Primer on Costs of Action/ Inaction and Communication to Policymakers

A Review of Methodologies to Support Future Decisionmaking in Comparing the Cost of Inaction with the Cost of Action in the Context of African ChemObs

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1. Introduction

To support the African ChemObs project (the Integrated Health and Environment Observatories and Legal and Institutional Strengthening for the Sound Management of Chemicals in Africa), we provide a critical review of methodologies for valuing the health damages from policy inaction associated with chemical exposures. In particular, we discuss how disability-adjusted life years (DALYs) and IQ loss should be valued. We conclude by providing advice on communicating the costs of inaction and the benefits and costs of action to policymakers.

By the *social costs of inaction*, we mean the private or market costs, as well as the external costs, from pollution exposures compared with no exposure. Knowledge of these damages can then lead to policies designed to force investment and operating decisions in the market to account for (internalize) such costs/damages. The costs of inaction can be distinguished from the benefits and costs of action. The benefits of action are the value of, for example, the health improvements from regulations or other forms of action. These actions usually come with a cost of resources to bring about such actions. The *net* benefits to society of an action are the benefits minus the costs of action. In general, as regulations of chemicals rarely eliminate all exposures, the costs of inaction generally exceed (in absolute terms) the benefits of action.

2. Approach

The material in this report is based on a review of the available conceptual and empirical literature on social cost estimation—in the context of health—to identify the strengths and weaknesses of the various methods used to estimate these costs. Advice on how to communicate results draws from a different literature on communicating costs and benefits to policymakers—in the United States, in other developed countries, and in developing countries—as well as our own experience and the experiences of ChemObs team members. We considered use of this report by project developers, planners, research analysts, and government policymakers.

3. Health Valuation

3.1. Overview of Approaches

The standard approach to estimating the health effects of environmental pollution is the damage function approach. Epidemiologists estimate the association between pollution and premature mortality, morbidity, or other health effects, such as the impact of pollution on cognitive development or functioning. These impacts may, in turn, be valued using either the cost-of-illness or willingness-to-pay approach.

The cost-of-illness (COI) approach to health valuation measures the direct medical expenditures associated with disability or illness, including hospital, physician, and medication costs, as well as long-term rehabilitation costs. The indirect costs of illness include time lost from work due to illness and the value of caregivers' time (Landrigan et al. 2018). It also includes losses in productivity over an individual's lifetime due to chronic medical conditions or a loss in cognitive function. When properly measured, these costs include out-of-pocket costs borne by affected individuals, as well as costs reimbursed by insurance or paid for by the government. When a person dies prematurely due to pollution, the COI approach measures this loss in human capital by the individual's lost output. For workers, this output is their earnings over the remainder of their working life. For people not in the workforce, there are approaches to measuring their "earnings," such as using market wages for providing services in the home (e.g., child-rearing services).

The COI approach does not capture the discomfort caused by illness, including the physical burden borne by people who do not receive treatment for their condition. The COI approach also fails to capture the anxiety and loss in enjoyment that a person facing death risks suffers, as well as losses by family members related to these risks are after his death.

The willingness-to-pay (WTP) approach is the theoretically correct approach to measure preferences of people to avoid being ill or dying prematurely. There are *revealed preference* approaches to capture these preferences through statistical analyses of individual behavior (such as by estimating the wage premium paid to workers in more risky jobs) and *stated preference* approaches, which use survey techniques to elicit and monetize preferences for improved health by posing hypothetical questions (Cropper et al. 2011). These approaches can, in principle, capture the pain, suffering, and loss of enjoyment that the COI approach cannot capture. An individual's WTP is, however, necessarily limited by income. Taking the distribution of income as a given is consistent with measuring the benefits to society of improving health (under modern welfare economics), but this caveat is important for understanding the context of such metrics. The WTP approach also may fail to capture costs that a person does not pay for, such as the cost of treatment in a government clinic.

3.2. Valuing Mortality

Epidemiological studies often link pollution exposures to mortality rates; for example, they may estimate how risk of death, by age and cause, is increased by exposure to ambient air pollution ($PM_{2.5}$), relative to some minimum level of exposure (GBD 2017 Risk Factor Collaborators 2018). The damages attributable to the current level of air pollution in a city (i.e., the costs of inaction) can be expressed as the number of deaths, by age and cause, attributable to current air pollution levels. These deaths can be expressed as death rates, such as 10 in 10,000 people in a city. The WTP approach asks how much people would pay to reduce their risk of death from this baseline.

The WTP approach estimates what a person would pay for a reduction in risk of death—for example, for a reduction in risk of death from 10 in 10,000 to 9 in 10,000. It sums these WTPs across individuals to determine what 10,000 people would pay for risk reductions that sum to one “statistical life.” This sum, termed the value of a statistical life (VSL), is multiplied by the number of statistical lives associated with air pollution to determine the cost of premature mortality associated with, for example, current $PM_{2.5}$ levels using the WTP approach. To illustrate, if each person in the city were willing to pay $25 to reduce the risk of death from 10 in 10,000 to 9 in 10,000, 10,000 people together would pay $250,000 for risk reductions that sum to one statistical life being saved. This implies a VSL of $250,000.

The COI approach, in contrast, would value the statistical lives lost due to pollution by the loss in output associated with each death. This would, in general, vary with age at death and would be measured by the present value of future output lost when a person dies prematurely.

3.2.1. The WTP Approach

In the mortality context, stated preference studies confront respondents with hypothetical situations asking them, for example, what they would pay for a medicine that would reduce the risk of death from 10 in 10,000 to 9 in 10,000 over the coming year. The revealed preference literature infers WTP from studies of wage differentials in the labor market that indicate how much workers must be paid to work in jobs carrying higher risks of death (Cropper et al. 2011).

Although dozens of WTP studies to value mortality risks have been conducted in Organisation for Economic Co-operation and Development (OECD) countries, fewer studies have been conducted in low- and middle-income countries (LMICs). While in-country studies are preferred, the lack of such studies implies that it is often necessary to transfer VSL results from high- to low-income countries. The most prevalent approach is to adjust the VSL according to per capita income (Robinson, Hammitt, and O'Keeffe 2019; Narain and Sall 2016). The VSL used by the OECD, $3.83 million (2015 US$), is approximately 100 times per capita income. The official VSL of the US Environmental Protection Agency (EPA), $9.4 million (2015 US$), is approximately 160 times per capita income. The ratio of the VSL to income, divided by 100, represents the fraction of income that would be given up for a 1 in 10,000 reduction in risk of death. EPA's VSL implies that a 1 in 10,000 reduction in risk of death is worth 1.6 percent of income; the OECD value implies that it is worth 1 percent of income (see Appendix B). Well-executed studies of the VSL in LMICs imply that the ratio of the VSL to per capita income falls as per capita income falls (Hammitt and Robinson 2011).

A recent Gates Commission study, after reviewing the international VSL literature, suggests transferring EPA's VSL to LMICs using an income elasticity of 1.5 (Robinson et al. 2019; Robinson, Hammitt, and O'Keeffe 2019). Table 1 shows the ratio of the VSL to per capita income implied by this approach. It presents gross national income (GNI) per capita in international (purchasing power parity, or PPP) dollars, as well as the VSL in international (PPP) dollars. The ratio of the VSL to per capita income (Y) is 21 times per capita income for a country with a per capita GNI of $1,000 international dollars, 48 times per capita income for a country with per capita income of $5,000 international dollars, and 67 times per capita GNI for a country with per capita GNI of $10,000 international dollars. Note that once the VSL/Y ratio is determined, it can easily be used to solve for the VSL at market exchange rates, since the VSL/Y ratio is identical in PPP and market exchange rate (MER) terms. Applying this transfer implies a VSL/Y ratio of 43 for Ghana, 42 for Zambia, 39 for the Côte d'Ivoire, and 37 for Kenya.

3.2.2. The COI Approach (also called the human capital approach)

The cost-of-illness approach uses forgone earnings, rather than the VSL, to measure the value of premature mortality. This is often referred to as the human capital approach, since an individual's output (or income) is often used as a measure of the person's human capital, or accumulated skills and knowledge. To illustrate, if a person dies at age 25, the output lost by his death is the present discounted value of what he would have earned (produced) over the remainder of his working life.

Earnings (output) at each age is weighted by the probability that a 25-year-old survives to each future age, times the probability that he is working at that age. This flow of output is discounted to the present at an appropriate rate of interest. (For details, see Appendix A.)

One way to measure earnings at each age is to use results from a national survey that records labor earnings; however, such data may not be available for all countries. In the Lancet Commission report (Landrigan et al. 2018), earnings per worker were approximated by output per worker, calculated by multiplying labor's share of gross domestic product (GDP) by GDP and then dividing by the number of workers employed. This number can also be adjusted to reflect the value of nonmarket output produced by labor, as described in Appendix A.

The value of the human capital lost when a person dies clearly depends on age at death. Other things equal, the output lost when a 60-year-old dies is less than the output lost when a 25-year-old dies: the human capital measure of mortality varies with age at death. Does this also hold for the VSL? Whether WTP to reduce risk of death varies with age is an empirical question—it depends on the utility people receive from living longer, as well as their wealth. How the VSL varies empirically with age is not well established (Krupnick 2007). For this and other reasons, policymakers in the United States (and other countries) apply the same VSL to deaths of all ages.

3.2.3. International Examples

The Global Burden of Disease program at the Institute for Health Metrics and Evaluation regularly publishes, by country, estimates of deaths associated with environmental risk factors, including outdoor air pollution, household air pollution, unsafe water and sanitation, and exposure to lead (GBD 2017 Risk Factor Collaborators 2018). The Lancet Commission report (Landrigan et al. 2018) valued the mortality burden associated with these pollution sources, by country, using both the human capital and VSL approaches to value damages. Table 2 shows the human capital losses as a percentage of GDP, aggregated by World Bank Income Group. Table 3 shows mortality losses, valued using the VSL, as a percentage of GNI, aggregated by World Bank Income Group.

A comparison of Tables 2 and 3 highlights the difference between the two approaches. For low-income countries, aggregating across pollutants, human capital losses range from 1.33 to 1.9 percent of GDP, depending on the rate used to discount future earnings to the present. The corresponding figure for mortality losses valued using the VSL is 8.33 percent of GNI. Two factors explain the differences: human capital losses last only over a person's working life, whereas the same VSL is applied to premature deaths at all ages. Table 2 uses the International Labour Organization's definition of working life as 15 to 64 years. A high percentage of deaths from environmental exposures occurs among persons over 65. The second factor is that because the VSL captures losses beyond productivity (i.e., earnings) losses, the VSL is a multiple of forgone earnings at all ages.

3.3. Valuing Morbidity

The difficulty in valuing morbidity lies in finding epidemiological studies linking pollution to specific illnesses and then valuing the consequences of these illnesses using COI or WTP studies. This is made difficult by the large number of illnesses associated with pollution and, for a given illness, variation in the severity and duration of the illness relative to the small number of valuation studies available.

One solution is to translate illness into years lived with disability (YLDs). Disability weights measure the level of disability associated with a particular disease (or condition), where a disability weight of 0 indicates no disability and a disability weight of 1 equals death (Salomon 2010). Equivalently, (1 – disability weight) indicates the fraction of a year in good health lost due to the disease. For example, a case of mild chronic obstructive pulmonary disease (COPD) might have a disability weight of 0.46; a severe case of COPD, a disability weight of 0.77. The Global Burden of Disease (GBD) estimates the YLDs, by age and gender, associated with 354 diseases for 195 countries. The GBD also estimates the fraction of YLDs, by disease and country, associated with various environmental risk factors (GBD 2017 Risk Factor Collaborators 2018).

One approach that has been taken to valuing YLDs is the human capital approach (see Appendix A). This assumes that the value of a YLD equals the average value of income (or output) per worker in the country, multiplied by the probability that a person is working. For example, the value of a YLD experienced by a 60-year-old would equal average labor income (output) multiplied by the probability that a 60-year-old is working. This value could be modified to allow for the value of nonmarket output (see Appendix A). This approach assumes that disability weights reflect an inability to work or productivity lost while working.

The human capital approach to valuing YLDs simplifies the valuation of illness but has limitations. It does not capture the medical expenditures (direct costs) associated with illness, nor does it capture pain and suffering. To estimate medical costs requires attributing medical costs to specific illnesses, and then attributing these illnesses to pollution. The GBD study provides a link between YLDs and pollution but does not provide an estimate of medical costs by country and disease. Such estimates may be available for some countries based on survey or administrative data. For example, estimates are available for the United States (Dunn et al. 2015) and other OECD countries (OECD 2013). Estimates of hospitalization costs, by disease, are available for India (Kastor and Mohanty 2018) and may be available for other countries.

3.3.1. Valuing DALYs

In describing the burden of ill health associated with pollution and other risk factors, YLDs are often added to years of life lost (YLLs) to calculate disability-adjusted life years (DALYs) lost. YLLs are measured by remaining life expectancy, based on life tables for the country in question. For example, a person who dies in India at age 25 has a remaining life expectancy of 48 years; hence his death is associated with 48 YLLs. To illustrate the calculation of DALYs, in India in 2017 the GBD estimates that 5.4 million YLDs and 1.24 million deaths were associated with particulate air pollution (both ambient and household air pollution). The 1.24 million deaths resulted in 31 million YLLs, implying that air pollution was associated with 36.4 million DALYs in India in 2017, about 8 percent of all DALYs (India State-Level Disease Burden Initiative Air Pollution Contributors 2018).

How should DALYs be monetized? If a human capital approach is used to value premature mortality and also YLDs, then by adding the monetized value of YLDs to the value of premature deaths, measured by the present value of lost output, one has valued DALYs. Using the approach described in Appendix A, in India, the present value of output (human capital) lost due to premature mortality associated with particulate air pollution was US$20.27 billion. The value of output lost due to YLDs was US$8.17 billion, implying a total loss of US$28.44 billion, or about 1.2 percent of India's GDP.

How can DALYs be valued using a WTP approach? It has been suggested that DALYs should be valued by apportioning the VSL into a value per statistical life year (VSLY) and using the VSLY to value each DALY. In practice, the VSLY is computed based on the mean age of respondents in a stated preference survey or the mean age of workers in a compensating wage study. The VSL is divided by the (discounted) remaining life expectancy of a person of the mean age to produce the VSLY. For example, if the VSL is $1,200,000 and the discounted remaining life expectancy of the average worker in the compensating wage study is 30 years, the VSLY is $40,000. A premature death at any age is then valued by multiplying the YLLs lost by the VSLY. A 25-year-old with 52 life years remaining would be assigned a value of 52 times the VSLY ($2,080,000), whereas a 75 year-old with 11 life years remaining would be assigned a value of $440,000. YLDs are valued by multiplying each YLD by the VSLY.

There are several issues with this approach. Valuing premature mortality using the VSLY implies that the value of a premature death declines with age, since the VSLY is constant and remaining life expectancy (YLLs) declines monotonically with age. The main criticism of this method of valuing premature mortality is lack of evidence that WTP to reduce risk of death declines monotonically with age (Krupnick 2007). To value YLDs using a metric that measures WTP to avoid risk of death is problematic, given that YLDs measure morbidity rather than mortality.

3.4. Valuing Cognitive Impairment

Much of the ChemObs project focuses on exposures to heavy metals. Some of these, such as lead, but also air pollutants such as fine particles ($PM_{2.5}$), can affect cognitive development, lower IQ, and reduce a child's potential for learning (Brockmeyer and D'Angiulli 2016). For lead, there is a literature linking blood lead levels to test scores and performance on IQ tests (Grosse et al. 2002; Lanphear et al. 2005). IQ, in turn, has been shown to affect lifetime earnings. Other costs associated with lead exposure include the costs of treatment to reduce high blood lead levels (chelation therapy) and the costs of additional schooling for children with high blood lead levels.

In the literature linking lead exposure to future earnings through its effect on IQ, there are at least two channels of effects: the effect of IQ on earnings and on the amount of education attained. Studies in the United States suggest that the total impact of a 1-point reduction in IQ is to reduce annual earnings between 0.75 and 0.9 percentage points for people in their early 30s and by about 1.4 percentage points for people in their early 50s (Grosse 2007). This, of course, reflects outcomes in US labor markets. A recent expert elicitation of US and Canadian labor economists to estimate the effect of IQ on earnings in India (Lutter et al. 2017) found that a 2-point decrease in IQ was associated with a 2 percentage point reduction in earnings each year from age 25 to age 60.

The above results suggest that a rough estimate of the impact of an IQ point on future earnings is about 1 percentage point. This can be applied to estimates of future earnings computed using the methods for estimating the present value of future earnings described in Appendix A.

4. Communicating to Policymakers

It is one thing to generate technical documents on the costs of inaction or the costs and benefits of possible government actions to reduce pollution. It is quite another to successfully communicate those results to appropriately and persuasively influence policymakers, who may lack economics training and are subject to tight timelines and influences from many sides. This section of the primer offers our thoughts on communication challenges and strategies, developed from interviews, our experiences, and what literature is available.

4.1. Prerequisites

It should go without saying that the analyses need to be on point, methodologically sound, transparent, and clearly written, and they should have executive summaries with clear headlines that can appeal to policymakers who may be unable to read the entire analysis. In addition, important assumptions need to be highlighted for transparency.

Also, the baseline must be clear and reasonably accurate. This is true both for a study that is describing the costs of inaction—the damages that will occur if pollution is not remediated—and for cost-benefit analyses (CBAs) that describe the costs and benefits of policies to reduce pollution. The baseline is what changes as a result of a rule or other government action. Costs and benefits are measured from the policy or activity-induced change to the baseline. The current baseline is factual and therefore can be checked (although a future baseline is obviously not observable). Errors in characterizing the current situation can seriously damage a study's credibility with decisionmakers.

4.2. What to Communicate

In this section, we consider the substantive issues of effectively communicating a study of the costs of inaction, a CBA, or other forms that a policy analysis might take.

In communicating pollution damages in a cost-of-inaction study, or benefits (i.e., reduced damages) in a CBA, damages (or benefits) should first be described in physical terms. This might include morbidity, mortality, impacts on IQ, or other impacts. It is useful to present physical impacts (when appropriate) by age, gender, and the geographic region in which they occur. When valuing these impacts, it may be prudent to present both conservative estimates of damages—e.g., estimates of the costs of illness associated with morbidity and earnings losses associated with premature mortality—as well as what economists call welfare benefits, which include what people would pay to reduce both the monetary and nonmonetary costs of illness, such as pain and suffering.

When estimating welfare benefits, such as what people would pay to reduce their risk of dying, it is often necessary to transfer estimates from other countries to the country where the CBA is being conducted—that is, to use benefits transfer. Benefits transfer (Johnston and Rosenberger 2009; Czajkowski et al. 2017) refers to using analyses, data, or results from one setting to apply to another setting or context. A widely practiced benefits transfer is to apply a value of statistical life (VSL) estimated from one country, such as the United States, adjusted for income differences, to an analysis in a country that does not have studies estimating the VSL for its own population. Multicountry comparisons of the burden of disease and health impacts of pollution (Narain and Sall 2016; Landrigan et al. 2018) use such income elasticities to make these transfers.

One way to avoid monetizing the benefits of a policy, especially when they can be expressed using a single metric, such as lives saved or DALYs avoided, is to use cost-effectiveness analysis (CEA). CEA divides the costs of the policy by a measure of effectiveness, such as lives saved, to obtain a cost per life saved. When computed for different options of an action or across several actions, one looks for the option with the lowest cost per effectiveness metric. This is consistent with a Eurocentric point of view that starts with setting targets for environmental improvements and then seeks to meet those targets at the lowest possible cost.

But this focus comes with several disadvantages. The main advantage of CBA is that it provides the net benefits of an action. Actions with positive net benefits improve social welfare—in other words, the efficiency of the allocation of resources. CEA lacks this normative element, although cost-effectiveness targets or benchmarks appear in the literature, along with the recommendation to reject options that fail to meet the target. But such targets are generally arbitrary. The second disadvantage is the construction of the effectiveness measure. Government actions usually deliver benefits over a number of physical endpoints, such as premature deaths and a variety of morbidity effects. Standard practice is to pick the most important endpoint as the effectiveness measure, but this leaves out the other endpoints. Seen in this light, the advantage of a CBA is that all the endpoints, in principle, are included, weighted by their monetary value. When a policy, action, or rule has one major metric, such as CO_2 emissions, and targets are set for that metric, then CEA can be used to identify the lowest-cost way to meet the target.

The rate of return (ROR) on investment is another popular metric. The rate of return is calculated to be consistent with the interest earned (i.e., the benefits realized) from costs "invested" in the policy. This type of metric may appeal to finance ministries more than a CEA or net benefit metric, but it is just another way of expressing net benefits. A further advantage is that the ROR on a government action can be readily compared with that of private projects or returns on financial investments, such as bonds, to help benchmark the efficacy of government actions.

Another issue is whether, and how, to communicate uncertainties in an analysis. It is a perennial complaint in reports from the U.S. National Academy of Sciences that government CBAs should do more to address uncertainties in benefits and costs (Abt et al. 2010). EPA's Council for Regulatory Environmental Modeling (CREM) has initiated several projects with implications for the treatment of uncertainty in regulatory impact analysis (RIA), such as a draft guidance document on environmental models (Gaber et al. 2009), an online Models Knowledge Base, and a series of regional seminars.

The first question an analyst must address is whether to present uncertainties in damages (benefits) and costs at all because of the complexities this adds to the narrative. The alternative is to present only best estimates, or perhaps to present uncertainty analyses in appendixes, where they can be ignored if desired. The latter approach emphasizes the analyst's best judgment but forecloses the judgment of the decisionmaker over uncertain outcomes. For instance, it is sometimes observed that decisionmakers are risk averse, meaning, by one interpretation, that they want to make the decision on the basis of a worst-case set of assumptions or forecasts. Such an approach is foreclosed unless uncertainty distributions are provided.

If uncertainties are to be presented, the next question is which type of uncertainties. There are both quantifiable uncertainties, which include statistical and model uncertainties, and unquantified uncertainties, which can be described qualitatively. A useful set of qualitative descriptors is provided by the Intergovernmental Panel on Climate Change (IPCC; Mastrandrea et al. 2010).

Statistical uncertainties refer to the error bounds around estimated relationships; these can also be error bounds around collections of study results, as in a meta-analysis. Model uncertainties refer to differences in results from different approaches taken to a problem. For instance, a concentration-response relationship could be estimated using a variety of assumptions for the shape of that relationship. While the results from each assumed shape (e.g., linear, log-linear, quadratic) can be described with their statistical errors, the differences in results across these assumed shapes can be described as model uncertainty.

Given that uncertainties of various types are to be presented, another question is in what form they should be presented. This issue is taken up below in the section on "How to Communicate to Decisionmakers."

4.3. With Whom to Communicate

Our interviews reveal that when groups outside of government are performing CBAs and other analyses, a local champion—a person with credibility and access to the senior decisionmakers relevant to the analyses in question—is needed.

Even so, based on our own experience, we have found that it is far easier to gain access to the top bureaucrats (i.e., civil servants) than to the political appointees at the top of an agency. The top bureaucrats typically have long tenures and are therefore more likely to be in networks both inside and outside the government. They also tend to be more technically oriented than their political bosses and thus more skilled at understanding analyses. In addition, such civil servants will rise to positions of importance in an agency precisely because they are good at communicating to political appointees above them. Depending on the government's norms, such top bureaucrats may also be able to consult on outside projects.

CBAs are often performed within agencies, as well. For instance, the US government requires that all major proposed and final rules be accompanied by a RIA, which includes a CBA. Trained economists often develop the RIAs and have direct access to the top civil servants and political appointees in their agencies. Access to ultimate decisionmakers may be limited, however, particularly for major controversial actions that are decided at the highest levels of the government.

Government decisionmakers are, of course, not the only group with which to communicate. Legislators who may be writing bills on the topic are an equally important audience. And public opinion, particularly in democratic systems, can provide leverage for implementing a policy. Thus a media strategy may be needed. Our interviewees recommended op-eds and news stories using various digital media platforms and covering all the major languages in a country. Meeting local editors will aid in getting pieces published, as will coauthoring such pieces with local champions of the work or local writers.

4.4. When to Communicate

For in-house CBAs, governments with extensive administrative procedures will have schedules for making the rules (whether in proposed or final form public, schedules for developing CBAs for rules or other actions, and possibly opportunities for public comment, setting their scheduling vis-à-vis the overall regulatory process.

Institutions or individuals offering analyses from outside the government should want those analyses made available as early in the regulatory process as possible to help shape decisions. But not all analyses are of single rules or actions. For instance, the Copenhagen Consensus Center (2017) offers estimates of the return on investments for a large list of possible actions a government could take. Such analyses are designed to help a government set priorities. Thus ideal timing for these priority-setting CBAs is at the start of new government leadership that is seeking to set its priorities or when new planning cycles begin, such as China's Five-Year Plans. Our interviewees advise that one avoid releasing and pushing such analyses in the lead-up to a leadership change, as the work and findings could become politicized or simply get lost in the politics leading up to an election or other political transition.

4.5. How to Communicate to Decisionmakers

We have already discussed some of the technical issues in communicating analytical information to policymakers evaluating prospective government policies, actions, and rules. This section provides some conclusions about communicating complex analyses to decisionmakers.

The form of the information, the relevance of the material to the expressed interests of the decisionmaker, and the uncertainty tied to the findings are all aspects to consider when addressing decisionmakers. While relevance can seem self-evident from the point of view of the scientist, the manner in which the information's importance is conveyed can influence the decisionmaker's acceptance of the information. Research in the medical field on translating scientific discoveries into public policy has highlighted the importance of getting the attention of and evoking interest in policymakers in order to convey significance (Brownson et al. 2018). One study emphasizes the effectiveness of story-focused briefings based in evidence and personalized in context, as compared with data-focused briefings, in getting policymakers to grapple with the relevance of a discovery in certain scenarios (Brownson et al. 2011).

4.6. Uncertainty

Much of the literature covers communicating about uncertainties. This section is based on Krupnick et al. (2006). Although a great deal of research has been conducted on the communication of uncertainty and risk, little attention has been focused on the means of communicating the results of such analyses to policymakers. Instead, the orientation has been toward understanding how to present uncertainty to lay audiences and help them put low-probability risks in appropriate context. The issue of communicating uncertainties associated with climate change to policymakers has been garnering increasing attention, with a focus on high-consequence outcomes (Webster 2003). But the issue of communicating uncertainty in a typical regulatory decisionmaking process remains less unexplored (van der Bles et al. 2019).

Experiments on the interpretation of standardized uncertainty language in IPCC reporting by nonprofessional participants suggest that jargon and discrepancies in understanding of probabilities are significant obstacles in disseminating uncertain information to those outside of the academic arena (Patt and Schrag 2003; Budesen et al. 2009). One study by van der Bles et al. (2019) proposes that while potential sources of uncertainty can be broadly broken into four categories—sample variability, measurement inadequacy, knowledge limitation, and expert disagreement—the independent effects of these different sources of uncertainty on audience understanding are not yet understood. Further, the issue of communicating uncertainty specifically in the regulatory decisionmaking process is underexplored.

Psychological research on decisionmaking under uncertainty has uncovered numerous instances in which decisions are influenced simply by the manner in which a problem is presented. Because decisionmakers (and even experts) are just as susceptible to these cognitive biases as the general population, the data analyst's choice of presentation format could influence a policymaker's decision. Furthermore, some evidence suggests that as the emphasis on uncertainties increases, so does the probability that decisionmakers will lose confidence in the overall analysis.

Ways to convey the importance of uncertain variables is one emerging area of interest. Some research has emphasized that the most effective means of communicating information and the associated uncertainties is largely dependent on the type of decisions facing the decisionmaker regarding the topic (Fischhoff and Davis 2014). Research on the effectiveness of different graphic techniques in communicating uncertainties has demonstrated that box-and-whisker plots, probability density functions, and cumulative density functions perform relatively well in allowing a well-educated audience to accurately extract quantitative information. Beyond standard tornado graphs, novel approaches such as radar graphs, cobweb plots, and pairwise scatterplots offer ways to present large amounts of information in an economical manner, although these approaches might be too complex for a nontechnical audience. Area and volume presentations can be misleading and cause viewers to underestimate large magnitudes and thus should be avoided.

We conducted in-depth interviews with seven former EPA assistant or deputy administrators in which we presented the basic results of the case study we conducted on tightening the US cap on power plant NO_x emissions. Using alternative metrics and graphics, we then solicited their opinions about these presentations. From their responses, a number of observations can be made. First, the interviewees were rather heterogeneous in backgrounds and in their interest in and familiarity with uncertainty assessments. This heterogeneity no doubt led to differences in the ease with which they interpreted alternative metrics and graphics portraying the results of our case study. Therefore, we found it difficult to generalize about the techniques used and challenges encountered in communicating these types of results. Nevertheless, even with the limited sample, interviewees were most comfortable with the use of probability density functions (PDFs) and simple tabular formats, rather than the complex graphics more commonly used by analysts (and favored by us), such as box-and-whisker plots, cumulative density functions, and circle charts. We conjecture that as the number of variables considered increases, the box-and-whisker plot would be increasingly useful and the PDFs less so.

Beyond PDFs and simple tabular formats, the former decisionmakers also favored other graphics. For example, they were particularly interested in the graphic displaying the relative importance of the various factors considered in the uncertainty analysis (Figure 1). On several occasions, they specifically asked about relative importance even before the graphic was presented. The interviewees also were interested in identifying any factors for which uncertainty might be an important issue but that had been excluded from formal uncertainty analysis.

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6. Tables and Figures

Figure 1. Relative Importance of the Factors Considered in the Uncertainty Analysis

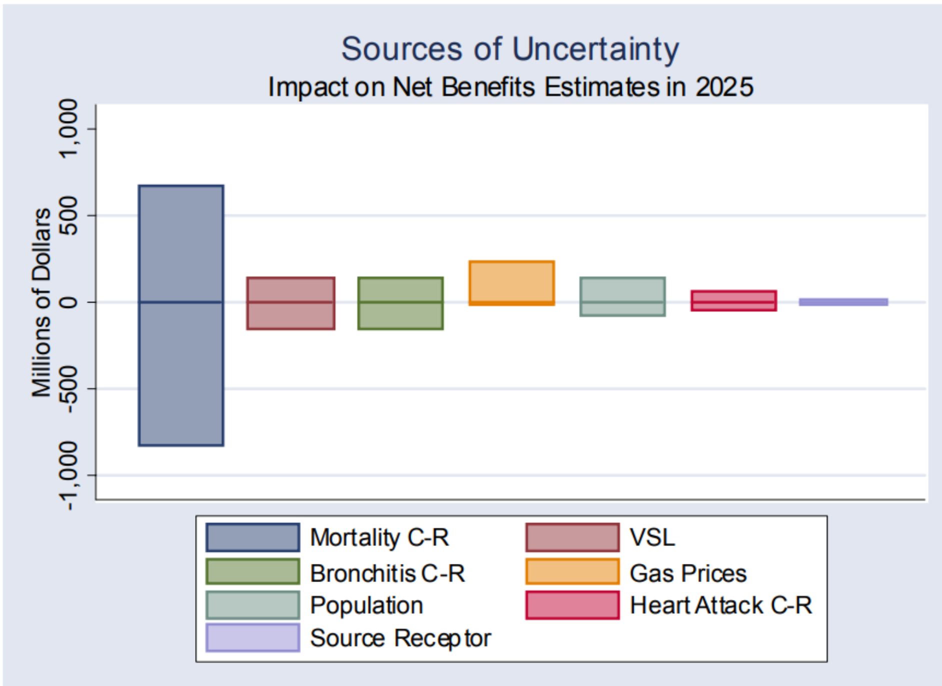

Table 1. Examples of Extrapolated VSL Estimates Using an Income Elasticity of 1.5 to Transfer the US VSL

	GNI per capita (2015 international dollars)					
Approach	$1,000	$5,000	$10,000	$15,000	$20,000	$25,000
Reference VSL = $9.4 million Elasticity = 1.5	$0.021 million (21*GNI per capita)	$0.24 million (48*GNI per capita)	$0.67 million (67*GNI per capita)	$1.2 million (83*GNI per capita)	$1.9 million (95*GNI per capita)	$2.7 million (110*GNI per capita)

Source: Robinson et al. (2019a).

Table 2. Productivity Losses as a Percentage of GDP by Pollutant and Income Group

World Bank Income region	World Bank Income region	UW and US combined[a]	Lead exposure	Total
High income	0.044% (0.048%)	0.0028% (0.0033%)	0.0027% (0.0029%)	**0.050% (0.054%)**
Upper-middle income	0.13% (0.15%)	0.019% (0.027%)	0.0054% (0.0059%)	**0.15% (0.18%)**
Lower-middle income	0.32% (0.40%)	0.28% (0.40%)	0.012% (0.013%)	**0.61% (0.82%)**
Low income	0.62% (0.86%)	0.70% (1.03%)	0.012% (0.013%)	**1.33% (1.90%)**
World	**0.092% (0.11%)**	**0.033% (0.047%)**	**0.0042% (0.0046%)**	**0.13% (0.16%)**

Source: Landrigan et al. (2018).

Note: Results in parentheses discount future output at the rate of growth in per capita GDP plus 1.5%. Base case results (those without parentheses) discount future output at the rate of growth in per capita GDP plus 3%.

[a] Includes no handwashing with soap.

Table 3. Welfare Damages in Billions of Dollars and as a Percentage of GNI by Pollutant and Income Group (2015 US$)

World Bank Income region	World Bank Income region	UW and US combined[a]	Lead exposure	Total
High income	1,691 (3.52%)	159 (0.33%)	303 (0.63%)	**2,153** **(4.48%)**
Upper-middle income	1,691 (8.37%)	89 (0.44%)	118 (0.59%)	**1,898** **(9.40%)**
Lower-middle income	367 (6.38%)	143 (2.49%)	28 (0.49%)	**538** **(9.36%)**
Low income	18 (4.83%)	12 (3.30%)	0.740 (0.20%)	**31** **(8.33%)**
Total	**3,767** **(5.06%)**	**404** **(0.54%)**	**451** **(0.61%)**	**4,622** **(6.21%)**

Source: Landrigan et al. (2018).

Note: Results in parentheses discount future output at the rate of growth in per capita GDP plus 1.5%. Base case results (those without parentheses) discount future output at the rate of growth in per capita GDP plus 3%.

[a] Includes no handwashing with soap.

Appendix A. Measurement of Output Losses due to Pollution

This appendix describes methods for measuring output losses associated with pollution morbidity (years lived with disability, or YLDs) and mortality (deaths associated with pollution) in a given year (e.g., 2017), following the human capital/cost-of-illness (COI) approach. It is assumed that the user has YLDs and premature deaths associated with pollution by age. Premature mortality is often measured using years of life lost (YLLs); however, the human capital approach calls for valuing the present value of output loss associated with each death, which will vary with age at death, rather than valuing YLLs. Valuing disability-adjusted life years (DALYs) using the human capital/COI approach thus calls for valuing YLDs and premature deaths separately.

The present value of lifetime earnings for a person of a given age represents the output lost if the person dies prematurely. It can also be used to value the impact of a decrement in IQ, if the loss in IQ points is expressed as a percentage reduction in earnings. This is discussed in section A.4.

A.1. Output Losses Associated with Pollution Mortality

We begin by estimating the present discounted value of the loss in gross domestic product (GDP) attributable to mortality associated with pollution in 2017. The loss in GDP in country i in 2017 if a worker dies is equal to labor's share of GDP (α) multiplied by GDP (Y_i), divided by the number of persons who are employed (L_i). We assume that workers of all ages in a country produce the same output per worker. Because not all persons of age j are working, the expected value of GDP per worker for a person of age j (W_{ij2017}) is equal to ($\alpha Y_i/L_i$) times the ratio of the number of workers of age j, L_{ij}, to the population of age j, N_{ij},

$$W_{ij2017} = (\alpha Y_i/L_i)*(L_{ij}/N_{ij}) \qquad (1)$$

In our calculations below, we assume that labor's share of GDP (α) is constant over time. We also assume that the ratio of L_{ij}/N_{ij} remains constant over time.

To calculate the loss in market and nonmarket output in 2017, we modify equation (1) to allow for household production. The US Bureau of Economic Analysis estimates that household production equals 25 percent of GDP (BEA 2019). The comparable estimate for Ghana is 35 percent (Ofosu-Baadu 2015) and for India is 30 percent (Pandey 2001). We therefore calculate W'_{ij2017} as

$$W'_{ij2017} = (\alpha Y_i/L_i)*(L_{ij}/N_{ij}) + \lambda_j(\alpha Y_i/L_i)*[1-(L_{ij}/N_{ij})], \quad (1')$$

where λ_j represents the fraction of output attributable to nonmarket production for a person of age j. For children and the elderly, $(L_{ij}/N_{ij}) = 0$, so the first term in (1') is zero. We also assume that nonmarket output is zero for children and the elderly. This implies, for example, that $\lambda_j = 0$ for $j < 15$ and $j > 84$, and $\lambda_j > 0$ for $10 < j < 85$.

If a person of age j dies in the current year, her contribution to GDP will be lost for all future years of her working life. To compute the value of GDP lost in future years, we assume that GDP per worker in country i grows at rate g_i. If labor's share of GDP and the fraction of population of working age (L_{ij}/N_{ij}) remain constant for all i and j, this implies that lost GDP at age t of a person currently of age j will equal $(\alpha Y_i/L_i)*(L_{it}/N_{it})*(1+g_i)^{t-j}$. This must be weighted by the probability that an individual would have survived to age t, where $\pi_{ij,t}$ is the probability that a person of age j in country i survives to age t. We therefore weight the loss in GDP in future years by the probability that an individual who dies this year would have survived to each future year of his working life. We discount the value of GDP lost in the future at the annual rate r_i.

Given the previous assumptions, the present discounted value of lost market and nonmarket output for a person of age j in country i who dies in 2017, PV_{ij}, is

$$PV_{ij} = \sum_{t=j}^{84} \pi_{ij,t} \left[\left(\frac{L_{it}}{N_{it}}\right)\left(\frac{\alpha Y_i}{L_i}\right) + \lambda_t \left(1 - \frac{L_{it}}{N_{it}}\right)\left(\frac{\alpha Y_i}{L_i}\right) \right] \left(\frac{1+g_i}{1+r_i}\right)^{t-j}. \quad (2)$$

In practice, equation (2) would be calculated for $j = 0, \ldots, 84$. The value of λ_t would presumably equal 0 for small children (e.g., $t = 0, \ldots, 14$) and would be set equal to a positive value (e.g., 0.3) for larger values of t.

The total output lost due to pollution is the product of PV_{ij} and D_{ij}, the number of deaths due to pollution in 2017 of persons of age j in country i, summed over all j.

A.2. Output Losses Associated with Pollution Morbidity

We compute the lost output due to morbidity associated with pollution in 2017 by multiplying the number of YLDs associated with pollution in 2017 by the expected loss in output per person, which is given by equation (1'). YLDs associated with pollution are assumed to be available by country *i* and age *j*, YLD_{ij}. The output loss associated with morbidity in 2017 for persons of age *j* in country *i*, M_{ij} is given by

$$M_{ij} = W'_{ij2017} * YLD_{ij} . \qquad (3)$$

A.3. Data

To compute GDP per worker, gross domestic product (Y_i) (World Bank 2019) is divided by the size of the labor force in country i (L_i) (World Bank 2019) to compute (Y_i/L_i). Labor's share of GDP (α) can be obtained from Penn World Table (Feenstra et al. 2015) or the International Labour Organization (ILOSTAT 2019).

Other parameters that vary by country include the ratio of worker to total population and survival rates. The ratio of worker to total population (L_{ij}/N_{ij}) for each country and age group can be obtained from ILOSTAT (2019). Because only aggregate data are reported for ages 65 and older, (L_{ij}/N_{ij}) can be estimated for each age over 65 by assuming that the worker-population ratio declines linearly from age 65 to age 85, becoming zero at age 85. The annual survival rate from age j to age t in each state, $\pi_{ij,t}$, can be computed from life tables provided by the Global Burden of Disease Study (GHDx 2019).

The present value of lost output depends on the rate of growth in output per worker (g_i) and the discount rate (r_i). As equation (2) indicates, it is the ratio of $(1+g_i)/(1+r_i)$ that determines the present discounted value of future earnings. Determining appropriate values of r_i and g_i for each country is difficult. Should this not be possible, a default is to use the assumptions underlying the Lancet Commission report (Landrigan et al. 2018)—in other words, that the discount rate exceeds the rate of growth in output per worker by (a) 1.5, (b) 3.0 percentage points. This implies that the term $[(1+g_i)/(1+r_i)]^{t-j}$ in equation (2) is replaced by $[1/(1+d)]^{t-j}$, where d = .015 or .03.

A.4. Valuing Output Losses due to Reductions in IQ

An extensive literature links the impact of lead exposure in children to IQ loss (see main text) and values the loss in IQ by its impact on lifetime earnings. If the total impact of the loss of one IQ point is to reduce lifetime earnings by, for example, 1 percent, then the present value of lifetime earnings (equation (2)) can be multiplied by .01 times the number of IQ points lost. An important question is the timing of the earnings loss. One approach is to calculate the loss discounted to the beginning of an individual's working life (i.e., to age 15). Exposure to lead may, however, occur earlier (e.g., between ages 0 and 7), which raises the question of whether the earnings loss should be discounted to the time of exposure. Attina and Trasande (2013) discount lifetime earnings to age 5.

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Appendix B. Willingness to Pay to Avoid Premature Mortality

B.1. Methodology

The willingness-to-pay (WTP) approach captures individuals' preferences for avoiding increases in risk of death by analyzing their behavior in risky situations (the revealed preference approach) or in hypothetical choice situations involving changes in their risk of death (the stated preference approach) (Cropper et al. 2011). An example of the former approach is a labor market study of jobs with different mortality risks, in which the analyst uses knowledge of those different risks and the wages that different jobs command to derive a wage premium (the willingness to be paid) for bearing extra risk (Viscusi and Aldy 2003). A good example of the latter is a survey that asks participants to choose among several hypothetical situations where mortality risks can be reduced at a cost (Lindhjem et al. 2011).

Either of these approaches yields values consistent with the centrality of individual preferences in modern welfare economics, in contrast to the human capital approach discussed in Appendix A, which is regarded as embedded in WTP values. The amount that a person would pay (or accept) in exchange for a small change in risk of death should reflect losses in output when the individual dies—losses that may exceed the person's contribution to gross domestic product (GDP). WTP should also reflect the utility received from living and should therefore exceed the value of output losses.

The value of mortality risk reductions is typically expressed in terms of the value per statistical life (VSL)—the sum of what people would pay for small risk reductions that sum to one statistical life saved. To illustrate, if each of 10,000 people were willing to pay $25 over the coming year to reduce their risk of dying by 1 in 10,000 during this period, on average, one statistical life would be saved and the VSL would equal $25 × 10,000, or $250,000. To evaluate WTP to reduce risk of death by 1 in 10,000, one would multiply the VSL by .0001.

A large body of literature has used revealed and stated preference approaches to estimating the VSL, primarily in Organisation for Economic Co-operation and Development (OECD) countries but also in middle-income countries (Lindhjem et al. 2011; Hammitt and Robinson 2011). Because many countries have no studies representing preferences of their population toward reducing risk of death, analysts typically transfer estimates from one country (a base country) to other countries, adjusting for differences in per capita income (Hammitt and Robinson 2011). This adjustment is made using the following equation, where Y denotes per capita income and ε denotes the elasticity of the VSL with respect to income:

$$VSL_{Transfer} = VSL_{Base} * (Y_{Transfer}/Y_{Base})^{\varepsilon} \quad (B.1)$$

The base value is typically selected based on VSL values in OECD countries. In the Lancet Commission report (Landrigan et al. 2018), a base VSL was selected based on a meta-analysis of stated-preference studies reported by the OECD (2012). This meta-analysis forms the basis of the VSL used by the OECD for policy analysis and is also the basis of VSL transfers by the International Monetary Fund in its computation of health-based fuel taxes (Parry et al. 2014). It is the same baseline value used in the Institute for Health Metrics and Evaluation (IHME)–World Bank study The Cost of Air Pollution (World Bank 2016). The base VSL is $3.83 million 2015 international dollars. In a recent Gates Commission study (Robinson et al. 2019), benefits transfers were based on the US Environmental Protection Agency's (EPA's) VSL of $9.4 million 2015 US$ (equivalent to $9.4 million 2015 international dollars). In transferring the VSL to other countries, per capita income is usually measured in international (i.e., in purchasing power parity, or PPP) dollars. This implies that the VSL is also measured in PPP terms.

What income elasticity (ε) should be used in transferring the base VSL? The elasticity of the VSL with respect to income (ε) represents the percentage change in the VSL for a 1 percent change in income (Y). If the VSL were proportional to income (i.e., if ε = 1), then the ratio of the VSL to income (Y) would be the same in all countries. Using the OECD VSL as a base value implies a ratio of VSL/Y of ~ 96:1. Studies in low- and middle-income countries (LMICs), however, suggest that the ratio of the VSL/Y falls as per capita income falls (Hammitt and Robinson 2011), implying a value of ε > 1.

The exact value of ε to be used should be guided by information on the VSL/Y ratio at different income levels. The ratio of the VSL to income, divided by 100, represents the fraction of income that would be given up for a 1 in 10,000 reduction in risk of death. EPA's VSL implies that a 1 in 10,000 reduction in risk of death is worth 1.6 percent of income; the OECD value implies that it is worth 1 percent of income. Well-executed studies of the VSL in LMICs imply that the ratio of the VSL to per capita income falls as per capita income falls. To achieve a target value of the VSL/Y at a particular income level, the value of ε must increase with the size of the base VSL. The Lancet Commission report used a value of ε = 1.2 in transferring the OECD VSL to low- and low-middle-income countries. The Gates Commission report (Robinson et al. 2019), using the EPA VSL as a base, recommends a value of ε = 1.5.

B.1.1. Treatment of Age

Both the Lancet Commission (Landrigan et al. 2018) and Gates Commission (Robinson et al. 2019) reports use the same VSL irrespective of age at death and use the same VSL for children as for adults. The age distribution of deaths associated with pollution varies widely, raising the question of whether the same VSL should be used to evaluate the deaths of children and the elderly, who lose very different numbers of life years. There is limited and contradictory evidence that VSLs are lower for elderly people than for younger adults (Krupnick 2007). In the case of children, the VSL should be based on parents' WTP to reduce their children's risk of death. There is a growing literature on parents' WTP; however, it consists primarily of studies in high-income countries (Alberini et al. 2010). Because of the lack of studies in low- and middle-income countries and differences in child mortality between high- and low-income countries, we do not recommend transferring studies of parents' WTP to reduce child mortality to low- and middle-income countries.

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