ozone are short enough that the pollutants are not globally mixed, and therefore the location of emissions of these pollutants determines the effect of these emissions on radiative forcing in each latitudinal band. Hence, for each pollutant that contribute to aerosol and ozone formation, four sets of linearised coefficients were produced from the GEOS-Chem adjoint model that quantify the sensitivity of radiative forcing in each latitudinal band to emissions of a pollutant in $2^\circ \times 2.5^\circ$ grids covering the globe. The calculation of these adjoint coefficient for latitudinal band radiative forcing are described in detailed in Lacey and Henze (2015). These coefficients also include scaling factors to incorporate species-specific biases and uncertainty ranges based on multi-model studies of aerosol radiative forcing (Boucher et al., 2013; Myhre et al., 2013). For each year and each scenario, the emissions of these pollutants in the target country, derived in LEAP, are multiplied by the coefficients to determine the time-dependent change in radiative forcing in each latitudinal band (F_{lat}) due to emissions in the target country (Equation (8)).

$$F_{\mathrm{lat}} = E\lambda\alpha \tag{8}$$

where E are the time and species dependent emissions, λ are the adjoint sensitivities, and α are the radiative forcing scaling factors. Radiative forcing in individual latitudinal bands then results in a localized temperature response in each of the four latitudinal bands (i.e. a change in radiative forcing in the arctic produces a temperature response in the northern mid-latitude, tropics, and southern hemisphere extratropics regions, as well as in the arctic itself) as shown in Shindell and Faluvegi (2009). These regional temperature potential coefficients quantify the sensitivity of the temperature response in one region to a radiative forcing in another region, relative to the global mean temperature sensitivity. Hence for a given year after emission, the net change in radiative from all regions was weighted using absolute regional temperature potentials (δ) and translated into the temperature change using multi-model mean results for the integrated transient climate sensitivity (Geoffroy et al., 2013) (Equation (9)).

$$\Delta\mathrm{Tregion} = \int_{t_0}^{t_f} \sum_{i=1}^{4} F_i \delta_{i,r} x \frac{1}{18.498} x (2.507 x e^{\frac{t_f - t}{4.1}} + 0.027 x e^{\frac{t_f - t}{219}}) \tag{9}$$

where the summation of regional radiative forcings is the weighted radiative forcing from short-lived species calculated using the RTP coefficients (Lacey and Henze, 2015; Shindell and Faluvegi, 2009), and t is the year of interest between t_0 (baseline) and t_f (endpoint). For short-lived species the change in radiative forcing is considered to be instantaneous and felt within the year of emission. The first exponential term in the integral relates to the response of the surface and shallow seas, and the second exponential term relates to the thermal inertia of the deep ocean. Finally, for each pollutant, for each year, for each scenario, a global area-weighted mean temperature change is then calculated from the latitudinal band temperature changes.

2.1.5.2. Greenhouse gases.

For GHGs like CO_2 and CH_4, the change in RF resulting from their emission in a particular year is not confined to the year in which they were emitted, but as a function of time from the year of emission due to their longer atmospheric lifetimes. Hence for an emission of CO_2 and CH_4, it is assumed that their emission from any location becomes globally mixed, and therefore the first step in estimating temperature change from CO_2 and CH_4 is to estimate the change in global CO_2 and CH_4 concentrations due to shifts in emissions in the target country. Therefore, in the year of emissions, a 1 Gt change in emissions of CO_2 and CH_4 were associated with a 0.128 ppm and 0.278 ppm change in global CO_2 and CH_4 concentrations, respectively. The decay in CO_2 and CH_4 concentrations in the years following emission were then represented by impulse response functions (IRF), shown in Equations (10) and (11), respectively.

$$IRF_{CO2} = 0.217 + 0.224{*}e^{\left(\frac{-y+b}{394.4}\right)} + 0.282{*}e^{\left(\frac{-y+b}{36.5}\right)} + 0.276{*}e^{\left(\frac{-y+b}{4.304}\right)} \tag{10}$$

$$IRF_{CH4} = e^{\left(\frac{-y+b}{12.4}\right)} \tag{11}$$

where y is the year of interest after emission and b is the year of emission. The parameters of $\mathrm{IRF}_{\mathrm{CO2}}$ were derived from model calculations in Joos et al. (2013). The IRFs are used to calculate the time-dependent response of concentrations in year t owing to emissions changes from years b to y.

$$[C]_y = \beta{*}\mathrm{sum}(\sigma(y){*}\mathrm{IRF}(y)\,) + [C]_b \tag{12}$$

where β is the unit conversion from global annual emissions (in gigatonnes) to parts per million for CO_2 and parts per billion for CH_4 and N_2O, σ is the change in emissions in gigatonnes in year y, and C_b is the global background concentration in the base year b. Following the calculation of CO_2 and CH_4 concentration changes, the change in global radiative forcing in each year due to these concentration changes are calculated. For CO_2, the change in global RF was calculated using Equation (13), and for CH_4, Equation (14) was used, and were derived in Aamas et al. (2013).

$$RF_{CO2} = 5.35{*}\ln(\frac{[CO_2]_y}{[CO_2]_{ref}}) \tag{13}$$

$$\begin{aligned} RF_{CH4} = {} & 0.036{*}(({[CH_4]_y}^{0.5} - {[CH_4]_{ref}}^{0.5}) - 0.47{*}ln(1 \\ & + 2.01x10^{-5}{*}\left([CH_4]_y{*}[N_2O]_{ref}\right)^{0.75} \\ & + 5.31x10^{-15}{*}[CH_4]_y{*}\left([CH_4]_y{*}[N_2O]_{ref}\right)^{1.52}) + 0.47{*}ln(1 \\ & + 2.01x10^{-5}{*}\left([CH_4]_{ref}{*}[N_2O]_{ref}\right)^{0.75} \\ & + 5.31x10^{-15}{*}[CH_4]_{ref}{*}\left([CH_4]_{ref}{*}[N_2O]_{ref}\right)^{1.52}) \end{aligned} \tag{14}$$

where $[CO_2]_y$, and $[CH_4]_y$, represents the global CO_2 and CH_4 concentrations in the year of interest for a particular scenario, accounting for the change in concentration due to emissions in the target country in all years between the base year and the year of interest. The variables $[CO_2]_{ref}$, $[CH_4]_{ref}$, and $[N_2O]_{ref}$ represent global average concentrations of each pollutant in a reference year, and were set at 378 ppm, 1726 ppb, and 318 ppb, respectively, corresponding to their values in 2010, the base year of the analysis (Lacey et al., 2017). From this global radiative forcing, the temperature change resulting from CO_2 and CH_4 emissions in Bangladesh were calculated in each year using Equation (9). In these cases the sensitivity of the temperature response in each region uses global radiative forcing with the global mean temperature sensitivity, also derived in Shindell (2012).

2.1.5.3. Additional climate feedbacks. Changes in the emissions of some pollutants also change atmospheric composition in a way that feeds back on other radiatively active components; such feedbacks need to be taken into account when estimating the overall climate impact of a particular change in emission magnitude. Therefore, the impact of changes in NO_x, CO, and VOC emissions on CH_4 concentrations and associated climate impacts are accounted for. Increases in NO_x emissions reduce CH_4, because of the increased CH_4 sink through O_3 formation. Increases in CO and VOC emissions increase CH_4 RF due to the lower availability of oxidants to react with CH_4. The response of CH_4 RF to changes in VOC and CO emissions was taken from a multi-model experiment assessing the RF responses of decreases in pollutant emissions described in Fry et al. (2012). Between the different regions assessed, there was a fairly consistent response to CH_4 RF for a change in CO and VOC emissions, which was on average 66% and 127% of the change in O_3 RF due to the same change in VOC and CO emissions, respectively. Hence, to account for the change in CH_4 RF due to changes in these emissions, the estimated change in O_3 RF due to VOC and CO emissions, described above was scaled by these factors.

The estimated change in CH_4 RF due to a change in NO_x emissions differed by region. We therefore developed regional factors (unit mW m^{-2} Tg NO_x emission^{-1}) that quantify the change in CH_4 RF for a change in NO_x emissions based on the work of Naik et al. (2005). The temperature responses to these additional changes in RF were calculated using Equation (9) for each latitudinal band, then aggregated to an area-weighted global mean.

Lastly, we also consider the RF impacts of the emissions of BC aerosol by altering the albedo of snow and ice upon which BC may deposit, as described in Lacey and Henze (2015). The total global snow/ice albedo effect of -0.15 W/m^2 is apportioned across all BC sources using the results of an additional adjoint model calculation. This calculation considered as a model response the deposition of BC onto snow and ice. The results then relate the BC emissions in any grid cell to the amount of BC deposited on snow and ice. The impact of this radiative effect on transient temperature estimates follows the treatment of other short-term RF using Eq. (9).

2.2. Application to air pollution and climate change mitigation in Bangladesh

The application of the LEAP-IBC modelling framework shown in Fig. 1, and described in Section 2.1 aimed to evaluate the effect on air quality and climate change of two key strategies, Bangladesh's NDC (Ministry of Environment and Forests, 2015), and National Action Plan to reduce SLCPs (Bangladesh Department of Environment, 2018). The first step was to develop a LEAP model application that estimated national total emissions of GHGs, SLCPs and air pollutants from all major source sectors, in alignment with the results of National Greenhouse Gas inventory, and meeting the requirements for compatibility with the IBC module for assessing air pollution and health impacts (described in Section 2.1.1). The base year for the Bangladesh LEAP model was 2010, and projections were made to 2030 and 2040.

The methods and data used to develop the LEAP model for Bangladesh are outlined comprehensively in Department of Environment (2018). Table 1 summarises the key data used to estimate emissions from all major energy and non-energy source sectors, including the methods used for projecting emissions into the future for a business as usual scenario. The LEAP model developed was the first emission inventory and scenario assessment for Bangladesh that estimated emissions of all GHGs, SLCPs and air pollutants in a single, consistent analysis. However, Bangladesh has developed dedicated GHG emission inventories and projections as part of the UNFCCC climate change reporting processes (i.e. within National Communication and Biennial Update Reports). Therefore, to ensure that the emission estimates of SLCPs and air pollutants were consistent with official GHG inventories and mitigation assessments, data and projection assumptions in the LEAP model were aligned with those used in the GHG mitigation assessment conducted for Bangladesh's Third National Communication (Ministry of Environment Forest and Climate Change Bangladesh, 2018). For each source sector, emissions were calculated by multiplying an activity variable by pollutant specific emission factors. The specific activity variables, as well as the source of emission factors are described in Table 1 for each of the source sectors included in the analysis.

For the majority of energy demand sectors, the activity variable was the total fuel consumption for that sector extracted from International Energy Agency (IEA) energy statistics (International Energy Agency, 2015). For these sectors, emission factors for the GHGs were Tier 1 factors from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for Greenhouse Gas Inventories (IPCC, 2006), and for other species were Tier 1 and Tier 2 factors from the EMEP/EEA (2016) Emission Inventory Guidebook (summarised in detail in Vallack et al. (2020), and available at https://leap.sei.org/default.asp?action = IBC. More detailed methods were used to estimate emissions from brick kilns, rice parboiling and road transport. Brick kiln emissions were estimated as the product of the total number of bricks produced per year, disaggregated between 'traditional' and 'improved' kilns, the energy intensity per brick produced for each type of brick kiln, and kiln-specific emission factors for each pollutant. For rice parboiling, emissions were calculated as the product of the total rice parboiled, the energy consumption per tonne of rice parboiled, and emission factors for traditional and improved rice kilns. For the road transport sector, the number of vehicle-km travelled by passenger cars, light duty vehicles, heavy duty vehicles, motorcycles, three wheelers and urban buses were estimated, and disaggregated between vehicles using different fuels (gasoline, diesel, CNG etc.), and meeting different vehicle emission (Euro) standards. Tier 2 default emission factors (g pollutant per km travelled) from the EMEP/EEA (2016) Emission Inventory Guidebook were used to estimate emissions of all pollutants except CO_2, SO_2 and CH_4, where emission factors were used based on total fuel consumed. For all energy sectors (including transport), the uncontrolled fuel combustion emission factors for SO_2 were derived from the sulphur (S) content of the fuel assuming all the S is ultimately oxidised to SO_2, after accounting for S retention in ash for solids fuels.

Emissions from the energy transformation sectors were calculated based on the demand for fuels for each of the energy demand sectors. For electricity generation, the share of electricity generated using different technologies and fuels was based on IEA energy balance statistics (International Energy Agency, 2015). Transmission and distribution losses in electricity generation were extracted from World Bank statistics (databank.worldbank.org). Finally, the emissions from other sectors were estimated using the activity data for each source described in Table 1. The calculation of GHG emissions for the majority of the non-energy sectors followed the Tier 1 methodologies outlined in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for Greenhouse Gas Inventories (IPCC, 2006) whereas estimates of emissions from all other pollutants followed the Tier 1 methods and emission factors given in the EMEP/EEA (2016) Emission Inventory Guidebook.

Table 1
Summary of emission source sectors included in the Bangladesh emission inventory, source of activity data and assumptions about development of baseline emission scenarios for analysis described in Department of Environment (2018). For all sources, emission factors were taken from IPCC (2006) for GHGs, and EMEP/EEA (2016) and other scientific literature for black carbon and other air pollutants, available at: https://leap.sei.org/default.asp?action=IBC.

Source Sector	IPCC Source Code	Activity Data and source	Baseline scenario projection method
Residential	1A4b	Number of households (UN DESA, 2019, 2018) Total fuel consumption: IEA energy balance for Bangladesh	Growth in energy consumption based on projection in Bangladesh Third National Communication
Commercial and Public Services	1A4a	Total fuel consumption: IEA energy balance for Bangladesh	Growth in energy consumption based on projection in Bangladesh Third National Communication
Transport	1A3	Road Transport: Total number of vehicles in each category: passenger cars, light commercial vehicles, heavy duty vehicles, motorcycles, buses (Bangladesh Road Transport Authority, www.brta.gov.bd); Fuel used and distance travelled (Wadud and Khan, 2013) Rail; Aviation; Shipping: Total Fuel Consumption: IEA energy balance for Bangladesh	Growth in energy consumption based on projection in Bangladesh Third National Communication
Industry	1A2	All industry except brick kilns: Total fuel consumption: IEA energy balance for Bangladesh Brick Production: Annual brick production Kiln composition Energy intensity (World Bank, 2011)	Growth in energy consumption based on projection in Bangladesh Third National Communication
Agriculture, Forestry and Fishing	1A4c	Total fuel consumption: IEA energy balance for Bangladesh	Growth in energy consumption based on projection in Bangladesh Third National Communication
Rice Parboiling	N/A	Tonnes of rice parboiled Energy intensity for traditional and improved methods (GIZ, 2016)	Growth in tonnes of rice parboiled assumed to grow with rice production rate
Other Energy Consumption	1A5	Total fuel consumption: IEA energy balance for Bangladesh	Growth in energy consumption based on projection in Bangladesh Third National Communication
Energy Industry Own Use	1A1b	Total fuel consumption: IEA energy balance for Bangladesh Oil and Gas genset use: World Bank Diesel Generator Study	Growth in energy consumption based on projection in Bangladesh Third National Communication
Electricity Generation	1A1a	Electricity matrix: IEA energy balance for Bangladesh	Electricity generation increases according to increases in electricity demand. Changes in electricity matrix based on projected changes made in Bangladesh's Third National Communication
Industrial Processes	2A-2D	Mineral Production: US Geological Survey Mineral Yearbook Chemical and food and drink production: FAO Stat	Growth in line with increases in industrial energy consumption
Agriculture	3A, 3C	Animal Numbers: Department of Livestock, http://dls.portal.gov.bd (assuming 60% cattle to be dairy cattle) Fertiliser consumption: FAO Stat Annual Harvested Area, Cultivation period: Third National Communication Annual Crop Production: FAO Stat Fraction burnt in the field (Haider, 2013)	Agricultural activity projected based on historical trends
Waste	4A, 4B, 4D	Waste sent to landfill: IPCC Tier 1 default values Waste openly burned (Wiedinmyer et al., 2014)	Waste generation projected in line with population increases

The assumptions used to project activity in each sector into the future for the baseline scenario are summarised in Table 1. For most energy demand source sectors the baseline projection of energy consumption to 2040 was assumed to follow the same trajectory as described in Bangladesh's 3rd National Communication submitted to the UNFCCC (Ministry of Environment Forest and Climate Change Bangladesh, 2018). The aim of this work was to evaluate the emission reduction potential, and impact reductions that could result from implementation of the NDC and National SLCP Plan measures in Bangladesh. Therefore, the selection of the official baseline projections from Bangladesh's 3rd National Communication were chosen so that the emission reduction potentials estimated in this work were being assessed relative to a baseline that was as consistent as possible with previous national analyses. Changes in electricity generation were based on changes in demand for those fuels, assuming the electricity matrix remained the same as in the base year. The assumptions for the non-energy sector are also described in Table 1.

Mitigation scenarios were developed that represented the implementation of individual policies and measures contained within Bangladesh's NDC and National SLCP Plan (Bangladesh Department of Environment, 2018; Ministry of Environment and Forests, 2015). The mitigation measures modelled from the NDC, and National SLCP Plan, including targets and timelines, are described in Table 2. The individual mitigation measures were then aggregated to create scenarios that

Table 2
Mitigation Measures modelled in different scenarios for Bangladesh.

Scenario	Source Sector	Measure	Measure description and Target
NDC Existing	Energy	Energy Efficiency (Energy Efficiency & Conservation Master Plan target)	15% reduction by 2021 and 20% reduction by 2030 in energy intensity in Agriculture, Forestry and Fishing, Commercial and Public Services, Energy Industry, Manufacturing and Construction, and Residential sector
NDC Existing	Power Generation	Renewable Energy	10% of electricity generated from renewables in 2020
NDC Existing	Industry	Improved Brick Kilns	100% traditional brick kilns converted to improved zigzag kilns by 2030
NDC Existing	Residential	Improved biomass cookstoves	1.5 million improved cookstoves replace traditional biomass stoves in 2015
NDC Additional	Power Generation	Supercritical coal power plants	100% of new coal based power plants use super-critical technology by 2030 (40% efficiency)
NDC Additional	Transport	Road transport fuel efficiency	15% improvement in fuel efficiency of passenger, heavy duty, light commercial vehicles, motorcycles, three wheelers and urban buses by 2030
NDC Additional	Power Generation	Wind and Solar	400 MW wind generating capacity by 2030 and 1000 MW of solar capacity by 2030
NDC Possible	Residential	Improved biomass stoves and LPG use for cooking	By 2030, all traditional biomass stoves replaced by improved biomass stoves (70%) and LPG (30%)
NDC Possible	Commercial and Public Services	Commercial Energy Consumption	25% reduction in energy intensity by 2030 in commercial and public services sector
NDC Possible	Agriculture	Alternate Wetting and Drying of Rice paddies	20% of all rice cultivation uses alternate wetting and drying irrigation
NDC Possible	Waste	Landfill gas capture	70% landfill gas captured by 2030
NDC Possible	Waste	Organic waste diverted from landfill to composting	50% organic waste diverted from landfill to composting
SLCP Action	Industry	Efficient rice parboiling units	100% of rice parboiling units converted to efficient units by 2040
SLCP Action	Agriculture	Reduce open burning of crop residues	No crop residue burned in fields by 2040
SLCP Action	Transport	Adopt Euro Standards in road transport	100% of vehicles meet Euro IV standard by 2030
SLCP Action	Transport	CNG conversion	Type II and Type II Passenger cars running on motor gasoline converted to CNG by 2040
SLCP Action	Agriculture	Livestock enteric fermentation	17% Reduction of CH_4 emissions from livestock through enteric fermentation by 2040
SLCP Action	Waste	Domestic Wastewater	100% domestic wastewater in urban areas treated through aerobic treatment plant, and 100% of domestic wastewater in rural areas through septic tanks by 2040
SLCP Action	Natural Gas		100% reduction in emissions from natural gas distribution and processing by 2040

represented different levels of ambition in terms of actions taken in different sectors to reduce emissions. In Bangladesh's NDC, the mitigation measures are disaggregated into three groups: existing measures that are being implemented, additional measures that are being planned to meet Bangladesh's climate commitments, and potential additional measures for which the emission reduction potential was not evaluated and whose implementation was not included as part of Bangladesh's climate commitment. Therefore, the NDC measures were disaggregated into three scenarios in this work, to assess separately the effect of currently implemented measures in the NDC (scenario: NDC existing), have been committed to (scenario: NDC additional), and that could make an additional contribution (scenario: NDC potential). Bangladesh's National SLCP Plan outlines a series of measures that have been identified as being effective in reducing SLCPs (i.e. that focus on major black carbon and methane sources). Some of these measures, or similar measures, were also included within Bangladesh's NDC because they are also effective at reducing GHGs. Therefore, to reflect the additional contribution that Bangladesh's SLCP Plan can make to improving air quality and mitigation climate change, an additional scenario (SLCP Action) models the implementation of measures that are included in the National SLCP Action Plan for Bangladesh, but which are not included within their NDC (described in Table 2). The combination of the NDC existing, NDC additional, NDC potential and SLCP Action scenarios provides the overall effect from implementing both Bangladesh climate commitments, and their plan for the reduction of SLCPs.

Finally, for the assessment of household air pollution health impacts, the residential sector emissions were modelled by specifying the number of households in 2010 and for future projections, by dividing the total population in Bangladesh, from UN Population Division Statistics (UN DESA, 2018), by the average household size (4.5 people per household, (UN DESA, 2019)). The proportion of households cooking using different types of fuels and technologies (which were disaggregated between traditional biomass stoves, improved biomass stoves, electricity, natural gas, kerosene and LPG) was based on the residential energy consumption of these different fuels, reporting in the IEA energy balance for Bangladesh (International Energy Agency, 2015). The impacts of household-derived $PM_{2.5}$ exposure on human health was estimated only for those households cooking using solid biomass, consistent with other studies assessing household air pollution (Stanaway et al., 2018; WHO, 2018). The average household size in Bangladesh was split between primary cooks (assuming 2 per household), children under 5 (based on the fraction of the population under 5 (UN DESA, 2018)), and other adults (calculated by subtraction). For traditional biomass stoves, a personal exposure of 337 $\mu g\ m^{-3}$ was assigned to the primary cook, and other adults were estimated to have 60% of the primary cook exposure, and children 85% of the primary cook exposure, consistent with the WHO methodology for quantifying household air pollution health impacts (WHO, 2018). WHO (2014) estimated that improved biomass stoves on average reduced kitchen $PM_{2.5}$ concentrations by 60%, and this reduction was applied to the personal exposure of primary cooks (and the other population groups) cooking using improved biomass stoves in Bangladesh.

Other inputs for the air pollution health impacts assessment were the population of Bangladesh (exposed to ambient $PM_{2.5PW}$), which were extracted from UN DESA (2018) for both historical and future years. Mortality rates for the 5 disease categories for which the ambient and household $PM_{2.5}$ health burden were estimated were extracted from the Global Burden of Disease (GBD, Abajobir et al., 2017)) for historical years. Future changes in mortality rates were projected from the GBD values based on the change in overall death rate projected in UN DESA (2018) (i.e. it was assumed that the mortality rates for all diseases had the same relative change as the overall mortality rate).

3. Results

The LEAP-IBC modelling framework shown in Fig. 1 and described in

Section 2 provides several outputs that are relevant for an integrated assessment of air pollution and climate change mitigation. These include i) emission estimates of GHGs, SLCPs and air pollutants for historical years, baseline projections and scenarios that model the implementation of policies and measures, ii) $PM_{2.5}$ concentrations representing the exposure to ambient air pollution by the population in the target country, iii) impacts on human health from this exposure, and from exposure to household-derived $PM_{2.5}$ concentrations, and iv) climate impacts in terms of global average temperature change. The LEAP tool can also provide additional information, such as energy demand and supply statistics, quantification of the costs of implementation of mitigation measures, and the economic impacts of different emission trajectories. This can allow for an even more comprehensive assessment of the impacts of different policies and measures on multiple sustainable development goals.

3.1. *Emissions outputs from LEAP-IBC modelling framework*

The LEAP model provides the first estimate of national total emissions of air pollutants and SLCPs, alongside GHGs in Bangladesh. The national total emissions are shown in Table 3, and Fig. 3 shows the substantial overlap between the major sources of GHGs, SLCPs and air pollutants in Bangladesh. The residential sector is a major source of particulate emissions, including primary $PM_{2.5}$ emissions, and components such as BC and OC resulting mainly from cooking using wood and charcoal. It also makes substantial contributions to emissions of GHGs (CH_4 and CO_2) as well as the tropospheric ozone precursors CO, NO_x and NMVOCs. Open burning of municipal solid waste is the other major source of particulate pollutants, with agriculture (crop residue burning), and industry (brick kilns and rice parboiling) making smaller, but not insubstantial contributions. Agriculture contributed more than half of CH_4 emissions, from enteric fermentation and manure management and rice cultivation. The waste sector, predominantly domestic wastewater, contributed most of the remaining CH_4 emissions. Precursors of tropospheric ozone, including NO_x and VOCs, resulted from the residential and transport sectors, as well as contributions for a wide range of other sectors. Increases in energy consumption (driven by population and economic growth) results in a baseline scenario in which emissions of all pollutants are projected to increase substantially in 2040 (Table 3). The major source sectors expected to contribute to different pollutants are also projected to remain similar to 2010 over time (Fig. 4).

Emissions of GHGs (CO_2 and CH_4) are comparable with those estimated in Bangladesh's 3rd National Communication (TNC) (Ministry of Environment Forest and Climate Change Bangladesh, 2018). Total CO_2 emissions in Bangladesh estimated in this study are within 10% of those estimated in Bangladesh's TNC both for the base year (2010), and for future projections to 2040. Most CO_2 emissions in Bangladesh result from energy consumption. For those SLCPs and air pollutants whose emissions are quantified here for the first time, the energy sectors also contributed the majority of emissions. The similarity of emission estimates for CO_2 in this study and Bangladesh's TNC suggests that the emissions of SLCPs and air pollutants are consistent with previous official national inventories for GHGs. Methane emissions had larger differences, with methane estimates 36% higher in 2010 in this study compared to the TNC. The rice cultivation and domestic wastewater sectors were the sources that were primarily responsible for this difference.

Table 3
National total emissions (kilotonnes) in 2010, 2020, 2030 and 2040 for the baseline scenario in Bangladesh.

Pollutant	2010	2020	2030	2040
Carbon Dioxide	81,968	131,798	283,381	325,500
Carbon Monoxide	4,108	4,838	6,066	6,467
Methane	2,690	3,047	3,359	3,585
Non-Methane Volatile Organic Compounds	965	1,193	1,639	1,711
Nitrogen Oxides	520	745	1,285	1,487
Particulates PM10	5	7	13	14
Sulfur Dioxide	568	667	877	922
Ammonia	165	270	658	804
Particulates PM2pt5	956	1,047	1,157	1,287
Black Carbon	479	567	760	798
Organic Carbon	73	89	139	148

The reduction in emissions from implementing each mitigation scenario are shown in Table 4 and Fig. 4 for the successive implementation of the measures in the NDC Existing, NDC Additional, NDC Potential and SLCP Action scenarios in that order. The analysis shows that implementation of the existing NDC actions, i.e. the measures identified and committed to meet Bangladesh's climate commitment, could result in a much wider set of emission reductions than just GHGs. In addition to reducing CO_2 emissions by 17% in 2030 compared to a baseline scenario, the NDC existing measures also reduce black carbon emissions by 19%, and NO_x emissions by 11%. The most effective of the existing NDC measures were improving brick kilns and improved biomass cookstoves in the residential sector for reducing both CO_2 and BC emissions, highlighting that individual measures can make substantial contributions to both greenhouse gas and SLCP mitigation. The additional NDC measures did not make a substantial additional contribution to reducing black carbon, methane or air pollutant emissions (Fig. 4). The potential NDC measures were described in the NDC of Bangladesh, but the emission reduction potential of these measures was not quantified or included in the GHG reduction target. However, the potential NDC measures have the largest potential to simultaneously reduce GHG, SLCP and air pollutant emissions. Implementation of the potential NDC measures alone was estimated to reduce BC emissions by 20%, methane emissions by 18%, and OC emissions by 31% in 2030 compared to the baseline scenario. Emission reductions across GHGs, SLCPs and air pollutants are achieved mostly through action in the residential sector and increased use of improved biomass stoves LPG for cooking (Table 4).

The SLCP Action scenario includes additional measures included in the National SLCP Action Plan of Bangladesh (that are not already included within the suite of measures in Bangladesh's NDC). These additional measures reduce black carbon and methane emissions in 2030 by 8% and 15%, respectively compared to implementing all measures included in Bangladesh's NDC. These measures also lead to an additional reduction in CO_2 (5%), but larger reductions in co-emitted air pollutants such as NO_x (22%). The key measures included in the SLCP Action scenarios for reducing black carbon are adopting efficient rice parboiling units, implementation of higher Euro emission standards for road vehicles and reducing open burning of crop residues. Improving domestic wastewater systems and implementing action to reduce emissions from livestock enteric fermentation were the most effective to achieve further reductions in methane emissions.

Taken together, the implementation of Bangladesh's NDC and National SLCP Plan could simultaneously almost halve emissions of black carbon, and other particulate pollutants, substantially reduce emissions of other air pollutants (e.g. NO_x, 36% reduction in 2030 compared to the baseline), and reduce carbon dioxide and methane emissions by>25% by 2030 compared to the baseline scenario. Ammonia is the pollutant that is reduced least by these measures (20% reduction in 2030 through improved manure management).

3.2. *Air pollution and climate change impacts of emission scenarios*

The LEAP-IBC framework extends the assessment of different future scenarios from changes in emissions of GHGs, SLCPs and air pollutants to estimate the change in impacts of ambient and household air pollution exposure on human health (premature mortality) and climate change (global average temperature change). In the LEAP-IBC application in Bangladesh, the population-weighted annual average ambient $PM_{2.5}$ concentration ($PM_{2.5PW}$) in 2010 was 52 μg m^{-3}. Approximately half (50%) of $PM_{2.5PW}$ was estimated to derive from national emissions,

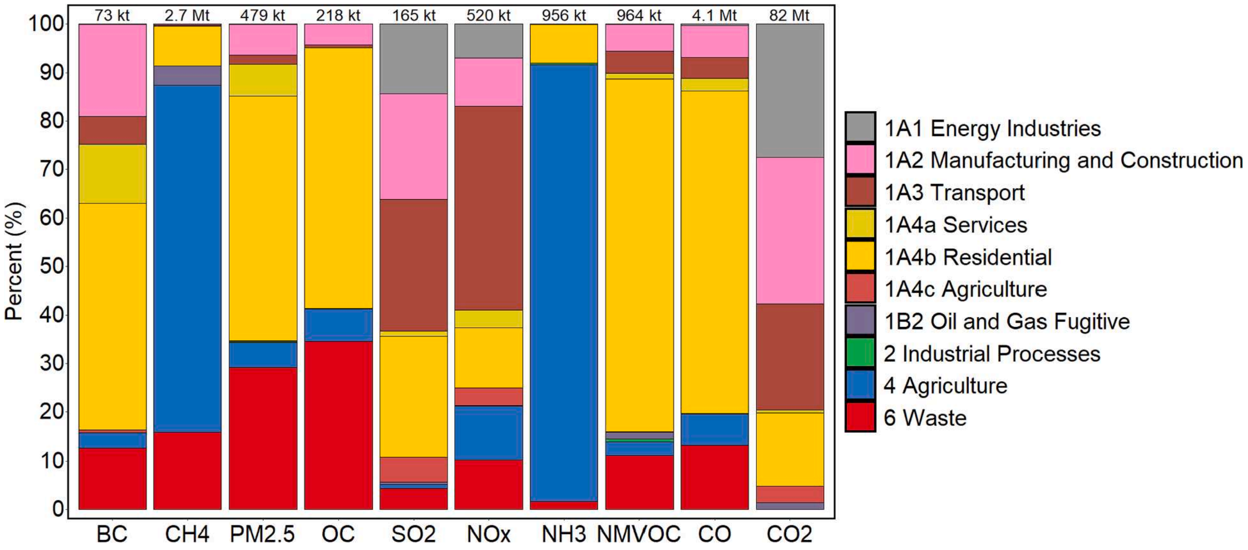

Fig. 3. Sectoral contributions to greenhouse gas, short-lived climate pollutant and air pollutant emissions in Bangladesh in 2010.

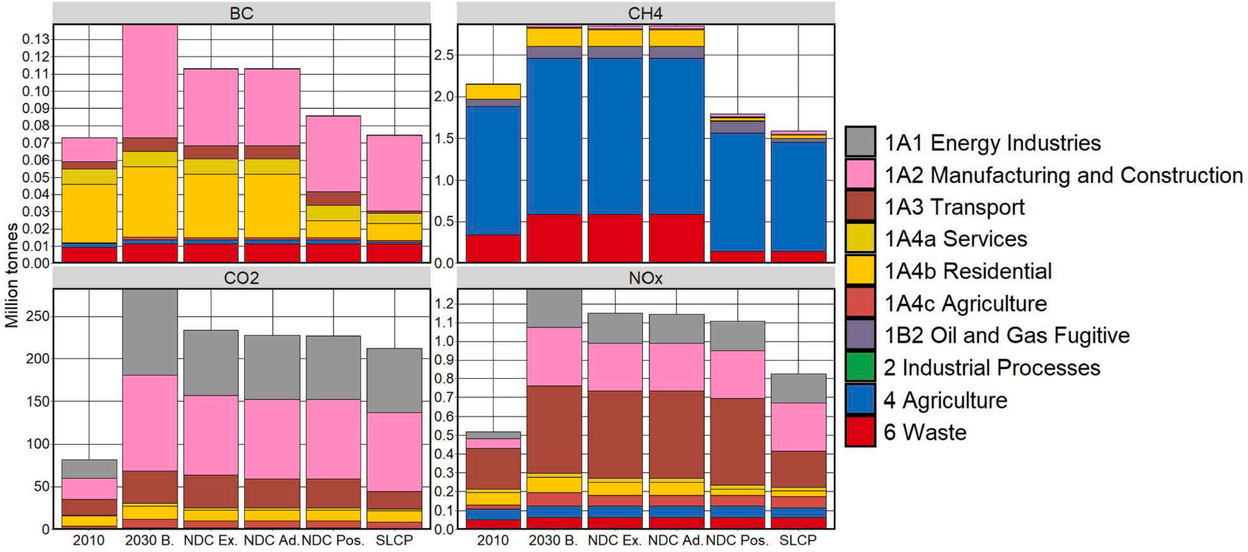

Fig. 4. Emissions of a) Black carbon, b) methane, c) carbon dioxide, d) nitrogen oxides in Bangladesh, split by contribution from different source sectors for 2010, and in 2030 for 5 scenarios (2030B. – Baseline, NDC Ex. – Existing NDC measures, NDC Ad. – Additional NDC measures, NDC Pos. – Possible NDC measures, SLCP – Additional actions to reduce SLCPs). Note each 2030 scenario includes all measures in the previous scenario (i.e. SLCP scenario includes the implementation of all measures in the 3 NDC scenarios).

with 37% from anthropogenic emission sources outside the country, and 13% from natural background (Fig. 5). $PM_{2.5PW}$ was estimated to increase to 72 μg m^{-3} in Bangladesh in 2030 (Fig. 6). Over this time period the contribution from Bangladesh emissions was also projected to increase slightly to 55% of $PM_{2.5PW}$ in 2030.

In 2010, exposure to ambient $PM_{2.5}$ across Bangladesh was associated with an estimated 107,000 premature deaths, 10% of which were infant mortality (Table 5). Premature mortality attributable to ambient $PM_{2.5}$ exposure is estimated to increase substantially in the future to 187, 000 premature deaths in 2030 in the baseline scenario (Table 5, Fig. 5). This increase results from both increased ambient $PM_{2.5}$ concentration as described above, but also demographic and baseline mortality rate changes. The population of Bangladesh is forecast to increase from 152 million in 2010 to 186 million in 2030 (UN DESA, 2018), considerably increasing the number of people exposed to ambient $PM_{2.5}$ and its adverse health impacts. In addition, due to the age distribution in the underlying epidemiological studies, outdoor $PM_{2.5}$ health impacts were only estimated for the adult population over 30, and the majority of $PM_{2.5}$ attributable premature deaths are for people over 70 years old (Table 5). Between 2010 and 2030, the proportion of the population in Bangladesh over 30 years increased from 39% to 52%, and the number of people over 70 years from 4.4 million people to 8.2 million (UN DESA, 2018). Hence a substantially larger number of older people were exposed to the estimated increased outdoor $PM_{2.5}$ concentrations.

The implementation of all the mitigation measures in Bangladesh's NDC and SLCP Action Plan was estimated to reduce ambient $PM_{2.5PW}$ across Bangladesh by 13 μg m^{-3} (18%) in 2030, compared to the baseline scenario (Fig. 6). This reduction is substantially lower than the reduction in total emissions of some of the $PM_{2.5}$-precursor pollutants. This is in part because some of the key $PM_{2.5}$ precursor pollutants within Bangladesh, specifically ammonia, were not substantially reduced from the implementation of these measures. However, the primary reason was that a substantial fraction of $PM_{2.5PW}$ in Bangladesh were estimated

Table 4
Change in emissions of key greenhouse gases, short-lived climate pollutants and air pollutants from implementation of mitigation measures in Bangladesh. Values are change in emissions relative to the baseline in 2030 (in kilotonnes). The percentage reduction compared to the 2030 baseline is shown for the 5 main scenarios.

Scenario	Source Sector	Measure	Organic Carbon	Black Carbon	$PM_{2.5}$	NH_3	SO_2	NO_x	VOCs	CH_4	CO	CO_2
NDC Existing	Energy	Energy Efficiency (Energy Efficiency & Conservation Master Plan target)	−21	−12	−43	−1	−86	−116	−100	−11	−200	−41,775
NDC Existing	Power Generation	Renewable Energy	−0	−0	−0	−0	–	−10	−0	−0	−4	−6,445
NDC Existing	Industry	Improved Brick Kilns	−0	−11	−13	0	−7	−4	−2	−0	−106	−1,177
NDC Existing	Residential	Improved biomass cookstoves	−9	−2	–22	−3	−2	−8	−99	−15	−240	−1,057
NDC Additional	Power Generation	Supercritical coal power plants	−0	−0	−0	−0	−7	−4	−0	−0	−0	−1,917
NDC Additional	Transport	Road transport fuel efficiency	–	–	–	–	−12	–	–	−2	–	−4,880
NDC Additional	Power Generation	Wind and Solar	−0	−0	−0	−0	–	−10	−0	−0	−4	−6,445
NDC Possible	Residential	Improved biomass stoves and LPG use for cooking	−119	−29	−247	−91	−37	−45	−760	−174	−2,733	−847
NDC Possible	Commercial and Public Services	Commercial Energy Consumption	−0	−0	−0	−0	−13	−8	−0	−0	−1	−4,183
NDC Possible	Agriculture	Alternate Wetting and Drying of Rice paddies	–	–	–	–	–	–	–	−9	–	–
NDC Possible	Waste	Landfill gas capture	–	–	–	–	–	–	–	−363	–	–
NDC Possible	Waste	Organic waste diverted from landfill to composting	–	–	–	–	–	–	–	−260	–	–
SLCP Action	Industry	Efficient rice parboiling units	–	−3	−11	–	−0	−6	−4	–	−38	–
SLCP Action	Agriculture	Reduce open burning of crop residues	−10	−1	−16	−7	−1	−7	−19	−8	−175	–
SLCP Action	Transport	Adopt Euro Standards in road transport	−1	−7	−13	−0	−49	−268	−30	−1	−83	−15,809
SLCP Action	Transport	CNG conversion	0	−0	−0	0	−0	0	1	0	−8	–232
SLCP Action	Agriculture	Livestock enteric fermentation	–	–	–	–	–	–	–	−69	–	–
SLCP Action	Agriculture	Manure Management	–	–	–	−211	–	–	–	−35	–	–
SLCP Action	Waste	Domestic Wastewater	–	–	–	–	–	–	–	−281	–	–
SLCP Action	Natural Gas	–	–	–	–	–	–	–	−11	−96	–	−1,307
NDC Existing			−30	−26	−79	−5	−95	−136	−201	−26	−549	−49511
NDC Existing (% reduction)			−8%	−19%	−10%	0%	−14%	−11%	−12%	−1%	−9%	−17%
NDC Additional			0	0	0	0	−17	−3	0	−2	0	−6414
NDC Additional (% reduction)			0%	0%	0%	0%	−3%	0%	0%	0%	0%	−2%
NDC Possible			−110	−27	−225	−87	−37	−39	−661	−609	−2494	−571
NDC Possible (% reduction)			−31%	−20%	−30%	−8%	−6%	−3%	−40%	−18%	−41%	0%
SLCP Action			−11	−11	−41	−218	−43	−281	−63	−489	−304	−14942
SLCP Action (% reduction)			−3%	−8%	−5%	−19%	−7%	–22%	−4%	−15%	−5%	−5%
All measures			−151	−64	−345	−310	−192	−459	−925	−1126	−3347	−71438
All Measures (% reduction)			−43%	−46%	−45%	−27%	−29%	−36%	−56%	−34%	−55%	−25%

to result from emissions from other countries and natural background, neither of which were mitigated by the measures implemented in Bangladesh. In terms of the fraction of $PM_{2.5PW}$ which Bangladesh can control (i.e. due to its own emissions), the implementation of all measures reduces this fraction of $PM_{2.5PW}$ in Bangladesh by 28% in 2030.

The implementation of Bangladesh's NDC and National SLCP Plan was estimated to avoid approximately 12,000 premature deaths per year attributable to ambient $PM_{2.5}$ exposure in 2030. This represents a 6% reduction in the total mortality burden from outdoor $PM_{2.5}$ exposure. The reduction in premature mortality is smaller than the reduction in $PM_{2.5PW}$ due to the non-linearity of the IER function used to quantify the relative risk from a particular $PM_{2.5}$ exposure. At the level of $PM_{2.5}$ exposure estimated for Bangladesh in 2030, the shape of the exposure response function is less steep than at lower concentrations. Therefore, a change in $PM_{2.5}$ exposure results in a smaller change in the relative risk than an equivalent change in exposure at lower $PM_{2.5}$ concentrations, i.e. a larger reduction in $PM_{2.5}$ concentrations is required when population $PM_{2.5}$ exposure is relatively high, to achieve the same health benefit from a smaller change in $PM_{2.5}$ concentrations when the exposure is lower. This means that additional emission reductions, in combination with the measures included in Bangladesh's NDC and National SLCP Plan, could yield even larger health benefits.

In addition to the health impacts from ambient $PM_{2.5}$ exposure, in 2010, the household-derived $PM_{2.5}$ exposure to people living in

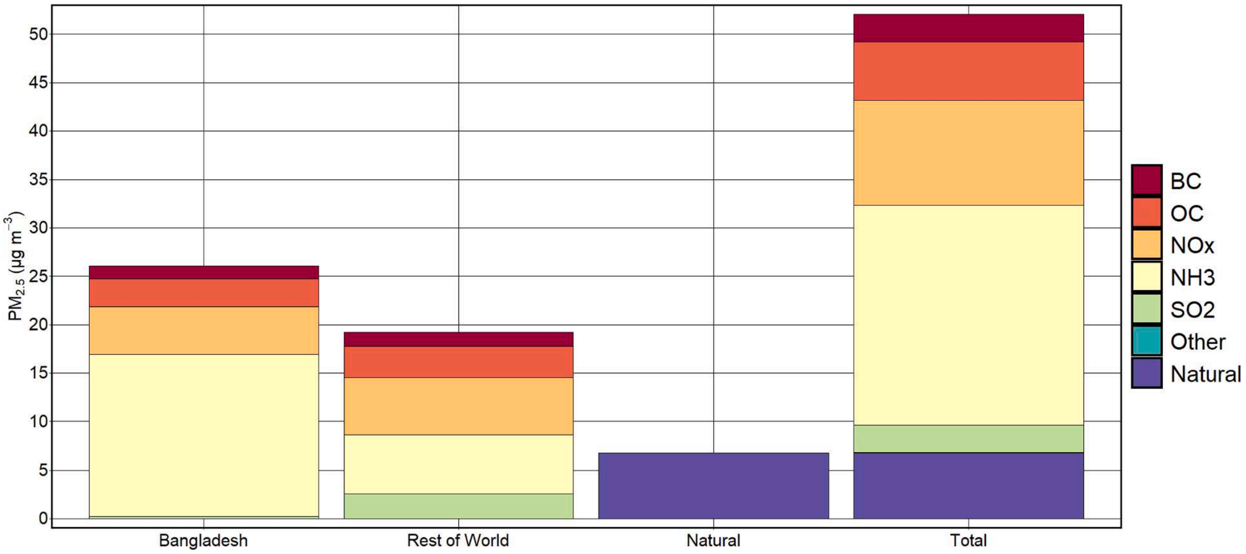

Fig. 5. Population-weighted annual average $PM_{2.5}$ across Bangladesh in 2010 disaggregated by contribution from different pollutant emissions within the country (National), outside the country (rest of the world) and from natural background.

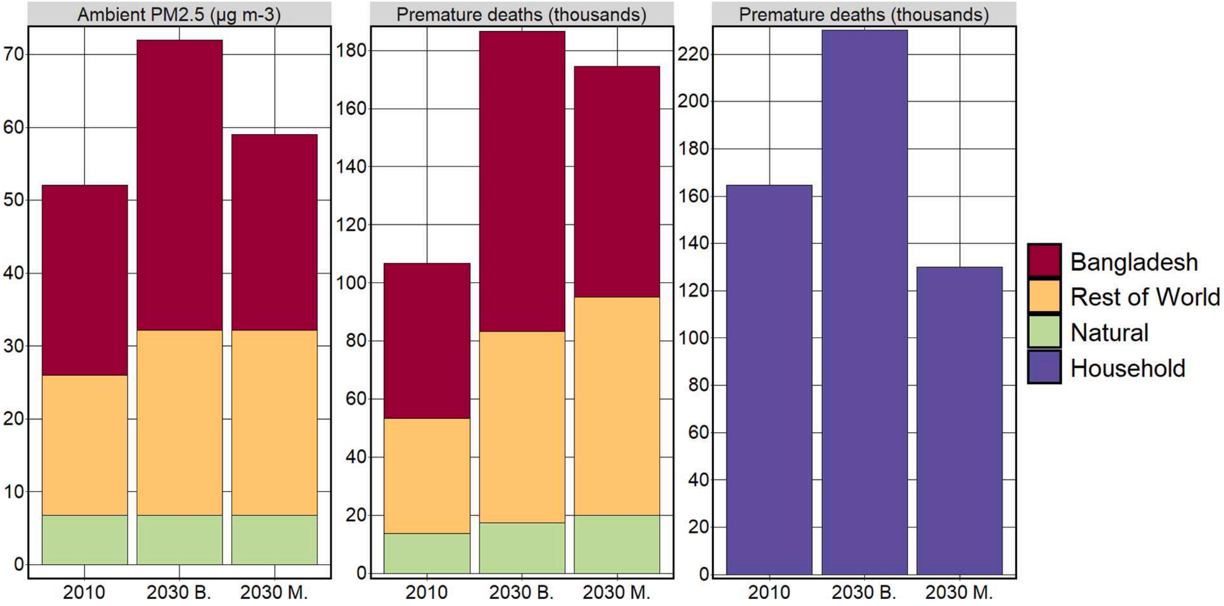

Fig. 6. a) Population-weighted annual average ambient $PM_{2.5}$ concentrations, b) premature deaths attributable to ambient (outdoor) $PM_{2.5}$ exposure, and c) premature deaths attributable to household air pollution exposure in 2010, and in 2030 for a baseline (2030B.) and mitigation (2030 M.) scenario. The mitigation scenario represents the full implementation of the measures included in the 3 NDC scenarios, and additional SLCP actions.

households cooking using solid biomass was associated with an estimated 165,000 premature deaths, including 29,000 infant deaths (Table 5). The population changes and demographic shifts described above increased the household air pollution health burden to an estimated 230,000 premature deaths in 2030 in the baseline scenario. There was a small reduction in the health burden from household $PM_{2.5}$ exposure from the NDC existing scenario, which includes a measure to distribute 1.5 million improved biomass cookstoves. As outlined in Section 2.2, switching to cooking using improved biomass cookstoves was estimated to reduce household $PM_{2.5}$ exposure by 60% for occupants of homes cooking using biomass (equivalent to a reduction from 337 μg m^{-3} to approximately 135 μg m^{-3}) for primary cook exposure. Similarly as for the reduction in ambient $PM_{2.5}$ exposure outlined above, the flatter shape of the IER function at $PM_{2.5}$ exposures in the household $PM_{2.5}$ exposure range described above results in a smaller reduction in relative risk than an equivalent change in $PM_{2.5}$ exposure at lower $PM_{2.5}$ exposures. However, a much larger reduction in household $PM_{2.5}$-attributable premature deaths could be achieved from the NDC possible scenarios, which includes 30% of households switching to cooking using LPG, and the remainder using improved biomass cookstoves. The implementation of this measure could reduce the health burden from household air pollution by over 40% in 2030. When households switch to cooking using LPG, household $PM_{2.5}$ exposure is estimated to be reduced by 100%. This is a larger reduction in $PM_{2.5}$ exposure compared to the reduction in ambient $PM_{2.5}$, and household $PM_{2.5}$ from switching to efficient biomass stoves. However, this larger reduction in household $PM_{2.5}$ exposure translates into a proportionally even larger reduction in relative risk, as the household $PM_{2.5}$ exposure of residents in households now cooking using LPG is estimated to have reduced below the range of $PM_{2.5}$ exposures for which the IER function is relatively flat. Therefore, a

Table 5
Premature deaths associated with $PM_{2.5}$ exposure for the base year and future scenarios, disaggregated by age category and source of $PM_{2.5}$ exposure (ambient and household). 95% confidence intervals are shown in parentheses for total premature deaths attributable to ambient and household air pollution exposure separately.

Air Pollution Exposure	Age category	2010 (thousand premature deaths)	2030 baseline (thousand premature deaths)	2030 NDC existing (thousand premature deaths)	2030 NDC existing + NDC additional (thousand premature deaths)	2030 NDC existing + additional + NDC potential (thousand premature deaths)	2030 NDC + SLCP Action plan scenarios (thousand premature deaths)
Ambient	Less than 5 years	11	5	5	5	5	4
Ambient	30–50 years	11	15	15	15	14	14
Ambient	50–70 years	33	65	64	64	63	60
Ambient	Over 70 years	52	102	101	101	99	96
Ambient	Total	107 (51–147)	187 (94–258)	185 (92–256)	185 (92–256)	181 (90–252)	175 (85 – 245)
Household	Less than 5 years	30	11	11	11	5	5
Household	30–50 years	15	17	16	16	9	9
Household	50–70 years	46	76	75	75	43	43
Household	Over 70 years	74	127	124	124	72	72
Household	Total	165 (88–233)	230 (129–325)	226 (116–320)	226 (116–320)	130 (55–193)	130 (55–193)

combination of the larger reduction in $PM_{2.5}$ exposure, and the shape of exposure–response functions used to estimate health burdens results in the substantially larger reductions in premature mortality attributable to household $PM_{2.5}$ exposure compared to ambient $PM_{2.5}$ exposure from implementation of Bangladesh's NDC and National SLCP Plan.

Finally, the baseline emission projections for Bangladesh result in an estimated global average temperature increase of 0.006 °C in 2040, relative to 2010. This temperature change accounts for the climate impacts of long-lived GHGs like CO_2, which makes the largest contribution to warming from Bangladesh emissions in 2040, as well as methane, and other short-lived climate forcers (ozone, warming and cooling aerosols). The implementation of Bangladesh's NDC actions could reduce the total contribution of Bangladesh emissions to global average temperature change by 16% by 2040. This is composed of 21 and 26% reductions in the warming contribution of CO_2 and CH_4 emissions from Bangladesh, which is offset slightly by a reduction in the overall cooling impact of non-methane short-lived climate forcers, primarily organic carbon and secondary inorganic aerosol (Fig. 7).

4. Discussion

4.1. Limitations of LEAP-IBC modelling framework

LEAP-IBC is a tool designed to be used by planners in LMICs to rapidly assess the likely effects of implementing different policies on air pollution and climate change. To achieve this, several simplifications and assumptions have been introduced into the modelling framework to increase its utility for this application that should be considered when interpreting the results. For example, as outlined in Section 2, for a LEAP emission and scenario model to be compatible with the IBC impact

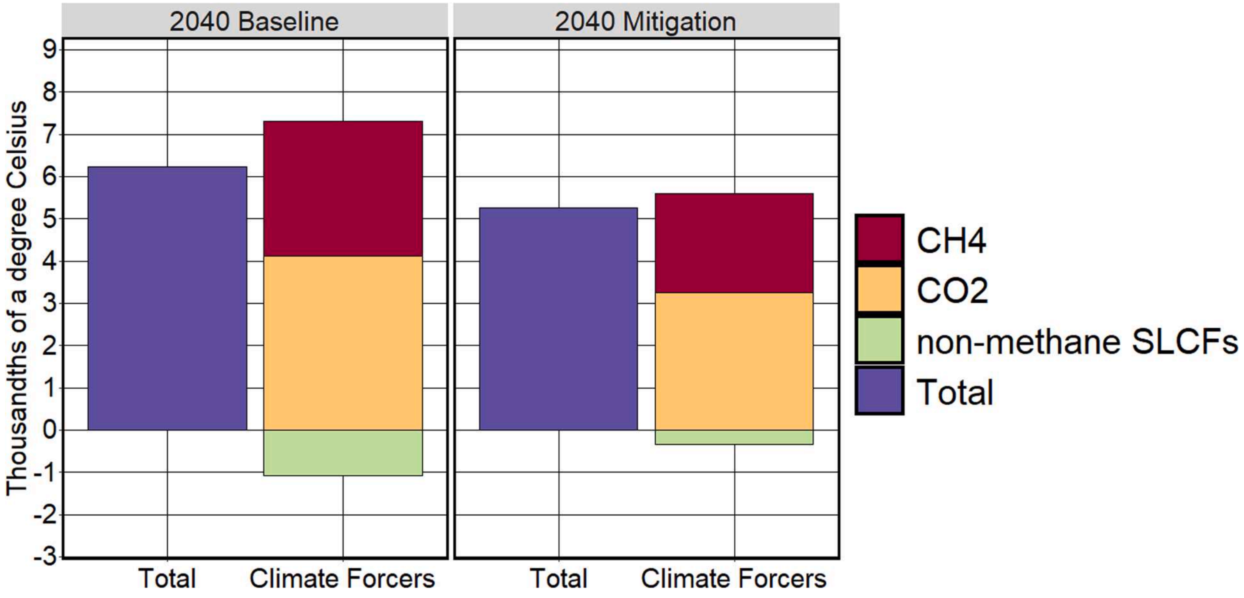

Fig. 7. Global average temperature change in 2040 relative to 2010 due to emissions from Bangladesh for a) baseline, and b) mitigation scenarios. The mitigation scenario results represent the implementation of all measures in NDC existing, NDC additional, NDC potential and SLCP Action scenarios. Global average temperature change is shown as the net total for all climate forcers (long-lived greenhouse gases and short-lived climate forcers), and the separate contributions of GHGs (CO_2 and CH_4) and non-methane short-lived climate forcers (SLCFs), including black carbon, organic carbon, secondary inorganic aerosol and tropospheric ozone.

calculations, it must estimate emissions of all GHGs, SLCPs and air pollutants from all major source sectors. A default LEAP model has been developed that meets these requirements, and was adapted and used in Bangladesh in this case study. This default LEAP model includes default emission factors for GHGs, SLCPs and air pollutants (described in Vallack et al. (2020) and available at: https://leap.sei.org/default.asp?action=IBC). These emission factors are taken from IPCC (2006) and EMEP/EEA (2016) guidelines, as well as other peer-reviewed studies. These default data can be changed where more appropriate local data are available. The advantage of this approach is that, with relatively little locally-specific data, a comprehensive initial emission inventory can be produced that can iteratively be improved as new data become available, e.g. as shown in the Bangladesh application with the more detailed modelling of key sources, such as rice parboiling and brick kilns, using more detailed national data. It also means that more details can be added to the key source sectors of interest, while ensuring that emissions from all other source sectors are quantified. The limitation is that many of the default emission factors were not derived in the country where they are being applied and may have been derived in different contexts and under different conditions. Further studies are required to assess the appropriateness of emission factors for use in a particular application for a particular source. In addition, while variables entered into LEAP, such as emission factors, are currently required to be entered as single values, LEAP’s Application Programming Interface (API) can be used to link to software that can define probability distributions for values and run Monte Carlo simulations to explore uncertainty in emission (or other) outputs (see https://leap.sei.org/help for more details).

The ability to rapidly assess multiple mitigation measures and their effect on $PM_{2.5PW}$ and global temperature change results from the application of linearised coefficients from the GEOS-Chem model developed at the global scale. These coefficients quantify the sensitivity of national $PM_{2.5PW}$ to changes in emissions across $2^\circ \times 2.5^\circ$ grids globally. Limitations associated with their application are that atmospheric chemistry and transport is only represented at a coarse global grid resolution, and therefore finer scale transport and chemical reactivity is not captured within these coefficients. Applying these linearised coefficients assume that a change in $PM_{2.5}$-precursor emissions in a grid results in a linear change in $PM_{2.5PW}$ in the target country. Therefore, non-linear interactions between, e.g. SO_2, NH_3 and NO_x to form secondary inorganic aerosol, are not accounted for in the application of these coefficients. Tests of this linearisation have been included in previous applications of this model (e.g., Henze et al., (2012)); for aerosol radiative forcing, the response estimated by the coefficients for perturbations of up to 100% had a strong correlation with forward model responses ($r = 0.76$ and linear regression slope of 0.9). Deviations were largest for NOx; for the other aerosol species the correlations was even stronger ($r = 0.98$).

In the case of Bangladesh, the ambient $PM_{2.5PW}$ in 2010, progression to 2040, and the expected benefits from implementing the mitigation measures considered here may be underestimated in this work. There are few studies that have measured $PM_{2.5}$ concentrations at ground stations in Bangladesh, and none with the spatial density to derive a population-weighted $PM_{2.5}$ exposure estimate for the whole country. Khan et al. (2019) measured an average $PM_{2.5}$ concentration of 86.1 μg m^{-3} at an urban background site in Dhaka, and at three sites in the vicinity of Dhaka $PM_{2.5}$ concentrations were measured between 95 and 100 μg m^{-3} between 2013 and 2014 (Rana et al., 2016b). Shaddick et al. (2018) estimated population-weighed ambient $PM_{2.5}$ concentration for Bangladesh of 82 μg m^{-3} in 2010 (95% confidence intervals: 50–124 μg m^{-3}), based on a combination of satellite observations, atmospheric chemistry transport modelling, and calibration against ground observations. The 52 μg m^{-3} estimated in this study (based on $PM_{2.5}$ concentrations developed in van Donkelaar et al. (2016)) is therefore lower than available ground-based measurements (that are concentrated in urban areas), and other satellite-based estimates, which may underestimate the baseline health burden associated with $PM_{2.5}$ exposure. Shaddick et al. (2018) used a Bayesian Hierarchical Modelling framework to calibrate a gridded surface of $PM_{2.5}$ concentrations for each country in the world against available monitoring data at the national, regional and super-regional scale (dependent on the number of monitoring sites in a given area). South Asia was one of the two regions (with Sub-Saharan Africa) with the largest uncertainty in derived population-weighted $PM_{2.5}$ concentrations (root mean square error (RMSE) for population-weighted $PM_{2.5}$ in South Asia and Sub-Saharan Africa were 22.0 and 32.2 μg m^{-3}, respectively, compared to 12.1 μg m^{-3} and 2.7 μg m^{-3}, globally and in high-income countries, respectively). Additionally, of the 3275 direct $PM_{2.5}$ ground measurements globally used to calibrate the (taken from the World Health Organisation Global Ambient Air Quality Database), only 46 were taken in South Asia, of which 25 were in India (31 were in Sub-Saharan Africa). This underlies the greater uncertainty in estimating population-weighted annual $PM_{2.5}$ concentrations using satellite-based products in South Asian countries such as Bangladesh, as well as in sub-Saharan Africa, compared to other regions.

In addition, previous studies also highlight the substantial contribution transboundary transport makes to $PM_{2.5}$ concentrations in Bangladesh, even in cities such as Dhaka (Begum et al., 2013; Rana et al., 2016a). Few studies have measured the composition of ambient $PM_{2.5}$ in Bangladesh. The modelling in this study indicates that emissions of secondary inorganic aerosol precursors, specifically NO_x and NH_3, make the largest contribution to $PM_{2.5}$ concentrations in Bangladesh. Snider et al. (2016) measured $PM_{2.5}$ at a site in Dhaka and estimated that ~ 20% of $PM_{2.5}$ concentrations were secondary inorganic aerosol, while other studies have estimated that organic matter contributes approximately 46% to $PM_{2.5}$ at a measurement site in Dhaka, and black carbon approximately a third (Begum et al., 2012, 2011). Li et al. (2017) estimated the composition of $PM_{2.5}$ in different regions based on GEOS-Chem forward modelling. For South Asia, it was estimated that approximately 40% of population-weighted $PM_{2.5}$ was organic aerosol, with approximately 40% secondary inorganic aerosol (sulphate, nitrate and ammonium). Secondary organic aerosol is not included in the adjoint coefficients applied in the IBC module to estimate $PM_{2.5}$ concentrations from changes in emissions, which may explain some of the difference between the emission contribution to $PM_{2.5}$ in this work, and the regional composition estimated in Li et al. (2017). Further work is required to determine $PM_{2.5}$ composition in Bangladesh, but a larger carbonaceous fraction would result in greater reductions in ambient $PM_{2.5PW}$ from implementation of the mitigation measures considered here, leading to a larger improvement in air quality and associated health impacts.

The derived population-weighted ambient $PM_{2.5}$ concentrations, and exposure to household-derived $PM_{2.5}$ was combined with an exposure–response function to estimate health impacts (premature mortality). The underlying epidemiological studies used to derive the IER functions were almost exclusively conducted in North America and Europe (Burnett et al., 2014; Cohen et al., 2017), and their application therefore assumes an equivalent risk from air pollution exposure in Bangladesh, and other countries outside these regions. This ‘flattening’ of the exposure response function at higher levels of $PM_{2.5}$ exposure means that it is assumed that in countries such as Bangladesh, a larger reduction in $PM_{2.5}$ exposure is required to achieve the same health benefits as a smaller reduction in $PM_{2.5}$ exposure at lower levels. The shape of the exposure response function has been widely discussed (Nasari et al., 2016; Pope et al., 2015; Pope and Dockery, 2006), and, as outlined in Section 3.2, is important in determining the relative health benefit from reductions in ambient and household $PM_{2.5}$ exposures, and individual mitigation strategies. Therefore, the change in $PM_{2.5PW}$ is also output from IBC alongside estimates of the number of premature deaths. The number of premature deaths estimated in 2010 (107,000) is similar to the 1990–2014 average number of $PM_{2.5}$ premature deaths attributed to $PM_{2.5}$ (163,000 premature deaths) in Shi et al. (1999), and those estimated in Health Effects Institute (2018) (95,322 premature deaths), in which population-weighted $PM_{2.5}$ exposure as described above was estimated to be higher. Finally, the estimated benefits in terms of reduction in premature deaths attributable to air pollution exposure may also be underestimated in this study because exposure to other pollutants (e.g. ozone, (Malley et al., 2017a) was not taken into account, or non-fatal health outcomes associated with air pollution exposure (Anenberg et al., 2018; Malley et al., 2017b). The LEAP-IBC modelling framework will be progressively extended to account for a wider range of air pollution health impacts.

4.2. Application of the LEAP-IBC tool and implications for integrated air pollution and climate change planning in Bangladesh

This application of LEAP-IBC in Bangladesh quantifies for the first time the change in emissions of SLCPs and air pollutants associated with implementation of Bangladesh's NDC. The results show that there are substantial air pollutants and SLCP emission reductions that result from Bangladesh achieving its climate change commitment, which would yield local benefits in terms of air quality and health in the near-term. In addition, 'Possible' actions, specifically the transition to cooking using LPG and improved biomass cookstoves, identified in Bangladesh's NDC that do not contribute to the climate change commitment, were estimated to have the largest public health benefits from reducing household air pollution health impacts. For developing countries with low levels of GHG emissions, as well as significant development challenges and priorities, undertaking an integrated analysis of GHG, air pollutants and SLCP emissions and prioritising measures that have local development benefits such as improved air quality could provide further motivation to achieving and enhancing ambition within their climate planning.

This analysis highlights additional factors that could be considered as part of air quality and climate change mitigation planning in Bangladesh. Firstly, it is important to consider emissions of all $PM_{2.5}$-precursor pollutants within air quality planning activities within Bangladesh. While there are substantial emission reductions associated with many of the $PM_{2.5}$-precursor pollutants from implementing the NDC and SLCP actions, such as black carbon and organic carbon, there is less reduction of secondary inorganic aerosol precursors such as NO_x, SO_2 and, in particular, ammonia. Secondary inorganic aerosol was estimated to make up a large fraction of $PM_{2.5PW}$ and therefore measures that focus on major sources of NH_3 (agriculture), NO_x (transport) and SO_2 (power generation) should all be considered to reduce $PM_{2.5}$. Additional efforts aimed at curbing secondary organic aerosol, which is not considered here, are also likely warranted. Secondly, there was a substantial contribution to $PM_{2.5PW}$ estimated from rest of the world emissions. Therefore, without any action in countries in the region, Bangladesh will be limited in the extent to which it can improve air quality and minimise health impacts. Regional cooperation could play a role in strengthening action, such as envisioned by the Malé Declaration in South Asia (Hicks et al., 2001). Thirdly, the additional mitigation measures included in Bangladesh's National SLCP Plan that are not currently included in Bangladesh's NDC were also shown to lead to additional reductions in greenhouse gases such as methane and carbon dioxide (Fig. 4). Therefore, as many countries are currently in the process of revising their NDCs (United Nations, 2015), the integration of these mitigation measures into an update to Bangladesh's NDC provides an opportunity increase the climate change mitigation ambition that Bangladesh commits to, in a way that would achieve substantial local benefits in Bangladesh through reductions in air pollutant emissions, as outlined in CCAC SNAP (2019).

Finally, quantifying global average temperature change due to Bangladesh emissions places on the same scale the contribution of GHGs, and short-lived climate forcers. This is important for integrated planning on climate change and air pollution because emissions of many $PM_{2.5}$ precursors have a cooling effect on the atmosphere, therefore their reduction to improve air quality could lead to a climate disbenefit if not accompanied by GHG or SLCP emission reductions. This study indicates that implementing Bangladesh's NDC and National SLCP Plans successfully achieve this, and that reductions in emissions of cooling aerosols are balanced by reductions in warming pollutants. This results in the achievement of simultaneous improvement of air quality and reduction in the contribution to climate change in the near-term from Bangladesh emissions. However, the progression of global average temperature change due to Bangladesh emissions in this study was only estimated for the near term (to 2040) due to the time period over which emission projections were produced. A long-term emission development strategy could be used to assess the progression of temperature change over the long-term (e.g. to 2100) due to Bangladesh emissions and accounting for the balance of changes in emissions of GHGs, SLCPs and cooling pollutants envisioned for Bangladesh much further into the future.

5. Conclusions

There are substantial benefits in linking mitigation of air pollution and climate change as i) some pollutants contribute to both warming of the atmosphere and health and vegetation impacts of air pollutants (short-lived climate pollutants), ii) because many major sources of air pollution are also major sources of greenhouse gases and therefore some can mitigate climate change while improving air quality, iii) some necessary air pollution policies, required to reduce aerosols to protect human health and the environment, will lead to the unwanted effect of accelerated warming, because of the removal of the 'cooling' effect of these aerosols on climate.

These are strong arguments to look at both air pollutants and greenhouse gases in an integrated way to ensure that the most efficient measures for both aspects are selected and possible trade-offs considered and compensated.

In low- and middle-income countries, there is a lack of planning tools that can be used by national planners to quantify the air pollution and climate change impacts of different plans, strategies policies and measures to support the development of integrated air pollution and climate change plans. The modelling framework developed within the LEAP-IBC tool provides a practical planning tool to assess the air pollution and climate change implications of different actions. This framework involves the development of a model that estimates emissions of greenhouse gases, short-lived climate pollutants and air pollutants in a consistent way, for historical years, and for future projections for baseline and mitigation scenarios. These emissions are then converted into estimates of changes in population-weighted ambient $PM_{2.5}$ concentrations, exposure to household-derived $PM_{2.5}$ concentrations, and attributable ambient and household air pollution health impacts, as well as impacts on climate in terms of global average temperature changes.

The Bangladesh case illustrates the application of LEAP-IBC for integrated air pollution and climate change mitigation analysis quantifies the overall consequences for air quality and climate from implementation of two key policy documents in Bangladesh, the Nationally Determined Contribution that outlines Bangladesh's climate change mitigation commitment, and Bangladesh's National Action Plan to reduce SLCPs. The LEAP-IBC application in Bangladesh estimated that the full implementation of the mitigation measures included in Bangladesh's NDC and National SLCP Plan would result in substantial reductions in greenhouse gas (25% reduction in CO_2 emissions in 2030 compared to the baseline), SLCP (46% and 34% reduction in black carbon and CH_4 emissions, respectively) and air pollutant emissions (45% and 36% reduction in primary $PM_{2.5}$ and NO_x emissions, respectively). These emission reductions were estimated to reduce population-weighted ambient $PM_{2.5}$ concentrations by 9% in 2030 compared to the baseline. This could reduce ambient air pollution health burdens by 12,000 premature deaths per year (5% of the total health burden), in addition to 100,000 avoided premature deaths from reduced household air pollution exposure and reducing Bangladesh's contribution to global temperature change. A substantial transboundary contribution to population-weighted $PM_{2.5}$ in Bangladesh was also identified, highlighting the need for regional emission reductions to improve air quality and reduce health impacts in Bangladesh.

CRediT authorship contribution statement

Johan C.I. Kuylenstierna: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Charles G. Heaps:** Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing. **Tanvir Ahmed:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Harry W. Vallack:** Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing. **W. Kevin Hicks:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Mike R. Ashmore:** Methodology, Writing - original draft. **Christopher S. Malley:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Guozhong Wang:** Methodology, Software. **Elsa N. Lefevre:** Methodology, Formal analysis, Writing - review & editing. **Susan C. Anenberg:** Conceptualization, Methodology, Writing - review & editing. **Forrest Lacey:** Methodology, Software. **Drew T. Shindell:** Conceptualization, Methodology, Writing - review & editing. **Utpal Bhattacharjee:** Formal analysis, Writing - review & editing. **Daven K. Henze:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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