World Health Organization

Health benefits of raising ambition in Colombia's Nationally Determined Contribution (NDC): WHO technical report

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Figures and tables

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Acronyms and abbreviations

ALRI	Acute lower respiratory infection
BAU	Business as usual
BC	Black carbon
BCA	Benefit–cost analysis
CAI	Clean Air Institute
CaRBonH	Carbon reduction benefits on health
CEA	Cost-effectiveness analysis
CI	Confidence interval
COPD	Chronic obstructive pulmonary disease
CRF	Concentration response functions
DM	Type 2 diabetes mellitus
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
GEMM	Global Exposure Mortality Model
GHG	Greenhouse gas
HiAP	Health in all policies
HRAPIE	Health risks of air pollution in Europe
IBC	Integrated benefits calculator
IER	Integrated Exposure Response
IHD	Ischemic heart disease
IPCC	Intergovernmental Panel on Climate Change
LC	Lung cancer
LEAP	Low emissions analysis platform
LRI	Lower respiratory infection
LULUCF	Land use and land use changes and forestry
MER	Market exchange rate
NAMA	Nationally appropriate mitigation actions
NCD	Noncommunicable disease
NDC	Nationally Determined Contribution
NMVOC	Non-methane volatile organic carbon
OC	Organic carbon
OECD	Organisation for Economic Co-operation and Development
PAHO	Pan-American Health Organization
PLR	Price level ratio
PM	Particulate matter
PPP	Purchasing power parity
RR	Relative risk
SDG	Sustainable Development Goal
SEI	Stockholm Environment Institute
SLCP	Short-lived climate pollutant
SR	Source Receptor
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VSL	Value of a statistical life
WHO	World Health Organization
6-COD	Six causes of death of the Global Burden of Disease Study

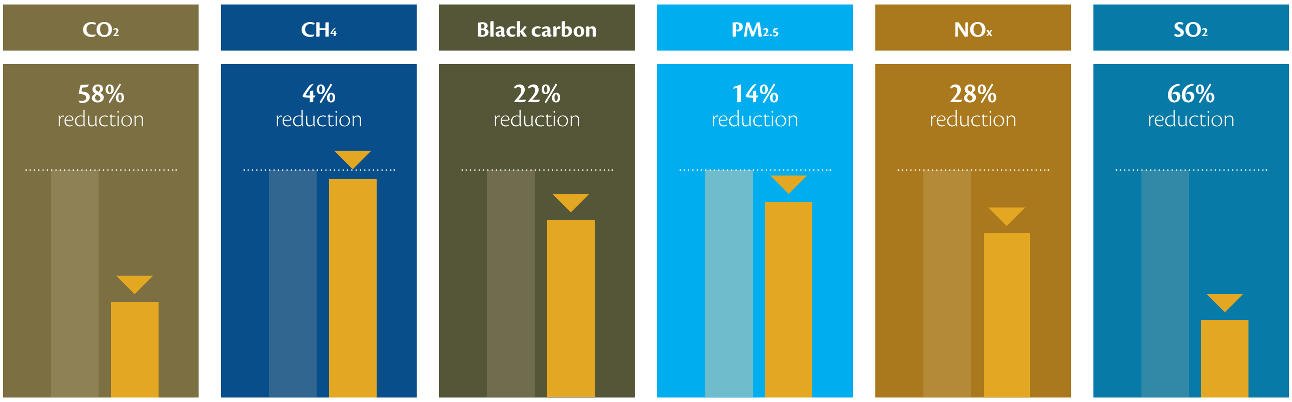
Abstract

The following technical report outlines the rationale, process and results of a joint research study, coordinated by the World Health Organization (WHO) and the Pan-American Health Organization (PAHO), co-chaired by the Ministry of Health and Social Protection and the Ministry of Environment and Sustainable Development in collaboration with the Climate and Climate Air Coalition, the Stockholm Environment Institute, the Clean Air Institute and leading international and national experts. A rationale section describes the links between greenhouse gas (GHG) emissions, short-lived climate pollutants, air pollution and adverse health outcomes. A summary of the research study describes how scenarios were modelled to examine the health and economic implications of raising ambition in Colombia's Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC).

Ongoing work at CIAT's headquarters in Colombia, to measure the greenhouse gas emissions of rice production, Colombia, 2011
© Neil Palmer Photography / CIAT

Key findings

We considered 3 scenarios, consisting of a business as usual (BAU) reference scenario (Reference), a low ambition scenario (Mitigation Scenario 2) and a high ambition scenario (Mitigation Scenario 3) (See table 2). The results of the study indicate that by 2030, implementing Mitigation Scenario 3, compared to the Reference Scenario, could lead to a reduction in the following parameters (Figure below):



These GHG emissions reductions would be accompanied by significant air quality improvements that could:

- prevent more than **3 800** premature deaths annually from ambient air pollution in 2030
- in economic terms, this result represents an annual cost of **US$1.9 billion** (2017 prices) (0.64% of Colombia's projected GDP in 2030).[1]

In terms of avoided health burden, it is predicted that the higher ambition Mitigation Scenario 3 would provide 20% greater health and economic benefits than the lower ambition Mitigation Scenario 1 (see Table 2 for a list of mitigation measures under each scenario).

The process outlined in this technical report can serve as a template for future studies that seek to demonstrate how strong, ambitious national climate commitments can result in significant health gains.

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[1] Only a small fraction is actually a market cost. Mortality is valued using the VSL, which refers to the "social" cost -- this is an intangible monetary benefit (what society values as the benefit to prevent a death).

Policy recommendations based on study findings

The significant health benefits and associated health savings in the scenarios modelled provide a strong argument and investment case for setting ambitious climate targets in Colombia's NDC.

By implementing the following **five health recommendations**, the Government of Colombia could ensure health considerations remain a focus; contribute positively to climate ambition; maximize synergies and optimize trade-offs between climate, economic and health objectives; and thereby support a more coherent overall approach to sustainable development.

1. **Increase sector-wide mitigation ambition to save lives**.
   This study found that Mitigation Scenario 3 (see Table 2) would result in CO_2 reductions of approximately 58% in 2030 compared to the NDC Reference Case scenario. Actions to reduce GHG emissions could prevent more than 3 800 premature deaths annually by 2030 due to the simultaneous reduction in air pollutants. In economic terms, health gains from the higher mitigation pathway would be equivalent to 0.64% of Colombia's projected GDP in 2030.

2. **Put health at the centre of Colombia's NDC, in line with WHO guidance and recent research**.
   Focusing NDC implementation on health could help achieve health co-benefits and establish connections between health and other sectors crucial to climate change mitigation. Putting health in NDC ambition strengthens the investment case for climate change mitigation and adaptation.

3. **Adopt a health in all policies (HiAP) approach particularly in the energy, transport and agriculture sectors**.
   A HiAP approach will ensure that the health implications of climate mitigation and adaptation decisions are systematically taken into account. It will promote sector-wide synergies while avoiding harmful health impacts.

4. **Establish mechanisms to facilitate collaboration between health and other sectors**.
   Dialogue and collaboration between the Ministry of Health and Social Protection and other health determining sectors such as the environment, energy, transport, agriculture and land use are key to ensuring that the interlinkages between health and climate change are properly included in political decisions. All stakeholders can work together to inform the population about the benefits of specific policy options.

5. **Continue to obtain reliable data on health co-benefits of climate ambition in Colombia to inform policies in various sectors**.
   There is a key role for the health sector in providing and communicating to different stakeholders authoritative and evidence-based advice about health risks and benefits associated with different climate mitigation policies. This entails building the capacity of health professionals on climate change and health to identify climate-related causes of specific diseases, raise awareness among the population, and collect empirical data for relevant national and sectoral documentation.

Lessons learned

As the climate crisis and its threat to health become more apparent and evidence grows on the potential health benefits of climate mitigation action, further research in line with this study is encouraged. Lessons learned from this study are summarized here and can be extrapolated for further research activities in Colombia or similar studies in other countries.

1. **Creating multidisciplinary teams can help tackle the complex interrelations between different aspects of climate and health**. The study modelled the connections between greenhouse gas emissions, short-lived climate pollutants and health outcomes, which required expertise in the health, environment, finance, air quality and meteorology sectors. This study was a collaboration between government ministries, national and international organisations, researchers and UN agencies.

2. **Focusing on multiple co-benefits of ambitious climate policies, including environmental, health and economic benefits, can highlight the advantages of such policies to policy-makers and the public**. This study found that Mitigation Scenario 3 (see Table 2) would result in CO_2 reductions of approximately 58% in 2030 compared to the NDC Reference Case scenario. Actions to reduce GHG emissions could prevent more than 3 800 premature deaths annually by 2030 due to the simultaneous reduction in air pollutants. In economic terms, health gains from the higher mitigation pathway would be equivalent to 0.64% of Colombia's projected GDP in 2030. At the same time, governments should consider the high cost of inaction.

3. **Sharing the methods and findings of this research study in the region and internationally can be useful in helping other governments undertake similar assessments in their own countries**. More studies are needed, and countries should be encouraged to produce similar simulations. In many cases, the availability of national and detailed data is presented as a hurdle. But, while national and detailed data allow for a better estimation of the modelling outcomes, this should not be a limiting factor to conduct these types of studies. There are international data available and other approximations that can provide some notion of the health impacts of climate policies, and which provide sufficient inputs into climate negotiations and policy-making processes.

Woman working in a recycling factory, Colombia, 2018
© Andrer / Getty Images

Background

The burning of fossil fuels creates air pollution that leads to noncommunicable diseases (NCDs), including cardiovascular diseases, chronic respiratory conditions, acute lower respiratory infections (ALRIs) and certain cancers *(1)*. Fossil fuels are also the main contributor to greenhouse gases (GHGs) that cause climate change, which, in turn, is strongly linked to environmental risk factors for NCDs and other health impacts *(2)*. In addition to burning of fossil fuels, other contributors to climate change, such as agriculture, and waste, can also contribute to air pollution and its impacts on human health.

The World Health Organization (WHO) recommends that health co-benefits, in particular policies that reduce air pollution and short-lived climate pollutants (SLCPs), should be prioritized in Nationally Determined Contributions (NDCs). SLCPs contribute to air pollution-related mortality, as well as having high global warming potential *(3)*. Some countries have already included health co-benefits in their NDCs, but these are still limited in numbers and there is room for more focus on the health and economic gains of climate action in country strategies. Although 70% of NDCs submitted as of December 2019 include public health considerations, only 10% (18 out of 184) highlight the health co-benefits of GHG mitigation policies *(3)*. More progress is needed for commitments to monitor the health co-benefits of climate action and to inform decision-making.

Recently, Colombia updated its NDC outlining its aim to: reduce GHG emissions by 51% by 2030 compared to a baseline scenario; reduce black carbon emissions, a short-lived climate pollutant (SLCP), by 40% by 2030 compared to its 2014 emission level; and to adapt to the impacts of climate change. The Colombian NDC is articulated within the context of the Sustainable Development Goals (SDGs) and the long-term strategy E2050 that was announced at the 26th Conference of the Parties (COP26) United Nations Climate Change Conference in November 2021 (NDC Colombia, 2020).

Rationale and scope

The scope of this work was to quantify the health and economic co-benefits associated with improvements in ambient air quality from implementation of Colombia's NDC. Implementation of pledges put forward in the NDC, according to Colombia's national circumstances, capabilities and priorities, will contribute to the country's commitment to a successful transition to a low-carbon economy, which combined with the efforts of the rest of the global community under the 2015 Paris Agreement *(4)* seeks to limit the growth of the mean global surface temperature by the end of the 21st century to well below the target of 2 °C above pre-industrial times. Further, the proposed NDC targets will put in place national measures that aim to build up a robust and climate-resilient society, capable of successfully adapting to and surviving future climate change residual hazards.

In addition to dealing with and mitigating the undesirable economic, environmental and social consequences of climate change, climate policies will achieve health co-benefits from reduced emissions of major air pollutants, such as ambient air releases of particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and organic compounds, as well as micropollutants such as heavy metals and SLCPs (e.g. black carbon). Reduction of these pollutants would directly or indirectly influence local and national air quality across Colombia, as well as regionally (neighbouring countries) through mediation of transboundary pollutant transport. Therefore, climate policies that have the potential to reduce carbon emissions can deliver a win–win outcome by simultaneously limiting emissions of climate altering pollutants and the consequential adverse environmental impacts and health risks, and by delivering gains in healthy life years for citizens. Further, climate policies contribute to promoting the UN SDGs agenda, such as SDG 13 – *Take urgent action to combat climate change and its impacts*.

Research methods

Summary of modelling framework and approach

When it comes to determining the impacts of climate change and health, policy decisions and economic, social and natural systems interact together to form a national policy context. These systems are complex with non-linear outcomes, making them difficult to predict. Models replicate these systems as best as possible to better forecast the impacts of policy decisions on health, the environment and other outcomes.

To quantify the health benefits that could be achieved from the implementation of Colombia's updated NDC, three models were used (Figure 1). These followed a staggered approach, with outputs from one model fed into the next to capture the full chain of causality between fossil fuel use and health outcomes.

The modelling framework characterises the link between: i) emissions of air pollutants; ii) their transport and chemical reactivity in the atmosphere that determines levels of exposure to fine particulate matter ($PM_{2.5}$); iii) the consequences of this exposure on the incidence of fatal and non-fatal health outcomes; and iv) the economic impact of these air pollution-attributable health impacts. The emissions, exposure, health and economic impacts are characterised for historical years (up to 2014) and for future projections to 2030 for different mitigation scenarios. The 2030 baseline scenario reflects the magnitude of these variables in Colombia for a scenario that projects socioeconomic development in Colombia continues according to the current trajectory, without the implementation of additional policies and measures specifically designed to reduce emissions. The 2030 mitigation scenarios reflect futures in which packages of policies and measures included in Colombia's NDC are implemented. The magnitude of the emissions, exposure, health and economic impacts in the future scenarios, therefore, allow the benefits from implementing the mitigation measures in Colombia's NDC to be determined. The 2030 baseline scenario provides a reference point against which the different mitigation scenarios can be compared in terms of air pollution, health and economic impacts.

A combination of three modelling tools was used to estimate the health benefits of changes in air pollution associated with the implementation of Colombia's NDC. First, emissions of air pollutants in historic and future years were estimated using the Low Emissions Analysis Platform (LEAP) tool *(5)*. LEAP has been widely used for GHG mitigation assessments, including for NDCs, and is increasingly used for integrated air pollution and climate change mitigation analyses. For Colombia's NDC, LEAP was the tool selected to quantify the GHG emission reduction potential of different mitigation measures being considered for inclusion in the NDC. Integrating air pollutant emissions into LEAP allowed for the development of consistent estimates of GHGs, SLCPs and air pollutant emissions. This ensured the air pollutant emission reductions from implementation of the mitigation measures included in the NDC were consistent with the GHG emission reduction potential included in the NDC. Within the LEAP software, the Integrated Benefits Calculator (IBC) module has been developed to quantify the impact of changes in air pollutant emissions on air pollution exposure and health impacts. The IBC module grids national emission estimates of all pollutants that contribute to $PM_{2.5}$ concentrations in the atmosphere. It combines those estimates with default emission estimates for the rest of the world and outputs from an atmospheric chemistry transport model to estimate the population-weighted annual average $PM_{2.5}$ concentration across Colombia that results from a given set of historic or future emissions.

The IBC module within LEAP includes an air pollution health impact assessment calculator. However, in this project, the population-weighted annual average $PM_{2.5}$ concentration for Colombia for each year and scenario was output from IBC and used as an input to the Carbon Reduction Benefits on Health (CaRBonH) tool which performs a comprehensive impact analysis considering both morbidity and mortality events *(6)*. CaRBonH is an integrated exposure, health and economic assessment tool developed by WHO and has been used to model health effects from air pollutants in countries across the globe.

CaRBonH was used to estimate the impact of air pollutants on various health outcomes, including avoided morbidity and premature mortality, under the baseline and mitigation scenarios. Finally, the economic benefit of avoided morbidity and premature mortality was calculated using Colombia-specific unit cost data. In the case of averted premature deaths, the value of a statistical life (VSL), determined using the Organisation for Economic Co-operation and Development (OECD) benefit transfer methodology *(7)*, was used.

The three modelling tools were chosen because of their flexibility to adapt to the Colombia context, their ability to use national-level data as inputs, and because of their use and validation by world-leading organizations in the field. These tools together can provide a representation of Colombia's dynamics that reflects, as closely as possible, using international best practices, the country's complex reality. Various scenarios can be tested with different assumptions to forecast the consequences of policy decisions.

Figure 1

Modelling framework to undertake the health impact assessment of Colombia's NDC

Tool	**LEAP**	**Integrated Benefits Calculator (IBC)**	**Carbon-H**
Methods	• GHG. SLCP and air pollutant emission quantification • Scenario and projection analysis	• Gridding emissions • Emissions to $PM_{2.5}$ exposure estimate	• Population weighted exposure to $PM_{2.5}$ • Quantification of morbidity and mortality outcomes • Economic valuation of health outcomes
Inputs	• Activity for energy demand, and supply sectors, industrial production, livestock and crop production, and waste generation • Emission Factors • Projections of key socioeconomic drivers	• GEOS-Chem Adjoint coefficient sensitivities parameterised for Colombia • Rest of world emission estimates from ECLIPSE dataset • LEAP emission outputs	• Exposure response functions • Baseline disease incidence rates • Population
Outputs	• National total historical (2010-2014) GHG, SLCP and air pollutant emission estimates from energy, IPPU, AFOLU and waste • Projected (2015-2030) emissions of GHGs, SLCPs and air pollutants from all sectors	• Population-weighted annual average $PM_{2.5}$ concentrations for Colombia	• Avoided pre-mature mortality from $PM_{2.5}$ • Economic benefits expressed in millions of US dollars, 2019 nominal prices

LEAP

The assessment of air pollutant emissions mitigation from implementation of Colombia's NDC was undertaken using the LEAP tool *(5)*. Air pollutant emissions were estimated for three scenarios (shown in Figure 2): i) historical emissions between 2010 and 2014, ii) baseline projections of emissions between 2015 and 2030, and iii) future emission estimates to 2030, estimated to simulate the implementation of policies and measures that aim to reduce emissions in key source sectors and that were included in the NDC. The key equation used to estimate emissions from all major sources of the pollutants listed above is the multiplication of an activity variable by an emission factor (Equation 1). The activity variable quantifies how big a particular sector or process is in a country (e.g. the number of terajoules of fuel consumed in a particular sector; the number of tonnes of production of a particular mineral, chemical or other product). Emission factors quantify the mass of pollutant emitted per unit of activity (e.g. the kilograms of black carbon emitted per terajoule of fuel consumed).

Equation 1: Emissions = activity x emission factor

The specific activity data, emission factors and methodologies used to quantify emissions in each source sector were defined according to international guidelines on the quantification of air pollutant emissions. Specifically, the methodologies followed the Intergovernmental Panel on Climate Change (IPCC) 2006 emission inventory guidelines *(8)*. The IPCC 2006 guidelines provide methodologies for the quantification of GHG emissions. They also recommend that for other pollutants the European Monitoring and Evaluation Programme / European Environment Agency (EMEP/EEA) air pollution emission inventory guidebook is used *(9)*.

The overall air pollutant emission mitigation assessment was developed using LEAP. LEAP is a widely used software tool for energy policy analysis and climate change mitigation assessment that has been actively developed for more than 30 years. LEAP is an integrated, scenario-based modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector GHG emission sources and sinks. In addition to tracking GHGs, LEAP can also be used to analyse emissions of local and regional air pollutants and SLCPs, making it well-suited to studies of the climate co-benefits of local air pollution reduction. LEAP is intended as a medium- to long-term modelling tool. Most of its calculations occur on an annual time-step, and the time horizon can extend for an unlimited number of years. Studies typically

Figure 2
Stages in conducting the GHG mitigation assessment

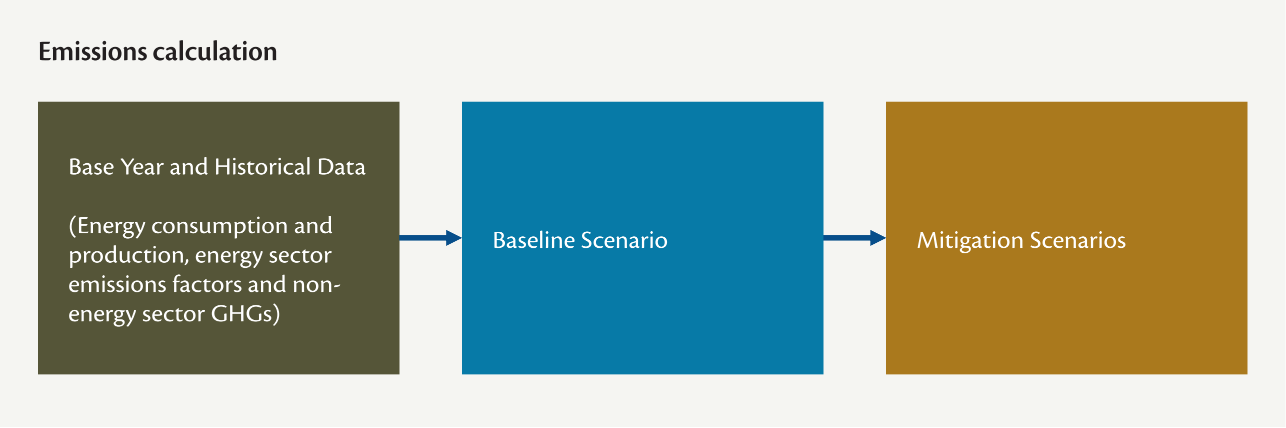
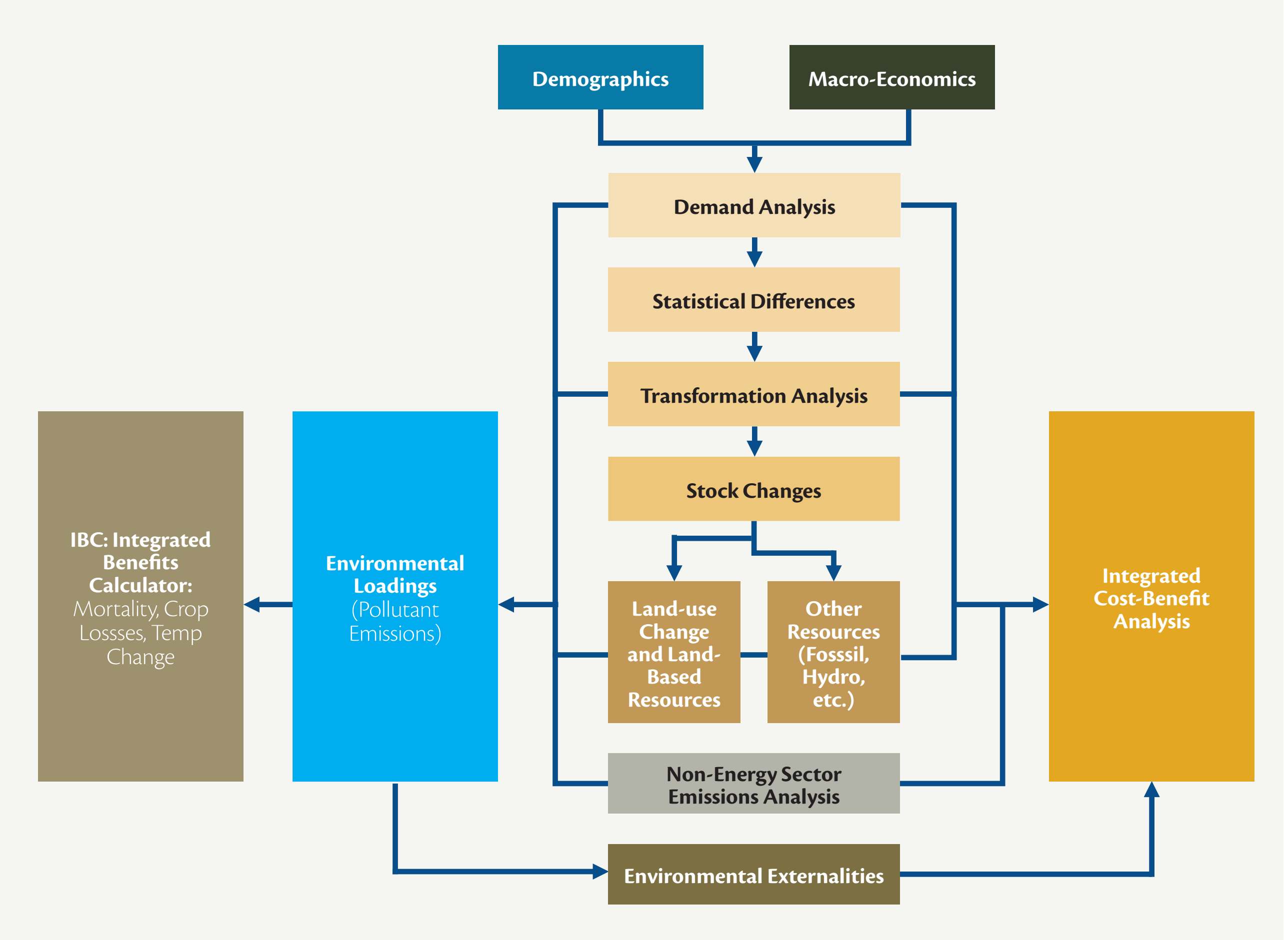


Figure 3

Representation of LEAP modelling framework



include both a historical period known as the Current Accounts, in which the model is run to test its ability to replicate known statistical data, and multiple forward-looking scenarios. Typically, most studies use a forecast period of between 20 and 50 years. The overall LEAP modelling framework is shown in Figure 3. As well as accounting for emissions, LEAP also links energy supply and demand modelling, meaning that interactions between energy supply and demand are taken into account in the development of baseline and mitigation scenarios. In Colombia, LEAP was the tool used to conduct the GHG mitigation assessment and analysis of black carbon mitigation for the NDC. Air pollutant emissions were added and integrated into these existing analyses to provide the estimated changes in air pollutant emissions in a way that was consistent with the emission projections of GHGs and SLCPs that underpin Colombia's NDC.

The GHG and black carbon emission assessments using LEAP are described in reports developed as part of the NDC update, and the results are included in Colombia's updated NDC. The additional air pollutant emissions were included to allow a consistent estimate of changes in air pollutant emissions to link to the health impact assessment. To do this, emission factors were added to the GHG and black carbon LEAP analysis for all pollutants contributing to $PM_{2.5}$ concentrations in the atmosphere, both primary $PM_{2.5}$ emissions and gaseous pollutants that react in the atmosphere to produce $PM_{2.5}$. The pollutants, in addition to GHGs and black carbon, added into LEAP were:

- **Particulate matter ($PM_{2.5}$ and PM_{10})**: Particulate matter (with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10})) are small solid particles in the atmosphere. They make the largest contribution to the impact of air pollution on human health through, for instance, effects on the cardiovascular and respiratory systems. The emissions of $PM_{2.5}$ and PM_{10} calculated here represent the direct emissions to the atmosphere of particulate matter. However, other gaseous pollutants, like nitrogen oxides, sulphur dioxide, ammonia and volatile organic compounds, also contribute to the $PM_{2.5}$ and PM_{10} concentrations people are exposed to, through chemical reactions in the atmosphere that convert gaseous pollutants into solid particles.

- **Nitrogen oxides (NO_x):** An air pollutant that is a precursor to the formation of particulate matter and tropospheric ozone, NO_x is made up of two pollutants – nitrogen oxide (NO) and nitrogen dioxide (NO_2).

- **Sulphur dioxide (SO_2):** An air pollutant that is a precursor to the formation of particulate matter.

- **Ammonia (NH_3):** An air pollutant that is a precursor to the formation of particulate matter.

- **Organic carbon (OC):** A component of direct PM emissions that contributes to the negative effects of air pollution on human health.

- **Non-methane volatile organic compounds (NMVOCs):** A collection of different organic molecules emitted from a range of emission sources. NMVOCs are precursors to the formation of tropospheric ozone and particulate matter. Common NMVOCs emitted from anthropogenic processes include propane, butane, benene and toluene.

- **Carbon monoxide (CO):** A gaseous air pollutant which contributes to the formation of tropospheric ozone.

Emissions of these pollutants were quantified from all major source sectors in Colombia, categorized according to the IPCC source sector categorization (8). This categorization groups pollutants within four overarching sectors: i) energy; ii) industrial processes and product use; iii) agriculture, forestry and other land use; and iv) waste. The sources included are shown in Table 1.

Table 1
Source sectors covered in emissions inventory

Source sector	Sub-sector
1 – Energy	1A1a Main activity electricity and heat production
	1A1c Manufacture of solid fuels and other energy industries
	1A2 Manufacturing industries and construction
	1A3b Road transportation
	1A3c Railways
	1A4a Commercial / institutional
	1A4b Residential
	1A4c Agriculture, forestry, fishing, fish farms
	1A5 Non-specified
	1B1a Fugitive emissions from coal mining

Table 1 cont'd.

Source sectors covered in emissions inventory

Source sector	Sub-sector
2 – Industrial processes	2A Mineral industry
	2B Chemical industry
	2C Metal industry
	2D Non-energy products from energy and solvent use
	2F Product uses as substitutes for ozone-depleting substances
3 – Agriculture, forestry and other land use	3A Livestock
	3B Land
	3C Aggregate sources and non-CO_2 emission sources on land
	3D Other
4 – Waste	4A Solid waste disposal on land
	4B Biological treatment of solid waste

To track GHG, black carbon and other pollutant mitigation pathways, the reduction potential of different measures were evaluated. The actions committed in pursuit of reducing Colombia's GHG emissions are mentioned in Table 2, where all the measures are encompassed in Mitigation Scenario 1 and greater ambition for some measures were evaluated and included in Mitigation Scenario 3 *(10)*.

Mitigation Scenario 2 was a medium ambition scenario that was not included in this analysis. Detailed information on GHG mitigation measures included in Mitigation Scenario 2 were not available.

Table 2

GHG mitigation measures in Colombia's NDC

GHG mitigation measure	Mitigation Scenario 1	Mitigation Scenario 2 (information not available)	Mitigation Scenario 3
Widespread technology adoption for rice production (AMTEC arroz)	Included		Included
Landfill biogas exploitation	Included		Greater ambition
Sustainable cement	Included		Included
Beam compressors	Included		Included
Brick kilns development	Included		Included
Promoting the development of sustainable urban infrastructure	Included		Greater ambition
Diversifying the energy matrix	Included		Greater ambition
Agricultural efficiency	Included		Included
Energy efficiency in refineries	Included		Included
Energy efficiency in mining	Included		Included
Thermal generators efficiency	Included		Included

Table 2 cont'd.

GHG mitigation measures in Colombia's NDC

GHG mitigation measure	Mitigation Scenario 1	Mitigation Scenario 2 (information not available)	Mitigation Scenario 3
Industry efficiency	Included		Greater ambition
Efficient wood-burning stoves	Included		Greater ambition
Energy demand management	Included		Included
Wastewater treatment plant biogas management	Included		Greater ambition
Carbon tax	Included		Included
Chemical industry	Included		Included
Public lighting	Included		Greater ambition
Nationally appropriate mitigation actions (NAMA) for coffee	Included		Included
NAMA for sustainable livestock	Included		Included
NAMA for domestic refrigeration sector	Included		Greater ambition
NAMA for panela	Included		Included
NAMA for transit oriented sector (NAMA-ToD)	Included		Included
Glycol optimal use	Included		Included
Forest plantations	Included		Included
Landfill biogas burning	Included		Greater ambition
Recycling paper, plastic and glass	Included		Greater ambition
Recovery systems in storage tanks	Included		Included
Reducing deforestation	Included		Greater ambition
Resolution 0549	Included		Greater ambition
Ecological restoration	Included		Greater ambition
Biological mechanical treatment systems	Included		Greater ambition
Industry replacement	Included		Greater ambition
Substances causing depletion of the ozone layer substitution	Included		Included
Transport – aviation	Included		Included
Transport – Bogota Metro	Included		Included
Transport – Bogota train	Included		Included
Cargo transportation	Included		Included
Transport – logistics	Included		Included
Transport – electric mobility	Included		Greater ambition
Road freight transport mode to fluvial – Río Magdalena	Included		Included
Transport – active transportation and demand management (Tandem)	Included		Greater ambition
Transport – train	Included		Included
Strategies for reducing GHG emissions of cocoa production (cacao)	Included		Included
Wastewater treatment for coffee and panela	Included		Included
Methane exploitation – hydrocarbons	Included		Included
Methane exploitation – open-pit mining	Included		Included

A total of 102 measures represent the mitigation scenarios for GHG mitigation (Mitigation Scenario 1 and Mitigation Scenario 3, which includes higher ambition for some measures). However, to target some key sectors identified as main black carbon emissions sources, three additional measures related to the improvement of air quality were analysed. These actions with technical or political viability were:

- reduction of agricultural residues burning
- implementation of Euro IV and Euro VI emission standards for new diesel vehicles
- new off-road machinery with Tier 4I emission standards for construction and industrial sectors.

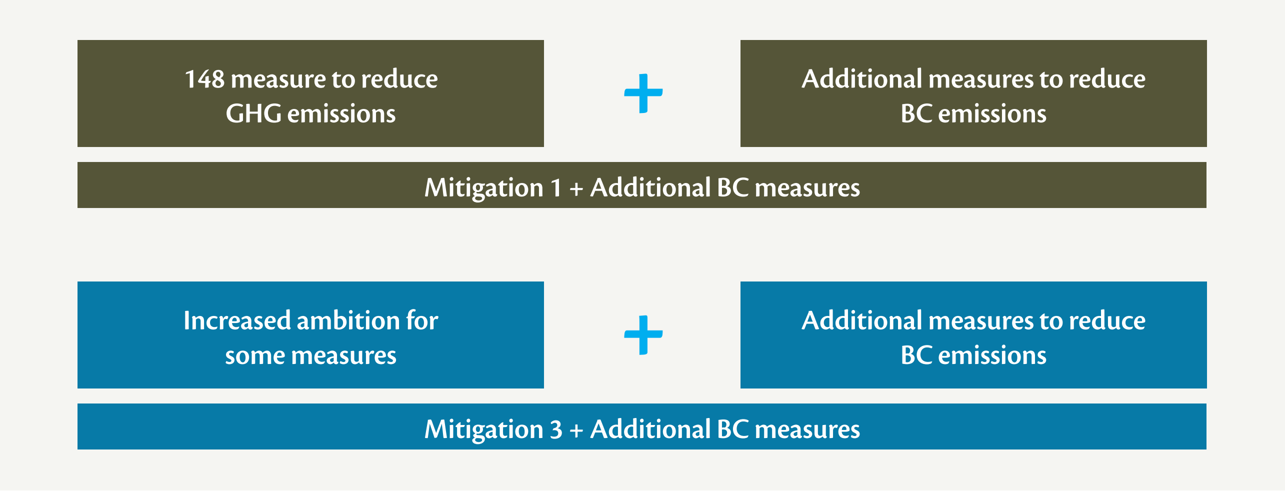
Colombia's updated goal in the NDC of 51% reduction for GHG emissions and 40% for BC emissions by 2030, is a step towards carbon neutrality and climate resilience. The mitigation scenarios were defined as a result of the efforts of sectors and territories towards the achievement of Colombia's objectives of development, peace, equity and education in the medium term; and sustain them in the long term. The total emissions for GHG, black carbon and other atmospheric pollutants were obtained by adding up the values for the two approaches, therefore, the results are given in emissions from each mitigation scenario plus the black carbon additional measures (Figure 4).

IBC

The LEAP model outputs the emissions of air pollutants for historical years (2010–2014) and for projections (2015–2030) for the baseline scenario, and alternative mitigation scenarios reflecting the implementation of climate change mitigation measures included in Colombia's NDC. To link the emissions in each of these scenarios to changes in exposure to particulate matter, the Integrated Benefits Calculator, an add-on to LEAP, was used. The IBC module takes national total emissions for a target country (Colombia) and converts them into estimates of air pollution exposure. The exposure metric used is the population-weighted annual average $PM_{2.5}$ concentrations for Colombia. Population-weighted annual average $PM_{2.5}$ concentrations were estimated by combining the emissions estimated in LEAP for each $PM_{2.5}$ and $PM_{2.5}$ precursor pollutant for Colombia in each year and scenario with outputs from an atmospheric chemistry transport model, GEOS-Chem adjoint *(11)*. 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 were spatially distributed into 2 ° x 2.5 ° grids covering the country

Figure 4

Mitigation scenarios in Colombia's NDC



to match the scale of the GEOS-Chem adjoint model results (see next paragraph). The proportion of national total emissions of each pollutant assigned to the 2 ° x 2.5 ° grids covering the country was based on the spatial distribution of emissions across Colombia in an existing gridded emission dataset, the IIASA GAINS ECLIPSE emissions dataset *(12)*. 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) *(13)*. This ensured 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 the target country.

Next, to translate gridded emissions to population-weighted annual average $PM_{2.5}$ concentrations, accounting for transport and chemical processing in the atmosphere, the gridded emissions were combined with parameterized output from the adjoint of the GEOS-Chem global atmospheric chemistry transport model *(14, 11)*. The GEOS-Chem adjoint model output quantifies the relationship between emissions of a particular pollutant that contributes directly to $PM_{2.5}$ (black carbon (BC), organic carbon (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 sources (e.g. ocean, volcanic, lightning, soil, biomass burning, biogenic, dust) and anthropogenic sources (e.g. transportation, energy, residential, agricultural). 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, accounting for all the mechanisms related to aerosol formation and fate. These sensitivities were output from the GEOS-Chem adjoint as gridded coefficients, which were then multiplied by emission estimates in IBC to estimate the change in population-weighted annual average $PM_{2.5}$ concentrations in Colombia for each year and emission scenario.

Adjoint coefficients were produced for each pollutant that contributes to population-weighted annual average $PM_{2.5}$ 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. For the base year, 2014, the population-weighted annual average $PM_{2.5}$ concentration was set to the value for Colombia from the State of Global Air database of national population-weighted $PM_{2.5}$ concentrations for all countries derived from remote-sensed data, atmospheric modelling, and ground-based monitoring calibration *(15)*. The adjoint coefficients are applied by multiplying, in each grid and for each pollutant, the coefficient by the change in emissions of each pollutant between 2014 and the year/scenario of interest in each grid, and summing across all grids to estimate the change in population-weighted annual average $PM_{2.5}$ concentrations for a particular year for a particular scenario compared to the 2014 value.

CaRBonH

CaRBonH is an integrated climate, air quality and health benefit assessment tool designed to calculate the health co-benefits of climate policies (6). Health benefits, in this context, are defined as fewer episodes of illnesses (morbidity) and avoided premature mortality, especially among children, older people, and people in the general population with pre-existing conditions aggravated from exposure to ambient air pollution. The reduced health effects have an economic consequence that considers the benefit cost on local and national economic productivity, health care budgets, personal income and savings, and also lead to intangible benefits for society from avoided disability due to pain and suffering, and gains in social well-being.

CaRBonH follows an impact pathway analysis (Figure 5). The approach explicitly traces the fate of pollutants from the moment they are released into the environment, followed by atmospheric dispersion, and removal by deposition, through ground and cloud interactions, and through chemical transformation to form secondary airborne species.

Vulnerable population subgroups, such as sick people, children and older people, who are exposed to atmospheric contaminants through inhalation and/or ingestion pathways are at a higher health risk of suffering from adverse health effects, ranging from mild discomfort to more serious life-threatening conditions requiring medical attention, or premature mortality. Health burdens are calculated using concentration–response functions. Lastly, physical burdens are monetized.

The output of CaRBonH may feed into the decision analysis process by informing policy-makers and stakeholders on the health gains achieved, as input to cost effectiveness analyses (CEAs) or benefit cost analyses (BCAs), or be used to promote consideration of more ambitious carbon reduction policies in a feedback loop.

The core user inputs to CaRBonH consist of the reduced emissions of PM, SO_2, NO_x and NH_3, or any combination of these four pollutants, that result from changes in GHG budgets consistent with the 2030 proposed NDC commitment. Reduced GHG emissions (Table 2) could be achieved through improvements in energy efficiency, fuel quality standards, a shift to less polluting technologies and fuels in the power generation or mobility sectors, innovations in industrial manufacturing processes, interventions that target emission reductions from buildings, actions related to land use and land use changes and forestry (LULUCF), and financial mechanisms (e.g. the removal of government subsidies, carbon taxation, carbon trading), as well as by encouraging environmentally friendly consumer behaviour (e.g. eating less red meat, decisions based on imposed monetary disincentives or taxes on carbon-intensive products).

Figure 5

CaRBonH model framework

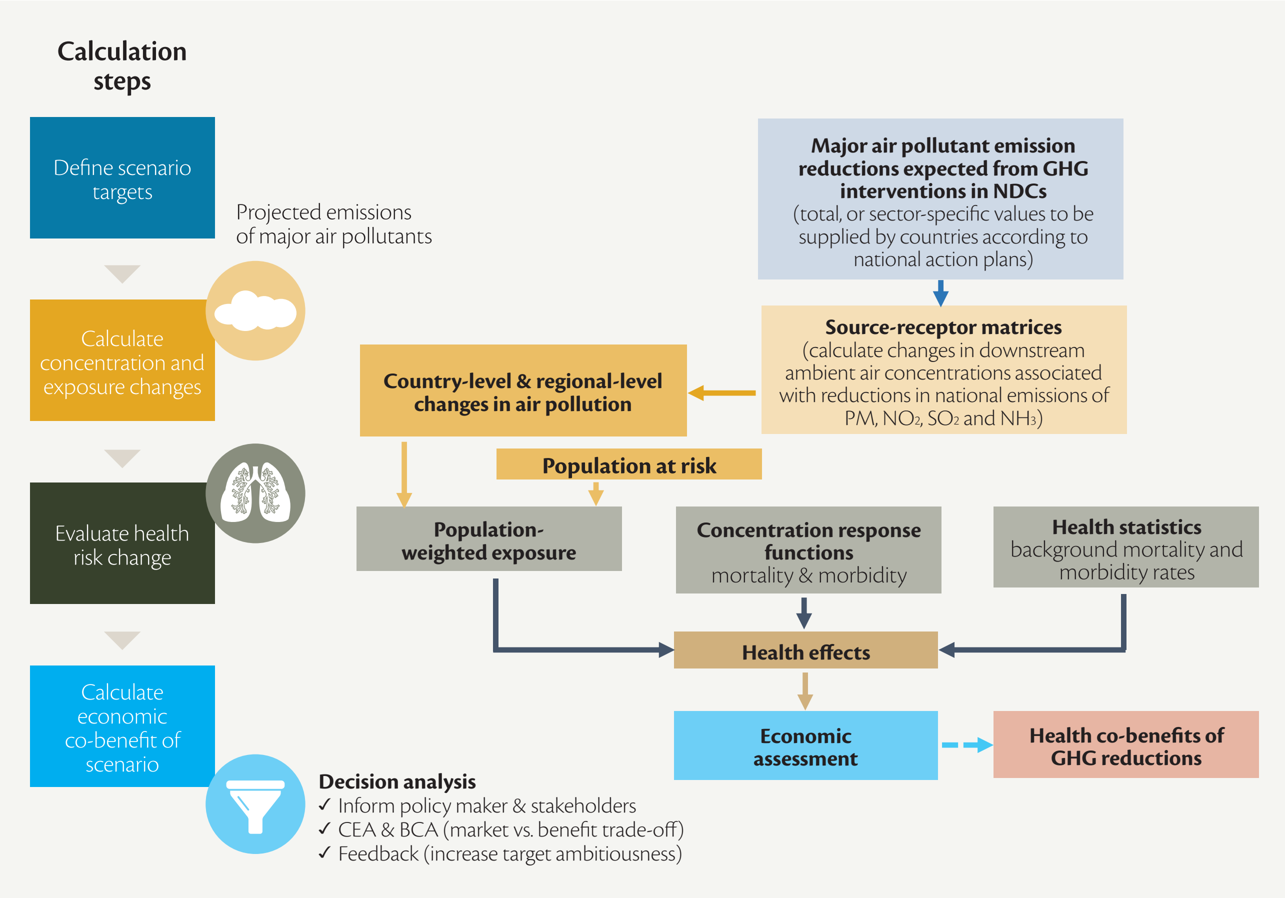
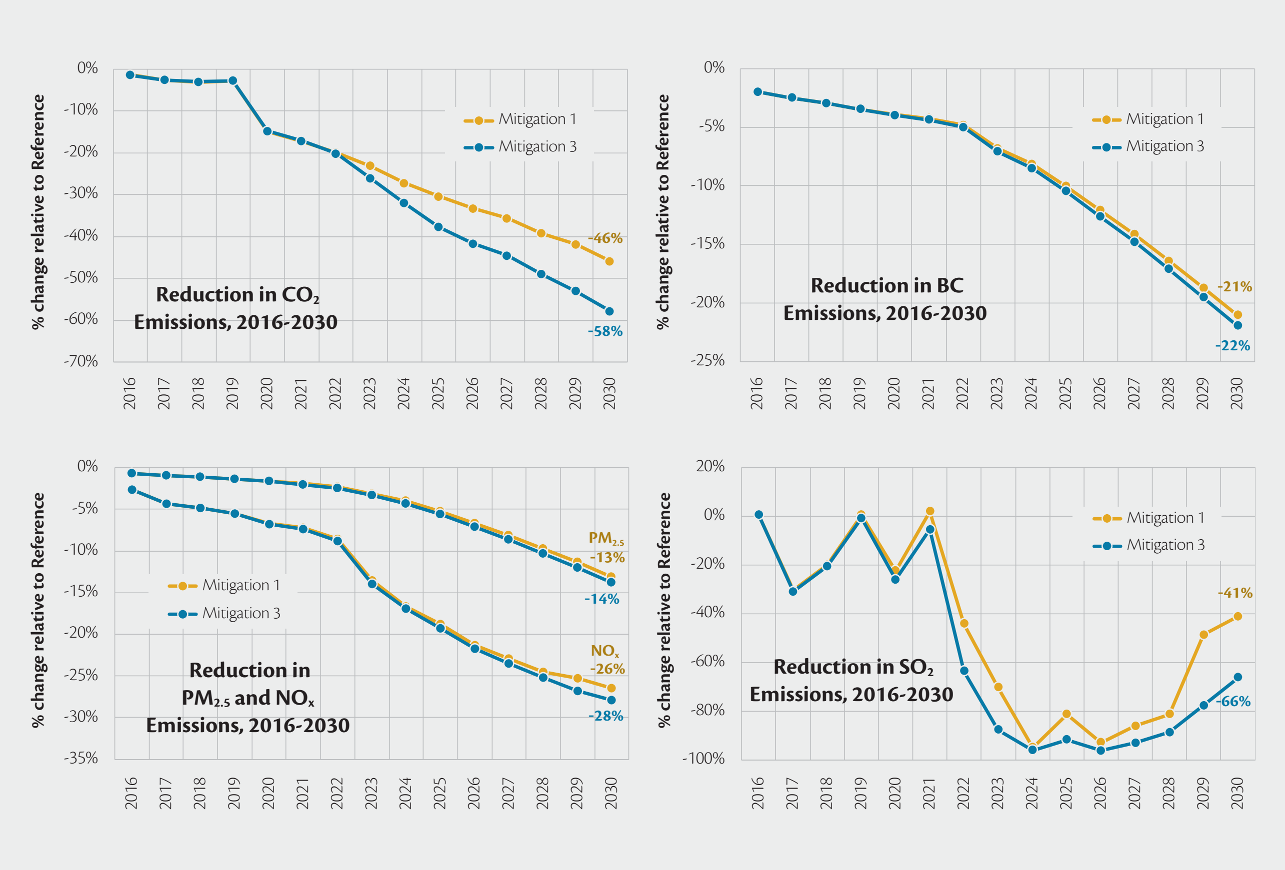


Figure 6

Percent change in ambient air emissions in Colombia during 2016–2030 for two mitigation scenarios relative to the Reference (BAU) scenario



Normally, source-receptor (SR) or transfer matrices[2] are used to link air emission changes to improvements in ambient air quality within the emitter country itself and a downstream location or receiver country in response to reduced cross-boundary pollutant transport. In this work, the population-weighted PM$_{2.5}$ concentration change in Colombia due to PM$_{2.5}$, SO$_2$, NO$_x$ and NH$_3$ emission changes during the 2016–2030 time period for the two carbon mitigation scenarios (Figure 6) have been estimated using LEAP. The contribution to PM$_{2.5}$ from NO$_2$, SO$_2$ and NH$_3$ emissions comes from the production of secondary aerosols; these are the products of chemical reactions in which these precursor pollutants combine with other species present in the atmosphere to produce inorganic nitrate and sulphate aerosols.

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[2] Examples of source-receptor matrices for Europe are available from EMEP at https://www.emep.int/mscw/mscw_srdata.html#SRtables.

The insert chart (box and whiskers plot) in Figure 7 shows the change in the $PM_{2.5}$ concentration in 2030 relative to the business as usual (BAU) scenario. The reference year is 2030. That is the year the health impact assessment is carried out with CaRBonH, as it is the first reporting year in the NDC process. The vertical lines indicate the 95% confidence interval (CI). The concentration uncertainty is modelled assuming a lognormal distribution characterised by a geometric standard deviation (σ_g) equal to 1.32, which implies the ratio of the upper-to-lower bound estimate is 3. The σ_g was derived through consultations with the LEAP modellers, and takes into consideration the uncertainty in the emissions and the variability in the air dispersion modelling. The geometric mean (μ_g) is calculated from the mean change in $PM_{2.5}$ (μ) using the formula $\mu_g = \mu \cdot exp[-0.5 \cdot ln^2 (\sigma_g)]$.

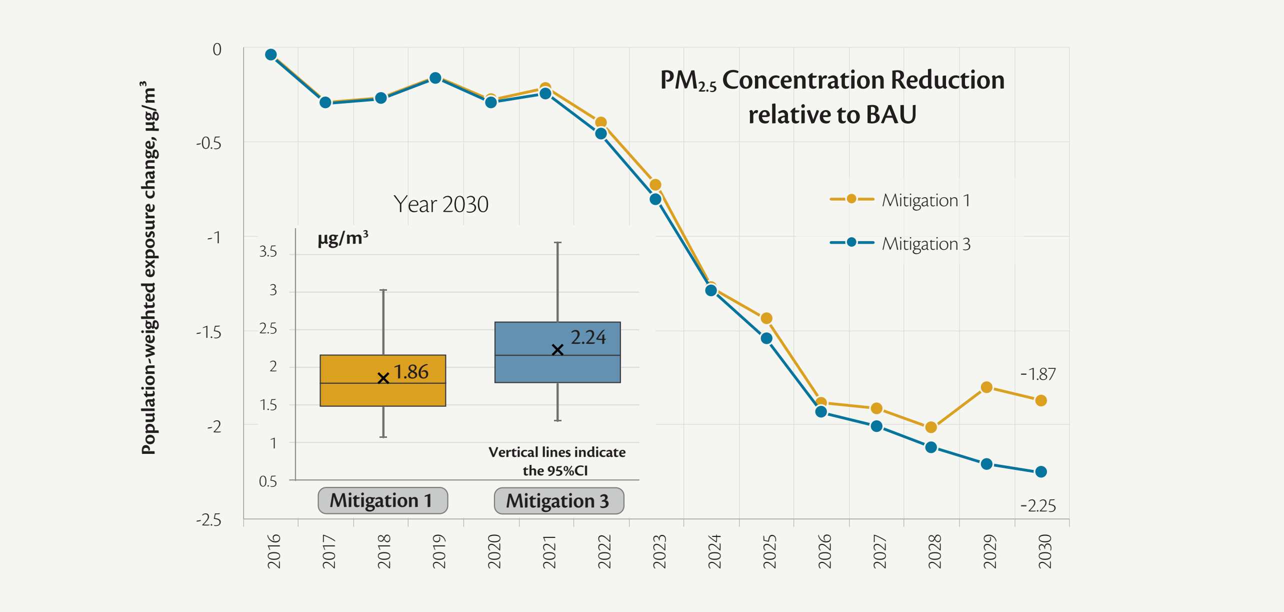
Health benefits, including preventable premature deaths and incidences of morbidity, are calculated using concentration–response functions (CRF). These epidemiological relationships relate a change in the health outcome of concern (e.g. a decrease in number of asthma attacks in children) to a change in the ambient air concentration of a particular pollutant (e.g. decrease in $PM_{2.5}$ concentration from implementation of the NDC targets). Only the health benefits from reductions in $PM_{2.5}$ concentration (either directly through reductions of primary $PM_{2.5}$ emissions or indirectly through reduced formation of secondary $PM_{2.5}$ aerosols) have been quantified in this impact study.

The relative risk (RR) is the ratio of the number of incidence of a particular health outcome between two groups of individuals each exposed to different levels of ambient air pollution. In the case of premature mortality, the RR is the ratio of deaths in the population at risk and those in the unexposed population. For assessments in low exposure environments, when the $PM_{2.5}$ ambient concentration is below 35 μg/m³, CaRBonH uses the WHO relative risks in Health Risks of Air Pollution in Europe – HRAPIE project *(16)* (Table 3).

In this work, the health benefits related to reduced levels of $PM_{2.5}$ concentration include avoided premature natural deaths in adults (25 years and older), along with avoided incidences of hospital admissions, PM-related onset of chronic bronchitis in adults, and childhood incidences of severe asthma attacks and chronic bronchitis. Although the full set of HRAPIE RRs includes other health endpoints, such as restricted activity days and work days lost, these were not quantified in this analysis due to the lack of information on the number of cases (baseline) of these outcomes

Figure 7

Population-weighted $PM_{2.5}$ concentration change during 2016–2030 in Colombia relative to the BAU (Reference) scenario



in Colombia. In addition to the HRAPIE RRs, CaRBonH also characterises the reduced mortality using alternative mortality–exposure relationships for adults, including the Global Exposure Mortality Model (GEMM) *(17)* and the Integrated Exposure Response (IER) functions of the Global Burden of Disease (revision 2019) *(18)*. As a sensitivity analysis, CaRBonH also quantifies the avoided premature deaths using the mortality RR of Chen and Hoek *(19)*. Avoided infant (less than 1 year old) deaths are quantified using the Heft-Neal, Burney, Bendavid and Burkeet *(20)* RR. These additional mortality-exposure associations are presented in Figure 8, Figure 9 and Figure 10.

Health benefits of future emission reductions are evaluated using (Equation 2):

Equation 2:

$$\begin{matrix}\textit{Health}\\ \textit{benefit}\end{matrix} = \begin{matrix}\textit{Outcome of interest}\\ \textit{baseline incidence}\end{matrix} \times \left[1 - \frac{RR(C_{back} - \Delta C)}{RR(C_{back})} \right]$$

C_{back} is the country-level modelled background population-weighted concentration in Colombia for the BAU scenario in 2030. According to the LEAP analysis, the mean background concentration in that year is expected to be 26.6 µg/m^3, assuming no additional climate control policies will be enacted. The concentration uncertainty is modelled assuming a lognormal distribution characterised by a geometric standard deviation (σ_g) equal to 1.32. ΔC (in µg/m^3) is the concentration reduction in 2030 (Figure 7). Relevant baseline data for the BAU (Reference) scenario are summarized in Table 3 for the HRAPIE RRs, and in Figure 8 and Figure 9 for the other mortality–exposure relationships.

Table 3

HRAPIE relative risk associations for health morbidity and mortality used in this work

Health outcome	Population at risk	RR per increment of 10 µg/m^3 PM$_{2.5}$ †	Baseline incidence (cases per year, 2030)
Natural mortality (all causes of death minus injuries and external causes such as deaths due to violence or self-harm)	Adults 25 years and older (both sexes)	1.062 (95% CI: 1.04–1.083) CI: confidence interval	260 000 (std dev: 10 000) std dev: standard deviation
Severe asthma episode	Asthmatic children 5–19 years old	1.058‡ (95% CI: 1.012–1.107)	58.6 million (std dev: 10.1 million)
Chronic bronchitis	Children 6–12 years old	1.170‡ (95% CI: 1–1.425)	17 200 (std dev: 6770)
Onset of chronic bronchitis	Adults 27 years and older	1.253‡ (95% CI: 1.083–1.423)	3180 (std dev: 965)
Respiratory hospital admission	All ages	1.019 (95% CI: 1–1.0402)	351 000 (std dev: 125 000)
Cardiovascular hospital admission	All ages	1.0091 (95% CI: 1.0017–1.0166)	236 000 (std dev: 81 000)
Work days lost	Workers 15–64 years old	1.046 (95% CI: 1.039–1.053)	No data for Colombia
Restricted activity days	All ages	1.047 (95% CI: 1.042–1.053)	No data for Colombia

† Interpretation: In the case of adult mortality, a reduction of 10 µg/m^3 PM$_{2.5}$ leads to a 6.2% reduction in the PM-related natural mortality. Note, natural deaths exclude accidental deaths and mortality related to violence or self-harm.

‡ The original RR was stated in terms of PM$_{10}$, and has been adjusted to PM$_{2.5}$ assuming a PM$_{2.5}$ to PM$_{10}$ mass ratio of 0.491 based on the *WHO Ambient air quality database, update 2018* (https://www.who.int/airpollution/data/cities/en/).

Figure 8

Concentration–response functions for infant mortality

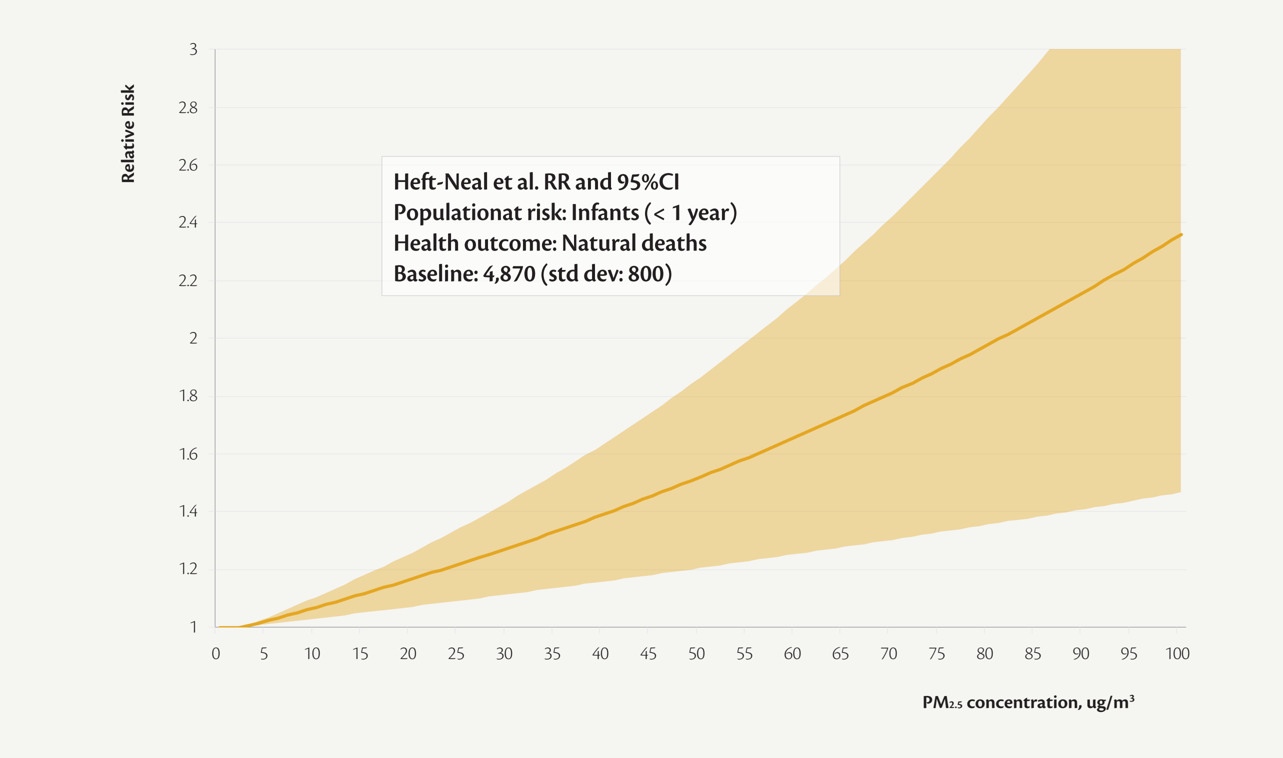


Figure 9

Concentration–response functions for adult mortality

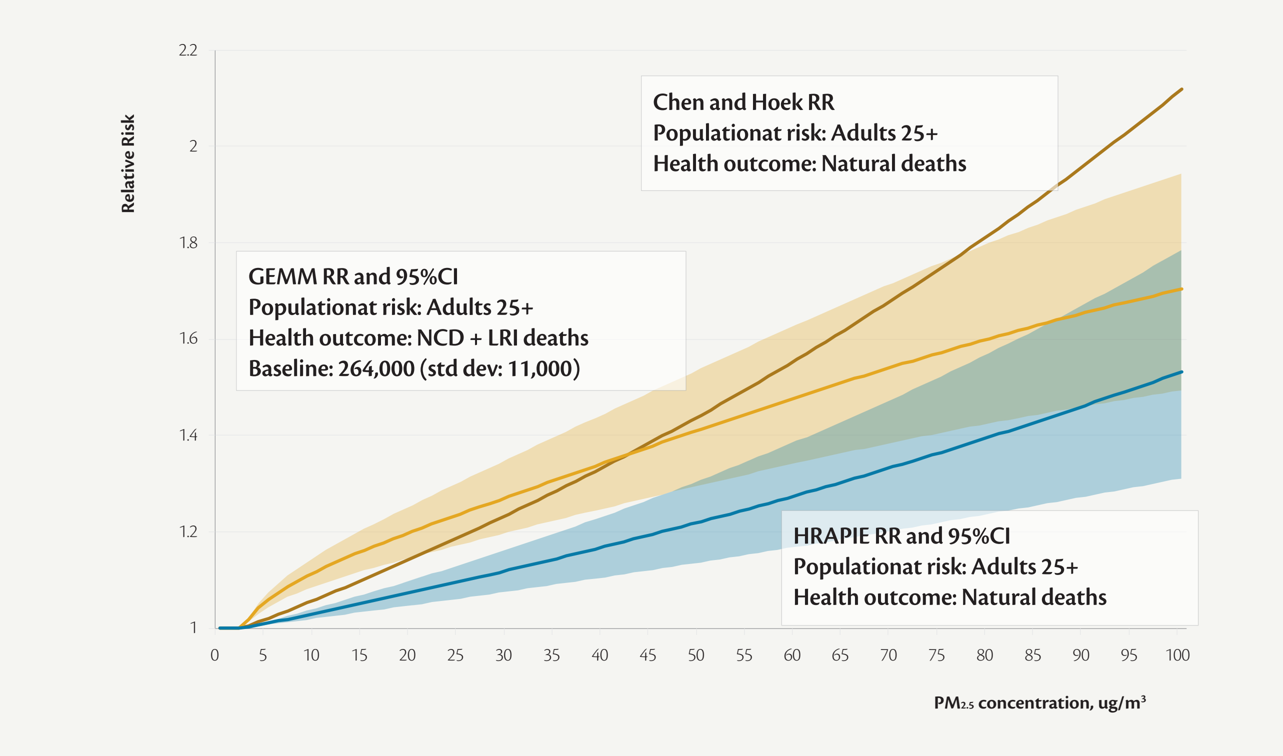
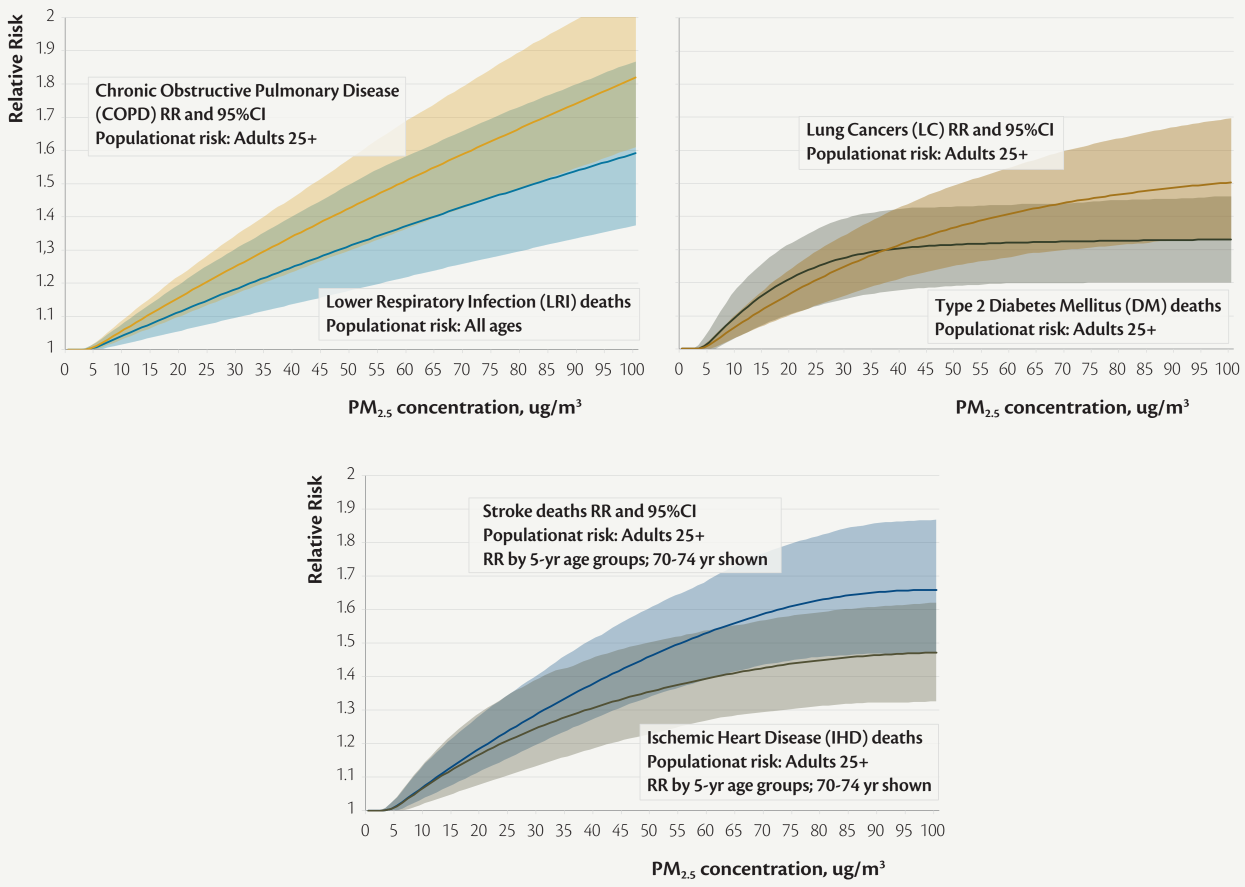


Figure 10

Integrated exposure response functions of the Global Burden of Disease (revision 2019)



Baseline incidences (cases per year and standard deviation, 2030)

Age	IHD	std dev	Stroke	std dev	COPD	std dev	LRI	std dev	LC	std dev	DM	std dev
25–29	88	15	73	10								
30–34	146	24	96	9								
35–39	257	34	194	17								
40–44	299	60	209	32								
45–49	505	73	307	59								
50–54	1210	120	544	84								
55–59	2180	123	902	65								
60–64	3480	264	1350	101								
65–69	4510	361	1630	174								
70–74	4790	371	1760	204								
75–79	6440	409	2410	271								
80+	29 400	1400	10 400	838								
25+					21 100	2720			7830	554	3810	724
All ages							12 000	1310				

Finally, the health co-benefits (avoided premature deaths and morbidity episodes) are multiplied by the cost per incident (e.g. cost per case of asthma avoided in children, or the value of a statistical life (VSL) in the case of an avoided premature death) to calculate the equivalent economic co-benefit from implementation of NDC-related climate policies. Benefits account for avoided costs of illness (COI), including avoided expenditures to individuals and more broadly to national health care budgets, economic gains in labour productivity, as well as intangible societal welfare benefits due to gains in quality of life from reduced pain and suffering across the affected population.
For the uncertainty analysis, a triangular distribution is assumed with the central, low and high unit costs presented in Table 4. Avoided infant mortality is valued at 1.5 × VSL, as recommended by OECD *(21)*. Purchasing power parity (PPP) prices are converted to nominal (market exchange rate (MER)) prices using a price level ratio (PLR) of 2.13 (MER = PPP / PLR). Future costs (in constant 2017 prices) are converted to present value prices assuming a 4.9% discount rate (discount factor = 1.049^{-10} = 0.62).

Table 4
Unit costs for valuing avoided health morbidity and premature mortality in this work

Health outcome	Central estimate US$ 2017 PPP price	Lower bound estimate US$ 2017 PPP price	Upper bound estimate US$ 2017 PPP price
Mortality (VSL)	1 495 000	1 029 000	2 172 000
Severe asthma episode	18	11	28
Chronic bronchitis in children	218	154	308
Chronic bronchitis in adults	40 700	10 300	161 000
Respiratory and cardiovascular hospital admission	6060	5770	6360
Work days lost	32	24	43
Restricted activity days	24	18	32

Study findings

For the five morbidity outcomes considered in this work, the results of the health impact analysis in 2030 are summarised in Table 5 and Figure 11. Results on avoided premature deaths are presented in Table 6 and Table 7, and illustrated in Figure 12, while the economic benefit results are shown in Table 8 and Figure 13.

The avoided incidence of morbidity and premature mortality and the corresponding economic costs for the more ambitious Mitigation Scenario 3 is 20% higher than the benefits predicted under the lower ambition Mitigation Scenario 1.

The total number of avoided morbidity episodes in 2030 for Mitigation Scenario 3 is 892 000 fewer cases (95% CI: 57 400–2.8 million), or a 10% reduction relative to BAU (no additional climate mitigation effort beyond current legislation).

Nearly all the **avoidable morbidity is related to severe episodes of asthma and chronic bronchitis in children** (99.7% of the total morbidity). Avoided hospital admissions amount to 2750 cases. Table 5 also shows the avoided incidence rate for each health outcome, for example, avoided episodes of childhood severe asthma attacks per 100 000 asthmatic children in the age group 5–19 years old. From an economic perspective, on the other hand, the morbidity benefit is nearly equally split between avoided hospital admissions, onset (new cases) of chronic bronchitis in adults and childhood asthma attacks (Figure 10). Avoided episodes of childhood chronic bronchitis account for less than 1% of the total morbidity benefit. Depending on the risk model used to assess preventable deaths, the morbidity cost ranges between 0.7% and 2% of the total (morbidity plus premature mortality) economic benefit (Table 8).

As mentioned earlier, avoided cases of restricted activity days (RAD) and work days lost (WDL) were not quantified due to a lack of baseline incidence data for Colombia. As a sensitivity analysis, inferred[3] baseline data for these two morbidity outcomes based on WHO's European Health for All database *(22)* suggests the morbidity benefit would increase five-fold, from US$13–16 million (Figure 12) to US$69–83 million, or between 3.5% and 10% of the total economic benefit, depending on the mortality risk model selected.

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[3] Baseline incidence for WDL are 157.6 million, assuming 7.6 days per worker per year and a 64% employment rate, while for RAD there are 576.6 million episodes, assuming 10.4 days per person per year.

Table 5

Health benefit results: avoided morbidity incidence in Colombia, 2030

<table>
<tr><th colspan="8">Mitigation Scenario 1 ($\Delta C = 1.87\ \mu g/m^3\ PM_{2.5}$)</th></tr>
<tr><th rowspan="2">Health outcome</th><th rowspan="2">Risk model</th><th rowspan="2">Population at risk (both sexes)</th><th colspan="3">Avoided cases</th><th rowspan="2">Incidence per 10^5 population at risk</th><th rowspan="2">Reduction compared to BAU</th></tr>
<tr><th>Value</th><th colspan="2">95% CI</th></tr>
<tr><td>Chronic bronchitis</td><td>HRAPIE <i>(16)</i></td><td>Children
6–12 years old</td><td>720</td><td>0</td><td>2870</td><td>13.3</td><td>10.6%</td></tr>
<tr><td>Severe asthma</td><td></td><td>Asthmatic children
5–19 years old</td><td>743 000</td><td>47 700</td><td>2.326 million</td><td>49 261</td><td>8.5%</td></tr>
<tr><td>Onset chronic bronchitis</td><td></td><td>Adults
27 years and older</td><td>160</td><td>12</td><td>520</td><td>0.47</td><td>10.9%</td></tr>
<tr><td>Respiratory hospital admissions</td><td></td><td>All ages</td><td>1750</td><td>0</td><td>6780</td><td>3.1</td><td>7.9%</td></tr>
<tr><td>Cardiovascular hospital admissions</td><td></td><td>All ages</td><td>530</td><td>14</td><td>1920</td><td>1.0</td><td>7.7%</td></tr>
<tr><th colspan="8">Mitigation Scenario 3 ($\Delta C = 2.25\ \mu g/m^3\ PM_{2.5}$)</th></tr>
<tr><td>Chronic bronchitis</td><td>HRAPIE <i>(16)</i></td><td>Children
6–12 years old</td><td>870</td><td>0</td><td>3420</td><td>15.8</td><td>12.8%</td></tr>
<tr><td>Severe asthma</td><td></td><td>Asthmatic children
5–19 years old</td><td>892 000</td><td>57 400</td><td>2.791 million</td><td>59 182</td><td>10.2%</td></tr>
<tr><td>Onset chronic bronchitis</td><td></td><td>Adults
27 years and older</td><td>190</td><td>14</td><td>620</td><td>0.56</td><td>12.9%</td></tr>
<tr><td>Respiratory hospital admissions</td><td></td><td>All ages</td><td>2110</td><td>0</td><td>8150</td><td>3.8</td><td>9.6%</td></tr>
<tr><td>Cardiovascular hospital admissions</td><td></td><td>All ages</td><td>640</td><td>16</td><td>2320</td><td>1.2</td><td>9.3%</td></tr>
</table>

The 95% confidence interval takes into consideration the uncertainty in the $PM_{2.5}$ concentration, the baseline morbidity, the relative risk of the relevant health endpoint, and, in case of economic valuation, the uncertainty in the unit cost. CaRBonH determines the overall uncertainty of the impact estimate using a Monte Carlo simulation.

Avoided infant (less than one year old) deaths were quantified using the CRFRR by Heft-Neal, Burney, Bendavid and Burkeet, while the adult (25 years and older) mortality benefit was calculated using three alternative mortality–exposure RRs: HRAPIE, GEMM and the IER functions for the six causes of death assessed by GBD (2019 revision). The total averted premature deaths are calculated as the sum of infant mortality, LRI deaths in the sub-population age group 1–25 years, and adult deaths. A sensitivity analysis was carried out using the recently published mortality risk by Chen and Hoek (RR = 1.08, 95% CI:1.06–1.09). Note, the 95% confidence interval takes into consideration the uncertainty in the $PM_{2.5}$ concentration, the baseline mortality, the relative risk factor, and, in the case of economic valuation, the uncertainty in the VSL. CaRBonH determines the overall uncertainty of the mortality impact using a Monte Carlo simulation.

Table 6

Health benefit results for Mitigation Scenario 1: avoided premature deaths in Colombia, 2030

Mitigation Scenario 1 ($\Delta C = 1.87\ \mu g/m^3\ PM_{2.5}$)							
Health outcome	**Risk model**	**Population at risk (both sexes)**	**Avoided premature deaths**			**Incidence per 10^5 population at risk**	**Reduction compared to BAU**
			Value	**95% CI**			
Natural deaths	Heft-Neal, Burney, Bendavid and Burkeet *(20)*	Infants (< 1 year)	91	15	250	13.1	8.8%
Natural deaths	HRAPIE *(16)*	Adults (25+ years)	3070	1010	6710	8.5	8.4%
NCD + LRI	GEMM *(17)*	Adults (25+ years)	2940	1350	5470	8.1	5.5%
IHD	IER *(18)*	Adults (25+ years)	*430*	*210*	*520*	*1.2*	
Stroke			*230*	*110*	*370*	*0.6*	
COPD			*300*	*110*	*590*	*0.8*	
LC			*83*	*41*	*120*	*0.2*	
Diabetes			*24*	*8*	*29*	*0.1*	
LRI		All ages	*130*	*33*	*280*	*0.2*	
6-COD		All ages	1190	510	1870	2.1	6.1%
Sensitivity analysis							
Natural deaths	Chen and Hoek *(19)*	Adults (25+ years)	3840	1590	7600	10.6	8.5%
Total avoided premature deaths							
Option 1		All ages	3160	1020	6970	5.7	8.4%
Option 2			3030	1370	5730	5.4	5.6%
Option 3			1280	530	2130	2.3	6.2%
Sensitivity (Chen and Hoek)			*3930*	*1600*	*7860*	*7.1*	*8.5%*

NCD + LRI: Noncommunicable diseases and lower respiratory infections; 95% CI: 95% confidence interval
IHD: Ischemic heart disease; COPD: Chronic obstructive pulmonary disease; LC: Lung cancer
6-COD: Six causes of death of the Global Burden of Disease study (sum of IHD, stroke, COPD, LC, diabetes and LRI)
Option 1: Calculated as the sum of avoided premature adult mortality (HRAPIE), LRI in age group 1–25 years (IER), and infant deaths.
Option 2: Calculated as the sum of avoided premature adult mortality (GEMM), LRI in age group 1–25 years (IER), and infant deaths.
Option 3: Calculated as the sum of avoided premature mortality in ages one year and older (IER), and infant deaths.
Sensitivity: Calculated as the sum of avoided premature adult mortality (Chen and Hoek), LRI for ages 1–25 years (IER), and infant deaths.
Numbers may not add up due to rounding.

Table 7

Health benefit results for Mitigation Scenario 3: avoided premature deaths in Colombia, 2030

Mitigation Scenario 3 (ΔC = 2.25 $\mu g/m^3$ PM$_{2.5}$)							
Health outcome	Risk model	Population at risk (both sexes)	Avoided premature deaths			Incidence per 10^5 population at risk	Reduction compared to BAU
			Value	95% CI			
Natural deaths	Heft-Neal, Burney, Bendavid and Burkeet *(20)*	Infants (< 1 year)	109	18	300	15.8	10.6%
Natural deaths	HRAPIE *(16)*	Adults (25+ years)	3690	1210	8060	10.2	10.1%
NCD + LRI	GEMM *(17)*	Adults (25+ years)	3540	1630	6590	9.8	6.7%
IHD	IER *(18)*	Adults (25+ years)	*510*	*250*	*630*	*1.7*	
Stroke			*280*	*130*	*440*	*0.8*	
COPD			*360*	*130*	*710*	*1.0*	
LC			*100*	*49*	*140*	*0.3*	
Diabetes			*29*	*10*	*35*	*0.1*	
LRI		All ages	*160*	*40*	*330*	*0.3*	
6-COD		All ages	1440	620	2250	2.6	7.3%
Sensitivity analysis							
Natural deaths	Chen and Hoek *(19)*	Adults (25+ years)	4610	1910	9120	12.7	10.2%
Total avoided premature deaths							
Option 1		All ages	3800	1230	8370	6.8	10.1%
Option 2			3650	1650	6900	6.6	6.7%
Option 3			1550	630	2560	2.8	7.5%
Sensitivity (Chen and Hoek)			*4720*	*1930*	*9430*	*8.5*	*10.2%*

NCD + LRI: Noncommunicable diseases and lower respiratory infections; 95% CI: 95% confidence interval
IHD: Ischemic heart disease; COPD: Chronic obstructive pulmonary disease; LC: Lung cancer
6-COD: Six causes of death of the Global Burden of Disease study (sum of IHD, stroke, COPD, LC, diabetes and LRI)
Option 1: Calculated as the sum of avoided premature adult mortality (HRAPIE), LRI in age group 1–25 years (IER), and infant deaths.
Option 2: Calculated as the sum of avoided premature adult mortality (GEMM), LRI in age group 1–25 years (IER), and infant deaths.
Option 3: Calculated as the sum of avoided premature mortality in ages one year and older (IER), and infant deaths.
Sensitivity: Calculated as the sum of avoided premature adult mortality (Chen and Hoek), LRI for ages 1–25 years (IER), and infant deaths.
Numbers may not add up due to rounding.

For Mitigation Scenario 3, the total avoidable premature mortality in 2030 ranges between 1550 (95% CI: 630–2560) deaths, based on the IER risk model, and 3800 (95% CI: 1230–8370) deaths, based on HRAPIE. These results imply a 6.7% to 10% reduction in premature deaths compared to BAU.

The avoided premature mortality using the Chen and Hoek RR (4720, 95% CI: 1930–9430 deaths) is 24% larger than the HRAPIE-based estimate. The preventable mortality rate (per 100 000 population of all ages) ranges between 2.8 and 6.8 deaths (8.5 deaths using Chen and Hoek).

In economic terms (Table 8), the total morbidity plus mortality benefit for Mitigation Scenario 3 ranges between US$780 (95% CI: US$210–1670) million, based on the IER analysis, and US$1900 (95% CI: US$410–5100) million, based on HRAPIE (Figure 13). The avoided morbidity contribution is around 1% to 2% of the total economic benefit. According to the sensitivity analysis using the Chen and Hoek RR, the benefit amounts to US$2320 (95% CI: US$650–5720) million. All costs are present value (2020) estimates, expressed in 2017 nominal prices applying an annual 4.9% discount rate. For context, the total economic benefit is equivalent to between 0.26% and 0.64% (0.78% if using Chen and Hoek) of Colombia's projected GDP in 2030.

Mitigation Scenario 3 benefit costs are 20% higher than Mitigation Scenario 1.

Table 8

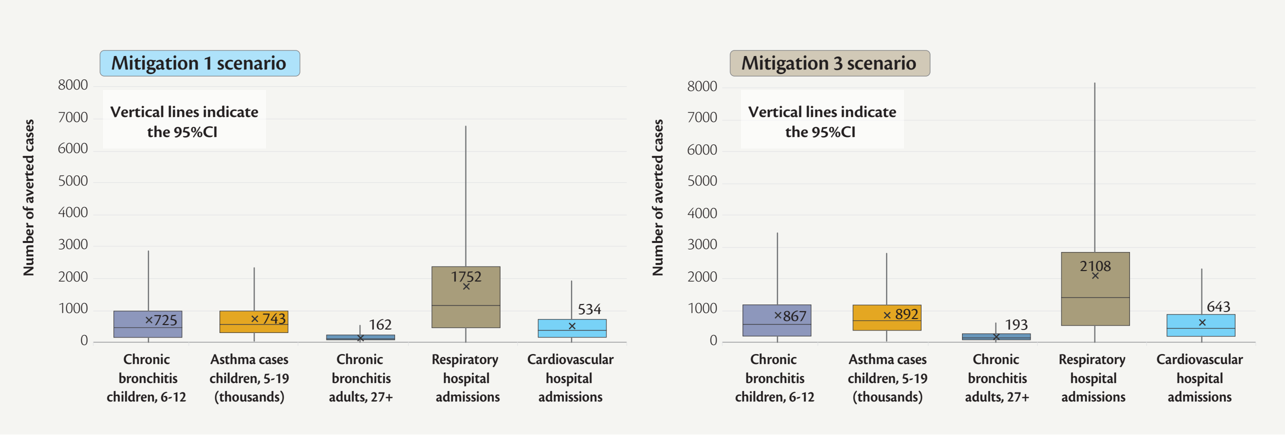
Economic benefit results from avoided morbidity incidences and premature deaths in Colombia, 2030

Mitigation Scenario 1 ($\Delta C = 1.87\ \mu g/m^3\ PM_{2.5}$)							
Adult mortality risk model	**Infant mortality risk model**	**Morbidity risk model**	**Million US$ 2017**			**Morbidity as % of total**	**Total as % of projected GDP**
			Total	**95% CI**			
HRAPIE *(16)*	Heft-Neal, Burney, Bendavid and Burkeet *(20)*	HRAPIE *(16)*	1580	340	4250	0.85%	0.53%
GEMM *(17)*			1490	460	3510	0.90%	0.50%
IER *(18)*			650	180	1390	2.1%	0.22%
Sensitivity Chen and Hoek *(19)*			1930	540	4770	0.69%	0.65%
Mitigation Scenario 3 ($\Delta C = 2.25\ \mu g/m^3\ PM_{2.5}$)							
HRAPIE *(16)*	Heft-Neal, Burney, Bendavid and Burkeet *(20)*	HRAPIE *(16)*	1900	410	5100	0.85%	0.64%
GEMM *(17)*			1800	550	4230	0.89%	0.60%
IER *(18)*			780	210	1670	2.1%	0.26%
Sensitivity Chen and Hoek *(19)*			2320	650	5720	0.69%	0.78%

Notes: Economic benefits are expressed in nominal 2017 prices and have been discounted to 2020 at a rate of 4.9% per annum.
The projected GDP of Colombia is US$300 billion (present value at nominal 2017 prices).
The 95% confidence interval takes into consideration the uncertainty in the $PM_{2.5}$ concentration, the baseline morbidity and mortality cases, the relative risk of the health endpoint of concern, and the uncertainty in the unit cost.

Figure 11

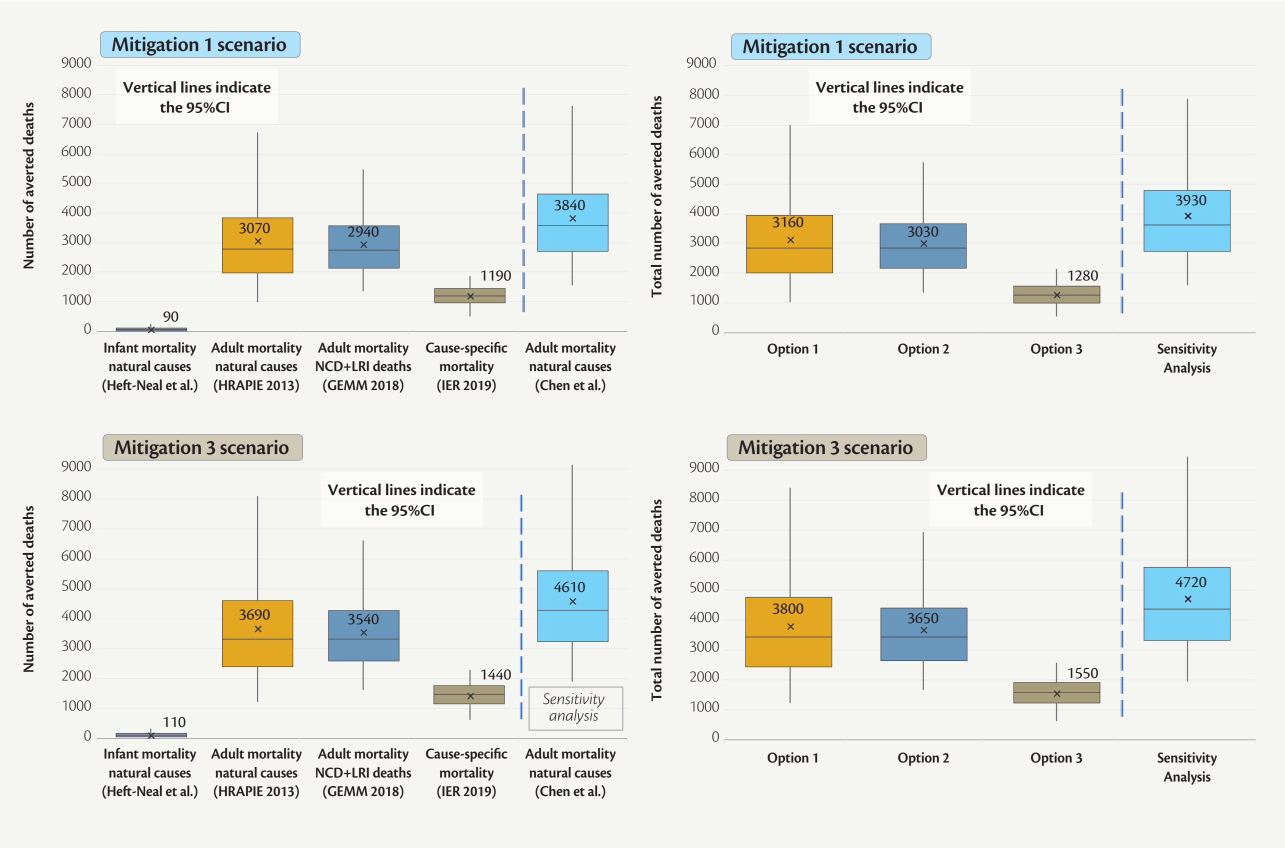
Avoided $PM_{2.5}$-related morbidity incidences from carbon reductions in Colombia, 2030



Note: cases of avoided severe asthma attacks in children are in thousands; 95% CI: 95% confidence interval.

Figure 12

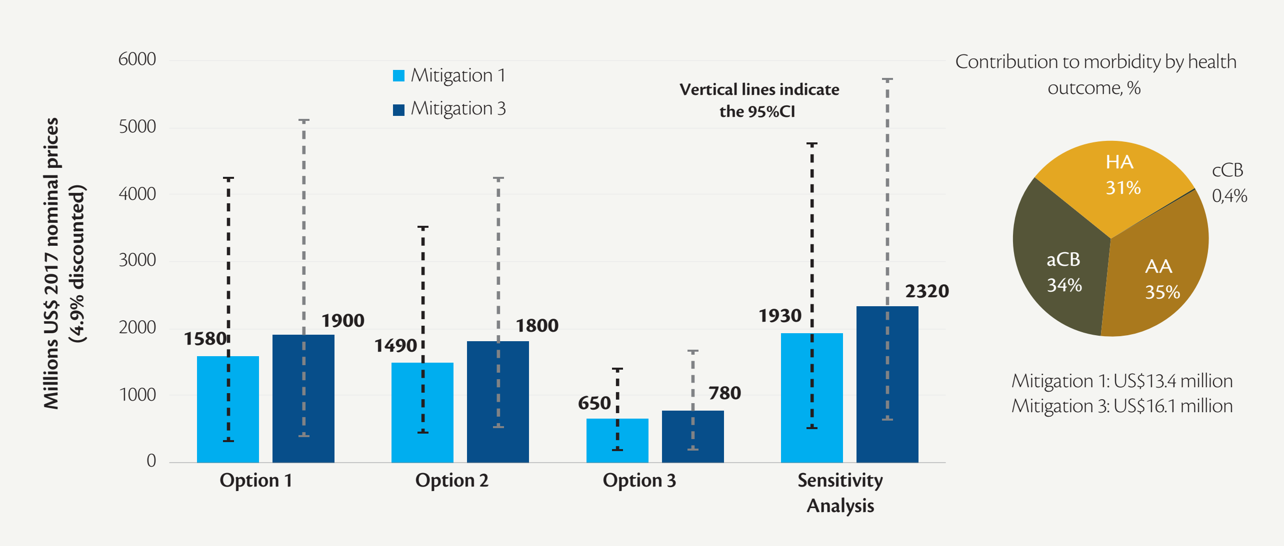
Avoided $PM_{2.5}$-related mortality from carbon reductions in Colombia, 2030



Option 1: Calculated as the sum of avoided premature adult mortality (HRAPIE), LRI in age group 1–25 years (IER), and infant deaths.
Option 2: Calculated as the sum of avoided premature adult mortality (GEMM), LRI in age group 1–25 years (IER), and infant deaths.
Option 3: Calculated as the sum of avoided premature mortality in ages one year and older (IER), and infant deaths.
Sensitivity: Calculated as the sum of avoided premature adult mortality (Chen and Hoek), LRI for ages 1–25 years (IER), and infant deaths.

Figure 13

Economic benefit from avoided $PM_{2.5}$-related morbidity and premature mortality incidences in Colombia, 2030



HA: Hospital admissions; cCB: Childhood chronic bronchitis; AA: Severe asthma attacks in children
aCB: Onset of adult chronic bronchitis; 95% CI: 95% confidence interval
Option 1: Calculated as the sum of avoided premature adult mortality (HRAPIE), LRI in age group 1–25 years (IER), and infant deaths.
Option 2: Calculated as the sum of avoided premature adult mortality (GEMM), LRI in age group 1–25 years (IER), and infant deaths.
Option 3: Calculated as the sum of avoided premature mortality in ages one year and older (IER), and infant deaths.
Sensitivity: Calculated as the sum of avoided premature adult mortality (Chen and Hoek), LRI for ages 1–25 years (IER), and infant death.

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Technical annex

Emission results from LEAP

Historic emissions from BC inventory

In Colombia, within the framework of the implementation of the Short-Life Pollutant Mitigation Strategy, the first *National Indicative Inventory of Criterion Pollutant Emissions and Black Carbon 2010-2014 (10)* was developed, allowing the prioritization of emission sources, in order to develop policies, strategies or guidelines for the reduction of these emissions. This inventory presents the total estimated emissions of five pollutants, which include:

- Black carbon (BC)
- Particulate matter less than 2.5 µm ($PM_{2.5}$)
- Carbon monoxide (CO)
- Nitrogen dioxide (NO_2)
- Sulphur dioxide (SO_2)

In developing this inventory, taking into account the levels of complexity and availability of information, a top-down approach was used. In addition, some sectors were estimated with a Tier 2 complexity level, while others with Tier 1 complexity *(10)*. It was estimated that in 2014, 21 581 tonnes of black carbon, 241 605 tonnes of $PM_{2.5}$, 2 565 694 tonnes of CO, 354 006 tonnes of NO_2 and 176 095 tonnes of SO_2 were emitted in Colombia *(10)*. For all pollutants evaluated, the magnitude of total emissions did not vary greatly between 2010 and 2014 (Figure A.1).

Figure A.1

Total emissions for BC and other criteria pollutants between 2010 and 2014 *(10)*

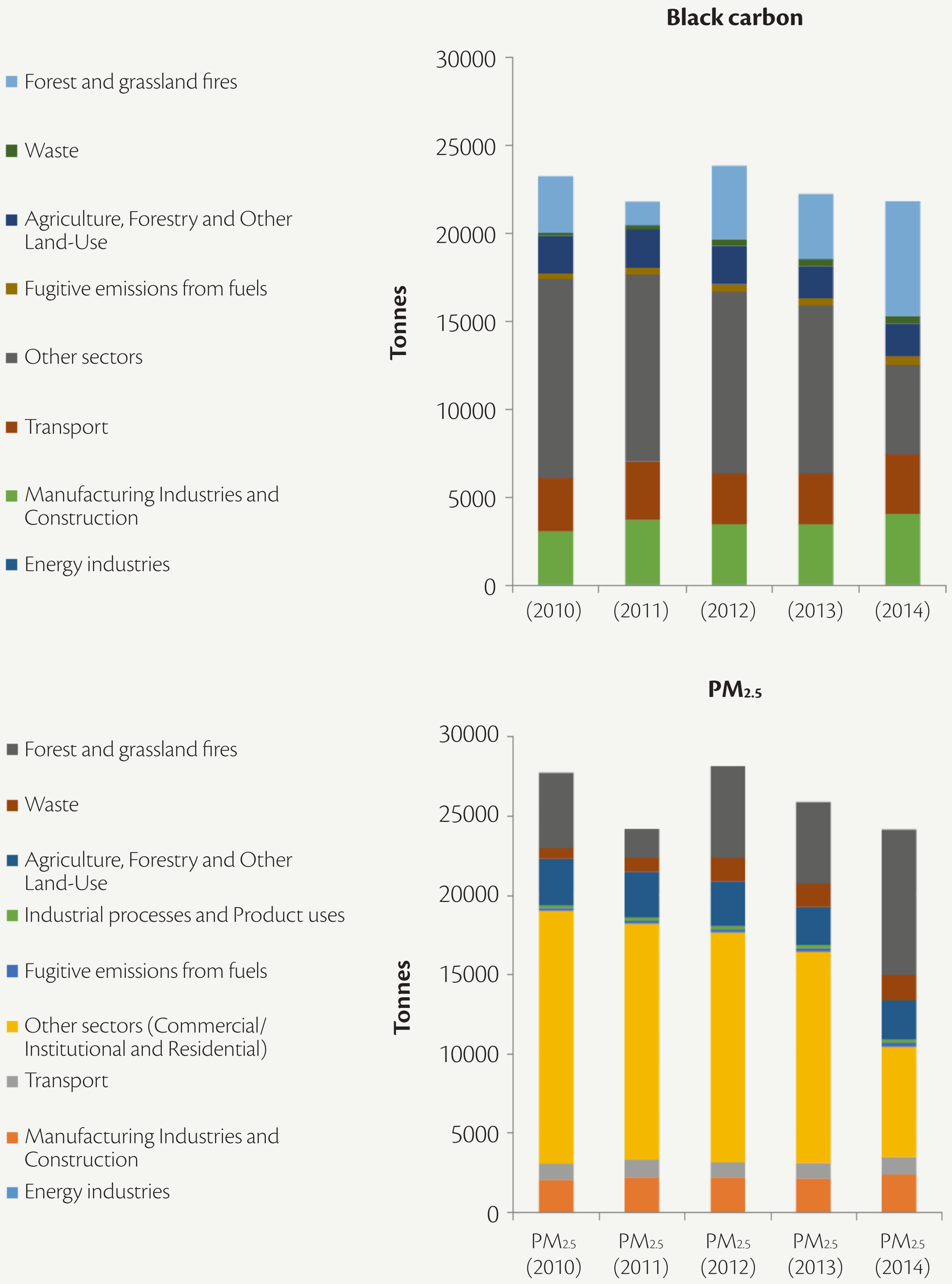
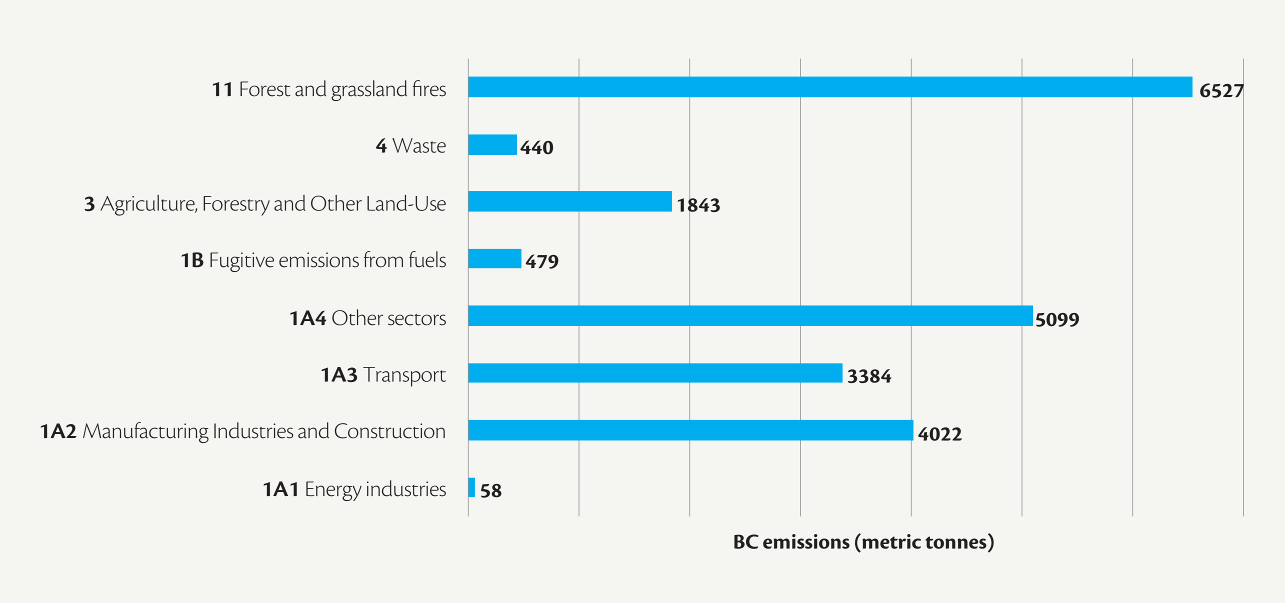


Figure A.1 cont'd

Total emissions for BC and other criteria pollutants between 2010 and 2014 *(10)*

In 2014, fuel combustion generated 57% of BC emissions. The main sources of this pollutant were forest and grassland fires, residential combustion (other sectors – residential and commercial sector), transportation and manufacturing industries (Figure A.2). Forest and grassland fires generated 30% of the total national emissions of BC, while the burning of fuels for residential use, especially for the use of firewood, contributed 17% of the total emissions of this pollutant *(10)*.

Figure A.2
Total black carbon emissions for 2014 (IDEAM)



Forest and grassland fires and the residential and commercial (other) sectors were major sources of $PM_{2.5}$ and CO emissions. Within the residential sector, the use of wood in rural areas contributed to most of the BC emissions in this sector, contributing to climate change, ambient and indoor air pollution, affecting the health of people who use wood for cooking. On the other hand, road transport was the main emitter of the entire transport sector, presenting the highest share of NO_2 and CO emissions *(10)*. Consequently, there is a great opportunity to identify actions and develop strategies to reduce SLCP emissions that will simultaneously improve air quality and mitigate climate change.

Baseline projections and emission reductions for different scenarios

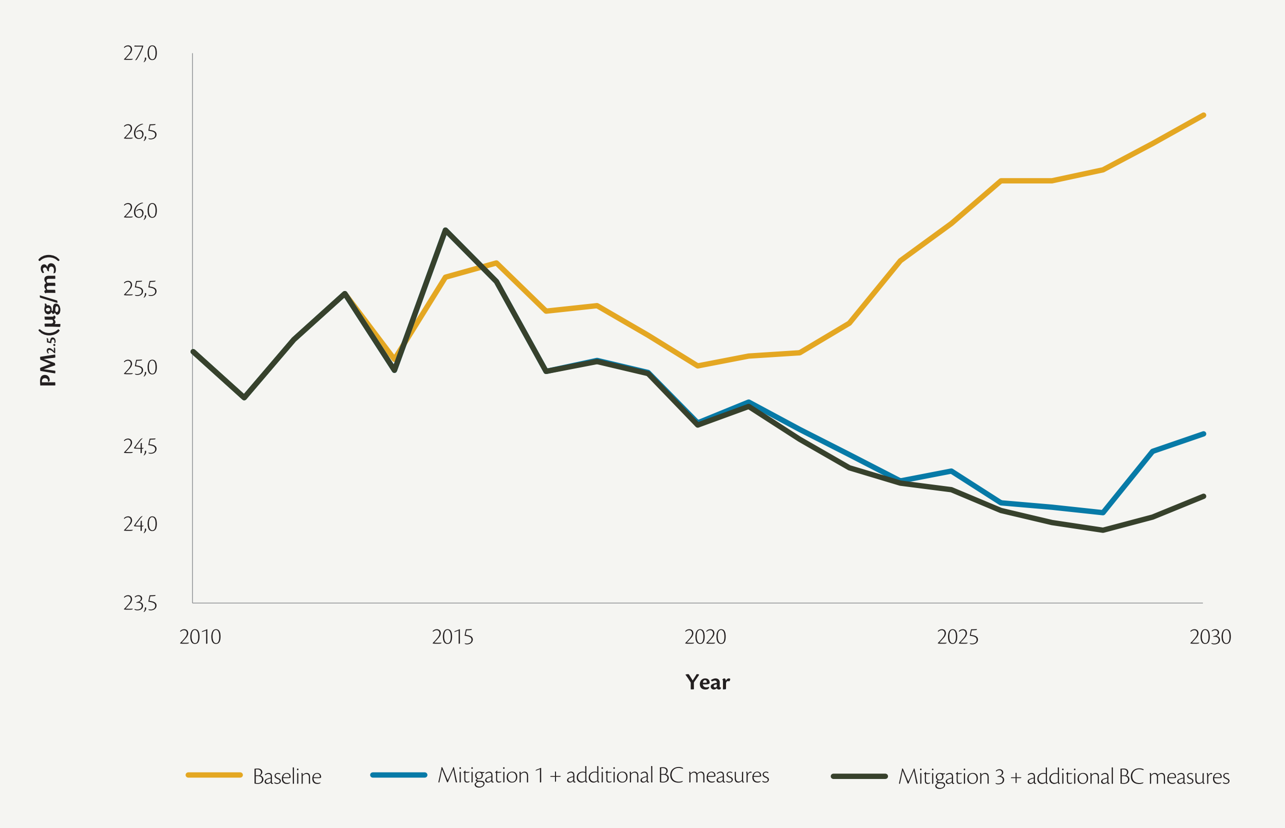
By projecting the activities for each evaluated sector using different drivers, such as population growth, production, transport renovation rates, among others, while maintaining current conditions, the emissions for the baseline scenario were estimated annually through to 2030. As for both mitigation scenarios, the activities were modified considering the changes in technology, efficiency, fuels, or others, defined for each measure. The total emissions and potential reductions in emissions projected by the climate change commitments in Colombia for CO_2, BC and other pollutants are shown in Figure A.3.

Figure A.3

Total emissions for CO_2, BC and other criteria pollutants between 2010 and 2030 *(10)*

As a result of the projected emissions and potential reductions, as described above, the population-weighted annual average $PM_{2.5}$ concentrations were estimated and are shown in Figure A.4. By the implementation of all the mitigation measures committed in Colombia's NDC, around 10% of $PM_{2.5}$ concentrations are projected to be reduced comparing the Mitigation Scenarios 1 and 3 with the baseline in 2030. The efforts in mitigating climate change, as a result of actions taken towards the reduction of GHG and BC emissions imply a reduction in overall $PM_{2.5}$ concentrations, therefore endorsing the importance of aiming towards a synergy between climate change and air quality policies, in order to move towards more efficient planning processes, climate change mitigation and air quality improvement.

Figure A.4
Population-weighted annual average $PM_{2.5}$ concentrations



Procedure for the estimation of premature mortality and morbidity as an input for the estimation of health co-benefits of Carbon Reduction Benefits on Health (CaRBonH) in Colombia

Mortality data sources and deaths estimate 2020–2030

We used two sources of mortality data for Colombia: data from the Global Burden of Disease (GBD) 2019 project and microdata from the Mortality Registry (non-fetal deaths) of Vital Statistics of the Administrative Department of Statistics (DANE).

Global Burden of Disease (GBD) 2019 source mortality data: The results consultation tool of the GBD 2019 project containing mortality information between 1990 and 2019 was used.[4] We selected deaths for Colombia between 1990 and 2019 with outcomes for deaths and rates and their respective confidence intervals. For the calculation of the 2020–2030 deaths, the data for the years 2010–2019 were used as input after observing the time series that shows a different trend pattern before 2010 that can be related to changes in the coding of mortality records. With these data, the linear trend of the data was estimated and from it the linear prediction was made using the constant and slope estimates to calculate the point estimates of the 2020–2030 values. For the calculation of the confidence intervals of the 2020–2030 estimates, the standard error values of the GBD estimates for 2019 were used and that value was used for the upper and lower confidence interval estimates.

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[4] GBD results tool. In: Global Health Data Exchange [website] (http://ghdx.healthdata.org/gbd-results-tool).

Mortality data source DANE Colombia: The databases of the official microdata portal of Vital Statistics – non-fetal deaths between 2005 and 2019 were used, and the results by number of deaths were obtained.[5] For the calculation of the 2020–2030 deaths, data from the years 2010–2019 were used after observing the time series that shows a different trend pattern before 2010. With these data, the linear trend of the data was estimated and from it the constant and slope estimates to calculate with these data the point estimates of the 2020–2030 values. The lower and upper confidence intervals of the constant and slope of the model were used to construct the 95% confidence intervals (lower and upper) of the 2020–2030 predictions.

For this report, queries of mortality codes for both sources GBD 2019 (1990–2030) and DANE Colombia (2005–2030) were used. GBD 2019 have queries by event groups aggregated by ICD-10 codes (and their equivalent for ICD-9). Below is the code comparison for each of the GBD and DANE cause groups:

Table A.1

ICD-10 Codes Comparison

Cause	GBD 2019 ICD10	DANE DATA
Total mortality	All codes	
Natural mortality	A00 – R99	
Postneonatal	All codes (age: 29–365 days)	
Noncommunicable diseases	See detailed code list further below	C00–N99, R00–R99
Respiratory diseases	A10-A14, A15-A19.9, A48.1, A70, B90-B90.9, B97.4-B97.6, H70-H70.9, J00-J02.8, J03-J03.8, J04-J04.2, J05-J05.1, J06.0-J06.8, J09-J15.8, J16-J16.9, J20-J21.9, J36-J36.0, K67.3, K93.0, M49.0, N74.1, P23.0-P23.4, P37.0, U04-U04.9, U84.3	J00- J99
Cardiovascular diseases	B33.2, G45-G46.8, I01-I01.9, I02.0, I05-I09.9, I11-I11.9, I20-I25.9, I28-I28.8, I30-I31.1, I31.8-I37.8, I38-I41.9, I42.1-I42.8, I43-I43.9, I47-I48.9, I51.0-I51.4, I60-I63.9, I65-I66.9, I67.0-I67.3, I67.5-I67.6, I68.0-I68.2, I69.0-I69.3, I70.2-I70.8, I71-I73.9, I77-I83.9, I86-I89.0, I89.9, I98, K75.1	I00-I99
Ischemic heart disease	I20-I25.9	I20-I25
Stroke	G45-G46.8, I60-I63.9, I65-I66.9, I67.0-I67.3, I67.5-I67.6, I68.1-I68.2, I69.0-I69.3	I60-I69
Chronic obstructive pulmonary disease	J41-J44.9	J40-J44
Diabetes mellitus	E10-E10.1, E10.3-E11.1, E11.3-E11.9, P70.2	E10-E11
Tracheal, bronchus, and lung cancer	C33-C34.9, D02.1-D02.3, D14.2-D14.3, D38.1	C33-C34
Lower respiratory infections	A48.1, A70, B97.4-B97.6, J09-J15.8, J16-J16.9, J20-J21.9, P23.0-P23.4, U04-U04.9	J12-J18, J20-J22

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[5] Archivo Nacional de Datos [website] (http://microdatos.dane.gov.co/index.php/catalog/MICRODATOS#_r=1624030271417&collection=&country=&dtype=1&from=1990&page=1&ps=&sid=&sk=EEVV&sort_by=titl&sort_order=&to=2020&topic=&view=s&vk=, accessed date).

Mortality data Colombia for CaRBonH: To obtain estimated data from the two sources, a new series of mortality data was created using the average of the GBD and DANE data. This was done for all causes except for mortality from diabetes mellitus which showed differences on average by a factor of 2.6 of the mortality reported in GBD with respect to that of DANE (at ages 25+), so for diabetes mellitus the value of the estimation variable only used data from DANE. For the calculation of deaths 2020–2030, data 2010–2019 were used. With these data, the linear trend of the data was estimated and from it the constant and slope, estimates to calculate with these data the point estimates of the 2020–2030 values. The lower and upper confidence intervals of the constant and slope of the model were used to construct the 95% confidence intervals (lower and upper) of the 2020–2030 predictions.

Procedure for estimating mortality data

1. Obtaining data by five-year age group from GBD sources 1990–2019 and non-fetal mortality databases of DANE 2005–2019.

2. Estimation of deaths 2020–2030 for each five-year age group using a linear model with the 2010–2019 data for GBD and DANE.

3. The confidence intervals of the DANE death estimates for each year were constructed using the lower and upper confidence intervals of the constant and slope of the 2020–2030 predictions model.

4. Estimates of negative numbers (which were obtained mainly for chronic causes in the five-year periods of children under 15 years of age) were replaced by 0.

5. The calculation of total mortality and age groups of 25 and over (25+) and 30 years and over (30+) for GBD and DANE was made from the sum of the death data obtained in the five-year age groups.

6. A value obtained from the average of the GBD and DANE mortality data for the general causes and specific causes of mortality was calculated as an estimate of deaths for CaRBonH Colombia, except for diabetes mellitus for which only the data of deaths from the DANE data (codes E10 and E11) was used. For deaths from ischemic heart disease in five-year groups of children under 15 years of age, only the GBD mortality data (0 deaths) was used, considering that the deaths recorded in DANE in these age groups probably correspond to coding errors.

7. The estimate of combined GBD-DANE deaths 2020–2030 was made for each five-year group using a linear model with the 2010–2019 data.

8. The confidence intervals of the combined death estimates for CaRBonH for each year were constructed using the lower and upper confidence intervals of the constant and slope of the 2020–2030 predictions model.

Morbidity data sources and estimates 2020–2030

Morbidity data were obtained from the platform of the Social Protection System (SISPRO) of the Ministry of Health and Social Protection. The data comes from the queries made to the Individual Registry of Service Provision (RIPS). The RIPS is the official registry that must be generated by all the institutions that serve users of the Colombian health system, and in it the diagnoses of care are recorded using ICD-10 codes. Data from care records per year for the years 2009–2019 were obtained for the following diagnoses and care services:

- Diseases of the circulatory system (ICD I00-I99)– hospitalization: total records and number of days of hospital stay

- Diseases of the respiratory system (ICD J00-J99) – hospitalization: total records and number of days of hospital stay

- Additionally, we obtained the data on the number of people treated per year with classification of new diagnosis (incident cases) for the years 2009–2019 for the following diagnoses:

- Bronchitis: people 27 years and older (ICD J41-J42), six to 12 years and six to 18 years (ICD J20-J41-J42)

- Asthma: five to 19 years (ICD J45-J46)

With the 2009–2019 data, the linear trend of the data was estimated and from it the constant and slope estimates to calculate with these data the point estimates of the 2020–2030 values. The lower and upper confidence intervals of the constant and slope of the model were used to construct the 95% confidence intervals (lower and upper) of the 2020–2030 predictions.

Population

This report uses the estimated population with DANE source between 1990 and 2030 for the total population, the population by five-year age groups, the population aged 30 and over (30+),the population aged 25 and over (25+) and the population under one year.

Complete list of ICD-10 codes for noncommunicable diseases used in GBD 2019

A46-A46.0, A66-A67.9, B18-B18.9, B33.2, B86, C00-C13.9, C15-C25.9, C30-C34.9, C37-C38.8, C40-C41.9, C43-C45.9, C47-C54.9, C56-C57.8, C58-C58.0, C60-C63.8, C64-C67.9, C68.0-C68.8, C69-C75.8, C81-C86.6, C88-C96.9, D00.1-D00.2, D01.0-D01.3, D02.0-D02.3, D03-D06.9, D07.0-D07.2, D07.4-D07.5, D09.0, D09.2-D09.3, D09.8, D10.0-D10.7, D11-D12.9, D13.0-D13.7, D14.0-D14.3, D15-D16.9, D22-D27.9, D28.0-D28.7, D29.0-D29.8, D30.0-D30.8, D31-D36, D36.1-D36.7, D37.1-D37.5, D38.0-D38.5, D39.1-D39.2, D39.8, D40.0-D40.8, D41.0-D41.8, D42-D43.9, D44.0-D44.8, D45-D47.9, D48.0-D48.6, D49.2-D49.4, D49.6, D52.1, D55-D58.9, D59.0-D59.3, D59.5-D59.6, D60-D61.9, D63.1, D64.0, D66-D67, D68.0-D69.8, D70-D75.8, D76-D78.8, D86-D86.9, D89-D89.3, E03-E07.1, E09-E11.9, E15.0, E16.0-E16.9, E20-E34.8, E36-E36.8, E65-E68, E70-E85.2, E88-E89.9, F00-F03.9, F10-F16.9, F18-F19.9, F24, F50.0-F50.5, G10-G13.8, G20-G20.9, G23-G26.0, G30-G31.9, G35-G37.9, G40-G41.9, G45-G46.8, G47.3, G61-G61.9, G70-G73.7, G90-G90.9, G93.7, G95-G95.9, G97-G97.9, H05.0-H05.1, I01-I01.9, I02.0, I05-I09.9, I11-I13.9, I20-I25.9, I27.1, I28-I28.8, I30-I31.1, I31.8-I37.8, I38-I41.9, I42.1-I42.8, I43-I43.9, I47-I48.9, I51.0-I51.4, I60-I63.9, I65-I66.9, I67.0-I67.3, I67.5-I67.7, I68.0-I68.2, I69.0-I69.3, I70.2-I70.8, I71-I73.9, I77-I89.9, I95.2-I95.3, I97-I98, I98.2, I98.9, J30-J35.9, J37-J39.9, J41-J46.9, J60-J63.8, J65-J68.9, J70-J70.9, J82, J84-J84.9, J91-J92.9, J95-J95.9, K20-K29.9, K31-K31.8, K35-K38.9, K40-K46.9, K50-K52.9, K55-K62.9, K63.5, K64-K64.9, K66.8, K67, K68-K68.9, K70-K70.3, K71.7, K74-K74.9, K75.1-K75.2, K75.4-K76.2, K76.4-K77, K77.8, K80-K83.9, K85-K86.9, K90-K91.9, K92.8, K93.8-K95.8, L00-L05.9, L08-L08.9, L10-L14.0, L51-L51.9, L88-L89.9, L93-L93.2, L97-L98.4, M00-M03.0, M03.2-M03.6, M05-M09.8, M30-M36.8, M40-M43.1, M65-M65.0, M71.0-M71.1, M72.5-M72.6, M80-M82.8, M86.3-M86.4, M87-M87.1, M88-M89.0, M89.5, M89.7-M89.9, N00-N08.8, N10-N12.9, N14-N16.8, N18-N18.9, N20-N23.0, N25-N28.1, N29-N32.0, N32.3-N32.4, N34-N34.3, N36-N36.9, N39-N39.2, N41-N41.9, N44-N44.0, N45-N45.9, N49-N49.9, N60-N60.9, N65-N65.1, N72-N72.0, N75-N77.8, N80-N81.9, N83-N83.9, N84.0-N84.1, N87-N87.9, N99-N99.9, P04.3-P04.4, P70.2, P96.0-P96.2, P96.5, Q00-Q07.9, Q10.4-Q18.9, Q20-Q28.9, Q30-Q36, Q37-Q45.9, Q50-Q87.8, Q89-Q89.8, Q90-Q93.9, Q95-Q99.8, R50.2, R78.0-R78.5, R95-R95.9, X45-X45.9, X65-X65.9, Y15-Y15.9

Summary of economic valuation methodology for the estimation of health benefits due to improvements in air quality

It is possible to quantify and assess several of the positive effects (co-benefits) on human health due to reduced pollution, including avoided premature mortality, avoided days of work lost, avoided health costs, among others. Table A.2 presents the parameters for the valuation of benefits required in the CaRBonH tool. Ideally, these values should be based on local information, but if not all the required information is available, it is possible to use value transfer techniques from the international literature to complete the missing information.

Table A.2

Parameters required by CaRBonH

Event type	Metric
Mortality	Value of a statistical life
	Value of a statistical life year
Morbidity	Hospital stays costs
	Loss of productivity due to a lost work day (individual and economy)
	Long-term cost for new cases of chronic bronchitis in adults
	Costs associated with bronchitis and asthma in children
	Days of restricted activity

Valuing avoided premature mortality: value of a statistical life and value of a statistical life year

Assigning a value to avoided premature mortality is necessary for estimating the benefits of public policies that would imply changes in mortality *(22)*.

In Colombia, there is no study to value avoided premature mortality in the context of air pollution. Because of this, we chose to transfer the value of a statistical life (VSL) from the international literature. Note that the VSL does not represent the value of individual lives but represents the economic benefit of avoiding premature mortality from the perspective of individual preferences and well-being. Using the willingness to pay approach, the VSL represents the value that large groups of people would be willing to pay for reductions in the individual risk of dying in a given year, such that in expected terms an average death within that group of people is reduced during the year.

In this study, the following VSL options are quantified for Colombia:

- VSL transferred from OECD countries, using elasticity of 1.2 for Colombia, according to its income level *(23)*
- VSL transferred from OECD countries, using elasticity of 0.8 for Colombia *(7)*
- VSL transferred from the United States, with an elasticity of 1.5 *(22)*
- VSL equal to GDP per capita multiplied by 100 *(22)*
- VSL equal to GDP per capita multiplied by 160 *(22)*

For transferring the VSL, we use GDP per capita and CPI according to the International Monetary Fund *(24)* and statistics for OECD countries.[6]

Sometimes, instead of valuing avoided premature deaths, the years of life lost avoided are valued, using the "value of the statistical year of life" or VSLY. This value represents the willingness of individuals to pay for a change in life expectancy, equivalent to the marginal rate of substitution between income and life expectancy. In the present analysis, we assume a ratio of VSL to VSLY of 26. 4, assumption used in the European version of CaRBonH. This value is among those reported by Robinson et al. *(22)* and Narain and Sall *(23)*.

Assessment of avoided morbidity

To obtain the unit values associated with medical treatments, we updated the values used in a World Bank study for Colombia *(25)*, in addition to transferring values used by the USEPA in the United States.

To update the values of medical costs, we use the historical variation in health prices registered by DANE in Colombia from 2009 onwards *(26)*.

Episodes of illness also entail costs of time lost during convalescence. To value the time lost due to diseases, we use average wages in Colombia in the agriculture, services and industry sectors, from ILOSTAT (*x*).[7] Moreover, it is assumed that the value of the days lost due to illness is equal to 75% of the average daily wage *(25)*. To project the increase in real wages, we use the growth rate of real per capita GDP.

To estimate the willingness to pay to avoid episodes of asthma and bronchitis in children, we transfer the unit value used in the United States (US$81.63 from 2015 per day). The transfer results in a value for Colombia of US$11 PPP from 2017 per day by assuming an elasticity of 1.5 and US$28 PPP from 2017 by assuming an elasticity of 0.8. It is assumed that the duration of an asthma episode is one day. With respect to episodes of bronchitis in children, it is assumed that the duration of an episode is 14 days in the "low" scenario (assumption used in Holland, *(28)*) and 28 days in the "high" scenario (assumption used in US EPA 2018, *(29)*).

In the case of chronic bronchitis, in addition to the cost update from the Golub et al. study *(25)*, we transfer the value used by the US EPA. This transferred value (using an elasticity of 0.8) is considered as the "high" value in the evaluation.

Summary of recommended values

Table A.3 presents the summary of the recommended unit values for Colombia, for year 2020 in international dollars of the year 2017 and in current Colombian pesos (year 2020). Low, high and central values are reported, according to the assumptions indicated in Table A.4.

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[6] CPI for OECD countries obtained from https://data.oecd.org/price/inflation-cpi.htm.

[7] ILOSTAT data is based on the Large Integrated Household Survey (data up to March 2021).

Table A.3

Recommended values for Colombia, year 2020, US$ 2017 PPP and thousands of Colombian pesos

Unit	Parameter	Low	High	Central*	Central**
US$ PPP 2017	Value of the statistical life	1 028 782	2 172 497	1 495 000	1 600 639
	Value of the statistical life year	38 969	82 292	56 629	60 630
	Bronchitis children	154	308	218	231
	Asthma in children	11	28	18	19
	Chronic bronchitis in adults	12 256	160 811	44 394	86 533
	Lost work day	28	51	38	40
	Restricted activity day	21	38	28	30
	Hospital admissions	6868	7570	7210	7219
US$ PPP 2017	Value of the statistical life	1 415 326	2 988 770	2 056 717	2 202 048
	Value of the statistical life year	53 611	113 211	77 906	83 411
	Bronchitis children	212	423	299	317
	Asthma in children	15	39	24	27
	Chronic bronchitis in adults	16 860	221 232	61 074	119 046
	Lost work day	39	70	52	54
	Restricted activity day	29	53	39	41
	Hospital admissions	9448	10 414	9919	9931

(*) Geometric average between low and high value. (**) Simple average between low and high value.

Table A.4

Summary of differences between "low" and "high" cost scenarios

	Low	High
Value of a statistical life	OECD Transfer elasticity 1.2	GDP per capita *160
Value of a statistical life year		
Bronchitis in children	14 days with symptoms (Holland, (28))	28 days with symptoms (US EPA, (29))
Asthma in children	Transfer elasticity 1.5	Transfer elasticity 0.8
Chronic bronchitis in adults	Update Golub et al. (25)	Value transferred from the US ($470 thousand in 2015 prices) assuming a transfer elasticity of 0.8
Lost work day	Based on salaries agriculture sector	Based on salaries service sector
Restricted activity day		
Hospital admissions	WTP (low scenario elasticity) and PP (low scenario, agricultural wages)	WTP (high scenario elasticity) and PP (high scenario, service wages)

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