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Implications of incorporating air-quality co-benefits into climate change policymaking

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Abstract
We present an analysis of the barriers and opportunities for incorporating air quality co-benefits into climate policy assessments. It is well known that many strategies for reducing greenhouse gas emissions also decrease emissions of health-damaging air pollutants and precursor species, including particulate matter, nitrogen oxides, and sulfur dioxide. In a survey of previous studies we found a range of estimates for the air quality co-benefits of climate change mitigation of \$2-196/tCO_2 with a mean of \$49/tCO_2, and the highest co-benefits found in developing countries. These values, although of a similar order of magnitude to abatement cost estimates, are only rarely included in integrated assessments of climate policy. Full inclusion of these co-benefits would have pervasive implications for climate policy in areas including: optimal policy stringency, overall costs, distributional effects, robustness to discount rates, incentives for international cooperation, and the value of adaptation, forests, and climate engineering relative to mitigation. Under-valuation results in part from uncertainty in climatic damages, valuation inconsistency, and institutional barriers. Because policy debates are framed in terms of cost minimization, policy makers are unlikely to fully value air quality co-benefits unless they can be compared on an equivalent basis with the benefits of avoided climatic damages. While air quality co-benefits have been prominently portrayed as a hedge against uncertainty in the benefits of climate change abatement, this assessment finds that full inclusion of co-benefits *depends on*—rather than substitutes for—better valuation of climate damages.

Keywords: co-benefits, climate policy, air pollution, health

1. Introduction

Changing the energy system in order to stabilize the climate is likely to have a wide variety of effects that are not directly related to greenhouse gas emissions, including human health, macro-economic, geo-political, eco-system, agricultural yields, and employment patterns. Those effects that are favorable to human welfare are often termed 'co-benefits'. The use of the term *benefits* reflects the situation that decisions related to whether, how, and how much to address climate change are typically made with some consideration of the costs and benefits associated with various policy options. These decisions however do not usually consider the full range of effects of actions to address climate change. Among the most important of known co-benefit effects are those associated with air quality and the resulting impacts on human health. Changes in the technologies used to produce and consume energy, as well as the level of energy consumption, have two effects related to air quality. First, many of the changes that would reduce greenhouse gas emissions would reduce other emissions as well, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter, and mercury, and the resulting pollution-related disease. Second, many of these changes would obviate the need for expensive pollution-control equipment—such as flue-gas desulfurization, selective catalytic reduction, and electrostatic precipitators—in order to comply with air quality regulations. How important are air quality (AQ) co-benefits? Why are they not considered in assessments of climate policy design? A primary finding is that the focus on cost minimization—rather than comparison of benefits and costs—diminishes the role of benefits in general. As a result, well-established AQ benefits are not a central part

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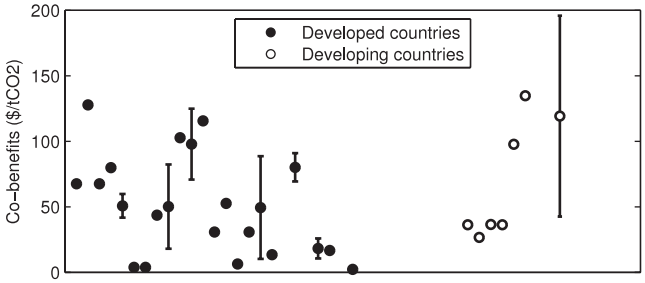

Figure 1. Estimates of the value of air quality co-benefits in developed (left) and developing country studies (right) in 2008$/ton$CO_2$. Within each category, data are reported from left to right by date of study (1991–2010). Absence of values indicates a co-benefit study for which health impacts were assessed, but valuation in $/t$CO_2$ was not.

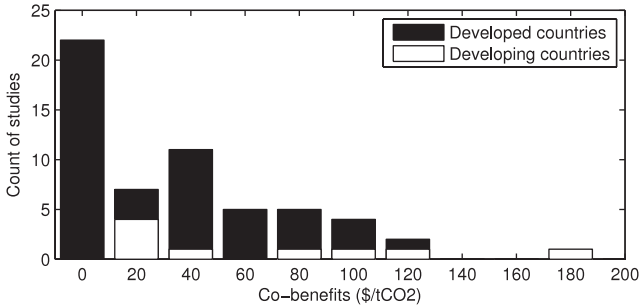

Figure 2. Frequency of values reported in air quality co-benefits studies.

of the climate policy discourse and probably rely on better characterization of climatic benefits in order to be fully valued.

We first review estimates of the value of air quality benefits of climate change policies and in section 3, the extent to which these co-benefits are valued in integrated assessment models. We then discuss the policy implications of including AQ co-benefit considerations in climate policy decision making and explore the reasons why economic policy models tend to ignore, even if they acknowledge, the value of co-benefits. We discuss data and modeling needs to resolve the existing impasse.

2. The value of AQ co-benefits is large

A large set of studies now makes clear that the magnitude of AQ co-benefits of climate change mitigation are non-trivial and have been observed across varied geographies, time periods, and sectors. We surveyed 37 peer-reviewed studies of AQ co-benefits (see the appendix). These studies provided 48 estimates of the economic value of air quality benefits of climate change mitigation, and span diverse geographies, time horizons, valuation techniques, and involve different mixes of economic sectors contributing to mitigation. Because the perspective of this study is on policy making amidst competing social priorities, we restricted our survey to those studies that (1) calculated an economic value of co-benefits, and (2) expressed values in terms of $/ton of CO_2 avoided. This restriction means that we do not include the results from a number of the studies we surveyed, and a larger portion of the studies of developing countries.

In figure 1, studies of developed countries are shown on left and those of developing countries on right. Within each category, data are reported from left to right by date of study (1991–2010), consistent with the studies reported in the appendix tables. Absence of values indicates a co-benefit study for which health impacts were assessed, but valuation in $/t$CO_2$ was not assessed. All values have been converted into constant 2008 dollars. Note that economic valuation was more frequent in developed country studies; 17 out of 24 developed country studies included $/t$CO_2$ estimates compared to 2 out of 13 developing country studies.

Figure 2 shows the frequency of values cited across all studies. The values for developed countries are in black and those for developing countries in white. For the 22 estimates from the 24 developed country studies the range was $2-128/t$CO_2$, the median was $31/t$CO_2$ and the mean $44/t$CO_2$. For the 7 estimates from the 13 developing country studies the range was $27-196/t$CO_2$, the median was $43/t$CO_2$ and mean was $81/t$CO_2$. Values are generally higher in developing countries, although the difference in means is not significant ($0.10 < p < 0.05$) in part due to variation in sector assessed and the dearth of developing country studies that assign economic value to co-benefits.

Heterogeneity in the distribution of study results is partially attributable to constraints on the scalability of AQ co-benefits at more stringent emissions reduction levels. At higher levels of greenhouse gas (GhG) abatement, abatement costs rise but AQ co-benefits remain constant (Burtraw *et al* 2003). Moreover, the apparently higher values in developing country studies result from these countries beginning with higher pollution levels, at which incremental health benefits are large. As emissions reductions become more aggressive, AQ co-benefits play a smaller role. Thus, valuation of AQ co-benefits is most important in the early stages of a long-term climate change mitigation strategy, and most important for developing countries lacking significant air quality management programs.

3. AQ co-benefits are not included in climate policy analyses

Even though the AQ co-benefits of climate change actions are well established, policy analyses typically do *not* account for them. We surveyed 13 major climate policy assessments based on integrated assessment models, selecting based on prominence and their intention to specifically inform policy decisions related to climate change. We drew from those used by the Intergovernmental Panel on Climate Change (IPCC), as well as government sponsored reports to model the impacts of specific policies in the UK and US. With one exception, the models reviewed are integrated assessments in that they combine assessments of both the physical and economic impacts of climate policies. Most of the models listed in table 1 (A, B, D–G, I, K–M) are partial or general equilibrium models, known as *top-down* models, which assess the direct and indirect economic effects of policies. Two (C, H) are systems engineering models that include technological detail and take a *bottom-up* approach. Model J is a benefit-cost analysis. In most cases the objective function is based on minimizing the abatement cost of meeting a climate emissions

Table 1. Treatment of AQ co-benefits in integrated assessment models of climate change policy.

	Venue	Model name	Time	GhG emissions	Value climate impacts	Estimate AQ co-b.	Value AQ co-b.	Include in final values
A	IPCC	IMAGE[a]	2100	Yes	No	No	—	—
B	IPCC	MERGE[a]	2150	Yes	No	No	—	—
C	IPCC	MESSAGE[a]	2100	Yes	No	No	—	—
D	IPCC	MiniCAM[a]	2100	Yes	No	No	—	—
E	IPCC	SGM[a]	2050	Yes	No	No	—	—
F	IPCC	WIAGEM[a]	2100	Yes	No	No	—	—
G	Nordhaus (2008)	DICE-2007[b]	2200	Yes	Yes	No	—	—
H	UK	C.C. Act of 2008 Assessment (MARKAL)[c]	2050	Yes	Yes	Yes	Yes	Yes
I	UK	Stern 2005/PAGE2002[d]	2200	Yes	Yes	Yes	Yes	No
J	US	C.B.O. (2009)[e]	2019	No	No	No	—	—
K	US	EIA NEMS (2008)[f]	2030	Yes	No	No	—	—
L	US	EPA ADAGE (2008)[g]	2050	Yes	No	No	—	—
M	US	EPA IGEM (2008)[g]	2050	Yes	No	No	—	—

[a]IPCC (2007). [b]Nordhaus (2008). [c]DECC (2008). [d]Stern (2006). [e]CBO (2009). [f]EIA (2008). [g]EPA (2008).

goal; climate damage costs are excluded. Only one (I) maximizes welfare by accounting for the benefits of avoided damages. The following section discusses why this final distinction is especially relevant to the treatment of AQ co-benefits.

Although 12 of the 13 models surveyed estimate emissions of greenhouse gases, only three (G, H, I) estimate the value of the resulting climate change damages. The others simply minimize the costs of achieving a specified set of annual emissions targets. Of the three that do estimate both costs and benefits of climate policy, only two (H, I) estimate air quality benefits—and only one of those (H) includes these values in the final cost estimates. The Stern review (I) does discuss AQ co-benefits and even quantifies them in dollar terms as 'up to 1% of GDP' (Stern 2006). But crucially, that study excludes this value in their highly publicized final results of the impacts and costs to address climate change. Only the UK Climate Change Act 2008 Impact Assessment (H in table 1) includes a value for improved air quality (£32b) in their final estimate (DECC 2008).

Beyond these high profile studies, recent work provides examples of more comprehensive inclusion of AQ co-benefits. Ostblom and Samakovlis (2007) include co-benefits in a CGE model for Sweden and find that the costs of climate policy are overstated if they are excluded. Bollen *et al* (2009) adapt a version of model B above to perform a cost-benefit analysis that includes both climatic and AQ impacts; they find the AQ co-benefits twice as large as climatic benefits. Early results from models such as GAINS combine estimates as well (Amann *et al* 2009).

An essential problem hindering inclusion of AQ co-benefits in policy decisions is that debates are framed in terms of minimizing the costs of climate policy. Because the benefits of avoided climate change are not explicitly considered, AQ benefits must somehow be compared to abatement costs[4]. Abatement levels are typically chosen exogenously with very little explicit justification for the specific targets adopted. For example, some targets attempt compliance with the ambiguous objective of avoiding *dangerous interference with the climate system,* as agreed on in the 1992 UN Framework Convention on Climate Change (Kriegler 2007). If full benefit-cost analyses were performed, the valuation of AQ co-benefits would be much simpler, as the addition of AQ co-benefits would imply a more stringent level of pollution abatement. The left panel of figure 3(a) shows that inclusion of air quality impacts would shift the marginal damages cost curve (MDC) upward so that its intersection with the marginal abatement cost curve (MAC) move to the right and as a result, the optimal level of pollution abatement would increase from q^* to q'. In practice, however, optimizing the level of emissions is not the objective of policy makers and is not the approach taken by analysis to inform them.

With exogenously specified targets, the marginal damages of climate change do not influence choices among policy options. Rather, the goal of policy design is to minimize the cost of meeting previously selected abatement levels. Inclusion of AQ co-benefits is less straightforward in this situation because policy debates are focused on the costs of pollution abatement; benefits are not a central part of the policy discourse. From this perspective, AQ co-benefits have to somehow affect the slope or position of the marginal abatement cost curve, rather than the damage curve. For example, the right panel of figure 3(b) shows that addition of AQ co-benefits could be interpreted as shifting the MAC curve downward. The marginal damage curve has been removed from that panel because it does not affect decisions. This shift requires the awkward re-interpretation of the AC as the sum of climate change abatement costs and AQ co-benefits ($MAC_{CC} + MDC_{AQ}$). The shift reduces the cost of climate policy such that the marginal cost, given the exogenously selected abatement level q^*, falls from p^* to p' as a result. The cost of the policy has gotten cheaper for the same level of emissions reductions. Most co-benefits studies and their normative policy claims result from conceiving of the abatement cost curve as this hybrid of climate costs and AQ benefits, even if estimation of p' is rarely explicit. For example, claims of 'no regrets'

[4] While it is optimal to use one policy instrument for each source of market failure, in reality the climate policies in discussion today include dozens of policy instruments within each piece of legislation. In part this is due to the presence of multiple market failures (Jaffe *et al* 2005).

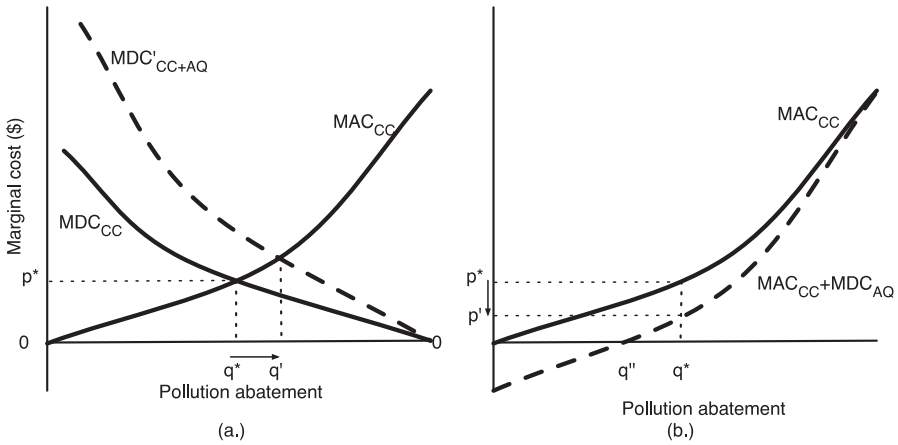

Figure 3. Effect of inclusion of air quality co-benefits on the marginal cost of climate policy. Left panel (a) shows air quality co-benefits interpreted as avoided damages. Right panel (b) shows air quality co-benefits interpreted as reducing abatement costs.

climate policy refer to the existence of abatement opportunities to the left of q'' where policy costs are below zero due to positive co-benefits. Rather, we are given p^* and told it is an overestimate—even in studies as thorough and as prominent as the Stern review. Full valuation of AQ co-benefits requires a more explicit discussion of how these cost impacts are calculated.

4. Implications of including AQ co-benefits

More thorough inclusion of AQ co-benefits would have several important effects on climate policy debates—both on optimal design and on positions held by stakeholders. The first implication is that inclusion of AQ co-benefits will reduce the societal cost of climate policy, as in figure 3(b). Alternatively, co-benefits may justify more stringent climate change policy by increasing the avoided societal damages, as in figure 3(a). Second, co-benefits improve the robustness of stringent climate policy. Acknowledging uncertainty in both the damage function and the abatement cost function, inclusion of AQ co-benefits provides a hedge against lower than expected climate damages or higher than expected mitigation costs. AQ co-benefits also occur earlier than climatic ones, making the social benefits calculation less sensitive to the choice of discount rate, thereby diminishing the significance of using low (Stern and Taylor 2007) or high discount rates (Nordhaus 2007). By increasing the robustness of climate policy to uncertain damages, abatement costs, and discount rates, co-benefits support more aggressive near term climate action even in the face of large uncertainty (Manne 1995).

An extension of this set of arguments on lower costs, higher stringency, and robustness is that inclusion of co-benefits provides stronger incentives for cooperation from developing countries than do climatic benefits alone. Due to lower incomes, an earlier stage of development, and negligible historical contribution to the stock of atmospheric greenhouse gases, rapidly growing developing countries are particularly sensitive to abatement costs and have shown little enthusiasm for reducing emissions. However, reducing their emissions from the trajectory of the last decade is essential to addressing the global problem. Game theoretic models show that the nearer term and more localized AQ co-benefits of climate change mitigation might be sufficiently important to developing countries that they would participate in international agreements (Pittel and Rubbelke 2008). Indeed, in figure 2 the value of AQ co-benefits in developing countries appears higher than in developed countries, although not significantly so given the few valuation studies in developing countries.

A second main implication is that including AQ co-benefits has a distributional effect because it changes the beneficiary of climate change actions. In particular, as the geographic benefits of international offset projects in the energy sector become more local, the value of offset projects for developing countries increases because the value of AQ co-benefits are added to the value of financial transfers from developed countries. As a result, entities in developed countries should expect to pay lower prices for offset projects in developing countries, while the value of domestic mitigation in developed countries will also increase. Thus, the cost of carbon mitigation decreases for both domestic and international abatement measures. A comparison of the value of co-benefits in developed countries in section 2 above (median $= \$31/\mathrm{tCO_2}$) to the prices paid for offsets at present ($\sim\$20/\mathrm{tCO_2}$) suggests that developed countries may prefer local mitigation, which creates AQ co-benefits, over purchasing international offsets; many international offset projects will be more expensive than domestic projects, even if international offsets would be cheaper with AQ co-benefits valued than without. The valuation of local AQ co-benefits is likely to have a diminishing effect on the flow of offset funds from developed to developing countries. This outcome suggests that the goal of financial transfer from developed to developing countries would be more effectively accomplished through direct support for activities, such as adaptation and poverty alleviation, rather than relying mainly on international offset projects as the transfer mechanism.

A related issue is that the geographic dispersion of the benefits of mitigation will become more closely tied to location of emissions. A fundamental justification behind GHG emissions trading is that the atmosphere is indifferent to the location of emissions since the six greenhouse gases

regulated under the Kyoto protocol are long lived and are well mixed throughout each hemisphere (for methane) or the globe (for others, including CO_2). The broadening of scope from climate benefits to air quality benefits raises the importance of the location of emissions. Given the wide dispersion in the costs to reduce GHG emissions, it is possible that trading could concentrate emissions in locations with high abatement costs (Farrell and Lave 2004). While the development of such *hotspots* does not affect the geographic incidence of climatic damages, it would introduce environmental justice concerns if air pollution health effects become concentrated as a result.

Third, actions that are equivalent in radiative forcing are not equivalent in value. Inclusion of AQ co-benefits increases appeal of transforming energy production and use relative to other means of addressing climate change, which have less pronounced effects on air quality. For example, the appeal of forest preservation will diminish relative to emissions mitigation when AQ co-benefits are included—though of course valuation of other co-benefits such as biodiversity would increase the relative appeal of forests. Similarly, AQ co-benefits reduce the attractiveness of adaptation and climate engineering relative to mitigation. To be sure, adaptation is still necessary, but its role as an appealing alternative to costly mitigation is diminished. Concerns about climate engineering schemes that propose reducing radiative forcing without necessarily changing emissions have been raised due to uncertainties about efficacy and side effects (Bengtsson 2006). Indeed, some solar radiation modification schemes have the potential to reduce air quality (Crutzen 2006, Victor 2008), and even those with no adverse affect must take into account the opportunity cost of missed air quality improvements. The observed under-prioritization of adaptation and climate engineering relative to mitigation (Pielke *et al* 2007) may be partially attributable to concern over the loss of AQ co-benefits, even if not explicitly expressed.

Finally, it is not obvious that all climate change mitigation actions that provide AQ co-benefits will be pursued. Policy makers may simply choose to address AQ directly since it is almost certainly cheaper to reduce local air pollution directly rather than via climate policy (Johnson 2001). This possibility seems especially pertinent in developing countries where, for the reasons discussed above, climate change mitigation has to date been considered a developed country responsibility. It may also be a concern at higher levels of GhG mitigation where abatement costs become expensive and AQ co-benefits start to look relatively small. It may become reasonable for countries, especially developing ones, to consider avoided climate change damages as a co-benefit of efforts to reduce air quality. If high-CO_2-emitting developing countries were to take such a perspective, it would complicate implementation of an international climate agreement. For example, emissions trading between countries would be difficult if one country were to set a national limit on GHG emissions while the other had a national limit on SO_2, NO_x, or other pollutants. Although it may ultimately prove essential to overcoming international collective action problems, it would require a high degree of flexibility and a tolerance for heterogeneity in national implementation plans that goes well beyond what has been agreed upon so far in the international climate regime.

5. Why are AQ co-benefits acknowledged but ignored?

Given these implications, ignoring co-benefits skews policy decisions and leads to sub-optimal social outcomes. Many studies discuss the benefits of a more comprehensive assessment and policy (IPCC 2007, Haines *et al* 2007, Bond 2007). If AQ co-benefits are so substantial and their implications so important, why do not they play a larger role in affecting climate policy design? Several characteristics of AQ co-benefits contribute to their under-valuation.

5.1. Uncertainty in climatic damages and abatement costs

Uncertainty about both the costs and benefits of climate change mitigation reduces the role of air quality benefits in policy debates because it complicates comparisons. This is in contrast to prominent arguments that assert that AQ co-benefits make *no regrets* climate policy possible because the greater certainty of AQ co-benefits reduces the importance of uncertainty over climatic damages. However, the large uncertainty over the benefits of avoided climate change has shaped the policy discourse so that policy design is framed as a problem of cost minimization; benefits are not counted explicitly because estimates are not sufficiently reliable. The resulting marginalization of climatic benefits has had the effect of excluding quantitative representation of benefits in general, including AQ benefits. AQ co-benefits have so far not diminished the importance of climatic uncertainty; rather, deep and persistent climatic uncertainty has led to a policy discourse in which it is extremely difficult for AQ benefits to play a central role.

Cooperation on climate change is difficult in part because the abatement costs in climate policy are so uncertain (Swart *et al* 2009). Claims are made both that climate policy will cost several per cent of gross world product and that climate policy will actually stimulate economic growth (Tol 2009). Estimates reported by the IPCC alone show a range of carbon prices from \$20-100/tCO_2 for 25% emissions reduction from business as usual by 2030 (Nemet 2010). That almost every climate policy proposal involves a quantity-based target rather than price-based target sustains cost uncertainty. In practice, assumptions about base case emissions growth, the supply of loss-cost energy efficiency investments, the cost of renewables, the diffusion of nuclear, and the availability of carbon capture and sequestration technology, as well as other items, leads to large dispersion in abatement costs. In contrast, the technologies involved in air quality improvement are less dynamic, have a longer history, involve a much more limited set of options, and do not require changes to existing infrastructures.

While the overwhelming portion of the discussion on climate policy is focused on abatement costs, the more important source of uncertainty for AQ co-benefits arises from in climate damages. More specifically, estimates of the climate-related damages *avoided* as a result of climate policy are the central concern for policy makers. Estimation of avoided damages involves 'deep uncertainty' because reliable probability distributions of possible outcomes are not available (Lempert 2002, Keller *et al* 2008, Gosling *et al* 2009). One recent survey of published estimates found a range of climate

damages from \$0-33 000/tCO_2, depending on assumptions related to risk aversion, equity, and time preferences (Anthoff *et al* 2009). Of particular concerns is the potential for positive feedbacks, irreversibility and rapid change to the climate system (Torn and Harte 2006). In contrast, estimation of AQ damages is less problematic, in part because the effects of air pollution on human health are nearer term, less geographically dispersed, and are well studied.

Even though damages are the ultimate motivation for climate policy, as shown above, they are not typically included in assessments of climate policy. One interpretation is that we simply distrust the reliability of climate impact studies. An alternative hypothesis is that since the uncertainties are so large and values hinge on choice about small changes in discount rates, that discussion quickly becomes philosophical, and not amenable to policy discourse. Another reason that damage values are infrequently discussed is that willingness to pay to avoid them appears quite low; a contingent valuation study of willingness of US residents to pay for the Kyoto Protocol estimated that households valued the benefits at just under \$191 per household per year (Berrens *et al* 2004), which implies political support for a carbon price in the mid-single digits of \$/tCO_2. More broadly, contingent valuation studies suffer from ignorance about what type of climate people actually want (Dietz and Maddison 2009). Finally, the characteristics of the risks being compared are different (Slovic 1987); the lethal aspects of the health impacts of air pollution may provide a catalyst for regulatory action that, at least at present, is missing in climate change.

5.2. Measurement and valuation

Another reason that AQ co-benefits are typically excluded is that valuation results are sensitive to choices about methodology and parameter values (Bell *et al* 2008). Even if the benefits are widely found to be substantial, standard metrics for economic valuation of health impacts do not exist, which is a particular problem in valuing loss of life and assessing heterogeneous sub-populations. Development of 'Health Impact Assessment' provides one avenue to remedy this problem (Patz *et al* 2008). Valuation of health and life is made worse by disagreement over the appropriate discount rate to use (Stern and Taylor 2007, Nordhaus 2007, Anthoff *et al* 2009). The smaller temporal and geographical scales of AQ impacts relative to climatic impacts make comparison difficult as well. The more diverse set of pollutants that need to be taken into account to optimize the pursuit of AQ and climate benefits, combined with the nearer term impact of AQ impacts, heightens the sensitivity of valuation results to choices of global warming potentials to compare gases (West *et al* 2007, Smith and Haigler 2008). Finally, some have suggested that the transactions and information costs associated with AQ co-benefits are so high that they would offset incremental benefits (Elbakidze and McCarl 2007); however, the values found in section 2 imply that those costs would have to be extremely high. The paucity of studies that value co-benefits in developing countries—for example in figure 1—suggests that the challenges of valuation are even more problematic in those contexts.

5.3. Institutions and epistemic communities

Institutional barriers, in both the scientific and political domains, also discourage inclusion of co-benefits. Scientifically, the networks of institutions and individuals contributing knowledge on air quality have little overlap with those on climate change (Swart 2004). The lack of shared assumptions, methods, and data makes integration of scientific results difficult (Norgaard 2004). The international policy regime reflects a similar separation; the UN Framework Convention on Climate Change and the Convention on Long-Range Transboundary Air Pollution remain separate despite calls for better integration (Holloway *et al* 2003). The adverse consequences of this division of international governance are likely to heighten if countries adopt divergent priorities on climate change and air quality. For example, large developing countries might value avoided climatic damage as a co-benefit of their pursuit of air quality improvement while developed countries might focus on climate impacts directly, with AQ as an ancillary benefit. In effect, climate change may become an 'impure' public good, with private gains from mitigation alleviating free-rider issues (Finus and Ruebbelke 2008). While heterogeneous pursuit of common outcomes might provide a promising context with which to resolve collective action problems, the separation of governance regimes is likely to impede progress. Finally, the implications described above may realign interest group coalitions that are affecting the political process in favor of action on mitigation. The relative decline in the attractiveness of afforestation, adaptation, and climate engineering once AQ co-benefits are taken into account, may threaten the cohesion of coalitions of support of climate policy at the national and international levels. Adding complexity to an already complex regime may reduce salience and consequent political feasibility as well (Young 1989, Rypdal *et al* 2005). This challenge need not be paralyzing; a US Senate committee passed a 'four pollutant bill' for CO_2, SO_2, NO_x, and Hg in 2002 (S.556) and Senators were discussing introducing a similar bill in late-2009.

6. Conclusion

The full inclusion of AQ co-benefits in the design and evaluation of climate policy would almost certainly enhance social outcomes because these co-benefits are large and because policy analysis has not valued them. Moreover, that AQ co-benefits are more local, nearer term, and health related has the potential to enhance incentives for cooperation by engaging actors that are averse to the costs of climate policy or unmotivated by avoided climatic damages. Still, a variety of barriers exist to their inclusion. The framing of the climate policy discourse is likely to continue as one of cost minimization until the benefits of avoided climate change can be more reliably estimated. As a result, a risk remains that AQ co-benefits will be treated as serendipitous and tangential, rather than as driving forces for strong climate policy. Full consideration of AQ co-benefits in policy debates will require improved evaluation techniques for *both* the climatic benefits and the air quality benefits of climate policy. Improving valuation of AQ co-benefits alone is unlikely to promote

more stringent climate policy, even if it helps justify more stringent air quality regulation. In a more general sense, the effort to fully consider the value of co-benefits with vastly different risk characterizations, as well as time and spatial scales, foreshadows challenges in considering other co-benefits of actions to reduce climatic damages. Additional benefits may include effects on crop yields, acid deposition, macro-economic shocks, and geo-political conflict.

Acknowledgments

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Appendix

Table A.1. Studies estimating the co-benefits of climate change mitigation in developed countries.

	Study	Geography	Sectors included	Value of co-benefits (2008\$/tCO_2)		
				Midrange	High	Low
1	Ayres and Walter (1991)	US	All	68	n.e.	n.e.
2	Ayres and Walter (1991)	Germany	All	128	n.e.	n.e.
3	Pearce (1992)	Norway	All	68	n.e.	n.e.
4	Pearce (1992)	UK	All	80	n.e.	n.e.
5	Alfsen *et al* (1992)	Norway	All	51	60	42
6	Holmes *et al* (1993)	US	Electric	4	n.e.	n.e.
7	Dowlatabadi *et al* (1993)	US	Electric	4	n.e.	n.e.
8	Goulder (1993)	US	All	44	n.e.	n.e.
9	Barker (1993)	UK	All	50	82	18
10	Barker (1993)	US	All	103	n.e.	n.e.
11	Barker (1993)	Norway	All	98	125	71
12	Viscusi *et al* (1994)	US	Electric	116	n.e.	n.e.
13	Rowe (1995)	US	Electric	31	n.e.	n.e.
14	Boyd *et al* (1995)	US	All	53	n.e.	n.e.
15	Palmer and Burtraw (1997)	US	Electric	6	n.e.	n.e.
16	EPA (1997)	US	Electric	31	n.e.	n.e.
17	Mccubbin (1999)	US	Electric	49	89	10
18	Caton and Constable (2000)	Canada	All	13	n.e.	n.e.
19	Syri *et al* (2001)	EU-15	All	n.e.	n.e.	n.e.
20	Han (2001)	Korea	All	80	91	69
21	Syri *et al* (2002)	Finland	All	n.e.	n.e.	n.e.
22	Bye *et al* (2002)	Nordic countries	All	18	26	11
23	Burtraw *et al* (2003)	US	Electric	17	18	15
24	Proost and Regemorter (2003)	Belgium	All	n.e.	n.e.	n.e.
25	Joh *et al* (2003)	Korea	All	2	n.e.	n.e.
26	van Vuuren *et al* (2006)	Europe	All	n.e.	n.e.	n.e.
27	Bollen *et al* (2009)	Netherlands	All	n.e.	n.e.	n.e.
28	Tollefsen *et al* (2009)	Europe	All	n.e.	n.e.	n.e.

Notes n.e. = not estimated in \$/CO_2 terms. Especially useful previous reviews include: Ekins (1996), Burtraw *et al* (2003), IPCC (2007).

Table A.2. Studies estimating the co-benefits of climate change mitigation in developing countries.

	Study	Geography	Sectors included	Value of co-benefits (2008\$/tCO_2)		
				Midrange	High	Low
29	Wang and Smith (1999)	China	Electric	n.e.	n.e.	n.e.
30	Cifuentes *et al* (2001)	Brazil	All	n.e.	n.e.	n.e.
31	Cifuentes *et al* (2001)	Mexico	All	n.e.	n.e.	n.e.
32	Bussolo and O'Connor (2001)	India	All	n.e.	n.e.	n.e.
33	O'Connor *et al* (2003)	China	All	n.e.	n.e.	n.e.
34	Dessus and O'Connor (2003)	Chile	All	n.e.	n.e.	n.e.
35	Aunan *et al* (2004)	China	Electric	36	n.e.	n.e.
36	Aunan *et al* (2004)	China	Electric	27	n.e.	n.e.
37	Aunan *et al* (2004)	China	Electric	36	n.e.	n.e.
38	Aunan *et al* (2004)	China	Electric	36	n.e.	n.e.
39	Aunan *et al* (2004)	China	Electric	98	n.e.	n.e.
40	Aunan *et al* (2004)	China	Electric	135	n.e.	n.e.
41	Kan *et al* (2004)	China	All	n.e.	n.e.	n.e.
42	Kan *et al* (2004)	China	All	n.e.	n.e.	n.e.
43	Morgenstern *et al* (2004)	China	Electric	119	196	43
44	West *et al* (2004)	Mexico	All	n.e.	n.e.	n.e.
45	McKinley *et al* (2005)	Mexico	All	n.e.	n.e.	n.e.
46	Li (2006)	Thailand	All	n.e.	n.e.	n.e.
47	Vennemo *et al* (2006)	China	Elec. & Industrial	n.e.	n.e.	n.e.
48	Zhang *et al* (2010)	China	All	n.e.	n.e.	n.e.

Notes n.e. = not estimated in \$/CO_2 terms. Especially useful previous reviews include: Ekins (1996), Burtraw *et al* (2003), IPCC (2007).

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