Prepared by the CCAC Scientific Advisory Panel

REVIEW OF RECENT PUBLICATIONS ON METHANE AND BLACK CARBON EMISSIONS AND IMPACTS

1. Background

Every year, the Climate and Clean Air Coalition's (CCAC) Scientific Advisory Panel reviews the latest scientific and policy-relevant publications on short-lived climate pollutants (SLCPs) of interest to the Coalition: methane, black carbon, tropospheric ozone and hydrofluorocarbons. This "Annual Science Update" is published as a background document for the first of two annual meetings of the Coalition's Working Group, which usually takes place during the first or second quarter of every year. This current document is part of a first draft of the "Annual Science Update 2016" focusing only on methane and black carbon topics relevant to the Scientific Advisory Panel workshop on "Metrics for Evaluating and Reporting on Black Carbon and Methane Interventions". A full "Annual Science Update 2016" which will contain a review of publications on hydrofluorocarbons as well as further topics on methane, black carbon and tropospheric ozone will be available before the Coalition's Working Group meeting scheduled for the week of 24 April 2017.

2. Methane emissions and inventories

2.1. Emission trends

Several studies in the past year have alluded to methane's increasing role in global warming, with many indicating increasing emissions and concentration of methane in the atmosphere. A World Meteorological Organization analysis of observations from the Global Atmosphere Watch, reported that methane concentrations (as well as that of carbon dioxide and nitrous oxide) reached new highs in 2015 at 1845±2 ppb. This is a 144% increase compared to the pre-industrial era. The 2014 and 2015 increase also exceeded observed growth between 2013 and 2014[1]. Furthermore, in an analysis of the global methane budget[2] and an editorial on the growing role of methane in anthropogenic climate change[3], Saunois and colleagues showed that methane concentration in the atmosphere started increasing in 2007 and surged in 2014 and 2015. They estimated a global methane emissions of 558 (range 540–568) $TgCH_4yr^{-1}$ between 2003 and 2012, with 60% (range 50–65 %) coming from human activities (Figure 1). Other studies were consistent with the WMO and Saunois findings. For example, Nisbet and colleagues also showed that methane concentration in the atmosphere increased between 2007 and 2013, with significant growth in 2014[4]. Two other studies also reported an increased atmospheric concentration of methane post-2006[5,6]. Similarly, a long-term trend analysis, using a top-down estimate from ethane and methane column observations[7] showed consistent methane increases each year since 2007 and an overall methane emission increase of 24–45 $Tgyr^{-1}$.

---

[1] WMO. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2015. WMO Greenhouse Gas Bulletin. 12, 24 October 2016. http://library.wmo.int/opac/doc_num.php?explnum_id=3084

[2] Saunois et al. The global methane budget 2000–2012. Earth Syst. Sci. Data, 8, 697–751, 2016

[3] Saunois et al. The growing role of methane in anthropogenic climate change. Environ. Res. Lett. 11, 2016.

[4] Nisbet et al. Rising atmospheric methane: 2007–2014 growth and isotopic shift. Global Biogeochem. Cycles, 30, 1356–1370, 2016.

[5] Schaefer et al. A 21st century shift from fossil-fuel to biogenic methane emissions indicated by 13CH4. Science, 10.1126/science.aad2705 (2016).

[6] Rice et al. Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. PNAS, 113, 10791–10796, 2016.

[7] Hausmann et al. Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007–2014): top-down estimate from ethane and methane column observations. Atmos. Chem. Phys. 16, 3227–44, 2016.

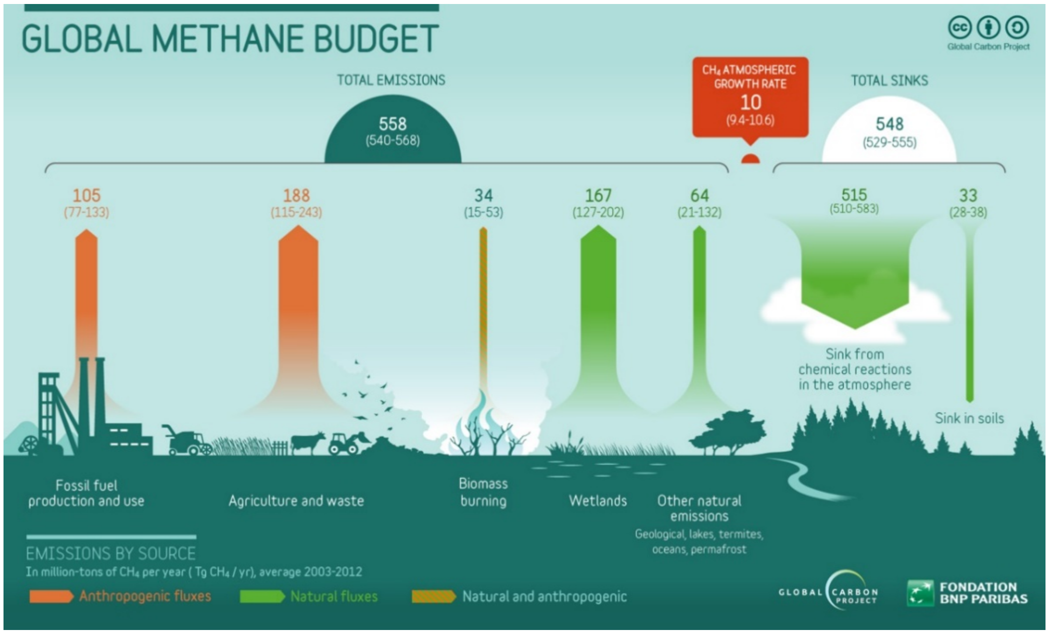


Figure 1: Global Methane Budget; source: http://www.globalcarbonproject.org/methanebudget/

At the national scale, satellite data and surface observations of atmospheric methane, suggested that United States emissions increased by more than 30% between 2002 and 2014 and could be responsible for 30–60% of the global growth of atmospheric methane in the past 10 years[8]. An analysis[9] of ethane and methane emissions from oil and natural gas extraction in North America from 2008-2014 showed methane emissions from oil and gas extraction grew from 20 to 35 Tgyr^{-1}. Another study[10] showed that a significant portion (more than 50%) of the methane emissions from natural gas systems in the United States is caused by just 5% of identified leakage sources. It must be noted however, that results from Saunois and colleagues indicates no significant trend in United States methane emissions despite the recent growth of the shale gas industry.

A global analysis[11] of methane emissions from oil and gas operations between 1980 and 2012 indicated that the Russian oil industry contributed significantly to global methane emissions. The analysis further suggests that the global decline in oil and gas methane emissions between 1990 and 2000 is linked to reduced Russian emissions as the industry stalled following the collapse of the Soviet Union and increased flaring, as opposed to venting, of unrecovered gas.

A study by Peng and colleagues[12] showed that China's methane emissions grew rapidly between 2000 and 2010 contributing more than 10% of the global methane emissions. The study, which looked at the eight major emissions sectors in China, highlighted an emission surge to 44.9 (range 36.6-56.40) TgCH$_4$yr^{-1} in 2010 from 24.4 (range 18.6–30.5) TgCH$_4$yr^{-1} in 1980, with most of the increase occurring in the 2000s and driven by coal exploitation which overtook rice cultivation as a major source (Figure 2).

---

[8] Turner et al. A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations. Geophys. Res. Lett., 43, 2218–2224, 2016
[9] Franco et al. Evaluating ethane and methane emissions associated with the development of oil and natural gas extraction in North America. Environ. Res. Lett. 11, 044010, 2016
[10] Brandt et al. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. Environ. Sci. Technol., 50, 12512−12520, 2016.
[11] Höglund-Isaksson. Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. Environ. Res. Lett. 12, 024007, 2017.
[12] Peng et al. Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. Atmos. Chem. Phys., 16, 14545–14562, 2016

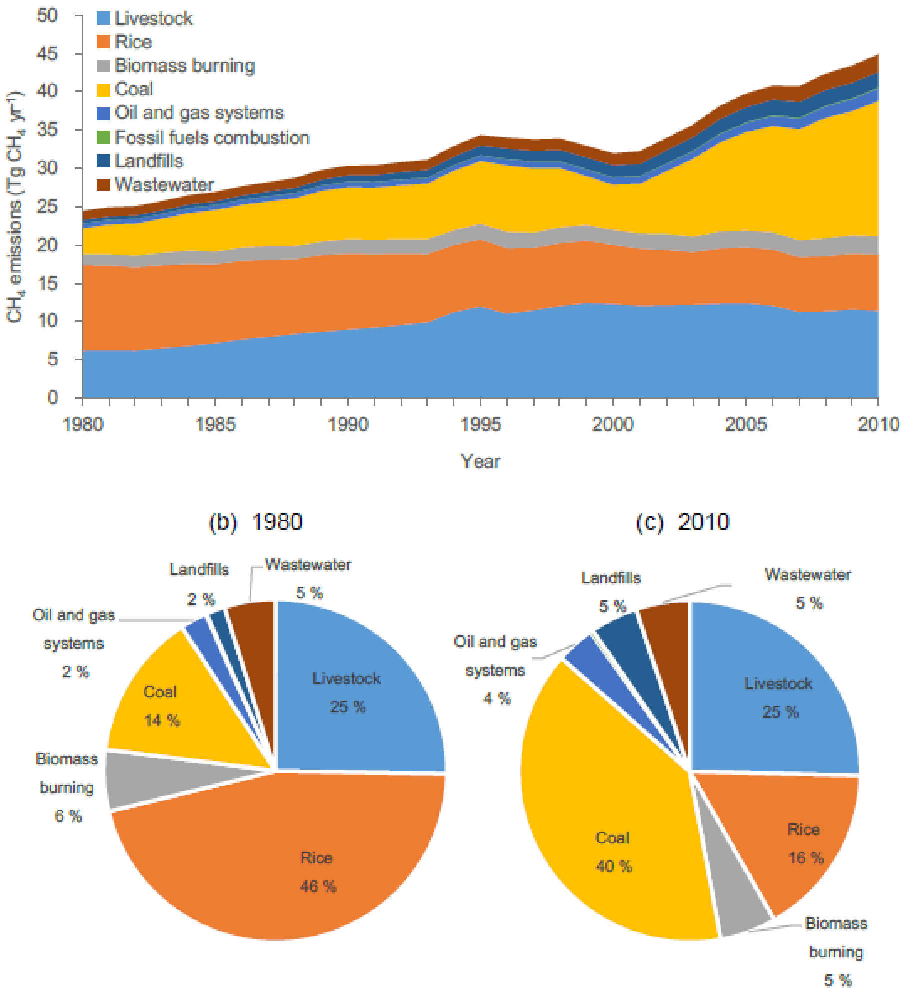


Figure 2: Methane Emissions in China between 1980 and 2010; source: Peng et al.[12]

The continued increase in methane emissions could thwart efforts to limit global warming to well below 2 degrees as agreed under the Paris Agreement. While CO_2 mitigation efforts must continue, they should be done simultaneously with methane mitigation actions, in order to increase the chance of meeting climate targets.

2.2. Emission sources

While there is overall agreement in recent publications that the atmospheric concentration of methane is growing, there are some divergent results on the emission sources. Some studies such as those by Saunois et al[2]; Nisbet et al.[4]; Schaefer et al.[5]; point to biogenic sources, specifically agriculture – including enteric fermentation and rice paddies – as the main culprit, other studies have suggested otherwise. For example, Haussmann and colleagues reported a strong connection between the increase in atmospheric methane and fossil fuels activities[13]. Similarly, Rice et al[14] suggested that fossil fuel-related methane emissions increased substantially between 2000 and 2009, although they

---

[13] Hausmann et al. Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007–2014): top-down estimate from ethane and methane column observations Atmos. Chem. Phys. 16, 3227–44, 2016

[14] Rice et al. Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. PNAS, 113, 10791–10796, 2016.

also highlighted increased emissions from other anthropogenic sources including agriculture - due to livestock population increase, and waste. Furthermore, Helmig and colleagues[15] as well as Kort and colleagues[16] reported a linkage between increased oil and natural gas activities in the United States and an increase in global atmospheric ethane emissions, which could suggest a significant increase in associated methane emissions.

However, a study by Schwietzke and colleagues[17], found that while total methane emissions from natural gas production has declined over the last 30 years -- from 8% to around 2% -- there is a need for an upward revision of current methane inventories from the fossil fuel industry due to an underestimation of between 20 and 60%. This is further supported by another study[18] which simulated methane emissions in over 100 countries. It showed that methane emissions from oil and gas were at times double, especially in the 1980s, global inventory estimates (Figure 3). The study also reported that overall oil and gas emissions have been fairly constant since 2005 due to increased emissions from shale gas production which countered emission reductions achieved through the increased adoption of methane recovery systems.

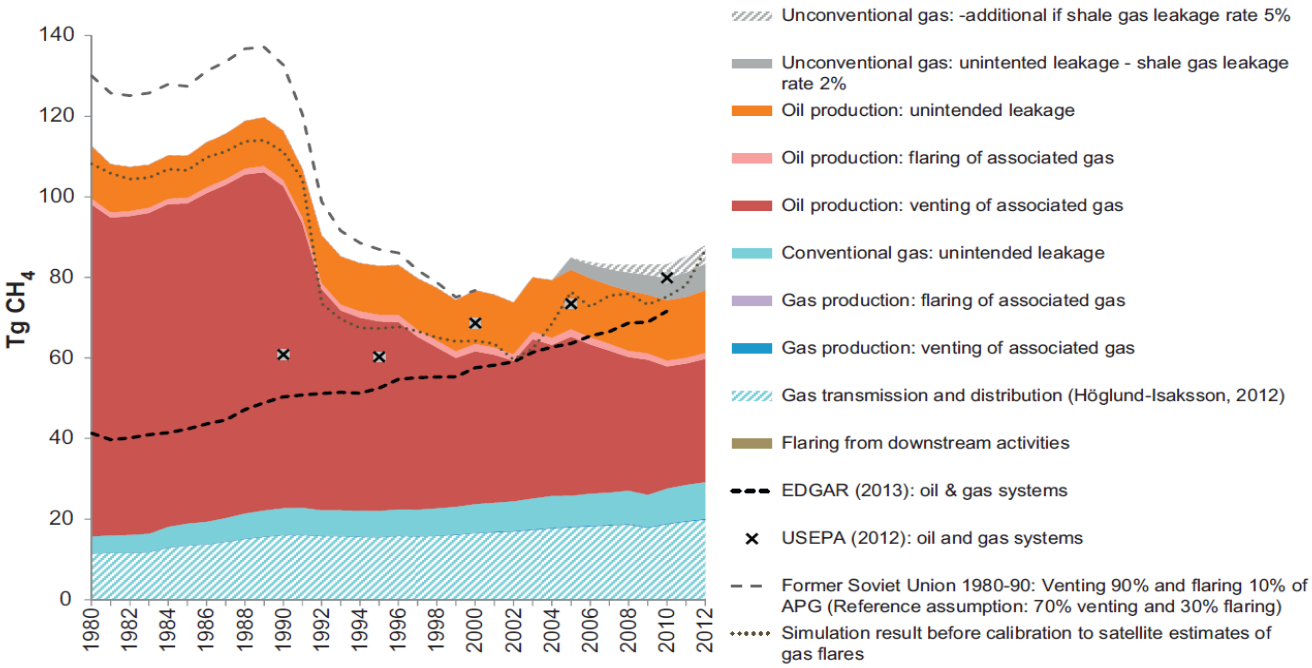


Figure 3: Global Methane Emissions from the fossil fuel industry; that is from the production and usage of natural gas, oil and coal. Source: Höglund-Isaksson, L.[18]

These findings highlight the need for a reassessment of current climate prediction emissions scenarios to account for revised values for anthropogenic methane emissions. The findings also suggest that there is a need for a robust assessment of methodological differences in the estimation of anthropogenic methane emissions in order to determine the source of the current spike in atmospheric concentrations. Furthermore, the findings also indicates that there is

---

[15] Helmig et al. Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production. Nature Geoscience 9, 490–495, 2016.
[16] Kort et al. Fugitive emissions from the Bakken shale illustrate role of shale production in global ethane shift. Geophys. Res. Lett., 43, 4617–4623, 2016
[17] Schwietzke et al. Upward revision of global fossil fuel methane emissions based on isotope database. Nature, 538, 88-91, 2016
[18] Höglund-Isaksson. Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. Environ. Res. Lett. 12, 024007, 2017.

greater potential to mitigate methane driven climate change from fossil fuel and agriculture industries than earlier thought.

3. Impacts of Methane

3.1. Climate impacts

Recent publications have improved our knowledge of the climate impacts of methane. For example, a study conducted by Etminan and colleagues[19] revealed that methane's impact on the climate has been largely undervalued because previous calculations excluded its shortwave absorption characteristics. The study reported that the direct climate effect of increased methane concentration in the atmosphere is 25% higher than the values used in the Intergovernmental Panel on Climate Change (IPCC) 2013 assessment, and estimated the 100 year global warming potential (GWP) of methane as 32 instead of 28 as indicated in the IPCC assessment. This new estimate means that the present day radiative forcing of methane is about one third that of carbon dioxide, relative to preindustrial values, instead of just above a quarter as reported in previous studies. Another publication[20] showed that the climate forcing from non-CO_2 greenhouse gases including methane is able to boost positive carbon cycle feedbacks[21] by a factor of more than 1.15 depending on how long the gas is present in the atmosphere. According to the paper, this enhances the effective strength of methane-like gases and increases their net warming of global climate by up to 25% after 150 years. They attributed this effect to the fact that non-CO_2 greenhouse gases warm the Earth but are not able to induce CO_2 fertilization effect in plants or enhance the ability of oceans to take up CO_2. The study therefore concluded that the interaction of climate forcing from non-CO_2 gases with carbon cycle feedbacks will increase their warming impacts, indicating a stronger warming effect than current GWP numbers suggest.

3.2. Impact on sea-level rise

Zickfeld and colleagues[22] showed that the impacts of methane and other short-lived greenhouse gases on sea-level rise have a longer term effect than previously thought. The paper, which analysed the impact of methane, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, and perfluorinated gases on sea-level rise, found that their effects persist long after they are present in the atmosphere. According to the study, despite the short lifetime of methane in the atmosphere, at least half of the methane-induced thermal expansion of the ocean - which is one of the factors responsible for sea-level rise - persist for more than 200 years even after emissions have completely ceased. This means that continued emissions of methane and other short-lived gases continues, will lock-in levels of sea-level rise, affecting many coastal and small island countries in the future, even if emissions stop immediately.

3.3. Impact on crop yield losses

With respect to crop yield impacts, one analysis showed that while carbon dioxide is the largest driver of climate change, the reduction in crop yield due to climate change will be primarily driven by non-CO_2 climate pollutants including methane, black carbon and halocarbons[23]. This is because CO_2 fertilizes crops thereby counteracting some of the damages caused by its warming ability, while methane only lead to minimal fertilization but increases surface ozone which together with its warming effect result in significant crop losses (Figure 4).The study show that human induced emissions to date have led to a 9.5±3.0% decrease in agricultural yields worldwide with about 93% of these losses caused by non-CO_2 emissions, in particular methane (-5.2±1.7%) (Figure 5a). The analysis also projected that

---

[19] Etminan et al. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophys. Res. Lett., 43, doi:10.1002/2016GL071930, 2016.

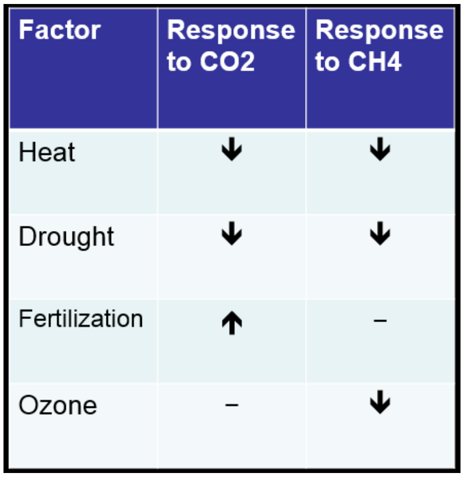
[20] MacDougall and Knutti. Enhancement of non-CO2 radiative forcing via intensified carbon cycle feedbacks. Geophys. Res. Lett., 43, 5833–5840, doi:10.1002/2016GL068964, 2016

[21] Carbon cycle feedbacks in this case are the interactions between temperature change, and the various parts of the carbon cycle including the atmosphere, ocean, and biosphere.

[22] Zickfeld et al. Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. www.pnas.org/cgi/doi/10.1073/pnas.1612066114, 2016.

[23] Shindell, D. T. Crop yield changes induced by emissions of individual climate-altering pollutants, Earth's Future, 4, doi:10.1002/2016EF000377. 2016.

following a low emissions trajectory would increase yields by 25±11% due to all climate forcing agents combined by year 2100 compared to a high emissions trajectory, with the largest benefits (15.6±5.1%) coming from reduced emissions of methane, highlighting the significant role of methane controls in reducing crop yield losses (Figure 5b).



Factor	Response to CO2	Response to CH4
Heat	↓	↓
Drought	↓	↓
Fertilization	↑	–
Ozone	–	↓

Figure 4: Comparing methane and CO2 crop damage impacts; credit: Drew Shindell

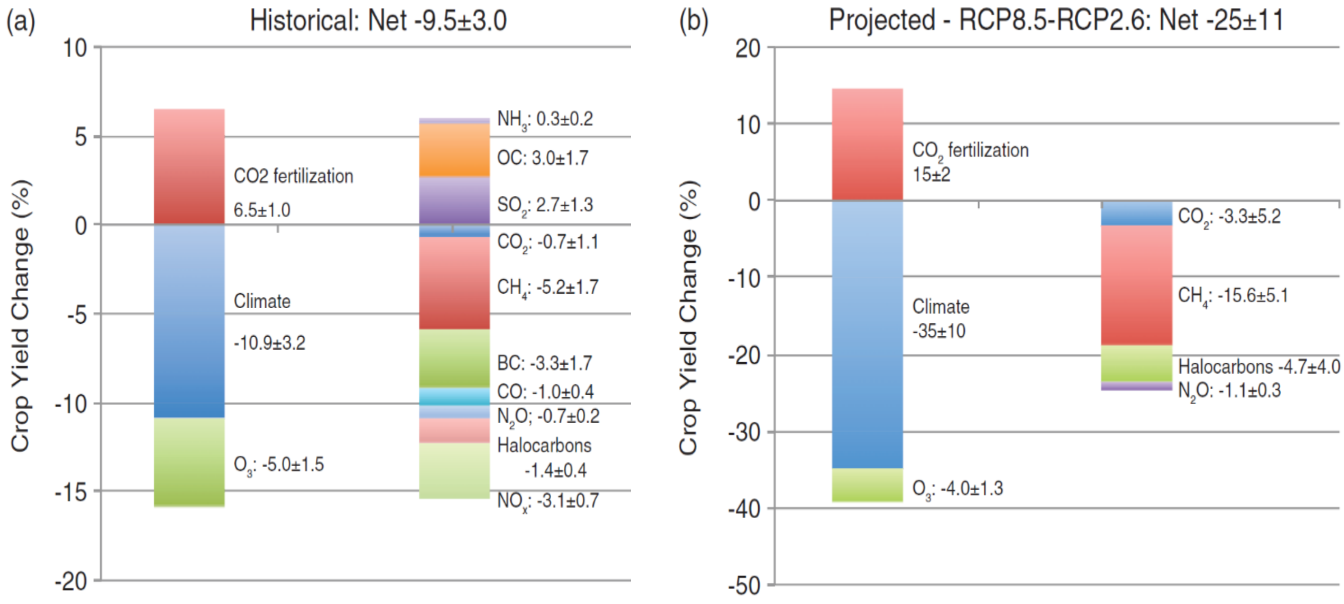


Figure 5: Historical and projected impacts of climate forcing agents on crop yield. Source: Shindell D.T.[23]

3.4. Ozone-related impacts – crop yield and health

Methane is one of the atmospheric substances responsible for forming tropospheric ozone – a major cause of crop yield losses globally. More and more publications[24] highlight not only ozone's damaging impact on crops but also its impacts on biodiversity[25]. This emphasizes the need to reduce emissions of all ozone precursors, including methane,

---

[24] For example, Lobell & Asseng. Comparing estimates of climate change impacts from process-based and statistical crop models. Environ. Res. Lett. 12, 015001, 2017. Karlsso et al. Past, present and future concentrations of ground-level ozone and potential impacts on ecosystems and human health in northern Europe. Science of the Total Environment, 576, 22–35, 2017. Hewitt et al. N-fixation in legumes – an assessment of the potential threat posed by ozone pollution. Environmental Pollution, 208, Part B, 909–918, 2016. Yi et al. The impacts of surface ozone pollution on winter wheat productivity in China – An econometric approach. Environmental Pollution, 208, Part B, 326–335, 2016.

[25] For example, Fuhrer et al. Current and future ozone risks to global terrestrial biodiversity and ecosystem processes. Ecology and Evolution 6: 8785–8799, 2016; Calvete-Sogo et al. Heterogeneous responses to ozone and nitrogen alter the species composition of Mediterranean annual pastures, Oecologia, 181: 1055. doi:10.1007/s00442-016-3628-z, 2016.

NO_X, carbon monoxide, and non-methane volatile organic compounds. The recent Convention on Long-Range Transboundary Air Pollution Scientific Assessment Report[26] suggested that increased methane emission, including from outside of Europe is an important factor contributing to ozone concentration in Europe. It postulated that the effectiveness of methane emissions controls within and outside of Europe will determine how much ozone concentration can be reduced in the region. Karlsson and colleagues also highlighted the need to include methane in ozone abatement actions in order to reduce concentrations in northern Europe[27].

Several studies have linked exposure to ozone with incidence of diseases and mortality. Jerrett and colleagues highlighted a positive relationship between ozone exposure and incidence of diabetes in African American women[28]. Turner and colleagues indicated that long-term exposure to ozone can contribute to risk of respiratory and circulatory mortality[29]. Bero and colleagues showed that short-term exposure to ozone is linked to a 1.72% increase in mortality in people with a previous history of cardiovascular diseases[30]. Silva and colleagues[31] found that various models shows that future change in ozone concentration relative to year 2000 levels could lead to increased global mortality burden from a range 121 000 to 728 000 deaths per annum in 2000 to between 1.09 and 2.36 million deaths per annum in 2100, with increase in methane emissions, climate change impacts, and population growth playing important roles in this increase.

3.5. *Societal/economic impacts*

In an attempt to assess the societal and economic cost of the climate and environmental damage caused by methane, Shindell and colleagues[32] used a framework that takes into consideration methane's atmospheric lifetime as well as properties that differentiate it from CO_2 -- such as its inability to induce ecosystem fertilization and it ozone-forming properties. They found that the social cost of methane could be up to $2400 and $3600 per ton using a 5% and 3% discount rates respectively (2010 US$) or 100 and 50 times greater than that of CO_2 using the same discounts rates. They also noted that increased methane emissions in the future could counter much of the societal benefits gained from reducing the rate of CO_2 emissions. Sarofim and colleagues[33] had shown that the global mitigation of methane and consequently ozone pollution reduction could provide a global premature mortality benefits estimated at USD 790 and USD 1775 per ton of methane based on changes in short- and long-term exposure, respectively (2011 US$).

4. Black carbon emissions and inventories

4.1. Emission trends

A recent assessment[34] of global anthropogenic particulate matter (PM) including black carbon put the emissions of black carbon in 2000 and 2010 at 6.6 and 7.2Tg respectively (Figure 6a & b). The study, which used GAINS integrated assessment model, shows that about 15% of global $PM_{2.5}$ emissions is black carbon with some $PM_{2.5}$ sources such as

---

Bergmann et al. Impact of tropospheric ozone on terrestrial biodiversity: A literature analysis to identify ozone sensitive taxa. Journal of Applied Botany and Food Quality. 90, 83 – 105, DOI: http://dx.doi.org/10.5073/JABFQ.2017.090.012, 2017.

[26] Maas et al. Towards Cleaner Air. Scientific Assessment Report 2016. EMEP Steering Body and Working Group on Effects of the Convention on Long-Range Transboundary Air Pollution, Oslo. http://www.unece.org/fileadmin/DAM/env/lrtap/ExecutiveBody/35th_session/CLRTAP_Scientific_Assessment_Report_-_Final_20-5-2016.pdf

[27] Karlsso et al. Past, present and future concentrations of ground-level ozone and potential impacts on ecosystems and human health in northern Europe. Science of the Total Environment, 576, 22–35, 2017.

[28] Jerrett et al. Ambient ozone and incident diabetes: A prospective analysis in a large cohort of African American women. Environment International, http://dx.doi.org/10.1016/j.envint.2016.12.011

[29] Turner et al. Long-Term Ozone Exposure and Mortality in a Large Prospective Study. American Journal of Respiratory and Critical Care Medicine. DOI: http://dx.doi.org/10.1164/rccm.201508-1633OC

[30] Bero et al. Short-term exposure to ozone & mortality in subjects with and without previous cardiovascular disease. Epidemiology, 27, 663-9. 2016

[31] Silva et al. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmos. Chem. Phys., 16, 9847–9862, 2016

[32] Shindell et al. The Social Cost of Methane: Theory and Applications. Faraday Discuss. DOI: 10.1039/C7FD00009J, 2017.

[33] Sarofim et al. Valuing the Ozone-Related Health Benefits of Methane Emission Controls. Environ Resource Econ, 66:45–63, DOI 10.1007/s10640-015-9937-6, 2017

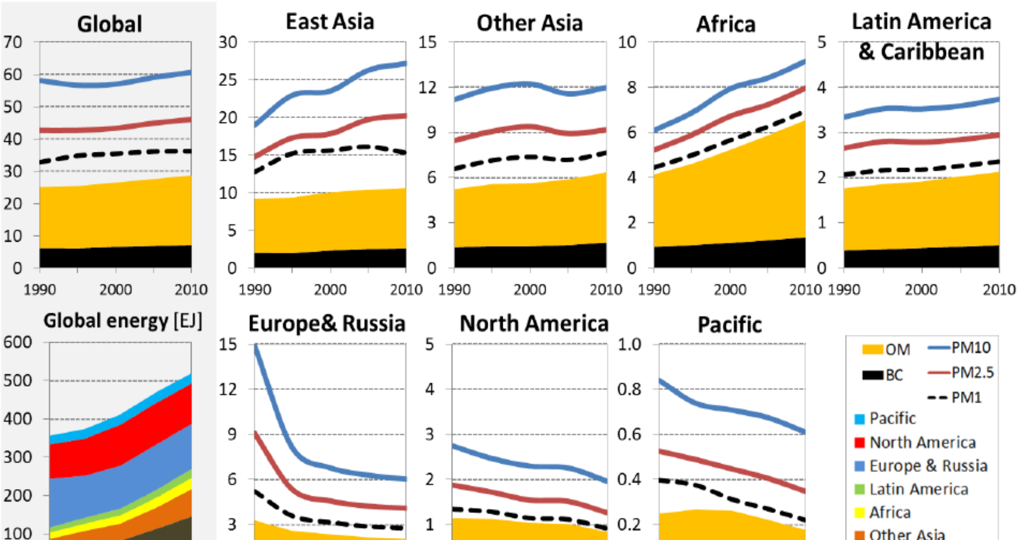
[34] Klimont et al. Global anthropogenic emissions of particulate matter including black carbon. Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-880, 2016.

traffic sources containing up to 50% black carbon. The study included sources that have not been accounted for or often misallocated in previous assessment such as kerosene lamps, gas flaring, diesel generators and trash burning leading to higher emissions estimations than previous studies. Another study[35], which looked at the future trend of black carbon emissions, projected a decline in emissions between now and 2100 as have been noted in other previous studies. The study, using different assessment models, indicated that under business as usual conditions, black carbon emissions will be dominated by the transportation and residential sectors between now and 2100. It further projected that implementing climate policies to reduce CO_2 emissions will affect black carbon emissions differently depending on the level of ambition. Moderate climate policies that aim to reduce CO_2 by 50% would lead to only a 10-20% reduction in black carbon emissions. However, ambitious climate policies aimed at negative CO_2 emissions by the end of the century, reduced black carbon emissions from 20 to 80% depending on the model assumptions. This analysis suggests that actions to reduce black carbon will still be required even with ambitious implementation of CO_2 mitigation actions.

4.2. Emission sources

One study[36] seeking to fill in the dearth of data on black carbon concentrations in the Siberian Arctic found the area to have higher black carbon concentrations compared to other Arctic sites closer to Europe, even though it is far less populated. The study used both observations and models to ascertain the sources of black carbon and found that transportation (38%) and residential heating (35%) are the main sources of black carbon in the region. This is contrary to previous research which had suggested gas flaring as a possible major source. It found that gas flaring only contributes 6% while open fires and power plants contribute 12 and 9% respectively. They further show that traffic emissions mostly from Europe, China and densely populated areas of Russia are responsible for the observed high transportation emissions. A 2015 observation study using samples from the Arctic region close to Norway also found that residential biomass burning and fossil fuels contributed substantially to black carbon concentrations, with 13 of the 16 samples analyzed indicating no significant contributions from gas flaring[37].

It should be noted however that an in-the-field measurement of black carbon emissions rates from oil and gas flaring by Conrad and Johnson[38] suggested that the overall black carbon-related impacts of gas flaring on global warming including in the Arctic may be underestimated. The study, which used measurement and imaging techniques to compute the instantaneous BC emission rate, suggested that the GAINS model emission factor used to estimate black carbon emissions from flaring could be low by almost a factor of two. They also found significant variability in the emission rates between flares with differences that span an order of magnitude of more than four, indicating the existence of individual super-emitter flares of importance for global emission inventories. The existence of super-emitters is supported by another recent study[39] that found that less than 100 out of 20,000 flares in the United States are responsible for over half of total emissions in current emission inventories of black carbon, methane and CO_2.



---

[35] Smith et al. Futu
[36] Winiger et al. Sil
[37] Winiger at al. Isc ol., 49,
DOI: 10.1021/acs.
[38] Conrad and Joh
[39] Allen et al. Carb 123, 2016

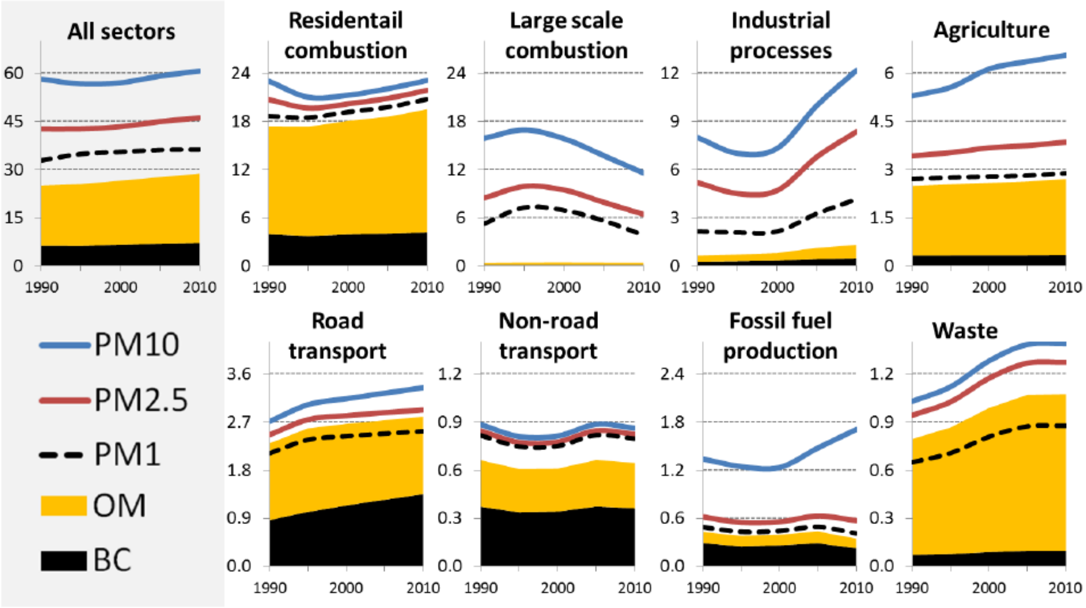
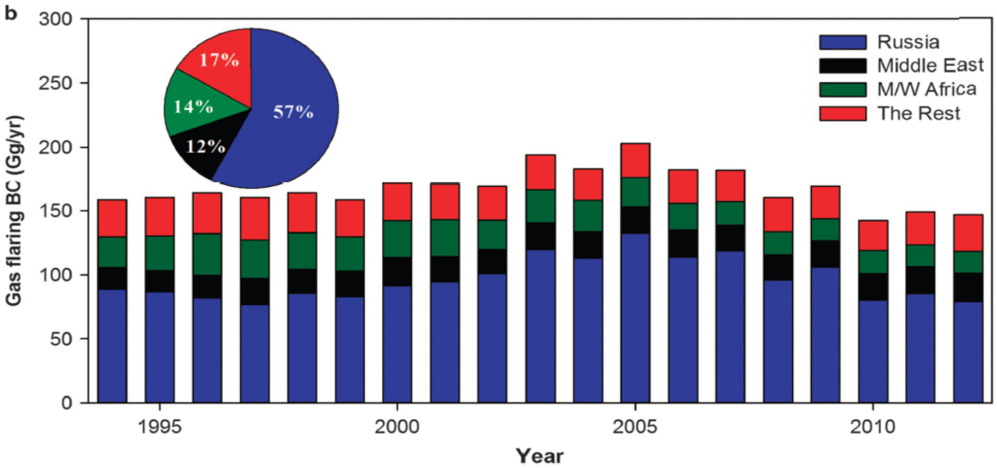


Figure 6b: Global and sectoral emissions of PM species including black carbon. Source: Klimont et al.[34]

A global black carbon emissions inventory from gas flaring was recently developed by Huang and Fu[40]. Their results show that Russia and Nigeria remain the top two highest gas flaring countries by volume globally. They found that black carbon emissions from flaring are on a generally declining trend since 2005 with emissions of about 180 Gg/yr in 2005 and about 150 Gg/yr in 2012. Russia significantly dominates total global emissions (57%), with the Middle East and Mid and West Africa contributing about 12 and 14%, respectively. The rest of the world contributes around 17% (Figure 7).



---

[40] Huang and Fu

5. Black carbon impacts

5.1. Climate impacts

Black carbon possesses warming characteristics because of its ability to absorb visible light, leading to disturbance of the planetary radiation balance and eventually to warming. Additionally, when BC is deposited on ice or snow, it reduces its ability to reflect light, thereby increasing both atmospheric warming and ice/snow melting rates due to increased heat absorption. Black carbon is however virtually always emitted along with other co-pollutants (at varying proportions, depending on the combustion source) including sulphates, nitrogen oxides (NOx), carbon monoxide, methane, non-methane volatile organic compounds, and organic carbon (OC), which includes brown carbon[41]. Brown carbon, like black carbon, also absorbs sunlight causing warming and is therefore termed a light-absorbing-organic carbon. Sulphates and other portions of organic carbon are cooling agents. Hence, the overall warming effect of BC from any particular source depends on the ratio of black carbon to co-pollutants.

Laboratory- and field-based results indicate that aging affects the radiative forcing of black carbon. Results have shown that as soot ages, its ability to absorb light could be altered depending on where in the atmosphere the soot particles are located and the prevailing chemical composition of the environment[42]. Peng and colleagues show that this aging process could amplify black carbon's light-absorbing properties by a factor of up to 2.4 within 2 to 18hrs in polluted and non-polluted urban environments respectively[43], which is larger than what is commonly used in global climate models. Recent results[44] also show that climate models need to consider the important role of brown carbon in the impact aerosols have on overall warming. This is because the light absorbing properties of organic carbon at short wavelengths – due to their brown carbon content – could contribute significantly to the total warming impacts of aerosols, yet this has been sometimes ignored in some climate models.

It is also important to consider the role of non-black carbon content of aerosols in the ability of black carbon to absorb light, thereby inducing warming. A new study shows that this light enhancement is dependent on the non-black carbon to black carbon mass ratio of aerosols. According to Liu and colleagues[45], enhanced light absorption was not observed

---

[41] Brown carbon is an atmospheric aerosol mainly emitted during biomass and coal combustion. It plays a key role in the warming of the atmosphere through its light absorbing characteristics, with strong absorbing characteristic of short wavelength solar radiation. It is termed the light absorbing-organic carbon

[42] For example, China et al. Morphology of diesel soot residuals from supercooled water droplets and ice crystals: implications for optical properties. Environ. Res. Lett. 10, 114010, 2015. Ueda et al. Light absorption and morphological properties of soot-containing aerosols observed at an East Asian outflow site, Noto Peninsula, Japan. Atmos. Chem. Phys., 16, 2525–2541, 2016; Fierce et al. Black carbon absorption at the global scale is affected by particle-scale diversity in composition. Nature Communications, 7:12361, DOI: 10.1038/ncomms12361, 2016; Wu et al. Black carbon radiative forcing at TOA decreased during aging, Scientific Reports, 6:38592, DOI: 10.1038/srep38592; Chen et al. Light absorption enhancement of black carbon from urban haze in Northern China winter, Environmental Pollution, 221, 418–426, 2017; Doner and Liu. Impact of morphology on the radiative properties of fractal soot aggregates. Journal of Quantitative Spectroscopy & Radiative Transfer 187, 10-19, 2017.

[43] Peng et al. Markedly enhanced absorption and direct radiative forcing of black carbon under polluted urban environments. PNAS, 113, 4266–4271, 2016.

[44] For example, Gustafsson & Ramanathan 2016, Convergence on climate warming by black carbon aerosols, Guang-Ming et al. 2016. Brown carbon in the cryosphere: Current knowledge and perspective, Advances in Climate Change Research 7 (2016) 82e89; Yuan et al. Light absorption of brown carbon aerosol in the PRD region of China. Atmos. Chem. Phys., 16, 1433–1443, 2016; Shamjad et al. Refractive Index and Absorption Attribution of Highly Absorbing Brown Carbon Aerosols from an Urban Indian City-Kanpur. Scientific Reports, 6:37735 | DOI: 10.1038/srep37735, 2016; Cui et al. Radiative absorption enhancement from coatings on black carbon aerosols. Sci Total Environ 551-552:51–56, 2016

[45] Liu et al. Black carbon absorption enhancement in the atmosphere determined by particle mixing state. Nature Geoscience. http://dx.doi.org/10.1038/ngeo2901, 2017

in aerosols with a non-black carbon to black carbon mass ratio of below 1.5, which is typical of emissions from fresh traffic sources. However, with a non-black carbon to black carbon mass ratio above 3 – which is common with soot from biomass burning – light absorption enhancement was detected. This was attributed to the coating of black carbon particles by non-black carbon particles leading to stronger interaction of black carbon particles with light. Another study[46] indicates that an increased absorption of between 1.3 and 2.2, depending on the time of the day in China, was associated with nitrate and sulphate content of aerosols. Cui and colleagues[47] also reported an enhancement ranging between 1.4 and 3 for fresh and aged China aerosol, with sulphates contents primary responsible for the enhancement.

5.2. Impacts on regional climate and weather pattern

Some studies have further linked anthropogenic aerosols, including black carbon, with changes in regional climates and the hydrological cycle. Fan and colleagues show that aerosols contributed to approximately 40% reduction in summer precipitation over Mt. Hua in China. They attributed this to heat absorbing aerosol, mainly black carbon, induced warming at the top of the mountain and cooling near the surface resulting in change in moisture movement (Figure 8)[48]. Similarly, Hodnebrog and colleagues, using global and regional models, showed that emissions of aerosol particles, in particular black carbon from local biomass burning activities, are linked to about a 20-30% decrease in rainfall in southern Africa, due to the warming and drying of the atmosphere[49]. Another study by Yoon and colleagues showed that carbonaceous aerosols, including black carbon and organic carbon, potentially led to reduced regional rainfall by about 25% over North Africa[50].

Furthermore, a recent review of existing literature and models suggest that aerosols, including black carbon, have influenced the monsoon and resulted in widespread solar dimming over both South and East Asia, consequently leading to an increase in atmospheric solar heating[51]. The study indicates that aerosols are responsible for a significant change to Asia's hydrologic during the 21st century, including a weakening of the Asian monsoon. This findings is further supported by another study by Lau and colleagues[52].

5.3. Impacts on crops

Black carbon affects ecosystem and agriculture productivity through its ability to alter weather and precipitation patterns. It can lead to increased frequency of drought and flood (see section 5.2), with negative effects on crop yield. Furthermore, the increased Earth warming effect of black carbon also impacts agricultural productivity. An analysis of the impact of emissions of individual climate-altering pollutants including black carbon, HFC, N_2O, organic carbon, SO_2, and NH_3 on crop yield, shows that black carbon will have the greatest agricultural damages per ton on crops in the first decades over the remainder of the 21st century, although this overall loss is reduced when the effect of co-emitted substances are taken into consideration[53].

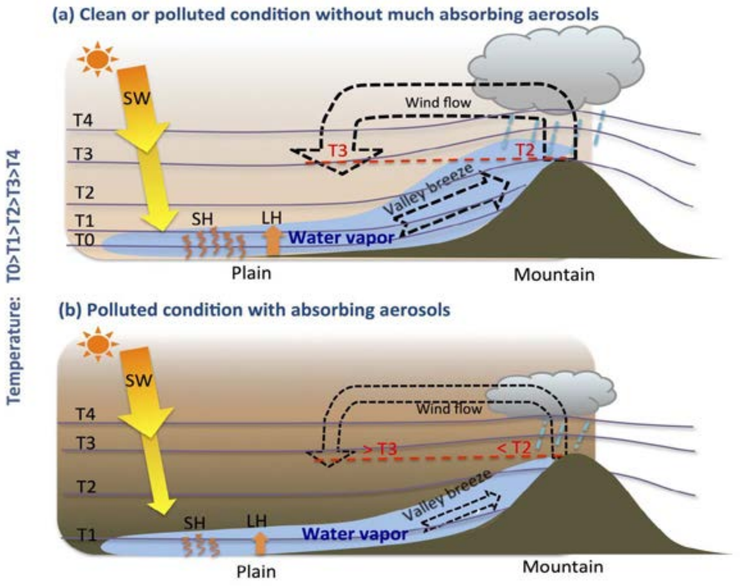


Figure 8: Mechanism leading to precipitation reduction due to increased black carbon pollution. Source: Fan et al.[48]

---

[46] Chen et al. Light absorption en , 2017
[47] Cui et al. Radiative absorption 016.
[48] Fan et al 2016. Mechanisms c os. Sci., 73, 1351–1366.
[49] Hodnebrog et al. Local biomas ons, 7:11236, 2016
[50] Yoon et al. The role of carbona .
[51] Li et al. Aerosol and monsoon
[52] Lau et al. Impacts of aerosol– cs. DOI 10.1007/s00382-016-3430-y
[53] Shindell, D. T. Crop yield char 77. 2016.

5.4. Health impacts

Black carbon, organic carbon and other co-pollutants are a significant component of fine particulate matter ($PM_{2.5}$). $PM_{2.5}$ is a major cause of ill health and premature deaths globally. Most studies usually assess the impacts of $PM_{2.5}$ on health rather than direct impacts of black carbon. However, a recent assessment[54] analysed the public health impact of black carbon concentrations in the United States in 2010. According to the assessment, approximately 14,000 deaths (Figure 9), as well as hundreds of thousands of illnesses including hospitalizations, emergency visits and minor respiratory symptoms can be attributed to black carbon. The study's sensitivity analysis further suggested that total black carbon-related deaths may be substantially more.

A study[55] looking at the role of air pollution, in particular black carbon, on the onset of respiratory disease shows that black carbon directly affects the leading bacteria responsible for respiratory infections - *Streptococcus pneumoniae* and *Staphylococcus aureus*. The study found that exposure of these bacteria to black carbon leads to structural, compositional and functional changes that could cause the bacteria to spread from the nose to the lower respiratory tract - an essential process before subsequent infection. They further show that black carbon alters bacteria antibiotic tolerance thereby increasing their resistance to multiple antibiotics, including penicillin – the leading treatment for pneumonia. Another study focused on exposure of children to black carbon loaded emissions from road traffic found that children living close to major roads had significantly poorer lung function than those living in less polluted areas. Kids living 100 meters away from traffic showed an average of 6 percent lower lung function than those living 400 meters or more away at the age of eight[56]. One study further showed that black carbon exposure of children living in urban areas diminishes the health benefits that would normally accrue from daily physical activities[57]. Another study on traffic-related $PM_{2.5}$ including black carbon, also showed that a higher incidence of dementia is associated with living in close proximity to major roads with heavy traffic[58].

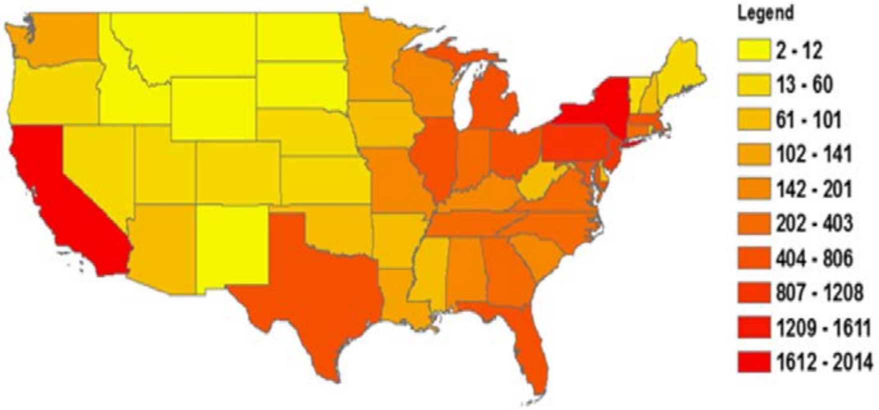


Figure 9: Annual premature mortality by State attributed to exposure to black carbon in the US. Source: Li et al[54]

---

[54] Li et al. Assessing public 016.
[55] Hussey et al. rs Staphyloc 2920.13686, 2017
[56] Rice et al. Lifetime Expos
10.1164/rccm.20150610580
[57] Lovinsky-Desir et al. Phys , 2016.
[58] Chen et al. Living near m 389, 718–726,
DOI: http://dx.doi.org/10.10

With respect to the overall impact of $PM_{2.5}$ emissions, a global estimate of the number of preterm births that are associated with $PM_{2.5}$ concentrations, indicates that about 2.7 million preterm births (18% of the total number of preterm births) globally may be associated with maternal exposure to ambient $PM_{2.5}$ concentrations. This is important as preterm birth is associated with a number of post-natal health outcomes, including infant mortality and in some cases life-long morbidity impacts in survivors[59]. Furthermore, focusing on specific sectors, a recent analysis by Liu and colleagues[60] indicated that increased emissions of $PM_{2.5}$ from ocean-going vessels in East Asia led to large adverse health impacts, especially near shore. They estimated a total of 24,000 (range 14,500–37,500) premature deaths annually in East Asia are associated with $PM_{2.5}$ and ozone emissions from shipping.

A study focusing on residential cooking and heating in China showed that an estimated 159000 (range 142000−172000) and 182000 (range 163000−197000) premature deaths can be attributed to the effects of heating and cooking emissions on outdoor (ambient) air quality, respectively; that is a total of 341 000 (range 306000−3700000) premature deaths from $PM_{2.5}$-related emissions from residential combustion, equivalent to a third of total deaths caused by all ambient $PM_{2.5}$ pollution in China[61].

---

[59] Malley, C.S. et al. Preterm birth associated with maternal fine particulate matter exposure: A global, regional and national assessment, Environment International, http://dx.doi.org/10.1016/j.envint.2017.01.023. 2017.

[60] Liu et al. Health and climate impacts of ocean-going vessels in East Asia. Nature Climate Change, DOI: 10.1038/NCLIMATE3083, 6, 2016

[61] Archer-Nicholls et al. The Regional Impacts of Cooking and Heating Emissions on Ambient Air Quality and Disease Burden in China. Environ Sci Technol., 6, 9416-23, doi: 10.1021/acs.est.6b02533. 2016.