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Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050

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Abstract

Reductions in greenhouse gas (GHG) emissions can bring ancillary benefits of improved air quality and reduced premature mortality, in addition to slowing climate change. Here we study the co-benefits of global and domestic GHG mitigation on US air quality and human health in 2050 at fine resolution using dynamical downscaling of meteorology and air quality from global simulations to the continental US, and quantify for the first time the co-benefits from foreign GHG mitigation. Relative to the reference scenario from which RCP4.5 was created, global GHG reductions in RCP4.5 avoid 16000 $PM_{2.5}$-related all-cause deaths yr^{-1} (90% confidence interval, 11700–20300), and 8000 (3600–12400) O_3-related respiratory deaths yr^{-1} in the US in 2050. Foreign GHG mitigation avoids 15% and 62% of $PM_{2.5}$- and O_3-related total avoided deaths, highlighting the importance of foreign mitigation for US health. GHG mitigation in the US residential sector brings the largest co-benefits for $PM_{2.5}$-related deaths (21% of total domestic co-benefits), and industry for O_3 (17%). Monetized benefits for avoided deaths from ozone and $PM_{2.5}$ are $137 ($87–187) per ton CO_2 at high valuation and $45 ($29–62) at low valuation, of which 31% are from foreign GHG reductions. These benefits likely exceed the marginal cost of GHG reductions in 2050. The US gains significantly greater air quality and health co-benefits when its GHG emission reductions are concurrent with reductions in other nations. Similarly, previous studies estimating co-benefits locally or regionally may greatly underestimate the full co-benefits of coordinated global actions.

Keywords

climate change; air quality; premature mortality; particulate matter; ozone; greenhouse gas; co-benefits

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1. Introduction

Exposure to fine particulate matter ($PM_{2.5}$) and ozone (O_3) is associated with both morbidity (e.g. hospitalizations, emergency department visits, school absences, and asthma-related health effects) and premature human mortality (e.g. deaths from cardiovascular and respiratory disease and lung cancer), as revealed in epidemiological studies (US EPA 2009, 2013). Several cohort studies have shown evidence for chronic effects of $PM_{2.5}$ on mortality (Laden *et al* 2006, Krewski *et al* 2009, Lepeule *et al* 2012), whereas fewer have demonstrated the chronic effects of O_3 on mortality (Jerrett *et al* 2009).

Previous research has quantified future air quality changes and their effects on human health under projected emission scenarios, at both the global (West *et al* 2007, Selin *et al* 2009, Silva *et al* 2016a) and regional scales (Fann *et al* 2013, Kim *et al* 2014, Jiang *et al* 2015, Sun *et al* 2015). Climate change can also affect air quality through several mechanisms, including photochemical reactions, natural emissions, deposition rates, and air stagnation events (Weaver *et al* 2009, Jacob and Winner 2009, Fiore *et al* 2012, 2015). Related studies have quantified the effect of global and regional climate change on air quality and human health (Bell *et al* 2007, Tagaris *et al* 2009, Post *et al* 2012, Fang *et al* 2013, Fann *et al* 2015). Post *et al* (2012) used an ensemble of atmospheric models to study the effect of climate change in 2050 on air quality and human health in the US, and found significant variability when using different models.

Many studies have also investigated the co-benefits of greenhouse gas (GHG) mitigation for air quality and avoided premature mortality, as actions to reduce GHG emissions also tend to reduce co-emitted air pollutants (Bell *et al* 2008, Cifuentes *et al* 2001, Nemet *et al* 2010). When monetized, the health co-benefits of GHG mitigation were found to range across the literature from \$2 to \$196/tCO_2 (Nemet *et al* 2010), comparable to the costs of GHG reductions. Other recent studies have also analyzed the effects of GHG mitigation on future air quality and human health co-benefits in the US (Driscoll *et al* 2015, Thompson *et al* 2014, Trail *et al* 2015, Plachinski *et al* 2014). Thompson *et al* (2014) studied the cobenefits of different climate policies in the US on domestic air quality in 2030, finding that human health benefits due to improved air quality can offset 26–1050% of the cost of carbon polices. Other studies also investigate the co-benefits of climate policy on food security, energy savings, and other health co-benefits of active transportation (walking, biking) and changes in diet (Capps *et al* 2016, Chuwah *et al* 2015, Friel *et al* 2009, Jakob 2006, McCollum *et al* 2013, Wilkinson *et al* 2009, Woodcock *et al* 2009), but they are not the focus of our study.

Previous co-benefits studies have been limited by only considering the co-benefits of regional or local climate policies on regional air quality and human health, neglecting (i.) the co-benefits of those actions for other nations or regions, and (ii.) the co-benefits gained domestically from global actions where one country's actions are coordinated with reductions internationally. Both $PM_{2.5}$ and O_3 have long enough lifetimes in the atmosphere to transport intercontinentally, suggesting that emissions from one source region can affect air quality and human health on multiple receptor regions (Anenberg *et al* 2009, 2014, Liu *et al* 2009, TF HTAP 2010). For O_3, the health benefits of O_3 precursor reductions may even be greater outside of the source region than within due to the greater population over several receptor regions (Duncan *et al* 2008, Anenberg *et al* 2009, West *et al* 2009). $PM_{2.5}$ has a much shorter lifetime than O_3, but the mortality impacts of intercontinental transport of $PM_{2.5}$ is comparable to that of ozone due to the stronger effects of $PM_{2.5}$ on mortality (Anenberg *et al* 2014). To address these limitations, West *et al* (2013, referred to as WEST2013 hereafter) were the first to use a global chemical transport model (CTM) to address the co-benefits of global GHG mitigation on air quality and human health. WEST2013 were also the first to estimate co-benefits via two mechanisms: reduced co-emitted air pollutants, and slowing climate change and its effects on air quality. They found that global GHG mitigation could avoid 2.2±0.8 million premature deaths in 2100 due to the improved air quality, accounting for both $PM_{2.5}$ and O_3 mortality. The co-benefits from the first mechanism of reduced co-emitted air pollutants are much greater than those from the second mechanism of slowing climate change and its effect on air quality. The monetized co-benefits for health were estimated at \$50–\$380/tCO_2, globally averaged, higher than previous estimates (Nemet *et al* 2010).

WEST2013 applied a global CTM (horizontally 2°×2.5°) to study the co-benefits. We increased the horizontal resolution using a limited area model framework to further investigate the co-benefits for US air quality in 2050 at much finer resolution (Zhang *et al* 2016). Here we use the simulations performed by Zhang *et al* (2016) and focus on quantifying the co-benefits of global GHG reductions for avoided air pollution-related mortality in the continental US in 2050. We study the total co-benefits through the two mechanisms, following WEST2013 and Zhang *et al* (2016), and separate the co-benefits of GHG mitigation in the US versus the contributions from foreign countries. By embedding this study within the previous global study of WEST2013, we are the first to investigate the co-benefits of foreign GHG mitigation for US air quality and human health. Previous studies have also investigated the effects of air pollution from specific emission sectors on premature mortality, both globally (Lelieveld *et al* 2015, Morita *et al* 2014, Yim *et al* 2015, Silva *et al* 2016b) and regionally (Caiazzo *et al* 2013, Fann *et al* 2012, 2013). Here we conduct three new sensitivity simulations to quantify the air quality and health co-benefits of GHG reductions in three US emission sectors: industry, residential and energy.

2. Methods

2.1 Air quality changes in the US in 2050 at fine scale

Air quality changes in the US under different GHG scenarios centered on 2050 were downscaled from WEST2013 by Zhang *et al* (2016). Meteorological fields from the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) atmospheric model AM3 (Donner *et al* 2011, Naik *et al* 2013), used by WEST2013, was first downscaled to the regional scale over the Continental US domain to a 36-km horizontal resolution using the Weather Research Forecast model (WRF, v3.4.1, Skamarock and Klemp, 2008). The WRF configuration applies spectral nudging to maintain the large-scale atmospheric circulation resolved by global model (Otte *et al* 2012, Bowden *et al* 2012,2013). Further information on the WRF configuration can be found in Zhang *et al* (2016). GFDL-AM3 was downscaled using WRF for two periods, a historical period (2000–2003; here considered 2000), and a future period

(2049–2052; here considered 2050) for the Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 scenarios with one year of spin-up. Global anthropogenic emissions from RCP4.5 and its reference scenario (REF) were directly processed to the regional scale using the Sparse Matrix Operator Kernel Emissions (SMOKE, v3.5, Houyoux *et al* 2000) program. Dynamical chemical boundary conditions were acquired from the global CTM outputs of WEST2013. The Community Multiscale Air Quality model (CMAQ, v5.0.1, Byun and Schere, 2006), with the CB05 chemical mechanism with updated toluene reactions and the latest aerosol module (AE6), was used to simulate air pollutant concentrations (*i.e.*, $PM_{2.5}$ and O_3) in 2000 and 2050. Most of the CMAQ simulations used in this study (table 1) were completed by Zhang *et al* (2016), but three new sensitivity simulations are performed here to quantify the co-benefits of GHG mitigation from domestic emission sectors in the US. The CMAQ simulations from Zhang *et al* (2016) and the three additional sensitivity simulations are run for 40 consecutive months, with the first four months as spin-up, and the results are presented as three-year averages.

The total co-benefits from global GHG mitigation are obtained by comparing scenarios S_RCP45 and S_REF (Table 1). As discussed by WEST2013 and Zhang *et al* (2016), RCP4.5 was developed based upon REF, which is a self-consistent representation of future energy and land use development, with regionally specific air pollutants emissions, developed consistently with the assumed future development to 2100 but without considering climate policy (Smith *et al* 2011). Relative to REF, RCP4.5 is created by applying a global carbon policy spanning all world regions and emission sectors (Thomson *et al* 2011); the only difference between these two scenarios is therefore the carbon policy. These self-consistent scenarios therefore uniquely isolate the effects of GHG mitigation (RCP8.5 is used as a proxy for REF meteorology, since no climate model simulated REF). The total co-benefits from global GHG mitigation are obtained by comparing scenarios S_RCP45 and S_REF (Table 1). As discussed by Zhang *et al* (2016), the sensitivity run S_Emis applies emissions from RCP4.5 and meteorology from RCP8.5. To separate the total co-benefits from the two mechanisms, we use S_Emis minus S_REF to give the co-benefits from co-emitted air pollutant reductions, and S_RCP45 minus S_Emis for the co-benefits from slowing climate change. The sensitivity simulation S_Dom applies GHG mitigation from the RCP4.5 scenario in the US only, so the co-benefits of domestic GHG mitigation are estimated as S_Dom minus S_REF, and foreign co-benefits as S_RCP45 minus S_Dom.

In addition, we simulate three more scenarios to identify the co-benefits from actions to reduce GHG emissions in individual sectors domestically. We choose to simulate reductions in the industry (S_indUS, manufacturing industries, industrial process emissions other than solvents, construction, mining, and agricultural machinery), residential and commercial buildings (S_resUS, primarily from cooking, heating and hot water), and energy sectors (S_eneUS, from electric power generation and energy extraction and transformation), because air pollutant emission reductions in RCP4.5 in 2050 are greatest from these sectors in the US. Although ground transportation is the largest contributor for most air pollutants in the US in 2000 and 2050, we did not select transportation as little air pollutants reductions are seen from this sector in 2050. The air pollutant emission reductions from the three sectors selected here account for more than 98% of the total SO_2 and NO_x reductions in RCP4.5 relative to REF in the US in 2050, 80% of the CO reductions, and more than 50% of the EC and OC reductions. However, these three sectors only account for 11% of the total non-methane volatile organic compound (NMVOC) decreases (Supporting info table S2).

2.2 Human health analysis

We use the environmental Benefits Mapping and Analysis Program–Community Edition (BenMAP-CE, v1.08) (US EPA 2014) to calculate the avoided human mortality associated with future surface air quality changes for both $PM_{2.5}$ and O_3. BenMAP-CE calculates the relationship between air pollution and certain health effects, using a health impact function (HIF) from epidemiological studies. The HIFs for $PM_{2.5}$ and O_3 used in this study are based on a log-linear relationship between relative risk (RR) and air pollutant concentrations defined by epidemiology studies (Jerrett *et al* 2009, Krewski *et al* 2009), which are also used by WEST2013. RR is used to calculate attributable fraction (AF), the fraction of the disease burden attributable to the risk factor, which is defined as:

$$AF = \frac{RR - 1}{RR} = 1 - \exp^{-\beta \Delta x} \tag{1}$$

where β is the concentration–response factor (CRF; i.e., the estimated slope of the log-linear relation between concentration and mortality) and ΔX is the change in air pollutant concentration between two scenarios. AF is multiplied by the baseline mortality rate (y_0), and the exposed population (*Pop*) to yield an estimate of excess deaths attributable to changes in air pollution ($\Delta Mort$):

$$\Delta Mort = y_0 \times \left(1 - \exp^{-\beta \Delta x}\right) \times Pop \tag{2}$$

We present results for all-cause mortality from the $PM_{2.5}$ changes, rather than cardiopulmonary disease (CPD) and lung cancer (LC), as all-cause mortality is the most comprehensive estimate of PM-related mortality appropriate for the US. However, we also estimate the PM-related mortality from CPD and LC to compare with the results of WEST2013. We also quantify the premature mortality from respiratory disease (RESP) associated with O_3 changes. The 90% confidence intervals (CI) presented in this study are calculated using a full Monte-Carlo analysis inside BenMAP-CE considering only uncertainty in the HIF.

BenMAP-CE uses county-level baseline mortality rates for the present day and projected to 2050 at five-year intervals, including RESP for O_3, and all-cause, CPD, and LC for $PM_{2.5}$ (RTI International 2015). Overall, the projected baseline mortality rates within BenMAP-CE decrease from 2005 to 2050. However, the baseline mortality rates used by WEST2013 are projected to increase in 2050 in the US, derived from the International Futures (IFs, version 6.54, Hughes *et al* 2011) under the UNEPGEO Base Case scenario. For population, BenMAP-CE includes the future population projection at county level in the US until 2040 only (totalling 403 million, Woods and Poole 2012), but our study is focused on 2050 (the RCP4.5 projected total population is 384 million in 2050, Clark *et al* 2007). To be consistent with WEST2013, we run BenMAP-CE with baseline mortality rates in 2005 and the population projection in 2040 (aged 30 and above), and then post-process the BenMAP-CE outputs by multiplying adjustment ratios to match the US population and US average baseline rates of WEST2013 (supporting information table S1). By doing so, we assume that future baseline mortality rates increase at a uniform national ratio in each county without age, gender or ethnic variations, and that the spatial distribution of population in 2050 of RCP4.5 is the same as that in 2040 projected by Woods and Poole (2012).

3. Results

The total US $PM_{2.5}$ concentration co-benefits in 2050 from global GHG mitigation (−0.47 $\mu g\ m^{-3}$ for three-year US annual average) are greatest in the East and California (CA), and less in the West (figure 1a). For O_3, we calculate the three-year average of the 6-month ozone-season average of 1-hr daily maximum O_3, to be consistent with Jerrett *et al* (2009), and the total US O_3 co-benefits in 2050 from global GHG mitigation (−2.96 ppbv for three-year US ozone-season average) are fairly uniform over the US domain (figure 1b), slightly higher over the Western US than the East. The population-weighted average (for the 2050 exposed population age 30 and older) for the $PM_{2.5}$ co-benefit (−0.84 $\mu g\ m^{-3}$ for US average) is almost twice the simple average (table 2), as $PM_{2.5}$ has a short lifetime and is therefore distributed locally to regionally (Punger and West 2013). Population weighting has less of an impact on the O_3 estimates as the longer lifetime of O_3 produces a more uniform spatial distribution.

For the human health benefits from the global GHG mitigation, our results show that 16000 (90% CI: 11700–20300) premature deaths will be avoided annually in the US in 2050 due to $PM_{2.5}$ decreases (table 3). The states with the most avoided deaths are CA (2500 deaths, CI: 1800–3200), New York (NY, 1300 deaths, CI: 1000–1700) and Texas (TX, 1200 deaths, CI: 800–1500) (Supporting info figure S1), with each state having large population and large $PM_{2.5}$ decreases (figure 1, supporting info table S4). For O_3, the total avoided deaths in the US are 8000 (CI: 3600–12400), 50% fewer than $PM_{2.5}$, and also highest in CA (1400, CI: 600–2200), NY (500, CI: 200–800) and TX (500, CI: 200–700). The spatial patterns of both $PM_{2.5}$ and O_3 related avoided premature mortality are shown in figure 2. We further quantify the human health co-benefits from global GHG mitigation by calculating the avoided mortality per capita (MPC, the avoided deaths per million people age 30 and older) in 2050, for both $PM_{2.5}$ and O_3 (supporting info figure S2, table S4). The MPC for $PM_{2.5}$ is much higher in the East than in the West (except for CA), with much greater variation than for O_3, consistent with the finding that the total concentration co-benefits vary locally to regionally for $PM_{2.5}$, and are more spatially uniform for O_3 (figure 1). Relative to the present, air quality improves and premature mortality decreases in the future under REF, due to the large projected emission reductions of conventional air pollutants (Silva *et al* 2016a, Smith *et al* 2011, West *et al* 2013, Zhang *et al* 2016).

We then compare the health results in this study with WEST2013 for the avoided deaths from 2000 to 2050 under the REF (S_REF-S_2000) and RCP4.5 (S_RCP45-S_2000) scenarios, and the total co-benefits in 2050 (S_RCP45-S_REF). Zhang *et al* (2016) concluded that future $PM_{2.5}$ changes are greater using the regional CMAQ model simulations than those in WEST2013 for both REF (S_REF-S_2000) and RCP4.5 (S_RCP45-S_2000) scenarios, while the future O_3 changes in 2050 were comparable between CMAQ and WEST2013. When quantifying human health impacts, figure 3 shows that the avoided premature mortality for $PM_{2.5}$ for both REF and RCP4.5 relative to S_2000 are higher in this study than WEST2013, especially for CPD, which is consistent with the greater reductions in $PM_{2.5}$ predicted here. The avoided premature mortality for O_3 for both REF and RCP4.5 relative to S_2000 are comparable between this study and WEST2013. The total co-benefits for the population-weighted air quality changes are higher for WEST2013 (4.56 ppbv for O_3 and 1.30 μg m^{-3} for $PM_{2.5}$, Figure S26 and S29 in WEST2013) than our estimations using the regional model (3.02 ppbv for O_3 and 0.84 μg m^{-3} for $PM_{2.5}$, Table 3), but the estimated total co-benefits for avoided mortality are similar (Fig.3 in this paper). The fact that the total co-benefits for avoided deaths are comparable between this study and WEST2013, even though air quality changes are different, may be in part due to the use of county-level baseline mortality rates here vs. the national average of WEST2013. Note that the total avoided deaths from the sum of CPD (24300 deaths yr^{-1}) and LC (3200 deaths yr^{-1}) is larger than the co-benefits calculated for all-cause mortality, as the RRs for CPD (1.13, 95%CI:1.1–1.16) and LC (1.14, 95%CI:1.06–1.23) are greater than that for all-cause mortality (1.06, 95%CI:1.04–1.08) (Krewski *et al* 2009).

We then separate the total co-benefits into the two mechanisms. The co-benefit of reductions in co-emitted air pollutants (the “emission co-benefit”) accounts for 98% of the total co-benefits (three-year population-weighted average of −0.84 μg m^{-3}, table 2) for $PM_{2.5}$, and 96% of the total (three-year population-weighted average of −3.02 ppb) for O_3, consistent with WEST2013 and Zhang *et al* (2016). When calculating the co-benefits for human health, the emission co-benefit also dominates the total co-benefits, with 15800 (CI: 11500–20000) avoided deaths for $PM_{2.5}$ (98% of the total), and 7600 (CI: 3400–11700) for O_3 (94% of the total) (table 3; figure 4). The difference between the total co-benefit and the emission co-benefit is accounted for by the effect of slowing climate change and its effects on air quality (the “climate co-benefit”). Notice that the climate co-benefit is negative in some locations, e.g. the Northern states for $PM_{2.5}$, and Southeast for O_3, where slowing climate change can cause concentrations and air pollution-related deaths to decrease as a result of more precipitation and lower temperature (see figure 1 in Zhang *et al* 2016). For the climate co-benefits, we only simulate three years, which may reflect climate variability in addition to climate change (Deser *et al* 2012). However, since we estimate that the emission co-benefits are much greater than the climate co-benefits, we conclude that more years of simulations would not affect this conclusion.

GHG reductions from foreign countries account for 2400 avoided deaths (CI: 1800–3100) for $PM_{2.5}$-related all-cause mortality, and 5000 (CI: 2200–7800) deaths for O_3-related RESP, which are 15% and 62% of the total deaths for $PM_{2.5}$ and O_3 (table 3). Foreign GHG mitigation likewise contributes 15% (−0.13 μg m^{-3} for the three-year US population-weighted average) of the total air quality co-benefits for $PM_{2.5}$, and 65% (−1.95 ppbv) of the total co-benefits for O_3 (6-month ozone season of 1-hr daily maximum), emphasizing that $PM_{2.5}$ is more influenced by emission reductions in US, while O_3 is more influenced by the global methane reductions and intercontinental air pollutant transport (Zhang *et al* 2016). Foreign co-benefits for both $PM_{2.5}$- and O_3-related mortality are centred in urban areas (figure 5), where population density is high, even though foreign GHG mitigation reduces surface O_3 pretty uniformly in the US (see supporting information figure S3). The contributions from domestic GHG mitigation on population-weighted average $PM_{2.5}$ (85% of the total) and O_3 (35%) are higher than those for the simple average (74% for $PM_{2.5}$ and 27% for O_3 in table 2), as air quality improvements from domestic GHG mitigation occur in densely-populated areas. CA has the largest human health benefits from foreign GHG mitigation, with 400 deaths (CI: 300–500) avoided from $PM_{2.5}$-related all-cause mortality, and 800 deaths (CI: 400–1300) avoided from O_3. We have calculated total, domestic, and foreign mortality co-benefits for each state (see supporting information tables S4 through S6). In quantifying the domestic co-benefits, we neglect the effect of US GHG mitigation on global climate change, and assume that global and regional climate will be controlled by foreign GHG emissions, which introduces a small error into our results. We also attribute the global methane concentration change to the effect of foreign GHG reductions, as US emissions are relatively small (6–10% of global emissions).

Among emission sectors, the residential sector has the largest co-benefits for $PM_{2.5}$-related human health, avoiding 2800 deaths (CI: 2000–3600), accounting for 21% of the total domestic co-benefits for $PM_{2.5}$, followed by industry (2100, CI: 1500–2700) and energy (1700, CI: 1300–2200). Residential also has the largest change in the population-weighted annual average $PM_{2.5}$ ($-0.15\ \mu g\ m^{-3}$), even though its simple annual average change is comparable to that from the industry sector, demonstrating that residential emissions have a greater influence near where people live. GHG mitigation from industry has the largest effect on O_3-related human health, avoiding 500 deaths (200–800) or 17% of the total domestic co-benefits for O_3, followed by energy (300, CI:100–500), and residential (200, CI:100–300). The total air quality co-benefits for O_3 are also highest in industry (population-weighted average of −0.20 ppb and simple average of −0.22 ppbv). These three sectors together account for 50% of the total avoided $PM_{2.5}$-related deaths from domestic GHG reductions and 33% of the total avoided O_3-related deaths, even though the sectors account for a larger fraction of emissions of most pollutants, possibly reflecting the smaller NMVOC emissions decreases from these sectors in RCP4.5. These findings of greater avoided deaths for residential GHG reductions suggest that residential sources might be targeted in policy efforts. Future research should attempt to evaluate air quality and health co-benefits for more specific GHG mitigation measures, including for other sources such as transportation, so that these co-benefits can be evaluated alongside the cost of GHG mitigation.

The total co-benefits of avoided premature mortality are monetized using high ($9.81 million) and low ($3.25 million) values of a statistical life (VSLs) for the US in 2050, as estimated by WEST2013 (in 2005 US$) based on projected income growth. Adding avoided mortality from O_3 and $PM_{2.5}$, and dividing monetized benefits by US CO_2 reductions in 2050, we estimate monetized co-benefits in 2050 of $137 ($87 to $187) per ton CO_2 reduced at a high VSL, and $45 ($29 to $62) per ton CO_2 reduced at a low VSL, very similar to the 2050 estimates of WEST2013 for the US. As for WEST2013, these monetized estimates do not account for avoided deaths outside of the US. These benefits at high VSL exceed the full range of GHG marginal abatement cost estimates from 13 energy-economic models (West *et al* 2013), and at low VSL are greater than the median cost. Of these total co-benefits, foreign GHG reductions are responsible for monetized benefits of $42 ($23 to $62) per ton CO_2 at high VSL, and $14 ($8 to $21) at low VSL, which is 31% of the total monetized benefits.

4. Conclusions

We quantify the co-benefits of global GHG mitigation under the RCP4.5 scenario on US air quality and human health in 2050 using dynamical downscaling. We find that 16000 (11700–20300) deaths yr^{-1} will be avoided for $PM_{2.5}$-related all-cause mortality, and 8000 (3600–12400) deaths yr^{-1} will be avoided for O_3-related respiratory mortality. When separating the total co-benefits into two mechanisms, the emission co-benefits have a larger impact than the climate co-benefits for both $PM_{2.5}$ and O_3, accounting for 98% and 94% of the total avoided deaths. Foreign GHG mitigation contributes 15% of the total $PM_{2.5}$-related and 62% of the total O_3-related deaths. Among the three domestic emission sectors with the greatest reductions in air pollutants under RCP4.5, residential has the highest co-benefits for $PM_{2.5}$-related mortality, leading to a reduction of 2800 deaths, and industry has the highest co-benefits for O_3, avoiding 500 deaths in the US. Monetized co-benefits of the GHG mitigation, accounting for avoided deaths from reductions in both $PM_{2.5}$ and O_3, are \$137 (\$87 to \$187) per ton CO_2 at a high VSL and \$45 (\$29 to \$62) at a low VSL. Of these co-benefits, 31% come from the influence of foreign GHG reductions. These benefits likely exceed the marginal costs of GHG reductions in 2050.

Significant uncertainties exist in our results. For $PM_{2.5}$, we compare the uncertainty for the future concentration change under RCP4.5 of −2.92±2.3% μg m^{-3} (−2.79±22.0% μg m^{-3} for the PM_{25} estimated as a sum of species) based on the spread of ACCMIP models (Silva *et al* 2013, Zhang *et al* 2016), and the uncertainty for the CRF is 0.0058±32.8%. For O_3, the uncertainty for the future concentration change under RCP4.5 is −5.87±48.8% ppbv, and the uncertainty for the CRF is 0.0039±69.2%. Therefore, the uncertainty in the CRF likely contributes more to the overall uncertainty than the uncertainty in modeled concentration changes, although, for ozone, concentration uncertainty is of similar magnitude to the CRF uncertainty. When quantifying the avoided deaths from improved air quality, we only account for adults above 30. Additional uncertainty arises from downscaling from the global to the regional scale chemistry model, including the conversion of chemical mechanisms in the models, particularly from the addition of new inorganic species for primary $PM_{2.5}$ (Zhang *et al* 2016). Different components of $PM_{2.5}$ may have different effects on human health, like black carbon particles (Li *et al* 2015, Zanobetti and Schwartz 2009). However, we consider all of the components of $PM_{2.5}$ to have equal toxicity. Only a single modelling system (AM3-WRF-SMOKE-CMAQ) is used in this study, and as pointed out previously (Post *et al* 2012, Silva *et al* 2013), results may differ among different models and ensembles of models can better characterize the range of results. Similarly, increasing the number of years simulated by the models used here can reduce uncertainty related to inter-annual variability (Deser *et al* 2012). Our conclusions are specific to the REF and GHG mitigation (RCP4.5) scenarios we choose, including their simulation of future emission pathways, which depend on economic drivers and air pollution control policies, and would differ for other scenarios. For example, the new Shared Socio-economic Pathways 4 (SSP4) have different climate policy assumptions considering economic, institutional and technological limitations (Rao *et al* 2017), and different emission reductions for co-emitted air pollutants in 2050 (supporting information table S4). We only account for the co-benefits from air quality changes due to the GHG mitigation, neglecting other impacts of climate change on health, like heat-waves, elevated temperatures, and infectious disease (Smith *et al* 2014). Despite these uncertainties, both those quantified and unquantified, our major conclusion that global GHG mitigation can have significant co-benefits for air quality and avoided mortality in the US is unlikely to be altered.

Future studies should estimate co-benefits at both the global and regional scales with finer-resolution air quality model simulations. Uncertainties could be reduced by improving emission estimates for multiple species, the chemical and aerosol mechanisms (CB05 and AE6), and using multi-year simulations and ensemble model experiments (Rao *et al* 2016). Future air pollutant reference-case emission trajectories are also uncertain (e.g., Rao *et al* 2017), and use of multiple future scenarios would also be valuable. Future studies should also evaluate benefits beyond health, such as for agriculture and energy. Previous studies have shown that using coarse resolution models tends to underestimate mortality near urban areas for $PM_{2.5}$ (Punger and West 2013, Li *et al* 2015). Improving horizontal resolution in future studies can produce more robust estimates of health benefits, and may cause estimates to increase.

Previous studies have estimated co-benefits of GHG mitigation mainly on local, national, or continental scales (Bell *et al* 2008, Cifuentes *et al* 2001, Nemet *et al* 2010). These studies have presumed that most co-benefits are realized on those scales, and that the contributions of foreign GHG mitigation to total co-benefits would be small. Here we show that the US can gain significantly greater co-benefits for air quality and human health, especially for ozone, when coordinating its GHG emission reductions with concurrent reductions in other nations to combat global climate change. Similar results would also be expected for foreign countries, which will likely also benefit from GHG mitigation in other countries. Previous studies, which only estimate co-benefits from regional or local GHG mitigation may significantly underestimate the full co-benefits of coordinated global actions to mitigate climate.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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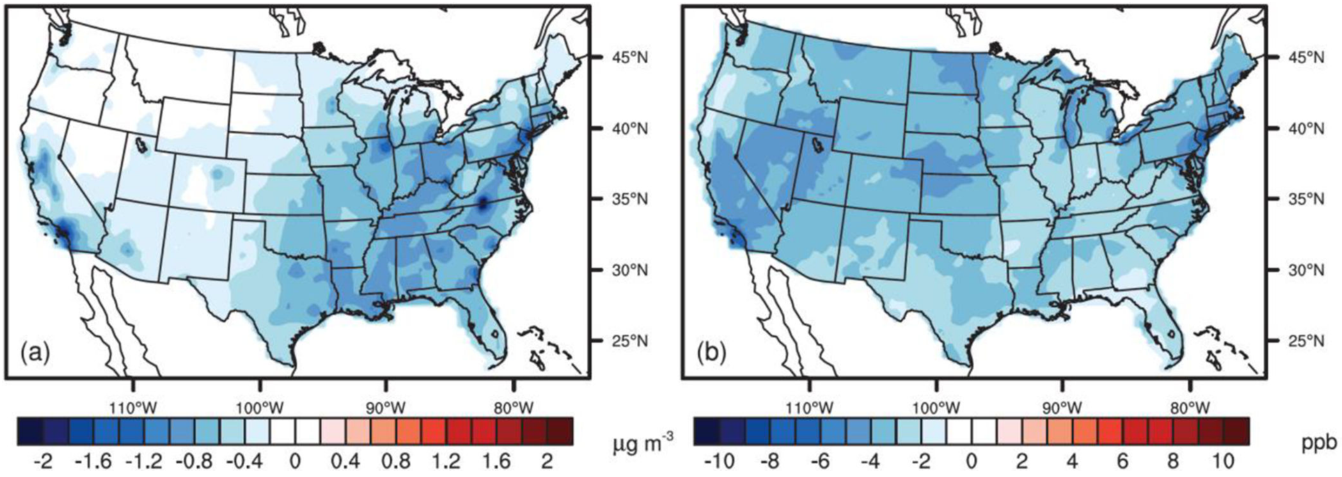

Figure 1.

Total air quality co-benefits (S_RCP45-S_REF) in 2050 for (a) annual average $PM_{2.5}$, and (b) 6-month ozone-season average of 1-hr daily maximum of O_3. Results are presented as three-year averages. Negative values (blue) indicate air quality improvements.

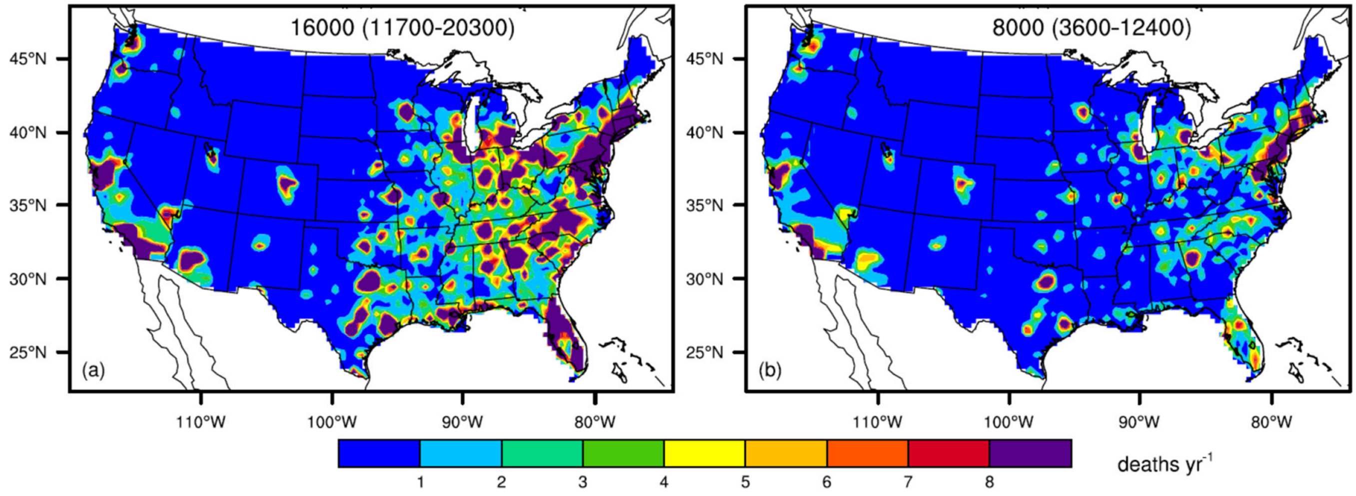

Figure 2.

Total co-benefits (S_RCP45-S_REF) for avoided premature mortality (deaths yr^{-1}) in the US in 2050, for (a) $PM_{2.5}$ (all-cause mortality), and (b) O_3 (respiratory mortality). Total avoided deaths and 90% confidence intervals are shown at the top of each panel. Positive values indicate fewer deaths.

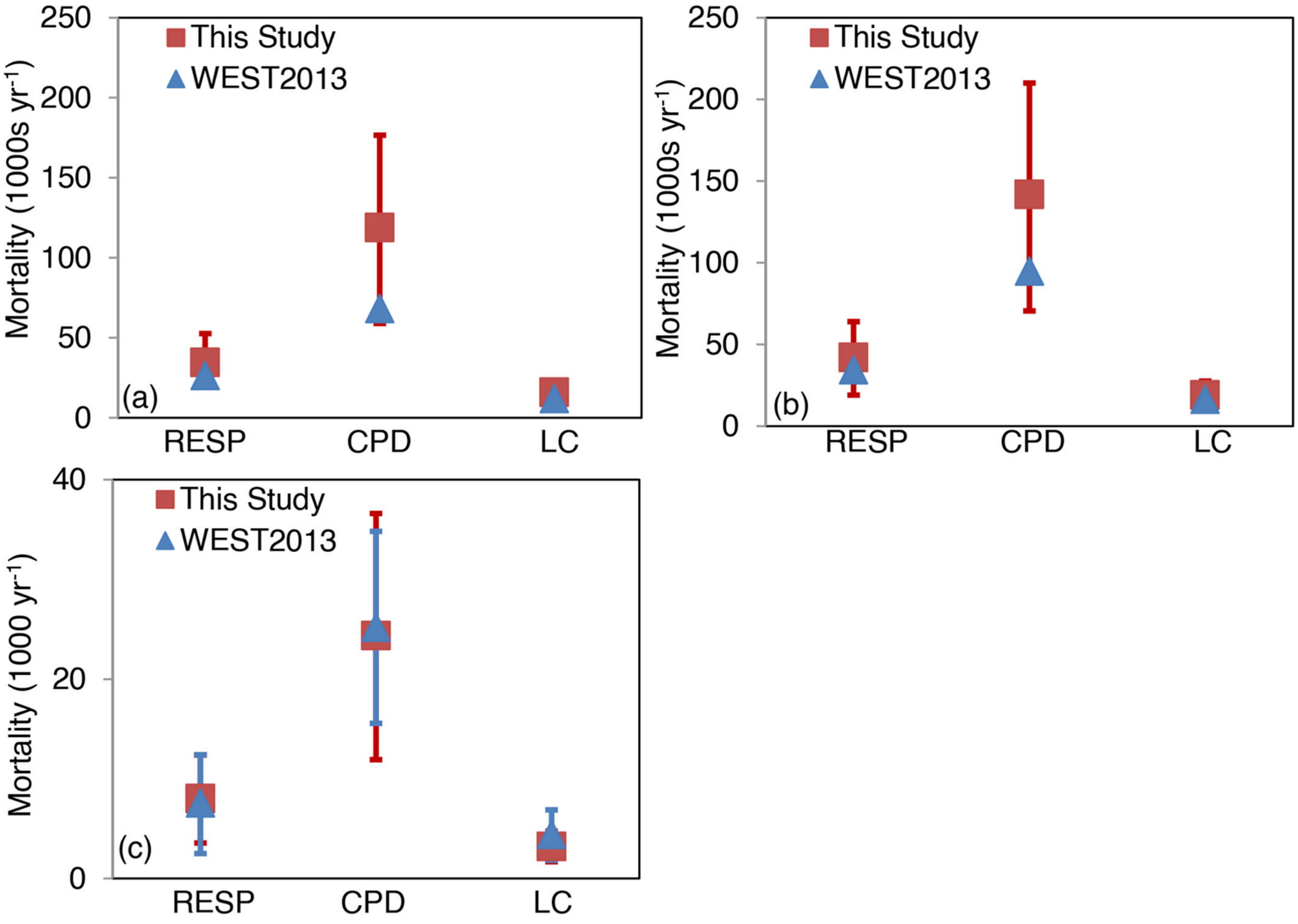

Figure 3.

Comparisons between this study (red) and WEST2013 (blue) of the avoided human mortality in the US (1000 deaths yr^{-1}) from air quality changes in 2050 compared with 2000, for (a) REF scenario, (b) RCP4.5 scenario, and (c) the total co-benefits in 2050. The red lines represent the 90% confidence intervals (CI) for this study, and blue lines are 95% CI for WEST2013. RESP indicates mortality from O_3-related respiratory deaths, CPD for $PM_{2.5}$-related cardiopulmonary deaths, and LC for $PM_{2.5}$-related lung cancer.

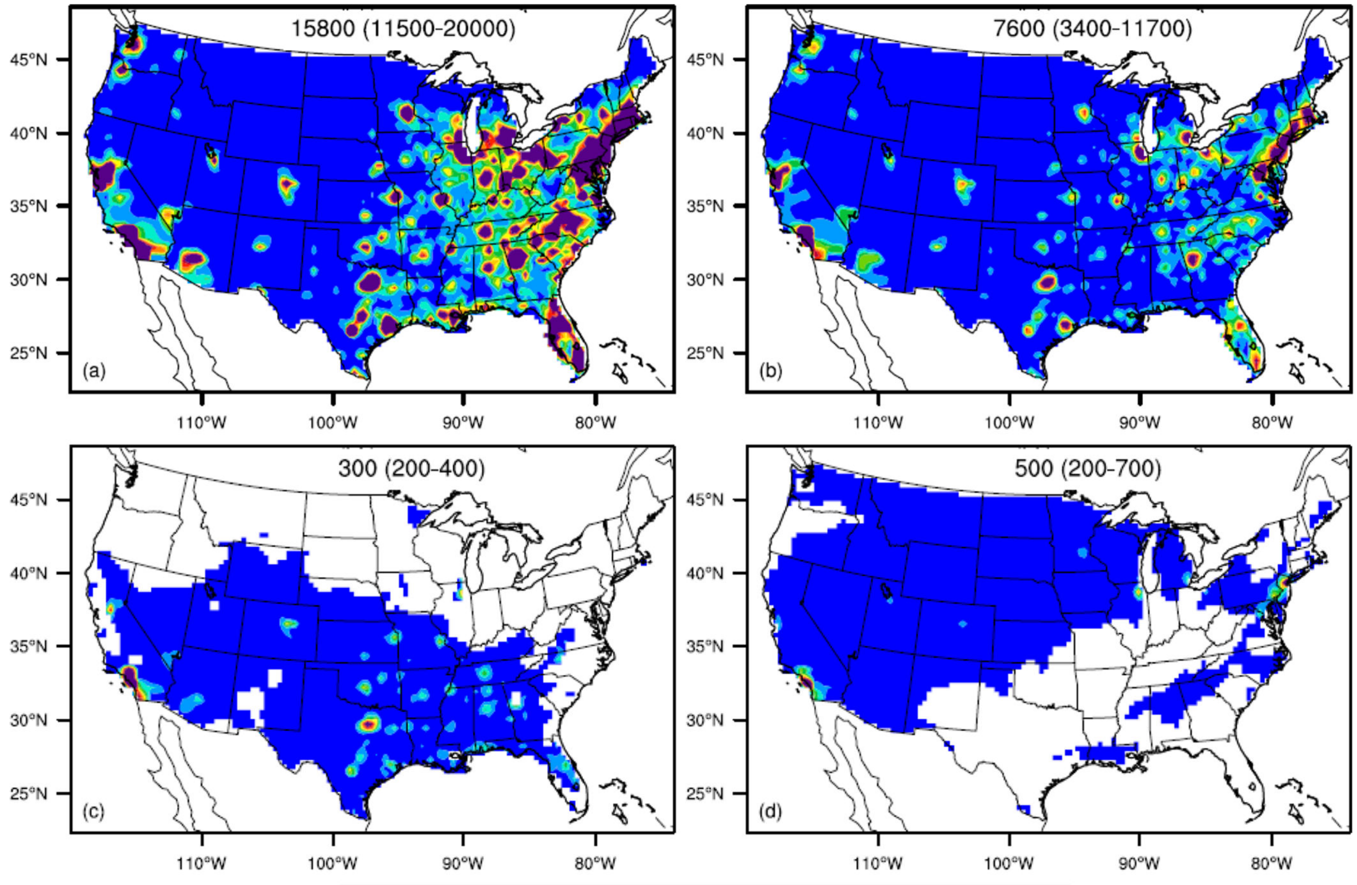

Figure 4.

The emission co-benefits (a, b) and climate co-benefits (c, d) for avoided human mortality in 2050 (deaths yr^{-1}) from $PM_{2.5}$ (a, c) and O_3 (b, d). White in panels c and d indicates increased mortality attributed to slowing climate change, from increases in air pollutant concentrations. Total avoided deaths and 90% confidence intervals are shown at the top of each panel. Positive values indicate fewer deaths.

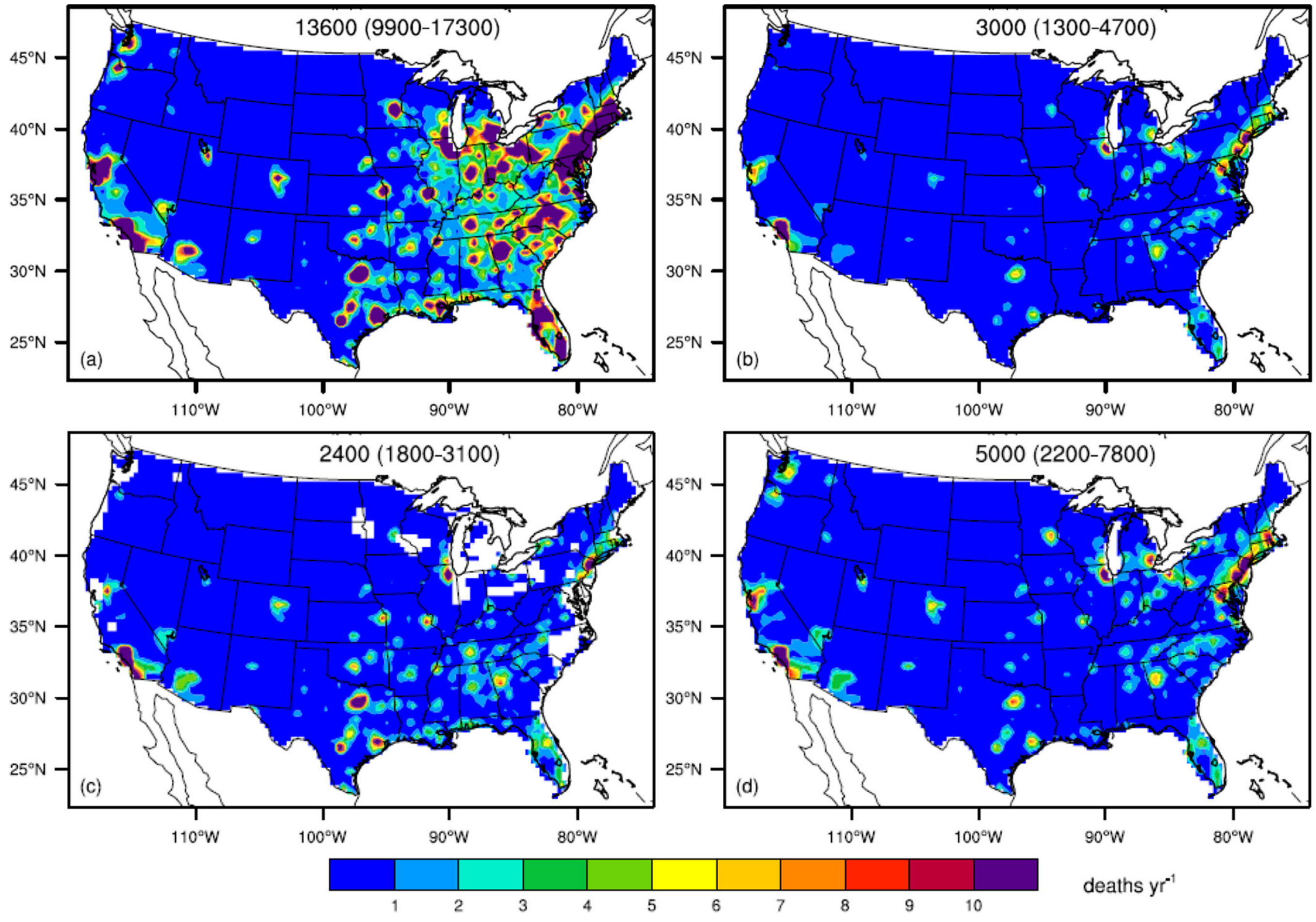

Figure 5.

Domestic (a, b) and foreign co-benefits (c, d) for avoided all-cause mortality from $PM_{2.5}$ (a, c) and respiratory disease from O_3 (b, d) in the US in 2050. Total avoided deaths and 90% confidence intervals are shown at the top of each panel. Positive values indicate fewer deaths.

Table 1.

Simulations used for health impact assessment in this study, conducted by Zhang *et al* (2016), and the three additional sector simulations for this study. Boundary conditions are from the MOZART-4 (MZ4) simulations of WEST2013. Global methane (CH_4) background concentrations are fixed in CMAQ, consistent with the RCPs and WEST2013. All the simulations are run for three consecutive years, with four months spin-up.

Years	Scenario	Emissions	Meteorology	BCs	CH_4
2000	S_2000	2000	2000	MZ4 2000	1766 ppbv
2050	S_REF	REF	RCP8.5	MZ4 REF	2267 ppbv
	S_RCP45	RCP4.5	RCP4.5	MZ4 RCP4.5	1833 ppbv
	S_Emis	RCP4.5	RCP8.5	MZ4 e45m85	1833 ppbv
	S_Dom	[a]RCP4.5 for US	RCP8.5	MZ4 REF	2267 ppbv
	S_indUS	[b]RCP4.5 for US Industry	RCP8.5	MZ4 REF	2267 ppbv
	S_resUS	[b]RCP4.5 for US Residential	RCP8.5	MZ4 REF	2267 ppbv
	S_eneUS	[b]RCP4.5 for US Energy	RCP8.5	MZ4 REF	2267 ppbv

[a] apply emissions from RCP4.5 in US and from REF in the parts of Canada and Mexico within the domain.

[b] only one sector of emissions from RCP4.5 (e.g., industry, residential and energy) are used, and emissions in other sectors over the US are from REF, as are emissions over Canada and Mexico in the domain.

Table 2.

Co-benefits for air quality changes in the continental US in 2050 from global, domestic and sectoral GHG mitigation. For $PM_{2.5}$ (μg m^{-3}) we use the three-year average, and for O_3 (ppbv), we calculate the 6-month ozone season of 1-hr daily maximum, and then average over three years. Co-benefits are estimated using RCP4.5 minus REF. Negative values indicate air quality improvements.

		$PM_{2.5}$		O_3	
		Simple Avg	Pop-Weighted Avg	Simple Avg	Pop-Weighted Avg
	Emission	−0.45	−0.82	−2.75	−2.89
	Climate	−0.02	−0.02	−0.21	−0.13
Total		**−0.47**	**−0.84**	**−2.96**	**−3.02**
	Domestic	−0.35	−0.71	−0.80	−1.07
	Foreign	−0.12	−0.13	−2.16	−1.95
Domestic	Industry	−0.057	−0.11	−0.22	−0.20
	Residential	−0.058	−0.15	−0.11	−0.058
	Energy	−0.046	−0.089	−0.13	−0.14

Table 3.

Estimated total co-benefits for avoided premature mortality in 2050 from $PM_{2.5}$-related all-cause mortality and O_3-related respiratory mortality (deaths yr^{-1}). The values in parenthesis are 90% confidence intervals (CI). Co-benefits are estimated using RCP4.5 minus REF. Positive values indicate fewer deaths.

		$PM_{2.5}$	**O_3**
	Emission	15800	7600
		(11500–20000)	(3400–11700)
	Climate	300	500
		(200–400)	(200–700)
Total		**16000**	**8000**
		(11700–20300)	**(3600–12400)**
	Domestic	13600	3000
		(9900–17300)	(1300–4700)
	Foreign	2400	5000
		(1800–3100)	(2200–7800)
Domestic	Industry	2100	500
		(1500–2700)	(200–800)
	Residential	2800	200
		(2000–3600)	(100–300)
	Energy	1700	300
		(1200–2200)	(100–500)