Economic Damage Costs for Nine Human Health and Environmental Impacts

Prepared for:
Oregon Department of Environmental Quality and Oregon Metro

State of Oregon
DEQ Department of Environmental Quality

Metro

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Final Report, July 2020

Acknowledgements: This report was substantially improved in accuracy, content and presentation by commentary, suggestions and edits from the Oregon Department of Environmental Quality-Oregon Metro review team and SRMG staff. Individuals involved were, in first name alphabetical order, David Allaway, Justin Gast, Luis Sandoval, Peter Canepa, Rosalynn Greene, and Shelley Morris. The author bears responsibility for any remaining errors or misinterpretations of information or estimates found in cited references.

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Oregon Metro (Metro), with financial assistance from the Oregon Department of Environmental Quality (DEQ), contracted with Sound Resource Management Group, Inc. (SRMG) to prepare a limited review of the literature estimating economic damage costs for nine human health and environmental impacts caused by releases of polluting chemicals and other harmful substances into air, water and onto land. SRMG was instructed to develop low and high estimates for damage costs based on its review of the literature. In total, SRMG reviewed more than 50 government documents, articles in professional journals, and other documents that seemed likely to contain estimates of damage costs for human health and/or environmental impacts from pollution. The 33 listed in this report's Bibliography section were used in developing low and high damage costs estimates for each of nine human health and environmental impacts.

Genesis for this project can be found in *Materials Management in Oregon - 2050 Vision and Framework for Action*, a state plan adopted by the Environmental Quality Commission in 2012. It is also consistent with Governor Kate Brown's more recent Executive Order 20-04, which states ". . . to the full extent allowed by law, agencies shall consider and integrate . . . *climate change impacts* . . . into their planning, budgets, investments, and *policy making decisions*." (emphasis added)

The 2050 Vision goes beyond climate impacts from greenhouse gas (GHG) pollutants to characterize costs of pollution in general that are not included in prices for goods and services used and consumed today. Specifically, the Vision states that today, "Prices do not reflect full environmental impacts, and full information is not available on all environmental impacts…the public bears the 'external' costs of environmental impacts." And, "Subsidies encourage some consumption, and product prices do not reflect their full costs, including environmental impacts." Furthermore, "Disposal and recovery prices do not reflect indirect and opportunity costs."

The Vision describes a desired future where, in terms of upstream supply chain costs, design costs and production costs for goods and services, "Responsibility is shared for full life cycle impacts. . .Prices reflect environmental and social costs." And, "Public policies support sustainable materials management at product end-of-life. All prices, including recovery and disposal prices reflect full costs. . ." Also, "Full life cycle costs are internalized into prices, so lower cost is yet another benefit of greener products."

Additionally, the 2050 Vision suggests actions that include:

- "Perform research on product and disposal prices to determine environmental and other potential costs not reflected in prices; develop tools, methods, and standards for determining full costs."
- "Adopt a DEQ policy to include environmental costs in internal department decisions."
- "Increase recycling collection opportunities in Oregon. . ." This includes 'reviewing the definition of 'recyclable material' to consider other costs not reflected in recycling and disposal prices. . . "

Today, however, entities producing pollution may not have to pay for some or all of the damages caused by their releases of pollutants to the environment. In that case, the costs for damages will be reflected in:

- Higher health care costs for humans impacted by those pollutants
- Lower property values
- Lower agricultural productivity
- Damages to wildlife habitats
- Lower plant and tree growth
- Other dis-amenities imposed in the fallout zones of pollutant releases.

From the perspective of conventional economic theory, the problem for a free-markets-based economy is that, if the entities producing pollution associated with a good or service do not pay full costs for their pollution, that good or service will be sold at a price that does not cover these human health and other environmental damage costs. That, in turn, may cause more of society's resources to flow toward production and consumption of this good or service than would be the case if the price for that good or service included these human health and other environmental damage costs.

One might regard these situations as free disposal of pollutants to air, water and land. Economists refer to these damages as external costs. Estimating externalized economic damage costs from releases of pollutants to the environment is a step toward fulfilling Oregon mandates and goals for policies and prices to reflect full consideration of environmental costs. This project's goal is to research and characterize externalized damage costs, also known as impact monetization factors, for nine categories of environmental impacts, including:

- Climate change
- Human respiratory disease and death from particulates
- Human disease and death from toxics
- Human disease and death from carcinogens
- Eutrophication
- Acidification
- Aquatic ecosystems toxicity
- Ozone depletion
- Ground level smog formation

All nine of these categories are defined and addressed later on in this report.

Based on damage cost estimates extracted from more than 30 studies, this report provides recommended values for low-end and high-end externalized damage costs for each of the nine environmental impacts, and reasoning for these recommendations.

A literature review summary data spreadsheet is available as supplemental information. The spreadsheet records damage cost estimates, and indicates methodology highlights, as well as strengths and challenges for most of the references reviewed for each environmental impact category.

I. Environmental Impacts and Their Reference Substances

There are thousands of harmful substances involved in the production, consumption, and waste management activities associated with goods and services. Some of these substances are released to the environment during natural resource extraction and refining of energy and material inputs for manufacturing goods and services. Some are released during manufacturing, transportation and/or consumption of goods and services, while others are released during the handling, recycling, composting and disposal of wastes. Still other chemical and non-chemical harmful substances are created and released to the environment during activities, such as combustion for heat and power, which may accompany any of these stages in the life cycle of a good or service.

The challenge for researchers and scientists is that policy makers cannot readily assess environmental impacts when looking at a report listing releases of thousands of individual chemical and other harmful substances. Grouping pollutant releases into a small number of environmental impact categories provides a solution to this conundrum. This resolution is perhaps best illustrated with a simple example of how climate changing pollutants are aggregated into a single climate change impact factor. The pollutants that cause climate change are often labeled as greenhouse gases (GHGs).

The United Nations Intergovernmental Panel on Climate Change (IPCC) has helped to develop and popularize an index that defines, in one number, the amount of climate forcing emissions released into Earth's atmosphere each year. The climate forcing strengths of GHG pollutants are characterized in global warming potentials (GWPs) for each atmospheric pollutant that contributes to trapping of incoming solar radiation. GWPs are updated each time the IPCC produces a new Assessment Report.

Examples from the IPCC *2014 Fifth Assessment Report* (AR5) of GWPs for GHGs range from 1 for carbon dioxide (CO_2), 28 for methane (CH_4), and 265 for nitrous oxide (N_2O) up to 23,500 for sulfur hexafluoride (SF_6). These examples of GWPs represent each GHG's average climate forcing effect over the 100 years following their release.

GWPs express the climate forcing potential of any greenhouse gas relative to that of carbon dioxide. Using GWP weights, then, one can sum up the relative global warming potential of a profile of GHG releases from an activity or pollution source. This sum is termed carbon dioxide equivalents and is denoted by eCO_2 or CO_2E. It facilitates comparison of an activity's total GWP to any other activity's total GWP, provided one has a GHG emissions profile for both. For example, GWP weight summations allow comparison of the climate impact potential among alternative methods for producing the same product or material, or carrying out the same waste management system activity such as disposal via burying versus burning municipal solid waste (MSW) discards.

In a similar vein, The US Environmental Protection Agency (EPA) has developed TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), a tool that implements comparative impact potential and summary assessment indicators for human health and environmental impacts in addition to climate change. As of TRACI version 2.1, this tool provides characterization factors for the public health and environmental impacts of 3,944 chemicals and other substances. There are characterization factors for each of these 3,944 pollutants for each of the nine environmental impact categories whose damage costs are estimated in this report.

Many chemicals and substances have TRACI characterization factors of 0 for some impacts, meaning that they do not contribute to damages for those particular environmental impacts. For example, for climate change only 91 of the 3,944 TRACI chemicals and substances have GWP characterization factors greater than zero.

For climate change the TRACI characterization factors are IPCC GWPs which can be summed to carbon dioxide equivalents. For the other eight impact categories, TRACI's characterization factors are based on dialogues with, and among, researchers and scientists on the relative effects of each pollutant in comparison to other pollutants that have the same environmental impact. For each environmental impact category, besides climate change, one can select a particular pollutant to serve as the reference indicator for that category of public health and environmental impacts, just as carbon dioxide equivalents serve as the widely used climate impact potential indicator for GHG emissions. This means that all pollutants in each category are converted to the units of the reference indicator so that they can be added up to obtain the total impact of all pollutants causing that impact category's environmental damages.

The upshot here is that, given a pollution emissions profile for the life cycle of a product, material, MSW activity or other pollution emitter of interest, TRACI 2.1 provides impact potentials for nine different human health and environmental impacts. EPA researchers who developed TRACI were involved in a multinational harmonization collaborative that reviewed relative environmental impacts for chemicals and other substances that are characterized in TRACI. These characterization factors codify that any given pollutant may have more than one environmental impact, while at the same time avoiding double counting. Some pollutants, such as sulfur dioxide, cause more than one type of environmental impact. TRACI's nine categories assess mutually exclusive environmental impacts to mitigate the double counting issue.

For example, substances that are scored by TRACI 2.1 as having human respiratory impacts greater than 0 include filterable and condensable particulate matter, sulfur dioxide (SO_2), nitrogen oxides (NO_x), and total suspended particulates. These substances all have 0 characterization factor scores for human health impacts from carcinogenic and toxic substances. What might seem like a possibility for double counting is thus avoided using TRACI methodology for keeping impacts mutually exclusive.[1]

The nine environmental impacts whose damage costs were researched for this project, and the reference substance used for each are:[2]

- **Climate change** – the potential increase in greenhouse effects due to anthropogenic emissions. Carbon dioxide (CO_2) from burning fossil fuels is the most common source of GHGs. Methane from anaerobic decomposition of organic material is another large source of GHG effects. The reference substance for climate change potential is carbon dioxide. Pollutants that have climate impacts are characterized and converted by the TRACI model into carbon dioxide equivalents, eCO_2.
- **Human respiratory disease and death from particulates** – potential human health impacts from anthropogenic releases of coarse particles known to aggravate respiratory conditions such as asthma, fine particles that can lead to more serious respiratory symptoms and disease, and particulate precursors such as nitrogen oxides and sulfur oxides. Activities that are large sources of coarse and fine particulate emissions include combustion of fuels such as coal, wood, and petroleum diesel. Grinding, combusting, or otherwise processing municipal solid wastes also generates particulate emissions. The reference substance for human respiratory disease potential is particulate matter no larger than 2.5 microns, $PM_{2.5}$. Emissions of pollutants that have respiratory health impacts are converted into reference pollutant equivalences, $ePM_{2.5}$.
- **Human disease and death from toxics** – potential human health impacts (other than particulates' respiratory and toxics' carcinogenic effects) from releases of chemicals that are toxic to humans. There are many chemical and heavy metal pollutants that are toxic to humans, including 2,4-D, benzene, DDT, formaldehyde, permethrin, toluene, chromium, copper, lead, mercury, silver, and zinc. Examples of these pollutants' human toxicity effects include heart diseases, kidney failure, reproductive disorders, cognitive effects, and disruption of the endocrine system. The reference substance for human non-carcinogenic toxicity potential used for this research report is toluene. Emissions of pollutants that have human toxicity impacts are characterized and converted by the TRACI model into toluene equivalents, eT.[3]
- **Human disease and death from carcinogens** – potential human health impacts from releases of chemicals that are carcinogenic to humans. There also are many chemical and heavy metal pollutants that are carcinogenic to humans, including 2,4-D, benzene, DDT, formaldehyde, kepone, permethrin, chromium, and lead. The reference substance for human carcinogenic potential is benzene. TRACI aggregates the pollutants that have human carcinogenic impacts into benzene equivalents, eB.

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[1] More information on TRACI is provided in the following: Jane C. Bare, *Developing a Consistent Decision-Making Framework by Using the U.S. EPA's TRACI,* U.S. Environmental Protection Agency, Cincinnati, OH, 2002; Jane C. Bare, Gregory A. Norris, David W. Pennington and Thomas McKone, TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *Journal of Industrial Ecology* 2003, 6(3-4): 49-78; and Jane C. Bare, TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental Impacts 2.0. *Clean Technologies and Environmental Policy*, 2011, 13(5) 687-696, provide expositions on the original and more recent versions of the TRACI model.

[2] These nine environmental impact categories were chosen because they are widely used in life cycle assessments, are also used in the scientific literature that assesses damage costs from environmental impacts, and they match the impact categories used in TRACI 2.1.

[3] Toluene for human toxicity, benzene for human carcinogenic diseases and 2,4-D for ecosystem toxicity were used as reference substances in earlier versions of TRACI. TRACI now codifies human health cancer, noncancer, and ecotoxicity in terms of comparative toxicity units (CTUs) – CTU_{cancer}, $CTU_{noncancer}$, and CTU_{eco}, respectively. Damage costs for these three categories are converted from eB, eT and e2-4-D, respectively, and expressed in these CTU units in Table A2 of Appendix A.

- **Eutrophication** – potential environmental impacts from the addition of macro nutrients to soil or water resulting from emissions of eutrophying pollutants to air, soil or water. The addition to soil or water of mineral nutrients, such as nitrogen and phosphorous, can yield generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water, nutrient additions tend to increase algae growth, which can lead to reductions in oxygen and death of fish and other species. The reference substance for waterways eutrophication potential is nitrogen. Pollutants that have waterways eutrophying impacts are characterized by nitrogen equivalents, eN.
- **Acidification** – potential environmental impacts from anthropogenic releases of acidifying compounds, principally from fossil fuel and biomass combustion, which affect trees, soil, buildings, animals and humans. The main pollutants involved in acidification are sulfur, nitrogen and hydrogen compounds – e.g., sulfur oxides, sulfuric acid, nitrogen oxides, hydrochloric acid, and ammonia. The reference substance for acidification potential is sulfur dioxide and the pollutants that have acidifying impacts are characterized by sulfur dioxide equivalents, eSO_2.
- **Aquatic ecosystems toxicity** – the relative potential for chemicals released into the environment that harm aquatic ecosystems, including wildlife. There are many chemical and heavy metal pollutants that are toxic to ecosystems, including 2,4-D, benzene, DDT, ethyl benzene, formaldehyde, kepone, permethrin, toluene, chromium, copper, lead, silver, and zinc. The reference substance for aquatic ecotoxicity potential used in this research is 2,4-dichlorophenoxy acetic acid (2,4-D). Pollutants that have toxicity impacts to aquatic ecosystems are characterized by 2,4-dichlorophenoxy acetic acid equivalents, e2,4-D.
- **Ozone depletion** – the relative potential for chemical compounds released into the atmosphere to cause degradation of the Earth's ozone layer. The reference substance for ozone depletion potential (ODP) is trichlorofluoromethane, CFC-11, where CFC is the acronym for chlorofluorocarbon. CFC-11 is sometimes called R-11. Pollutants that have ozone depletion potential are characterized by trichlorofluoromethane equivalents, eCFC-11.
- **Ground level smog formation** – the relative potential for chemical compounds released into the atmosphere to react with sunlight, heat and fine particles to form ozone (O_3). For example, nitrogen oxides and volatile organic compounds (VOCs) released during fuel combustion are some of the chemical compounds that contribute to ground level smog formation. The reference substance for smog formation is ozone itself, and pollutants such as NO_x are characterized by TRACI as ozone equivalents, eO_3.

II. Damage Cost Estimates for Each Environmental Impact Category

For each of the nine human health and other environmental impacts described just above, Table 1 lists SRMG's recommendations for a low-end and a high-end externalized damage cost for the nine reference substances that characterize and summarize human health and environmental damages from harmful substances released to the environment. Costs shown in the table for climate change, acidification, ozone layer depletion, ground level smog formation, and human health respiratory effects are for general, not geographically specific, releases to the atmosphere. Costs for human health cancer and non-cancer effects are for releases to urban air. Costs for waterways eutrophication and aquatic ecosystems toxicity are for releases to freshwater. All costs listed in Table 1 are expressed in 2019 dollars.

TRACI 2.1 provides characterization factors for each of 3,944 harmful substances for each of the nine categories of environmental impact shown in the table. In addition, for human health cancers and non-cancers TRACI 2.1 lists geographically specific characterization factors for each pollutant. Atmospheric releases to urban air and to continental rural air are separately and differentially characterized, as are releases to continental freshwater and to continental sea water, and releases to continental natural soil and to continental agricultural soil. For aquatic ecotoxicity TRACI 2.1 also provides separate characterization factors for releases to the same six geographic and media specific combinations.

Appendix A provides a table that translates the low and high human health damage costs specific to urban air to the other five geographic locale and media release specifications. That table also translates the freshwater releases for ecosystems toxicity to the other five geographic locale and media release combinations. These translations depend on the assumption that the TRACI 2.1 characterizations factors for benzene, toluene and 2,4-D are accurate representations of how damage costs change when these substances are released to other geographic locale – release media specific combinations than were used for developing the damage costs shown in Table 1.

Table 1: Recommended Low - High Reference Substance Damage Costs for Nine Environmental Impacts

Impact Category (reference substance)	Low -- High Damage Costs per Metric Ton of Reference Substance (2019 $)
Climate Change (CO_2)	$114 -- $311
Human Health:	
Respiratory Effects from Particulates ($PM_{2.5}$)	$550,000 -- $664,000
Non-Carcinogenic Effects from Toxics (T)	$224 -- $462
Carcinogenic Effects from Toxics (B)	$1,814 -- $3,098
Waterways Eutrophication (N)	$20,090 -- $29,836
Acidification (SO_2)	$239 -- $584
Aquatic Ecosystems Toxicity (2,4-D)	$1,582 -- $6,785
Ozone Layer Depletion (CFC-11)	$37,288 -- 76,472
Ground Level Smog Formation (O_3)	$6 -- $483

SRMG's recommended damage cost ranges for impact categories are within the ranges of results identified by the literature, but narrower than those ranges. The reasons for narrowing the ranges are several. First, there are many factors that can influence the actual estimate of a damage cost developed in a particular study. Averaging damage costs from a number of studies and computing confidence intervals for the sample average is one method for eliminating the influence of random factors and measurement errors in individual studies. Confidence intervals are inevitably narrower than the range of damage cost estimates from individual studies. Second, SRMG expects that damage cost factors may be used in concert, that is, in a full life cycle assessment that evaluates scenarios against several, or potentially all, of the nine impact categories shown here. In such a case, the inclusion of the wide range of results for each of several impact categories may lead to widely overlapping damage cost estimates for the scenarios which will make difficult or actually confound the ranking of scenarios.

The methods and reasoning for each set of low and high damage costs displayed in Table 1 are, as follows:

- ***Climate Change*** -- Integrated assessment models (IAMs) are used by research agencies such as the U.S. Interagency Working Group on the Social Cost of Carbon (IWGSCC) and economists such as William Nordhaus of Yale University to estimate economic damage costs from climate change. IAMs such as the dynamic integrated climate-economy (DICE) model developed by Nordhaus assess current year carbon emissions damages for all years between this year and 2300. This long assessment timeline is because some GHGs released in the current year remain in the atmosphere for hundreds of years. Current, future and far-future damage costs from GHG emissions in the present are typically presented as dollar costs per metric ton of carbon dioxide emissions in the current year. These estimates are often called the social cost of carbon (SCC).

  Long lasting climate impacts from current GHG emissions raise the problem of how to compare climate change damages in the future against the cost of lowering GHG emissions in the present. Economists and others use discount rates to measure the present value of future damages to compare against the current cost of GHG emissions mitigations.

  The Ramsey equation – introduced by economist Frank Ramsey in 1928 – is often used in the climate change economics literature as one way to think about the considerable problems encountered in choosing an appropriate discount rate for computing the present cost of economic damages in future years caused by current GHG emissions. This equation for the discount rate in the situation of no uncertainty is:

  $$r + (h*g)$$

  - r = the pure rate of time preference (PRTP)
  - h = the income elasticity of marginal utility
  - g = the annual growth rate of GDP, income or consumption.

  PRTP is the markup one would need to be paid next year to give up income of some amount this year. The elasticity factor (h) is a measure of the change in one's satisfaction relative to the change in income as one's income level increases.

  The meta-analysis by Wang et al (reference 33) found the mean for r equal to 1.9% and the mean for h equal to 1.11. Estimates for long--term real average growth in consumption or GDP cluster around 2%. Together these estimates imply a discount rate of 4% or 4.25%.

  However, intense climate change could cause real growth to be lower. Also, there is much discussion in the economics literature regarding whether PRTP should be very low or even zero due to ethical considerations when positive PRTPs are used to discount income for future generations. Table 2 displays current year discount factors for 2050, 2100, 2200 and 2300 under several discount rates. These factors are multiplied by future year economic damage costs. This yields the present value in the current year for those future damages caused by current GHG emissions. Note how little economic damages from current year GHG emissions matter in farther out future years for present value calculations at even low discount rates.

  For example, at a discount rate of only 3%, $1 in damages in the year 2100 caused by GHG releases in the current year only has a present value of $0.09 today ($1.00 * 0.09 = $0.09). This could be interpreted to imply that it is only worth spending 9 cents on GHG reductions today to prevent each dollar of climate change damages in the year 2100 caused by GHG releases today.

Table 2: Discount Factors for Low and High Discount Rates

Discount Rate	Current Year Discount Factor for Damages in Year Indicated			
	2050	2100	2200	2300
7%	0.13	0.005	0.000005	0.000000006
5%	0.23	0.02	0.0002	0.0000012
3%	0.41	0.09	0.005	0.00025
1%	0.74	0.45	0.17	0.062

There is also discussion in the economics literature regarding small probability but high-cost catastrophic climate impacts in the future from carbon emissions today. Discount rates below 2% and perhaps as low as 1%, or discount rates that decline as number of years between the present and a future year go up, are suggested to resolve issues regarding generational equity and/or potential catastrophic economic impacts of current carbon emissions.

Based on SCC estimates found in our review of often cited literature on climate change damage costs, the recommended SCC range is to use $114 per metric ton (MT) for the low-end estimate of the SCC. This low-end SCC estimate is the sample average for SCC estimates found in the references listed in the supplementary information Summary Matrix.[4]

The recommended high-end is $311, which is a midpoint between the Nordhaus (reference 16) estimate of $268 for an SCC that assumes global temperature increases of 2.5^{o} C (and assumes a discount rate of 4.25%), and the midpoint ($354) of two other estimates: the Nordhaus (reference 16) estimate of $351 for SCC using *Stern Review: Economics of Climate Change* discounting and the Ackerman and Stanton (reference 1) estimate of $356 for SCC at a 1.5% discount rate.

SCC estimates at any given discount rate have tended to increase since initial studies that estimated them. This is because IAMs have become more accurate and comprehensive, and because of the lack of sufficient actions to limit climate change by countries around the world as yet. The increasing accuracy of IAMs is associated in part with the observation that some effects of climate change – such as the collapse of polar-region ice sheets and glaciers – are occurring faster and with greater intensity than earlier models predicted; additional years of observation have allowed scientists to recalibrate IAMs.

Many of the earlier estimates of SCC found in the literature evaluated damages assuming that temperature increases would be limited to 2^{o} C or less. Yet on the current business as usual trajectory of global emissions,

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[4] Damage cost estimates used in developing the low & high damage cost estimates for impacts, except for human health effects from particulates and ozone layer depletion, include several confidential estimates from a source that is not among the references listed and discussed in the Summary Matrix. When used as part of the sample of damage cost estimates, these confidential estimates were either within the range of estimates for the listed references, contained estimates of damages not otherwise encompassed in the listed references, or augmented estimates from what was otherwise a very small number of studies found in the literature on a particular impact's environmental damage costs. Two of the confidential estimates for smog formation were not used in calculating the low or high damage cost because they may have included double counting of human health costs reflected in the human health impact categories.

global temperature increase is now projected by the DICE IAM to exceed 2° C by 2050.[5] Future emissions produce larger incremental damages as biophysical and economic systems become more stressed in response to accumulating carbon concentrations in the atmosphere, due to lack of effective climate change abatement responses thus far from global societies. Put differently, the damages from an additional 1° C of warming are higher if the total increase is 3° C vs. 2° C. Thus, SRMG's recommended SCC values may yet still underestimate the actual social cost of carbon.

- ***Human Health Respiratory Effects from Particulates*** – There have been few comprehensive peer-reviewed studies on human health damage costs from emissions of particulates to the atmosphere. Reference (26), An EPA technical support document (TSD) published in 2013 (reference 26) is the most comprehensive and robust of studies reviewed. That reference incorporates U.S. geographic-region-specific damage cost estimates for 17 economic/industrial sectors for the human respiratory health cost of direct PM2.5 emissions. This study's estimates enabled SRMG to calculate a 17-sector weighted average cost, using as weights the direct fine particulate emissions from each of those sectors. The study data also enabled SRMG to compute confidence intervals for the average human health damage cost from $PM_{2.5}$ emissions.

  The weighted average ($550,000) and the high end ($664,000) of a 90% confidence interval (CI) seem appropriate for low-high monetized environmental costs of fine particulate emissions.[6] Using the low end of the 90% CI for the low seems inappropriate given the use of 3% discounting over the 12 years of human mortality and morbidity human health effects that will result from 2020 emissions. That is, there are issues regarding the ethics of discounting even near-term future human health costs, just as there are for long-term climate change economic damages from current GHG releases. Furthermore, as the economy grows and population increases, the number of human receptors and the fine particulates they breathe both go up. Using an estimate for emissions cost that is too low could lead to tendencies to use this same low estimate for future year emissions.

- ***Waterways Eutrophication*** -- The recommended low $20,090 and high $29,836 damage costs for eutrophication caused by deposition of one metric ton of nitrogen in surface waters is based on using the mean of the estimates in the studies as the low end and the upper end of the 90% confidence interval for the sample mean as the high end. Using the average of study estimates as the low end is justified on the basis that none of the studies provide costs for algae blooms in freshwaters or coastal waters from nitrogen loadings to surface waters either from direct emissions of nitrogen to water or of cascading nitrogen emissions to water from releases to air or land. Using the mean rather than a lower estimate may help account for this additional, but unknown nitrogen eutrophication cost. Using the sample mean 90% confidence interval upper endpoint also partially accounts for the high cost estimate for fisheries decline due to eutrophication provided in Compton *et al* (reference 4). None of the other references provided estimates for the cost of fisheries decline due to eutrophication of surface waters from releases of nitrogen. This apparently can be quite severe as the "annual dead zone" -- an area of low oxygen that kills fish and other marine life in the Gulf of Mexico at the mouth of the Mississippi River -- indicates.

- ***Human Health Non-Carcinogenic Effects from Toxic Pollutants*** – Toluene emitted to urban air is the reference substance for this category. It was used as the reference substance for human health non-cancer health effects

[5] See Figures 3 and 4, page 348 in reference 16.

[6] The human health cost per ton for fine particulate emissions is high for several reasons – (1) fine and ultrafine particulates are very small and light, so that a ton of particulates can have serious health impacts for a large population, (2) it doesn't take much particulate matter to have serious health consequences when inhaled by a person, and (3) particulate emissions are widely dispersed due to their generation from combustion of various materials and fuels by sources providing heat, energy and/or transportation services.

in earlier versions of the TRACI characterization factors matrix. Most references for human health - non-cancer impact costs gathered for this review base their cost estimates on mercury emissions to air, some of which deposit in water. Once in water, mercury works its way up the food chain to contaminate fish species that are consumed by humans.

Mercury impacts on human health are both neurological and cardiovascular. The latter is not as well studied, so the estimates of mercury's cardiovascular impacts are more uncertain. There are also uncertainties in health impact estimates that arise from observed mercury dose-health response estimates. Observations can measure health responses only down to the lowest level of observed doses. Hence, when extrapolating a dose-response relationship to an entire population exposed to mercury emissions one must decide whether to project observed dose-response relationships down to low and very low doses. This projection is necessary if one assumes that there is no low threshold mercury dose below which health impacts do not occur.

About half of the reviewed studies include estimates for cardiovascular health effects. The Northeast States for Coordinated Air Use Management (NESCAUM), (reference 14), provides separate estimates for both neurological and cardiovascular effects. This study estimates that about 95% of total costs for both are from cardiovascular effects. At the same time, the NESCAUM study's total impact cost is nearly three times as large as the total estimate for the U.S. in Giang and Selin (reference 9) published more recently. This disparity is indicative perhaps of the uncertainty regarding mortality and morbidity rates from cardiovascular effects of mercury exposure.

Based on these considerations and uncertainties, the recommended low end for toluene's human health - non-cancer effect is the sample mean, $224 per MT toluene emitted to urban air. The high end is the upper end of a 90% confidence interval, $462 per MT toluene emissions to urban air. These estimates provide a balance between the low cost and more certain neurological health effects and the much higher cost but more uncertain cardiovascular effects of mercury, as well as between the threshold versus no threshold effects of mercury exposure.

- ***Human Health Carcinogenic Effects from Toxic Pollutants*** -- Benzene emitted to urban air is the reference substance for this category. It was used as the reference substance for human cancer health effects in the earlier TRACI characterization factors matrix. Several studies reviewed for cancer damage costs were focused on heavy metals. Some heavy metals have both carcinogenic and non-carcinogenic impacts, and all six metals covered in the references for damage costs for human health carcinogenic effects have both according to TRACI 2.1. Unfortunately, reference (3) does not distinguish between cancer and non-cancer mortalities for cadmium, lead, or mercury. Rabl and Spadaro (reference 19) for all four metals examined in that reference and the Nedellec and Rabl (reference 13) estimate for arsenic do separate the damage costs for cancer from non-cancer impacts.

  The recommended low end for benzene's human health cancer effects is the sample average $1,814, assuming cadmium and lead mortalities are all non-cancer related. The recommended high end $3,098 is the 90% confidence interval upper end point for the sample mean. The sample mean and the 90% confidence interval upper end are recommended for benzene's low-high costs to account for the likely inclusion of cancer impacts from cadmium and lead in the cost of mortalities estimated in Nedellec and Rabl (reference 13). Unfortunately, that source does not provide a breakdown on the relative importance for cancers and non-cancers in their damage cost estimates for cadmium and lead. It is very unlikely that the reference (3) damage cost estimates for cadmium and lead are from only non-cancer impacts. Using the mean and the 90% upper end at least gives some weight to that likelihood.

It is also worth noting the substantial increase in carcinogenic damage costs for arsenic and cadmium between the estimates in Rabl and Spadaro (reference 19) published in 2000 and the estimates in Nedellec and Rabl (reference 13) published in 2016. Both studies had the same scientist Rabl as one of the co-authors. This is another example of the tendency for damage costs for environmental impacts to increase over time due to better and more comprehensive emissions data, better modeling of dispersion and exposure from emissions sources to population receptors, better data on health effects of exposure, and economic and demographic growth that tend to increase fugitive emissions quantities and numbers of people exposed to emissions.

- ***Acidification*** – Sulfur dioxide (SO_2) emissions were one target of the 1970 Clean Air Act (CAA), and more especially of the Acid Rain Program established under Title IV of the CAA Amendments of 1990. Under Title IV the EPA has regulated SO_2 emissions since 1993 using a cap and trade system of tradable emissions allowance permits. Beginning in 1993 EPA held an annual auction of these emissions permits in which generators of SO_2 that need additional emission allowances can buy permits from generators who own more allowances than they currently need. There has been a substantial decrease in the spot clearing price reached during EPA's annual SO_2 Emission Permit Auction over the past 10 years. Average prices in the spot auctions have dropped below $1/metric ton compared with nearly $400 /MT in the previous 10 years. Causes for this decrease likely include:
  - The decline in demand for coal-fired power
  - The Great Recession (2008-2009) which substantially reduced overall demand for energy in general
  - The availability of cheap natural gas due to fracking technology and the consequent decline in costs of natural gas-fired power
  - The continued growth of solar and wind power and their falling prices

  Although the spot auction prices represent abatement costs more closely than damage costs, their decline may be indicative of a decrease in SO_2 emissions. It seems reasonable to conclude that the ongoing costs per ton of acidifying sulfur dioxide emissions may be declining, except for the lack of estimates for damages from SO_2 releases on agriculture and forests. The low end of a 65% confidence interval for the sample mean (excluding the high average auction prices during 2001-2010) is $239. The high end of that 65% confidence interval is $584, again with high spot auction price years 2001-2010 excluded. This high end may help account for the lack of estimates in much of the literature for damage costs from forestry and agriculture impacts of SO_2 emissions.[7]

- ***Aquatic Ecosystems Toxicity*** – The recommended low and high damage costs from aquatic toxicity are $1,582 and $6,785 per MT of 2,4-D released to freshwater. The low is based on the low end of a 65% confidence interval for the sample mean of $6,967. The high end is the upper end of the 65% confidence interval. With very few studies found that provide damage costs for aquatic toxicity, the 65% confidence interval in this case may mitigate against underestimating or overestimating aquatic toxicity impacts, while also providing mitigation against the lack of data on aquatic ecosystem costs from pollutant releases.

[7] SRMG used a 65% confidence interval around the sample mean for those environmental impact categories where there appear to be trends in emissions and damage costs that could move in either direction from the sample mean. In order to maintain some similarity to the .65 probability width of those 65% confidence intervals, for some impact categories SRMG used the upper end of a 90% confidence interval to stretch the probability width to 0.45 for an interval stretching from the sample mean to the high-end cost calculated using the upper end for a 90% confidence interval. The sample mean to the upper end of a 90% confidence interval are used as low-high damage costs for impact categories where there appears to be a substantial likelihood of continuing increases in damage costs.

- ***Ozone Layer Depletion*** -- Recommended low-high range is $37,288 to $76,472. The low is based on the low end of a 65% confidence interval. The high end is the sample mean. Only four studies were found that provide damage costs for stratospheric ozone layer depletion. Two are based on the same source. The highest estimate is based on politically developed ecotaxes in Sweden. Hence, the range between the 65% confidence low end and the sample average may prevent overestimating ozone layer depletion impacts, while also recognizing the lack of data on ozone layer depletion costs from ozone depleting pollutant releases.

- ***Ground Level Smog Formation*** -- Recommended low costs for damages as a result of ozone's role in ground level smog formation and smog damages is based on using the mean of five of the six studies reviewed (excluding the confidential study's estimates). The mean for these five studies is $6 per MT of ozone releases to the atmosphere. The high estimated cost is the upper end of a 65% confidence interval for all six estimates, which is $483 per MT of ozone emissions. The low end of that 65% confidence interval is negative because of the great disparity between damage costs for ozone estimated from the 5 listed studies and the confidential sixth study's estimates. The $6 estimate noted is a better low estimate for smog damages expressed in metric tons of ozone equivalents than a zero or negative damage cost, because none of the literature reviewed estimated that ground level smog had a positive environmental effect. The prevalence of NO_x emissions in some geographic areas combined with the likelihood of higher temperatures and sunny skies during certain weeks or months of the year as our climate warms justifies having the high-end recommended cost estimate as indicated. Also, the confidential study's estimates may capture some human health impacts of smog exposure which are not captured in the five studies and also are not fully encompassed in TRACI's human health impacts characterization factors for smog inducing pollutants such as NO_x, VOCs, methane, chlorine, carbon monoxide, turpentine, and ozone.

III. References

(1) Frank Ackerman and Elizabeth A. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, Economics (The Open-Access, Open Assessment E-journal), 2012, 6(10), 25 pages.

(2) Ahlroth and Finnveden, Ecovalue08-A new valuation set for environmental systems analysis tools, 2011, 19 1884-2003.

(3) Birch et al, Why metrics matter: Evaluating policy choices for reactive nitrogen in the Chesapeake Bay watershed, Environmental Science & Technology, 2011, 45 (1) 168-174.

(4) Compton et al, Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making, Ecology Letters, 2011, 14 804-815.

(5) Compton et al, Assessing the social and environmental costs of institution nitrogen footprints, Sustainability 2017, 10 (2) 114-122.

(6) Eastern Research Group, Inc. (ERG), Draft Report: Cost Benefit Analysis for Six "Pure" Methods for managing Leftover Latex Paint-Data, Assumptions, and Methods, Prepared for The Paint Product Stewardship Initiative and funded by The National Paint and Coatings Association, September 2006, Lexington, MA.

(7) Fann et al, The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution, Air Quality, Atmosphere and Health, 2009, 2 169-175.

(8) Fann et al, Characterizing the PM2.5 -related health benefits of emissions reductions for 17 industrial, area and mobile emission sectors across the U.S., Environment International, 2012, 49 141-151.

(9) Giang, A. and Selin, N. E., Benefits of mercury controls for the United States, 2016, Proceedings of the National Academy of Sciences, 113 (2) 286-291. (See page 288 second column for range of benefits per MT Hg reduction under MATS)

(10) Morris and Bagby, Measuring environmental value for natural lawn and garden care practices, International Journal of Life Cycle Assessment, 2008, 13(3) 226-234.

(11) Muller and Mendelsohn, Measuring the damages of air pollution in the U.S.- Journal of Environmental Economics and Management-2007 54(1) 1-14.

(12) Nicholas Z. Muller, Robert Mendelsohn, William Nordhaus, Environmental Accounting for Pollution in the United States Economy, American Economic Review, 2011, 101 (August), 1649-1675.

(13) Nedellec and Rabl, Costs of health damage from atmospheric emissions of toxic metals: Part 1 -- methods and results, Risk Analysis, 2016, 36 (11) 2081-2095.

(14) NESCAUM (Northeast States for Coordinated Air Use Management), Economic valuation of human health benefits of controlling mercury emissions from U.S. coal-fired power plants, prepared by Glenn Rice (Sc.D. candidate) and James K. Hammitt (Director Harvard Center for Risk Analysis), February 2005.

(15) William Nordhaus, A Question of Balance: Weighing the Options on Global Warming Policies, 2008, Yale University Press, New Haven, CT.

(16) William Nordhaus, Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies, American Economic Journal: Economic Policy 2018, 10(3): 333-360.

(17) Pacyna et al, An assessment of costs and benefits associated with mercury emission reductions from major anthropogenic sources, Journal of the Air & Waste Management Association, 2010, 60 (3) 302-315.

(18) Robert S. Pindyck, The social cost of carbon revisited, Journal of Environmental Economics and Management, 2019, 94 140-160.

(19) Rabl, A. and Spadaro, J. V., Public health impact of air pollution and implications for the energy system, 2000, Annual Review of Energy and the Environment, 25 601-627.

(20) Spadaro and Rabl, Global health impacts and costs due to mercury emissions, Risk Analysis, 2008, 28 (3) 603-613.

(21) Nicholas Stern, The Economics of Climate Change: The Stern Review, Cambridge University Press: Cambridge, England and New York, NY, USA, 2007.

(22) Sobota et al, Costs of reactive nitrogen release from human activities to the environment in the United States, Environmental Research Letters, 2015, 10 (2) 025006.

(23) Sundseth et al, Economic benefits from decreased mercury emissions: Projections for 2020. Journal of Cleaner Production, 2010, 18 386-394.

(24) Talberth et al, The Genuine Progress Indicator 2006: A Tool for Sustainable Development, Oakland, CA: Redefining Progress, 2006.

(25) Richard S. J. Toll, The Marginal Damage Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties, Energy Policy, 2005, 33(16): 2064-74.

(26) U.S. Environmental Protection Agency (EPA), Technical Support Document: Estimating the Benefit Per Ton of Reducing PM2.5 and PM2.5 Precursors from 17 Sectors, January 2013.

(27) U.S. EPA, Office of Air and Radiation, Technical Support Document (TSD) for the Cross-State Air Pollution Rule Update for the 2008 Ozone NAAQS, Docket ID No. EPA-HQ-OAR-2015-0500, August 2016.

(28) U.S. EPA, Regulatory Impact Analysis for the Review of the Clean Power Plan-Proposal, October 2017.

(29) U.S. EPA, SO2 Emissions Permit Trading Program under Title IV of Clean Air Act - Annual EPA Permit Auctions - Spot Auction Clearing Prices, auction reports for most years, 1993 through 2020.

(30) U.S. Interagency Working Group on Social Cost of Carbon (IWGSCC), Technical Support Document- Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866, February 2010.

(31) U.S. Interagency Working Group on Social Cost of Carbon (IWGSCC), Technical Support Document- Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866, May 2013.

(32) Van Grinsven et al, Costs and benefits of nitrogen for Europe and implications for mitigation, 2013, 47 (8) 3571-3579.

(33) Pei Wang, Xiangzheng Deng, Huimin Zhou, Shangkun Yu, Estimates of the social cost of carbon: A review based on meta-analysis, Journal of Cleaner Production, 2019, 209 1494-1507.

IV. Appendix A: Human Health Cancer and Non-Cancer Damage Costs and Ecosystem Toxicity Damage Costs for Geographic Locale – Release Media Specific Combinations Other Than Those Provided in Table 1

Table A1: Reference Substance Damage Costs for Other Geographic Locale – Release Media Specific Combinations

Impact Category (reference substance)	Urban Air		Continental Rural Air		Continental Freshwater		Continental Sea Water		Continental Natural Soil		Continental Agricultural Soil	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Non-Carcinogenic Effects from Toxics (T)	$224	$462	$23	$48	$41	$85	$2	$5	$19	$38	$22	$45
Carcinogenic Effects from Toxics (B)	$1,814	$3,098	$459	$784	$926	$1,582	$95	$163	$413	$706	$494	$843
Freshwater Aquatic Ecosystems Toxicity (2,4-D)	$201	$860	$189	$813	$1,582	$6,785	$226	$970	$335	$1,435	$335	$1,435

Note: Shaded Cells in Table A1 show reference substance low and high damage costs.

Table A2: Comparative Toxicity Unit (CTU) Damage Costs for Geographic Locale – Release Media Combinations

Impact Category for TRACI CTU Damage Cost	Urban Air		Continental Rural Air		Continental Freshwater		Continental Sea Water		Continental Natural Soil		Continental Agricultural Soil	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Non-Carcinogenic Effects from Toxics	$2,328,482	$4,802,495	$2,328,482	$4,802,495	$2,328,482	$4,802,495	$2,328,482	$4,802,495	$2,328,482	$4,802,495	$2,328,482	$4,802,495
Carcinogenic Effects from Toxics	$3,827,004	$6,535,865	$3,827,004	$6,535,865	$3,827,004	$6,535,865	$3,827,004	$6,535,865	$3,827,004	$6,535,865	$3,827,004	$6,535,865
Freshwater Aquatic Ecosystems Toxicity	$0.002	$0.008	$0.002	$0.008	$0.002	$0.008	$0.002	$0.008	$0.002	$0.008	$0.002	$0.008

V. Appendix B: Literature Review Summary Data Matrix Spreadsheet (attached)