Co-benefits of Global Greenhouse Gas Mitigation for Future Air Quality and Human Health

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Abstract

Actions to reduce greenhouse gas (GHG) emissions often reduce co-emitted air pollutants, bringing co-benefits for air quality and human health. Past studies[1–6] typically evaluated near-term and local co-benefits, neglecting the long-range transport of air pollutants[7–9], long-term demographic changes, and the influence of climate change on air quality[10–12]. Here we simulate the co-benefits of global GHG reductions on air quality and human health using a global atmospheric model and consistent future scenarios, via two mechanisms: a) reducing co-emitted air pollutants, and b) slowing climate change and its effect on air quality. We use new relationships between chronic mortality and exposure to fine particulate matter[13] and ozone[14], global modeling methods[15], and new future scenarios[16]. Relative to a reference scenario, global GHG mitigation avoids 0.5±0.2, 1.3±0.5, and 2.2±0.8 million premature deaths in 2030, 2050, and 2100. Global average marginal co-benefits of avoided mortality are $50–380 (ton CO_2)$^{-1}$, which exceed previous estimates, exceed marginal abatement costs in 2030 and 2050, and are within the low range of costs in 2100. East Asian co-benefits are 10–70 times the marginal cost in 2030. Air quality and health co-benefits, especially as they are mainly local and near-term, provide strong additional motivation for transitioning to a low-carbon future.

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Past studies have estimated that the human health co-benefits of GHG mitigation, by reducing co-emitted air pollutants, can be substantial[1–2], and when monetized, range across many studies from a small fraction of GHG mitigation costs to exceeding them[3–6]. Here we estimate the co-benefits of global GHG reductions for air quality and human health for the first time using a global atmospheric model and future scenarios. We account for the influence of international air pollutant transport on health[9], the effect of methane on global ozone[8], increases in population and susceptibility to air pollution[17], and economic growth that increases valuation. In addition to direct co-benefits of reduced co-emitted air pollutants (mainly local and immediate), we account for a second co-benefits mechanism, not previously quantified, in which slowing climate change decreases its effects on air quality (global and long-term). Climate change has been shown to increase ozone in the US and Europe (although the magnitude and patterns differ among studies), *e.g.*, through increased photochemical reaction rates and biogenic emissions, and meteorological changes, but decrease ozone in remote areas. Fine particulate matter ($PM_{2.5}$) may also increase in polluted regions, but these effects are less clear[10–12].

Global GHG emission reductions are modeled in the Representative Concentration Pathway 4.5 (RCP4.5) scenario[18]. The four RCP scenarios represent a range of global GHG emissions[16], but as these scenarios were developed by different groups, their projections of future air pollutant emissions are inconsistent with one another[19]. Rather than comparing different RCP scenarios, we compare RCP4.5 with its associated reference scenario (REF). REF is a self-consistent representation of the future development of energy and land use, assuming an intermediate pathway for economic development and population growth, and assuming no climate policy. Regionally-specific air pollutant emissions in REF were developed such that air pollutant concentrations in each world region are consistent with the assumed future economic development to 2100[20].

Relative to REF, RCP4.5 applies a global carbon price across all economic sectors including terrestrial carbon through an efficient market, such that 2100 CO_2 concentration decreases from 760 ppm to 525 ppm, and anthropogenic radiative forcing stabilizes at 4.5 W m^{-2}. Air pollutant emission controls in REF are assumed to stay in place as the climate policy is implemented in RCP4.5. REF and RCP4.5 are therefore entirely consistent in their underlying assumptions, allowing differences in air pollutant emissions to be attributed uniquely to the RCP4.5 climate policy. RCP4.5 reduces GHG emissions by decreasing fossil fuel use substantially (replacing it with nuclear and renewable energy, primarily wind) and energy demand modestly, and by increasing forest cover and biofuels. Carbon capture and geologic storage grows such that it applies to nearly all electricity generation from fossil fuels and biofuels by 2100[18].

In REF, worldwide population-weighted metrics of ozone and $PM_{2.5}$ in Fig. 1 decrease in 2100 relative to 2000. Industrialized regions reduce emissions and improve air quality throughout the century, while many developing regions have worse air quality in 2030 and/or 2050, before improving. Relative to REF, abating GHG emissions in RCP4.5 causes substantial reductions in ozone (8.1 ppb) and $PM_{2.5}$ (2.4 μg m^{-3}) in 2100. The 2100 ozone reduction is largely (89%) due to co-emitted air pollutants, with only 11% from the change in meteorology from climate change, and is strongly influenced by the large decrease in

methane emissions in RCP4.5. Changes in meteorology produce a small increase in global average $PM_{2.5}$ relative to REF. In Fig. 2, meteorological changes in 2100 cause regional increases or decreases in $PM_{2.5}$ that are small compared with the direct effect of co-emitted air pollutants. Slowing climate change decreases ozone in some polluted regions and over the Amazon where the increase in biogenic VOC emissions slows; it increases ozone in many remote areas, as it slows the increase of absolute humidity and HO_x radicals that destroy ozone[10].

In REF, global air pollution-related mortality increases in 2030 and then decreases, for both ozone and $PM_{2.5}$ (Fig. 3). In North America, mortality decreases throughout the century, whereas mortality peaks in 2030 in East Asia and in 2050 in South Asia as air pollution controls are implemented more aggressively as these economies grow. In Africa, $PM_{2.5}$ mortality peaks in 2050, but ozone mortality grows to 2100. The global co-benefits of GHG mitigation, estimated as the difference between REF and RCP4.5, total 0.4±0.2, 1.1±0.5, and 1.5±0.6 million avoided deaths yr^{-1} in 2030, 2050, and 2100 for $PM_{2.5}$, and 0.09±0.06, 0.2±0.1, and 0.7±0.5 million for ozone. In 2030, two-thirds of the global co-benefits occur in China (Fig. 4), as it has a large population and severe energy-related air pollution; the climate policy incentivizes changes away from conventional coal for electricity and industrial heat. In South Asia, there are little co-benefits in 2030 because of a shift toward biomass combustion in RCP4.5, and local $PM_{2.5}$ increases in India due to climate change-induced meteorological changes associated with the monsoon. But co-benefits are substantial in this region in 2050 and 2100 (0.5±0.2 and 1.1±0.4 million avoided deaths) as energy shifts away from fossil fuels and populations grow. In Africa, air pollution mortality increases in 2100 in REF, relative to 2000 concentrations, but deaths decrease in RCP4.5.

Co-benefits of avoided air pollution mortality are monetized using high and low values of a statistical life (VSLs), and are compared with the marginal costs of GHG reductions (the global carbon price) from 13 models meeting a 4.5 W m^{-2} target[21]. In 2030, the monetized mortality co-benefits exceed the median carbon price in all regions but Australia; in East Asia, co-benefits are 10–70 times the median cost (Fig. 5). In 2050, global average co-benefits exceed the carbon price at both VSLs. By 2100, GHG reductions and costs increase markedly, as more expensive reduction measures are implemented, and co-benefits are within the low range of the carbon price. In 2050 and 2100, marginal co-benefits (assumed equal to the average co-benefit) are greatest in South Asia and East Asia. Marginal co-benefits are largest in regions with high population affected by air pollution decreases, but also high in North America and Europe, reflecting high VSLs. Marginal co-benefits also do not vary strongly among time periods, but are highest in 2030 in more industrialized regions (including East Asia), because near-term reductions in air pollutant emissions leave less opportunity for co-benefits later. In less industrialized regions (*e.g.*, South Asia, Africa), co-benefits are highest in 2050 or 2100, reflecting rapid population and economic growth (increasing VSLs).

Monetized co-benefit estimates are \$50–380 (ton CO_2)$^{-1}$ for the worldwide average, \$30–600 for the US and Western Europe, \$70–840 for China, and −\$20–400 for India (range includes differences over three years, high and low VSLs, and uncertainty in the concentration-response functions (CRFs)). These are higher than previous estimates of \$1–

128 for the US and Western Europe, and \$6–196 for developing nations[3–5], as we use new relationships for chronic mortality, account for ozone as well as $PM_{2.5}$, model international air pollution transport and changes in global ozone from methane, and evaluate future scenarios in which population, susceptibility to air pollution, and VSLs grow. In a sensitivity analysis (Supplementary Information), we show that estimated future $PM_{2.5}$ mortality co-benefits may be substantially lower, under assumptions of a log-linear CRF or a high-concentration threshold. We also show that future demographic changes (population growth, baseline mortality rates, and VSLs) have strong influences on the monetized co-benefits, particularly in 2100, and are likely an important factor in the higher co-benefits estimated here than in previous studies (Supplementary Information).

Monetized co-benefits could alternatively be evaluated as an avoided cost of air pollution controls, which would be lower than our estimates where the benefits of pollution controls exceed the costs. This approach could be estimated as the avoided air pollution controls needed to achieve air quality standards or air pollutant emission targets[22,23]. However, future air quality standards are unknown and this approach would neglect substantial health improvements from reductions below relevant standards. Future work should evaluate global co-benefits as avoided air pollution control costs, or as a combination of health benefits and avoided costs where both are evaluated relative to standards or emission targets. For example, global climate mitigation has been shown to avoid \$100–600 billion yr^{-1} in air pollution control and energy security expenditures in 2030[24].

Co-benefits may be underestimated because we neglect people younger than 30, including effects on children and neonatal effects, and the benefits of avoided morbidity outcomes and ecosystem effects from reduced air pollution. Future work should quantify these additional air pollution co-benefits. In addition, the coarse spatial resolution of MOZART-4 likely underestimates $PM_{2.5}$ exposure in cities, and the RCP emissions omit primary inorganic $PM_{2.5}$ (fly ash), which is greatest in developing nations. We likewise neglect indoor air pollution, particularly from residential solid fuels[25], which would be alleviated by some measures in RCP4.5. We caution that applying CRFs from the US globally and into the future entails large uncertainties. Co-benefits via the effects of climate change on air quality are small compared to the reduction of co-emitted air pollutants, but we neglect effects on fires and dust, which may be substantial[26]. Co-benefits are presented for the specific reference and GHG abatement scenarios modeled here, and would differ for other scenarios. In particular, if the air pollution controls built into REF were less aggressive, there would be greater potential for co-benefits. On the other hand, REF may not be consistent with recent decreases in SO_2 emissions in China[27], which could cause an overestimate of co-benefits. Co-benefits also depend on mitigation technology choices and national participation; where lower income countries delay entry into a climate policy, their co-benefits would likely decrease, while overall mitigation costs increase[21].

In the global average and in many individual world regions, the co-benefits of avoided air pollution mortality can justify substantial reductions in GHG emissions, apart from other benefits of slowing global climate change. These results reflect the high premium that society places on avoiding death, through the VSLs used here. Decisions to mitigate GHG emissions should be motivated primarily by the benefits of slowing climate change, and air

pollutant emission reductions by the benefits of improving air quality. But decisions should also account for the full costs and benefits of proposed actions, as these results show the substantial air quality and health benefits of pursuing a low-carbon future. As these co-benefits occur mainly locally, in the near term, and with high certainty, they contrast with the long-term distributed global benefits of slowing climate change, and therefore may be attractive to nations considering GHG reductions. Not all individual measures would bring such co-benefits. Therefore, there is a need to investigate the air quality co-benefits of specific alternatives in specific regions, while accounting for the international impacts of air pollution and long-term effects via methane and climate change. For policy, there is a need to better coordinate actions on air quality and climate change. By addressing both problems simultaneously, they may be managed more effectively, at less cost, and with greater overall benefits.

Methods

The MOZART-4 global chemical transport model[28] is used to simulate ozone and $PM_{2.5}$ air quality in 2000, 2030, 2050, and 2100. Anthropogenic emissions inputs of many species for REF were processed through the same steps as RCP4.5, which include speciating volatile organic compounds (VOCs) to MOZART-4 species by matching similar species, adding monthly emissions distributions to the annual total emissions, and regridding to a $2° \times 2.5°$ horizontal grid used for the MOZART-4 simulations. Biogenic VOC emissions are calculated online within MOZART-4, and therefore respond to changing climate conditions. Other natural emissions are from Emmons et al.[28] and are assumed static, such that we neglect possible influences of climate change on emissions of dust, sea salt, and fires.

Meteorological inputs are from global general circulation model (GCM) simulations of RCP4.5 and RCP8.5[29] using the AM3 model. RCP8.5 climate is used as a proxy for REF climate since no climate simulations have been conducted for REF. The estimated global mean temperature change under REF is 3.6°C in 2095 (relative to the pre-industrial), while it is 4.5° for RCP8.5 and 2.3° for RCP4.5, using the MAGICC climate model. Co-benefits resulting from slowing future climate change are therefore biased high, but since these co-benefits are shown to be small (Figs. 1 and 2), this bias is of little importance. By simulating REF emissions with meteorology from RCP4.5 (eREFm45), we separate the influences of changes in co-emitted air pollutants from those caused by climate change. For each scenario-year combination, five meteorological years are simulated with the first used as a spinup, and the average of four years is reported here to reduce the effects of meteorological variability.

Model performance relative to observations of ozone and $PM_{2.5}$ species is comparable to other global models (Supplementary Information). Large contributions of dust made $PM_{2.5}$ estimates unrealistically large in arid regions, and so modeled dust concentrations were divided by 5 globally to roughly agree with the global surface concentrations of Brauer et al.[30]. We forced dust and sea salt concentrations to be the same in all simulations as we lack confidence in the modeled responses to changes in climate for these species; this choice does not influence our mortality estimates since mortality is based on the difference in $PM_{2.5}$ between simulations. We also compared our simulated changes in regional and global

average ozone and $PM_{2.5}$ concentrations in RCP4.5 in future years relative to 2000 against an ensemble of models, finding that our simulations are comparable (Supplementary Information). Concentrations in the lowest vertical coordinate are taken to represent ground-level exposure.

Premature human mortality is estimated from modeled air pollutant concentrations using the methods of Anenberg et al.[15] and CRFs based on the American Cancer Society study for chronic mortality from cardiopulmonary disease (CPD) and lung cancer for exposure to $PM_{2.5}$[13], and chronic respiratory mortality for exposure to ozone[14]. Consistent with these studies, we evaluate premature mortality from chronic exposures for adults (30 years and older) using the annual average $PM_{2.5}$ and the six-month ozone season average of 1-hour daily maximum ozone. These CRFs for cause-specific mortality are assumed to apply globally and into the future. Future population and baseline mortality rates are taken from International Futures (IFs)[17], with global population growing to 9.7 billion in 2100. IFs accounts for changing causes of baseline mortality, capturing the future increase in the fraction of deaths by respiratory and CPD causes, and therefore increased susceptibility to air pollution. We use IFs to estimate the population and baseline rates of CPD, lung cancer, and respiratory mortality for the population above 30, in each country, which is then gridded to the $2° \times 2.5°$ grid using a geographic information system. For gridded population, we also use the spatial distribution of present-day population at fine resolution to distribute population within each country. Mortality calculations are conducted on the $2° \times 2.5°$ grid used by MOZART-4.

Avoided mortality is monetized using low and high VSLs (based on 2005 VSLs of $1.8 million as a low value for Western Europe and $7.4 million for USA), which are adjusted to different world regions and into the future using an income elasticity of 0.5 (yielding 2030 global means of $1.2 and $3.6 million) (Supplementary Information). All monetary values are expressed as 2005 US dollars. As most mortality benefits are from $PM_{2.5}$ and influences of climate change on air quality are small, most avoided deaths result from co-emitted air pollutants in the same year; consequently, we simply compare marginal costs and benefits in the three modeled years, without discounting. The benefit curve with respect to CO_2 reductions is assumed to be flat, as there is little nonlinearity in the global air quality responses to changes in emissions and in the CRFs; marginal co-benefits are therefore estimated as the total co-benefits divided by the CO_2 reduction.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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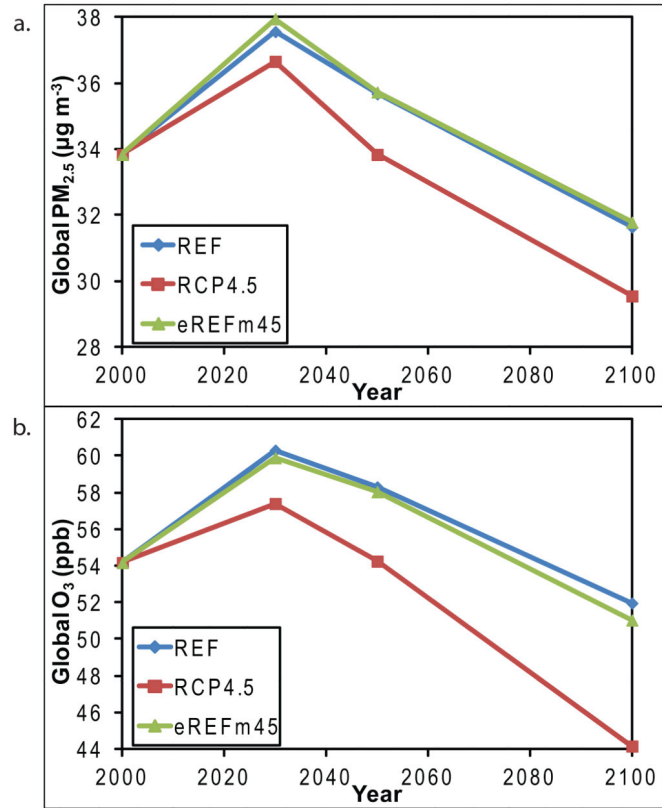
Fig. 1.
Global population-weighted surface (a) annual average $PM_{2.5}$, and (b) 6-month ozone-season average of 1-hr. daily maximum ozone, averaged over four model years, for the reference scenario (REF), the GHG abatement scenario (RCP4.5), and a simulation with REF emissions and RCP4.5 meteorology (eREFm45).
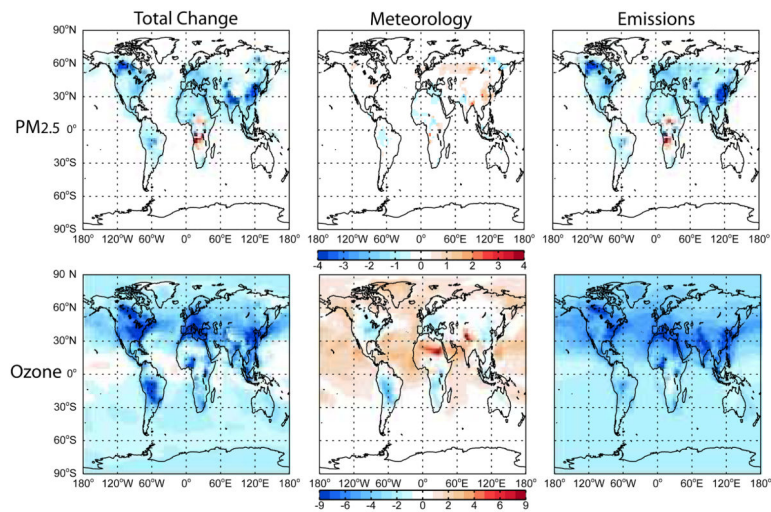
Fig. 2.
Effects of GHG mitigation on annual average PM$_{2.5}$ (µg m^{-3}) and the 6-month ozone season average of daily 1-hr. maximum ozone (ppb) in 2100, averaged over four model years, for the total change (RCP4.5-REF), and components due to changes in meteorology from climate change (eREFm45-REF), and emissions (RCP4.5-eREFm45).
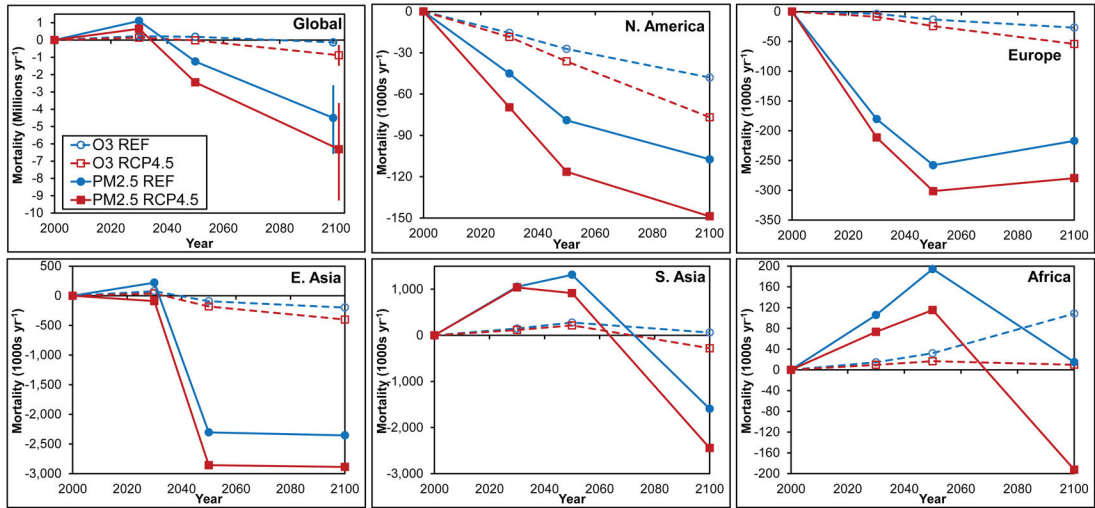
Fig. 3.
Premature mortality from PM$_{2.5}$ (CPD plus lung cancer) and ozone (respiratory), evaluated for future concentrations relative to 2000 levels, in the REF and RCP4.5 scenarios, globally and in selected world regions. Co-benefits can be estimated as the difference between REF and RCP4.5. In the global panel, points in 2100 are offset horizontally to show uncertainty bars, which reflect the 95% confidence intervals on the CRFs and neglect other uncertainties.
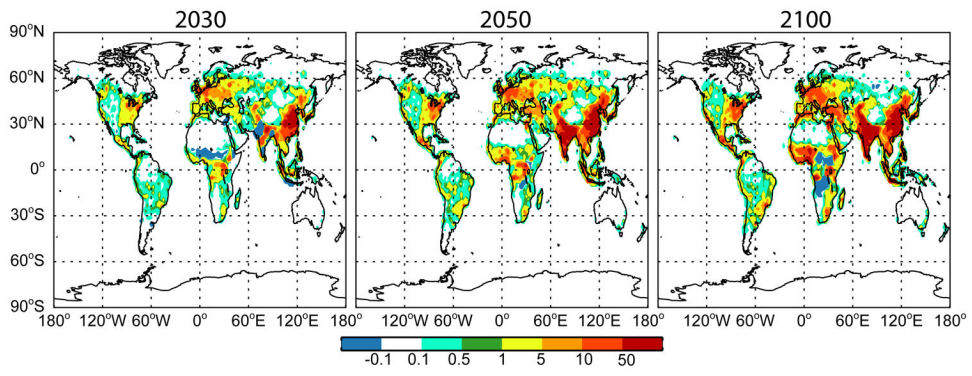
Fig. 4.
Co-benefits of avoided premature mortality from $PM_{2.5}$ (CPD plus lung cancer) and ozone (respiratory) in 2030, 2050, and 2100 (deaths per year per 1000 km^2).
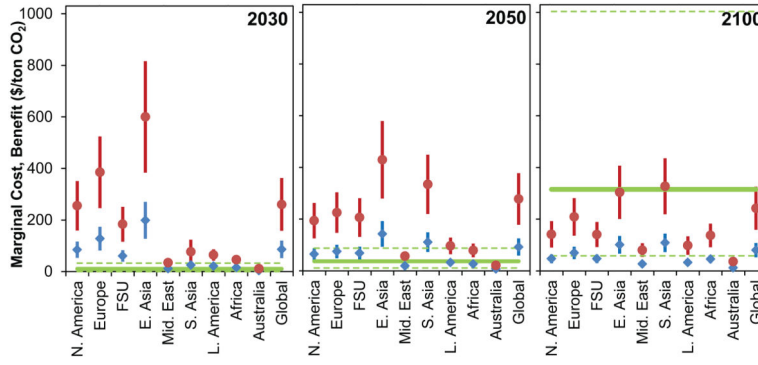
Fig. 5.

Regional marginal co-benefits of avoided mortality under high (red) and low (blue) VSLs, and global marginal abatement costs (the carbon price), as the median (solid green line) and range (dashed green lines) of 13 models[21]. Marginal benefits are the total benefits (sum of ozone respiratory, $PM_{2.5}$ CPD, and $PM_{2.5}$ lung cancer mortality) divided by the total CO_2 reduction, in each year under RCP4.5 relative to REF. Uncertainty in benefits reflects 95% confidence intervals on the CRFs.