Supplementary information: Human health and economic costs of air pollution in Utah: An Expert Assessment

Table S1: Specific wording of the questions (number of respondents in parentheses)

1. What is the number of disability-adjusted life years (DALYs) lost to air pollution in Utah each year? (9)
2. What percentage of Utahans experience the following shortening of life because of air pollution? (10)
3. What pollutants contribute most to your health burden estimates from Questions 1 and 2? (11)
4. What health conditions contribute most to your health burden estimates from Questions 1 and 2? (9)
5. What is the direct cost of air pollution to Utah's economy? (8)
6. What is the indirect cost of air pollution to Utah's economy? (8)
7. What actions would you recommend to reduce air pollution in Utah and how much could they reduce the health and economic costs estimated above? (13)

Brief analysis of air quality in the 2019 and 2020 legislative sessions

Despite the successful dissemination of the new estimates of state-level costs of air pollution, there were very different outcomes in the 2019 and 2020 legislative sessions. In 2019, the legislature appropriated a record amount of funding for air quality in Utah, investing $28 million in one-time projects such as wood stove conversion, electric vehicle charging infrastructure, air quality education, and a state telework program [1]. This investment was made possible by a revenue surplus of approximately $1 billion [2]. Additionally, several enforceable and funded bills were passed to regulate high-emissions vehicles, support public transportation, and accelerate community-level transition to renewable energy sources (Table S2). At the federal level, an additional $9.7 million for air quality projects was awarded by the US EPA, though more than half of that funding was earmarked for improvement of fossil fuel extraction infrastructure [3]. Many politicians and air quality advocates concluded that 2019 was a turning point likely to lead to more substantial changes in following years [1].

The outcome of the 2020 legislative session was very different. In addition to the COVID-19 crisis, a large tax reform package was defeated by statewide referendum at the beginning of the legislative session [4]. These developments eliminated discretionary spending and few of the proposed bills and resolutions associated with air quality were passed, except some cost-neutral or low budget legislation (Table S2). Approximately $10 million was appropriated for air quality, primarily to support ongoing projects. Additionally, the bills that were proposed were noticeably incremental (i.e. not likely to substantially alter the trajectory of air quality) compared with 2019 (Table S2).

1. Stevens, T. Legislature falls far short of governor's goal of investing $100M to improve air quality. Advocates say it's a good first step. *Salt Lake Trib.* 2019.
2. Roche, L.R. Big Utah budget surplus "too good to be true," could mean no tax cut, lawmakers say. *Deseret News* 2019.
3. Winterton, S.G. EPA awards $9.7M for air quality projects in Utah. *Deseret News* 2019.
4. Wood, B. Utah Legislature repeals tax reform in pair of overwhelming votes. *Salt Lake Trib.* 2020.

Table S2. List of bills associated with air quality in the Utah legislature's 2019 and 2020 sessions

Year	Bill	Status	Result*	Title	Policy summary
2019	HB0139	Passed	Positive	Motor Vehicle Emission Amendments	Increased penalties on illegal tampering with diesel engines. It is now a citable offense when affecting pedestrians, bicyclists, or other road users.
2019	HB0353	Passed	Positive	Reduction of Single Occupancy Vehicles Trips Pilot Program	3-year program where all UTA transportation will be free on certain days (about seven fare free days)
2019	HB0411	Passed	Positive	Community Renewable Energy Act	Creates mechanisms to support transition to 100% net renewable energy by 2030
2019	HB0357	Passed	Positive	Voluntary Wood Burning Conversion Program	Changed eligibility for conversion (assists more individuals to convert). Public campaign for best burning practices and effects of burning on air quality (targeting nonattainment areas).
2019	HB0148	Passed	Positive	Vehicle Idling Revisions	Highway authorities only need to give one warning citation instead of three to impose a fine for idling your vehicle
2019	SB0144	Passed	Positive	Environmental Quality Monitoring Amendments	Utah Inland Port Authority must now measure and report "Environmental Quality", including air quality (and associated impacts with air emissions). Sensor system set up to measure PM, O3, and NOx.
2019	HCR002	Passed	Positive	Concurrent Resolution Supporting Renewable and Sustainable Energy Options to Promote Rural Economic Development	Promotes continued and increased development of renewable energy in rural Utah
2019	HCR003	Passed	Positive	Concurrent Resolution Urging the Environmental Protection Agency to Update Switcher Locomotive Emission Standards	Urges EPA to develop and make more stringent emission standards for switcher locomotives
2019	HCR011	Passed	Positive	Concurrent Resolution Encouraging the Purchase of Tier 3 Gasoline	Encourages promotion and purchase of Tier 3 gasoline for retailers and consumers
2019	HB0218	Passed	Positive	Construction Code Modifications	Makes amendments to the residential building code to improve energy efficiency in newly-built homes
2019	HCR005	Passed	Positive	Concurrent Resolution Urging Policies That Reduce Damage from Wildfires	Urges the pursuit of common sense policies to improve forest management practices to help improve our air quality
2019	HB0433	Passed	Positive	Inland Port Amendments	Establishes renewable energy requirements and diesel truck emission guidelines
2019	SCR006	Passed	Positive	Concurrent Resolution in Support of Advanced Nuclear Reactor Technology	Encourages development of nuclear reactor technology
2019	*HB0288*	*Passed*	*Positive*	*Critical Infrastructure Materials*	*Division of Air Quality and legislators can deny expansion of gravel pits if it is contrary to the DAQ's approval order*
2019	SB248	Passed	Negative	Throughput Infrastructure Amendments	Supports development of international market for Utah coal
2019	HB0295	Failed	Negative	Vehicle Emissions Reduction Program	Provides incentives to replace vehicles that fail emissions tests
2019	HB0413	Failed	Negative	Tax Credit for Energy Efficient Vehicles	Provides tax credits of energy efficient vehicles
2019	HB0098	Failed	Negative	Freight Switcher Emissions Mitigation	Creates procedures and terms for grants issued for the reduction of freight switcher locomotive emissions and requests $2 million to help repower existing switcher engines in the non-attainment areas
2019	HB0304	Failed	Negative	Fossil Fuels Tax Amendments	Places a tax on carbon emissions
2019	**Total appropriations for air quality (approximate**)**				**$29 million**
2020	HB0059	Passed	Positive	Tax Credit for Alternative Fuel Heavy Duty Vehicles	Extends the income tax credit to 2029 for to certain alternative fuel heavy-duty vehicles, including electric
2020	HB0180	Passed	Positive	Emission Inspection Revisions	Creates an exemption for electric vehicles from emissions compliance fees
2020	HB0235	Passed	Positive	Voluntary Home Energy Information Pilot Program	Creates a committee to create rules and guidelines for a Voluntary Home Energy Information Pilot Program that will educate homeowners and sellers on home energy use

2020	HB0259	Passed	Positive	Electric Vehicle Charging Network	Requires the Department of Transportation to lead in the creation of a statewide electric vehicle charging network plan
2020	HB0396	Passed	Positive	Electric Vehicle Charging Infrastructure	Requires the Public Service Commission to authorize a large-scale utility to establish an electric vehicle charging infrastructure program, specifically focused on Rocky Mountain Power's $50 million investment
2020	SB0050	Passed	Positive	Clean Energy Act Amendments	Clarifies and makes technical changes to definitions in the state's pre-existing commercial property assessed clean energy (C-PACE) program.
2020	SB0148	Passed	Positive	Oil and Gas Modifications	Creates an account to collect penalties from oil and gass industry violations to be used for remediation
2020	SB0150	Passed	Positive	Transportation Governance Amendments	Expands the Utah Transit Authority's ability to enter into joint ventures with communities to develop around existing transit hubs
2020	SB0154	Passed	Positive	Interlocal Entity Amendments	Allows interlocal industries to apply for hydrogen, hydrogen energy storage, and nuclear projects to apply for and be funded by federal grants
2020	HB0415	Failed	Positive	Construction Code Amendments	Allows gas-fired water heaters that exceed emission limits.
2020	HB0489	Failed	Positive	Wind Energy Facility Siting Amendments	Requires additional permitting when constructing or operating a wind energy facility
2020	SB0041	Failed	Positive	Sales and Use Tax Modifications	Exempts oil and gas industry and electrical corporations from sales and use tax
2020	SB0239	Passed	Negative	Refinery Sales Tax Exemption	Extended tax breaks to oil refineries not able to meet the original timeline for transitioning to Tier-3 fuel
2020	HB0113	Failed	Negative	Trails Improvement Amendments	Allows eminent domain to be used to establish trails for alternative transportation
2020	HB0176	Failed	Negative	Vehicle Emissions Reduction Program	Provides incentives to replace vehicles that fail emissions tests
2020	HB0194	Failed	Negative	Clean and Renewable Energy Amendments	Set goals for utilities to transition to "clean" energy and expanded the definition of clean and renewable to include nuclear, biomass, waste gas recovery, and avoided consumption
2020	HB0281	Failed	Negative	Tax Credit for Alternative Vehicles	Enacts nonrefundable corporate and individual income tax credits related to certain alternative fuel vehicles
2020	HB0317	Failed	Negative	Nonroad Engine Study	Directs the Division of Air Quality to conduct a study into the number and type of nonroad engines in nonattainment areas of Utah.
2020	HCR011	Failed	Negative	Concurrent Resolution Supporting the Utah Roadmap for Positive Solutions and Leadership on Climate and Air Quality	Expresses support for the state-funded roadmap
2020	SB0077	Failed	Negative	Electric Energy Related Tax Credit	Enacts a corporate and individual income tax credit related to electric storage and vehicles
2020	SB0078	Failed	Negative	Energy Storage Innovation, Research, and Grant Program	Requests $5 million in one-time funding to create a grant program for people, companies, research organizations, or other entities who will advance the development and deployment of energy storage, facilitate the transition of energy storage into the marketplace, improve resiliency, or enhance job creation in the energy sector.
2020	SB0092	Failed	Negative	Statewide Comprehensive Rail Plan	Directs Utah transportation officials to create a comprehensive rail plan for the state
2020	SCR012	Failed	Negative	Concurrent Resolution Concerning Climate Action	Supports federal action to address climate change
2020	**Total appropriations for air quality (approximate**)**				**$7.5 million**

*Result indicates the estimated effect on air quality in Utah

**Because air quality efforts are funded via diverse policy avenues (direct support, tax breaks, rebates, etc.), the exact level of support is difficult to ascertain. Additionally, there are doubtlessly provisions in other bills and resolutions that are pertinent to air pollution, which we have missed in our survey of the 2019 and 2020 sessions.

Analysis of public response to news coverage of this study

Though a comprehensive assessment of the reception of our work by the public is beyond the scope of our project, we performed a simple analysis of public response as follows. We analyzed the comments on three articles [1–3] citing our work in the Salt Lake Tribune, the largest newspaper in Utah. While we do not assume that commenters are representative of the public overall, we classified perspectives and recorded "likes" for all comments on the three articles. The articles were all published in early 2020 and received a combined total of 92 online comments from 33 commenters. We classified comments into three categories:

1. Supportive of the article's content
2. Not engaging with the article's content
3. Antagonistic towards the article's content

Of the 92 comments, 27 were supportive of the article, 54 did not engage the content of the article, and 11 were against the content of the article (Table S3). Other readers could react to comments via several preset reaction buttons: 1. like, 2. genuine and kindhearted, 3. helpful, 4. thought provoking, and 5. entertaining. We grouped reactions 2 through 4 into a "positive" grouping for simplicity of analysis and because there were fewer reactions of these types (Table S3). Category 1 comments received the most "likes" per comment, with an average of 1.89 likes per comment, versus 1.17, and 0.27 for categories 2 and 3, respectively. Category 1 comments also received the most "positive" responses per comment, with an average of 1.63 positives per comment, versus 0.65 and 0.0 positives per comment for categories 2 and 3, respectively. Category 2 comments received the most "entertaining" reactions per comment, sometimes indicating sarcasm, with an average of 0.3 entertaining reactions per comment, versus 0.15 and 0.09 for categories 1 and 3, respectively.

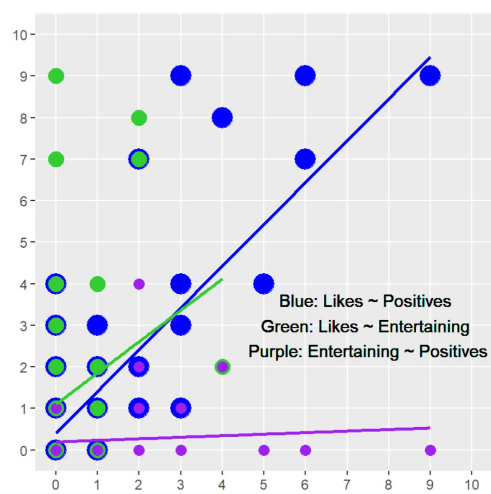

Figure S1. Relationships among the reaction types. The axes depend on the color, with the definition described in the legend. "Likes" are the number of times someone clicked the "thumbs-up" icon, "Positives" are the number of times someone clicked other generally positive buttons, and "Entertaining" is the number of times someone clicked the laugh or sarcasm button.

We used Pearson's product-moment correlation to test for relationships among the reaction types (Fig. S1). Likes and Positives were positively correlated ($r = 0.77$, $p < 0.0001$), Likes and Entertaining were positively correlated ($r = 0.21$, $p = 0.04$), but Entertaining and Positives were uncorrelated ($r = 0.1$, $p = 0.3$).

Table S3: Analysis of comments and reactions on three articles covering the air pollution report

Comment category	# of comments	# of likes	# of “positive” reactions	# of “entertaining” reactions
1: Supportive	27	51	44	4
2: Not engaging with article	54	63	35	16
3: Antagonistic	11	3	0	1

Together, these results suggest that there were 2.5-fold more supportive comments than antagonistic comments, and that the supportive comments received 32-fold more likes and positive reactions than antagonistic comments. We recognize that individuals who contribute to the comments section are not representative of the public but report this information as an indicator of the general tenor of the public response to locally-derived estimates of air pollution costs.

1. Maffly, B. Salt Lake City’s air quality is nation’s 7th worst among large metro areas. *Salt Lake Trib.* 2020.
2. Abbott, B.W.; Errigo, I.M.; Jarvis, D.K. Commentary: Utah air pollution is literally killing us. *Salt Lake Trib.* 2020.
3. Abbott, B.W. Ben Abbott: Earth Day at 50 has never been so relevant. *Salt Lake Trib.* 2020.

Narrative of the expert assessment and interactions with the state legislature

We have structured this section around the conceptual diagram in Figure 2 of the main manuscript. The activities and efforts were organized intentionally and accidentally around these themes or steps.

Scientific Understanding of the System

Beginning in September 2018, we began compiling information about air quality in Utah. We were motivated by the multiple, conflicting descriptions of the status and trend of air pollution in Utah we had heard from media, political, and private sources. As a part of an undergraduate research program (BYU’s College Undergraduate Research Award), we began a literature synthesis to answer three main questions: 1. What is the status of Utah’s air quality, 2. How does air pollution affect human health in Utah, and 3. What is the impact of air pollution on Utah’s economy? We developed these questions into a quantitative questionnaire, which we distributed to experts throughout Utah as described in the main manuscript.

Public and Political Perception of the System

As we continued to conduct background research and develop the expert assessment, we began to engage with political, research, and community actors focusing on air pollution in Utah. In December 2018, we attended a meeting at the University of Utah called the Dialogue on Collaboration – Air Quality. This meeting included a panel discussion and several breakout groups to facilitate discussion of the current air pollution problems and potential solutions. Participants were from universities, state government, regulatory agencies, research and medical groups, lobbyist organizations, and community groups from across the state. We used this as an opportunity to connect with experts and launch our efforts. From December 2018-January 2019, we (the undergraduate co-authors) compiled a one-page literature synthesis of more than 100 peer-reviewed journal articles on air pollution consequences. Once created, we worked with legislators and policy experts to improve the format and presentation for comprehensibility and relevance. After revision, we sent this summary to all 104 state legislators (75 representatives, 29 senators) via email in mid-January 2019 (summary available in Section 6 of this document). This email led to about 35 phone conversations and several in-person meetings with members of the Utah House and Utah Senate. As the outreach was led by students, the responses were overwhelmingly positive. We have included some typical responses below:

- *Thank you so much for this information! I am a strong proponent of improving our air quality, and it is so helpful to have this list of bills that promote clean air. My son-in-law and daughter--well educated, productive people--have chosen not to live in Utah because my grandson has severe asthma that is adversely affected by our air quality.*
- *It is always helpful to learn more and I am excited to see students engaging in public policy. I want to make one correction, air quality has actually continued to improve. Since 2002, per capita emissions have been cut in half, which is remarkable (See attached). The real challenge we face now is that there are very few additional policies that we can engage in that will yield the return on investment you mention. If you have specific examples of policies that will make a real difference, I would be interested in hearing about them.*
- *Air quality is something that I am passionate about, and I've worked on in the past during my time on the Salt Lake City Council. With more than two million Utahns living along the Wasatch Front, it means that the majority of our population in Utah is subject to inversion and poor air quality we see flare up during the winter. A few of the solutions the legislature is looking at this session to alleviate that include replacing locomotive engines for eco-friendly engines, providing grants for replacing wood burning stoves, and increasing accessibility for the UTA public transit system.*
- *Thank you!*

Though there were differing degrees of enthusiasm, most initial responses included some level of agreement about the problem and encouragement of our involvement. However, the phone and in-person meetings were more mixed. Perhaps because of the business of the legislative session and the informal format, many legislators frankly expressed differing priorities and assessments of how realistic change could be. It was mentioned more than once that science was immaterial to policy questions, which depended on political realities. Along with this dismissal of science, there was little understanding of the medical and atmospheric science of air pollution—even among legislators who were supportive of improving air quality. For example, none were familiar with numerical estimates of premature deaths or economic costs. There was also a lack of urgency and personal connection. For example, in one phone conversation a legislator repeatedly reassured us that their asthmatic coughing fits during the call were not associated with acute or chronic air pollution, despite the "red" air quality conditions in their location.

Expert Assessment and Rapid Transfer of Information Impacting Scientific Understanding of the System

Throughout 2019, we completed the questionnaire and continued to accept filled surveys. We stayed in contact with both supportive and skeptical legislators during this process by sharing anonymous results from expert participants as well as recent research on air pollution costs and solutions generally. Additionally, we engaged with the public by presenting the findings at conferences and community meetings. Though the results were not yet completed, we found that sharing the preliminary findings and inviting input greatly increased interest and understanding. Rather than just presenting a single "best" estimate, we emphasized the difficulty of quantifying air pollution costs and explained how such primary studies are conducted. This seemed to be informative for listeners and attendees at the events, and it also helped us understand what questions and priorities the public and policymakers had concerning air pollution. This two-way engagement facilitated rapid transfer of best available information via two mechanisms. First, it made our results available in nearly real time. Second, it created a network of citizens and policymakers who were aware of our effort and interested in the outcome—enhancing dissemination of the final results when they were ready (see next paragraph).

Long-term Increase in Trust and Understanding & Rapid Transfer of Information to Influence the Public and Political Perception of the System

Throughout 2019 and extending into 2020, we attended several meetings and conferences including the Utah Valley Chamber of Commerce Clean Air Task Force, Air Quality / Changing Climate Technical Advisory Team meeting at the Kem C. Gardner Policy Institute, the American Geophysical Union (AGU), a Clean Air Caucus press release, and numerous radio and television appearances. At these events we shared the updated results and continued to invite feedback and questions. These outreach activities expanded our understanding of political and public concerns, while building relationships of trust to improve communication and mutual understanding. Specifically, these interactions got the word out about our project across institutions throughout the state, introduced us to additional participants, and elicited feedback (positive and negative) on all aspects of the project. We shared updates and events on social media and traditional media outlets to involve the public in the scientific and the decision-making processes surrounding air pollution. For example, we published an op-ed and a full-length news article on air pollution in Utah and globally in the Salt Lake Tribune (details in last section).

In 2020, as the legislative session approached, we went through the same process as the previous year, though this time with the results from our expert assessment in addition to the general information on air pollution consequences. We worked with our co-author team to analyze and write up the results of our expert assessment into a nontechnical report, which is presented in Section 5 of this document. We solicited feedback from legislators prior to distribution to improve clarity and relevance for policymakers. We again distributed the report to all 104 legislators as well as media contacts. As before, this led to in-person and phone meetings in addition to sometimes animated email exchanges. The responses ranged from grateful to dismissive, though these exchanges were always cordial. As we mention in the main manuscript, one of the most common questions was, “has this been peer-reviewed yet?”

An unexpected advantage of this collaborative and transdisciplinary approach was that we have felt an added measure of motivation and responsibility to report back to those in the public and legislature who have been following this work. Consequently, we have plans for continuing this process after the publication of this paper. We will continue to engage with the legislators and the public in an effort to enhance science-informed policy to reduce air pollution and improve community health. As we prepare for the upcoming legislative session (January-March 2021), we will prepare a third executive brief with the most up-to-date research on the impacts of air pollution, including information from this article and other articles in the special issue of Atmosphere on air pollution in Utah. We will release the brief to all legislators via email, this time including detailed legislative options from local and national case studies. Additionally, we plan to utilize the network and resources of the full co-author team and their affiliated institutions to disseminate a press release on this article.

Estimating the health and economic costs of air pollution in Utah: an expert assessment

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1. Introduction

The goal of this survey is to document expert understanding of how air pollution is affecting the health and economic wellbeing of Utah. We recognize that interactions between natural and human systems are exceedingly complex and that many pertinent parameters are not definitively understood. Because precise empirical or model-based estimates of health and economic consequences of air pollution are unlikely in the near future, we are performing this expert assessment to integrate the best available quantitative and qualitative information on the subject. By administering this survey to multiple researchers with applicable expertise, this project generates an integrative assessment of current air pollution costs and identifies sources of uncertainty in those estimates to inform and support decision-making and future research.

Because participation in this survey entails a substantial time commitment and intellectual contribution (e.g. empirical results, model runs, and professional opinion), all survey participants who give feedback on the manuscript will have the opportunity to be co-authors on the report and peer-reviewed publication, which we will submit in 2019. Participant responses will be published in aggregated form without identifying information (i.e. individual estimates will be kept confidential and anonymous).

2. Background

When management decisions are pressing but uncertainty is high, expert judgements have long informed possible system response and risk of dangerous or undesired outcomes (Aspinall 2006; Bordley 2009; Zickfeld *et al.* 2010; Morgan 2014). While expert assessment cannot definitively answer questions of future system response, it complements modeling and empirical approaches by allowing the synthesis of formal and informal knowledge about the system to inform decision makers and researchers (Aspinall 2010; Schuur *et al.* 2013; Abbott *et al.* 2016) (Fig. 1). The approach is similar to the concept of ensemble models, where multiple estimates built on different assumptions and data provide a more robust estimate of central tendency and measure of variance (Baker & Ellison 2008). Because the experimental unit is an individual researcher, each data point integrates multiple types of knowledge available to that person; including information not yet formalized enough to integrate into traditional numerical models.

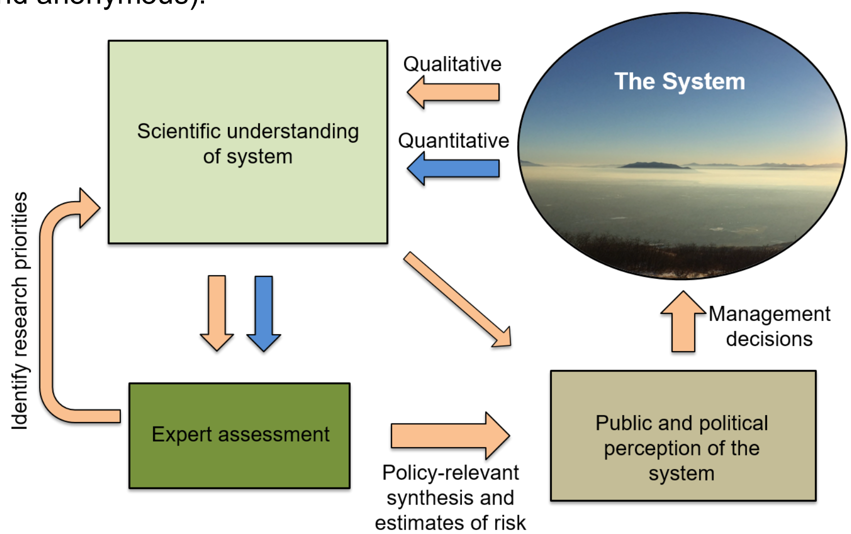

Figure 1. Conceptual diagram of the role of expert assessment in generating and communicating scientific understanding (modified from Abbott *et al.* 2016).

Air pollution is a complex problem with multiple drivers and diverse health and economic consequences (Caiazzo *et al.* 2013; Landrigan *et al.* 2017). Around the world, at least 5.5 to 6.5 million people die annually from poor air quality and economic damages exceed 5 trillion US dollars, at least 7% of the global gross domestic product (GDP) (OECD 2016; Landrigan *et al.* 2017). The link between air pollution and health is well understood for a wide range of conditions, including respiratory and cardiovascular diseases, central nervous system disorders, psychological and metabolic conditions, and reproductive harm (Vert *et al.* 2017; An *et al.* 2018; Gładka *et al.* 2018; Leiser *et al.* 2019; O'Donoghue 2019; Roberts *et al.* 2019). Additionally, many other adverse health conditions are known to be associated with air pollution, but they are not yet sufficiently quantified to integrate into health risk models (Lozano *et al.* 2012; Landrigan *et al.* 2017). Air pollution affects the economy directly via healthcare costs and lost productivity as well as indirectly via changes in immigration, tourism, and business investment (Ford *et al.* 2015; OECD 2016; Landrigan *et al.* 2017). As with the health burden effects, current estimates of the economic cost of air pollution almost certainly underestimate actual direct and indirect consequences of air pollution (OECD 2016).

In the Intermountain West, several factors have created poor air quality, including a quickly growing population, limited atmospheric mixing during winter inversions (Beard *et al.* 2012), and high levels of per-capita fossil fuel use due to heating and transportation infrastructure. While there is universal agreement in the research community that air pollution is degrading the health and economic wellbeing of Utahans (Ransom & Pope 1992; Lozano *et al.* 2012; Utah Division of Air Quality 2018; Leiser *et al.* 2019; O'Donoghue 2019), specific estimates of the direct and indirect costs vary widely (Ford *et al.* 2015). For example, estimates of annual mortality and morbidity due to air quality for Utah range from hundreds to tens of thousands (Samet *et al.* 2000; Bell *et al.* 2005; Dominici *et al.* 2006; Miller 2016; Pirozzi *et al.* 2017; Penrod 2018).

3. Questionnaire instructions

Because of the compound assumptions inherent to this kind of assessment, you will be asked to provide a subjective confidence interval around your estimate defined as follows:

Lower = I consider there to be a 95% chance that the actual value is greater than this estimate
Central = This is my best estimate of system response
Upper = I consider there to be a 95% chance that the actual value is lower than this estimate

For each question, you will have a chance to indicate your level of confidence and expertise concerning your answer, make comments on how you selected your estimates, and identify key sources of uncertainty concerning your estimate (e.g. what data or processes missing from current understanding would most improve our ability to predict system behavior). If there is not yet clear supporting evidence in the literature, but you have some basis for an estimate based on professional judgment, please make a note of that. These supporting questions allow us to compare responses from multiple experts and are just as valuable as your quantitative estimates. If you have no relevant expertise for a specific question, you may leave it empty.

The five-point "Confidence level" scale is defined as follows:

1= My answer is my best guess, but I am not confident in it; it could easily be far off the mark.
2= My answer is an educated guess; it could be far off the mark, but I have some confidence in it.
3= I am moderately confident in my answer; the true value is likely different from my answer, but in the general range.
4= I am confident in my answer; the true value is likely to be somewhat different from my answer, but it is unlikely to be dramatically different.
5= Given current understanding, I would be surprised if my answer were far off from the true value.

The five-point "Expertise level" scale is defined as follows:

1= I have little familiarity with the literature and I do not actively work on these particular questions.
2= I have some familiarity with the literature and I've worked on related questions but haven't contributed to the literature on this issue. It is not an area of central expertise for me.
3= I have worked on related issues and have contributed to the relevant literature but do not consider myself one of the foremost experts on this particular issue.
4= I am very familiar with relevant literature and have worked on related questions. This is an area of central expertise for me.

5= I contribute actively to the literature directly concerned with this issue, and I consider myself one of the foremost experts on it.

4. Questions

Question 1. What is the number of disability-adjusted life years (DALYs) lost to air pollution in Utah each year?

Note: *We use the DALY concept to integrate information on mortality and disease into a single number, which represents the number of years lost due to either death or substantial disability associated with exposure to air pollution (Landrigan et al. 2017). For reference, the average life expectancy for Utahans is 80 years (Utah Department of Health 2017), meaning that 8,000 DALYs = 100 complete lifespans, 80,000 DALYs = 1,000, etc.*

Your estimates in units of disability-adjusted life years			**Confidence level** (1-5)	**Expertise level** (1-5)
Lower	Central	Upper		

How did you generate these estimates (e.g. published studies, unpublished data, professional opinion)?	**What are the largest sources of uncertainty while making these estimates?**	**Additional comments:**

Question 2. What percentage of Utahans experience the following shortening of life because of air pollution?

Note: *This question complements Question 1 by assessing how the overall health burden of air pollution is distributed across the population (e.g. do a few, vulnerable individuals lose the majority of the DALYs or is the burden distributed across a larger portion of the population). As for the DALY concept in Question 1, we are seeking to assess the number of years lost due to either death or substantial disability associated with exposure to air pollution. Each column (Lower, Central, and Upper) should roughly sum to 100 (i.e. the whole Utah population should fall into one of the "Years of life lost" categories below).*

Your estimates in %				**Confidence level** (1-5)	**Expertise level** (1-5)
Years of life lost	Lower	Central	Upper		
0					
1					
5					
10					
>10					
How did you generate these estimates (e.g. published studies, unpublished data, professional opinion)?			**What are the largest sources of uncertainty while making these estimates?**		**Additional comments:**

Question 3. What pollutants contribute most to your health burden estimates from Questions 1 and 2?

Note: *This question seeks to rank air pollution parameters in order of their contribution to the health burden estimates you produced above. Please note in the bottom-right corner whether your response is for Utah overall or for a region (e.g. Utah-wide, Wasatch Front, Northern, Northeastern, Central, Castle, Southwest, Four Corners). If you desire to respond for more than one region, you may copy and paste the response table below.*

Ranked pollutants associated with air pollution			**Confidence level** (1-5)	**Expertise level** (1-5)
Order (highest to least contribution)	Pollutant	Estimate of percentage contribution to health burden		
1				
2				
3				
4				
5				
6				
7				
8				
How did you generate these estimates (e.g. published studies, unpublished data, professional opinion)?		**What are the largest sources of uncertainty while making these estimates?**		**Additional comments (Utah-wide or regional estimate):**

Question 4. What health conditions contribute most to your health burden estimates from Questions 1 and 2?

Note: *Rank as many health conditions associated with air pollution in order of their contribution to the estimates you produced above.*

<table>
<tr><th colspan="3">Ranked health conditions associated with air pollution</th><th rowspan="2">Confidence level
(1-5)</th><th rowspan="2">Expertise level
(1-5)</th></tr>
<tr><td>Order (highest to least contribution)</td><td>Health condition</td><td>Estimate of percentage contribution to health burden</td></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td></td><td></td></tr>
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Question 5. What is the direct cost of air pollution to Utah's economy?

Note: *This question aims to capture the direct costs (i.e. healthcare costs and lost earning potential due to days not worked, decreased productivity, or early career termination) of air pollution to Utahans. For reference, in 2018, Utah's GDP was approximately 171 billion US dollars* (Siebeneck *et al.* 2018)

<table>
<tr><th colspan="3">Your estimates in units of 2018 USD</th><th rowspan="2">Confidence level
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Question 6. What is the indirect cost of air pollution to Utah's economy?

Note: *This question aims to capture all other costs associated with air pollution not captured in the question above (e.g. decreased immigration/increased emigration, changes in tourism, behavioral changes due to actual or perceived air pollution, loss of potential business due to regulatory burden of Utah's serious nonattainment status).*

<table>
<tr><th colspan="3">Your estimates in units of 2018 USD</th><th rowspan="2">Confidence level
(1-5)</th><th rowspan="2">Expertise level
(1-5)</th></tr>
<tr><td>Lower</td><td>Central</td><td>Upper</td></tr>
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Question 7. What actions would you recommend to reduce air pollution in Utah and how much could they reduce the health and economic costs estimated above?

Note: *This question seeks to identify solutions to air pollution including but not limited to individual, community, state, and national action. Please note in the bottom-right corner whether your response is for Utah overall or for a region (e.g. Utah-wide, Wasatch Front, Northern, Northeastern, Central, Castle, Southwest, Four Corners). If you desire to respond for more than one region, you may copy and paste the response table below.*

Your recommendations and estimates of effectiveness					**Confidence level** (1-5)	**Expertise level** (1-5)
Proposed action	Is the action primarily individual, community, state, or national?	If the action were implemented, how much would air-pollution-associated health and economic costs decrease?				
		Lower	Central	Upper		

How did you generate these estimates (e.g. published studies, unpublished data, professional opinion)?	**What are the largest sources of uncertainty while making these estimates?**	**Additional comments (Utah-wide or regional estimate):**

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Human health and economic costs of air pollution in Utah[1]

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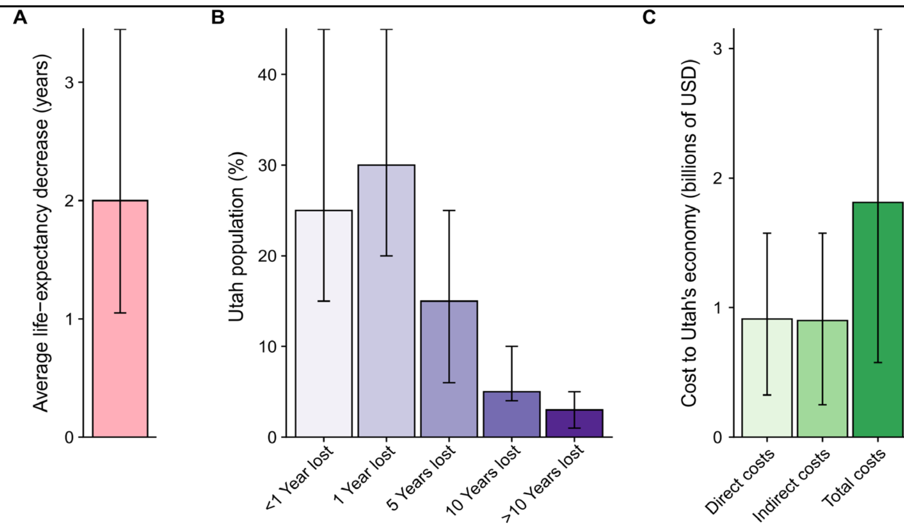
Understanding the costs and causes of air pollution in Utah is crucial to implementing effective solutions. To address disagreement in the public discussion of these costs, we compiled research from the best medical and economic studies and collected Utah-specific estimates and input from 21 researchers with expertise in medicine, public health, atmospheric science, or economics. This process—known as *expert assessment*—has proven highly reliable at compiling the best available evidence to solve time-sensitive issues in engineering, medicine, and many other research fields[1]. The Utah-based experts combined their own research and professional expertise with the broader scientific literature to provide integrative estimates of the costs, causes, and potential solutions for air pollution in Utah. Some key findings:

1. **Air pollution shortens the life of the average Utahn by 2** (1.1–3.5) **years** (Fig. 1A). This loss of life is distributed across most of the population rather than only affecting "sensitive groups." For example, 75% of Utahns lose 1 year of life or more because of air pollution and 23% lose 5 years or more (Fig. 1B). These estimates are directly in line with medical studies of the health effects of exposure to air pollution[2–4].
2. **Air pollution costs Utah's economy $1.8** ($0.58–3.2) **billion annually** (Fig. 1C). This economic damage is split roughly equally between direct costs (such as healthcare expenses and lost earning potential) and indirect costs (such as loss of tourism, decreased growth, regulatory burden, and business costs). These estimates are more conservative than those from national economic studies, which suggest that air pollution in Utah costs $7.4 ($6.2–8.6) billion annually when downscaled to Utah by population and GDP[2,5–7].
3. **Fossil fuel pollution causes or worsens many illnesses and conditions in Utah (Fig. 2)**. 85% of the pollutants causing health and economic harm are fossil fuel combustion products (fine particulate matter, ozone, and various oxides). Heart and lung diseases (congestive heart failure, heart attack, pneumonia, COPD, asthma, etc.) account for 62% of the pollution impact, with 38% from stroke, cancer, reproductive harm to mothers and children, mental illness, behavioral dysfunction, immune disease, autism, and other conditions[2,8–10].
4. **There are many state-level actions that could reduce air pollution while benefiting the economy (Fig. 3)**. Increasing efficiency of vehicles and buildings, investing in awareness, removing subsidies for nonrenewable energy, pricing carbon pollution, and expanding alternative transportation could all result in double-digit decreases in air pollution. Similar measures elsewhere have had immediate benefits for human health and a large economic return on investment, averaging $32 in economic benefits for every $1 invested towards improving air quality [2,11]. Utahns overwhelmingly support such measures[9,12].

Figure 1. Estimates of the human health impact and economic costs of air pollution in Utah. A shows the number of years lost by the average Utahn due to death or serious disability caused by air pollution. B shows the distribution of the loss of life expectancy across the Utah population (the percentage of Utahns losing different numbers of years). C shows the economic costs of air pollution in Utah. The median and 95% confidence range are shown based on quantitative estimates from 10 (A and B) and 8 (C) Utah researchers. Details about the methods and experts on the following pages.



[1] This work was supported by Brigham Young University through the College Undergraduate Research Awards program and the Department of Plant & Wildlife Sciences. *Contact ierrigo95@gmail.com or benabbott@byu.edu for more information.

Global and national costs of air pollution: Recent medical and economic research has found that air pollution causes much more damage to our health and economy than previously understood[8]. Worldwide, more than 6% of all deaths are attributable to air pollution—at least 8.8 million people each year[3,4]. That is 15 times more deaths each year than caused by all wars and acts of violence and 3 times more than caused by tuberculosis, malaria, and AIDS combined[2,4]. Globally, the economic damage of air pollution exceeds $5 trillion—more than 7% of the global gross domestic product[2,13]. In the U.S. alone, air pollution causes the premature deaths of 100,000 to 300,000 people each year and costs at least $886 billion annually[2,5–7]. Air pollution in the U.S. comes mainly from fossil fuel use, which creates toxic combustion products including particulate matter, ozone, and oxides of nitrogen, sulfur, and carbon[5,6,14,15].

Air pollution is a complex problem with multiple drivers and diverse health and economic consequences[2,5]. Unlike causes of death and economic harm that are directly observable (for example, a car crash), the effects of air pollution are widespread and diffuse. For this reason, air pollution is almost never recorded on a death certificate, though it contributes directly to many diseases and conditions that ultimately cause death (for example, heart attack, cancer, Alzheimer's disease, suicide, etc.)[8,16]. To estimate the health and economic effects of air pollution, researchers use several independent and complementary methods, including 1. Longitudinal studies: following a group of individuals through time as they experience different pollution levels, 2. Comparative studies: comparing the health of similar populations living in different pollution conditions, and 3. Exposure studies: quantifying toxicity directly by exposing animals to acute or chronic pollution[2,6,7,7,15,17]. These methods—which are the same used to measure the effects of smoking, obesity, or other long-term conditions on human health—are the gold standard in research because they integrate the acute effects associated with exposure to dirty air (stroke, heart attack, asthma, increased miscarriage, stillbirth etc.) as well as the chronic effects (cancer, neurological disorders, depression, suicide, etc.)[2,11,18].

The link between air pollution and health is well understood for a wide range of conditions, including respiratory and cardiovascular diseases, central nervous system disorders, mental health and psychological problems, metabolic conditions, and reproductive harm[19–25]. Additionally, many other adverse health conditions are known to be associated with air pollution, but they are not yet sufficiently quantified to integrate into health risk models[2,26]. Consequently, current estimates of the health burden should be considered as conservative and will likely grow as more data becomes

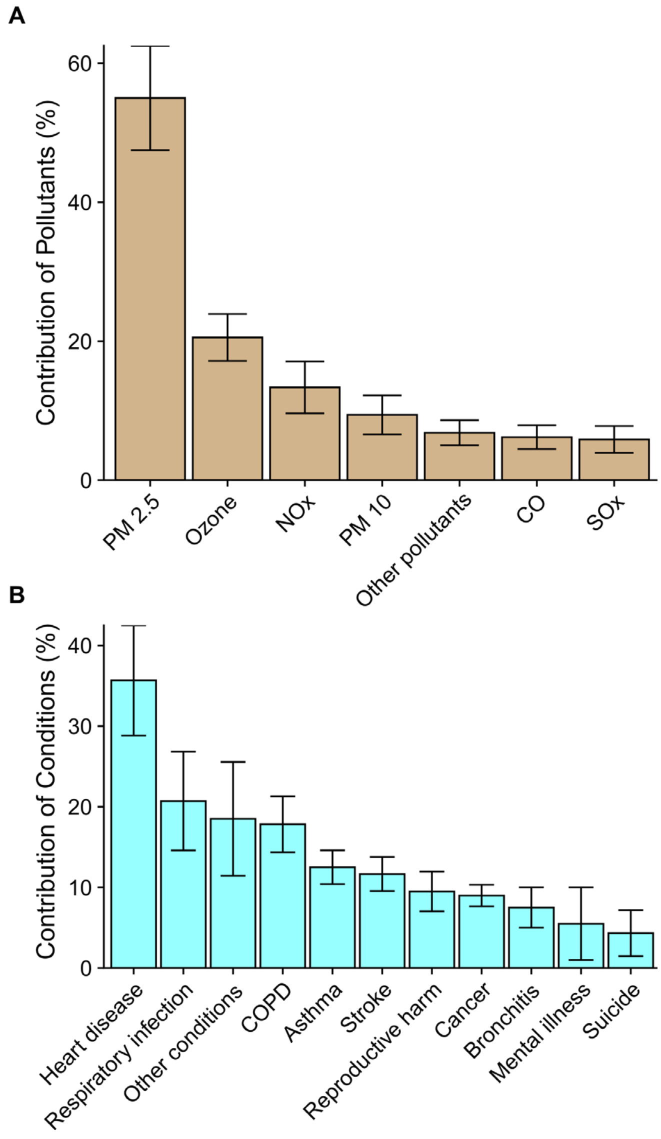


Figure 2. Estimates of the relative contribution of various pollutants (**A**) and health conditions (**B**) to the loss of life and economic productivity in Utah from air pollution. Bars show the average and standard error of estimates from 11 and 9 experts, respectively.

available[2,4]. Likewise, even when pollutants are below legal limits and the air quality is described as "healthy" or "good," pollution still degrades human health[7]. Air pollution affects the economy directly via healthcare costs and lost productivity (for example, missing work or school) as well as indirectly via changes in immigration, tourism, and business investment[2,13,27]. As with the health effects of pollution, current estimates of the economic cost of air pollution almost certainly underestimate actual direct and indirect consequences of air pollution[2,7,11,13].

Air pollution in Utah: In the Intermountain West, several factors have created poor air quality, including a quickly growing population, winter inversions trapping polluted air[28], and high levels of per-capita fossil fuel use due to heating and transportation infrastructure and power generation[9,29]. While there is universal agreement in the research community that air pollution is degrading the health and economic wellbeing of Utahns[22,23,26,30,31], specific estimates of the direct and indirect costs vary widely[27]. For example, estimates of annual mortality and morbidity due to air quality for Utah range from hundreds to tens of thousands, though even the most conservative estimates of the costs of air pollution to Utah's economy are substantial[7,32–37].

Though air pollution in Utah is a constant subject of discontent and discussion[9], the long-term perspective of air pollution is often left out of the public debate. In the 1970s and 1980s, there were large improvements in air quality and the overall air pollution index dropped by half[31,38]. These gains were attributable primarily to regulations (for example, the Clean Air Act and the Air Quality Act), which required removal of sulfur and lead from fuels, as well as technological and behavioral changes[39]. More recently, some air pollutants have continued to improve, while others have stagnated or gotten mildly worse[31,40]. Specifically, acute and long-term concentrations of CO, NO_x, and SO_x have continued to decrease in recent years, while ozone and particulate matter fractions ($PM_{2.5}$ and PM_{10}) show little improvement or even recent worsening, depending on the region within Utah[31,40]. Across the state, there is substantial geographic variation in air pollution, with

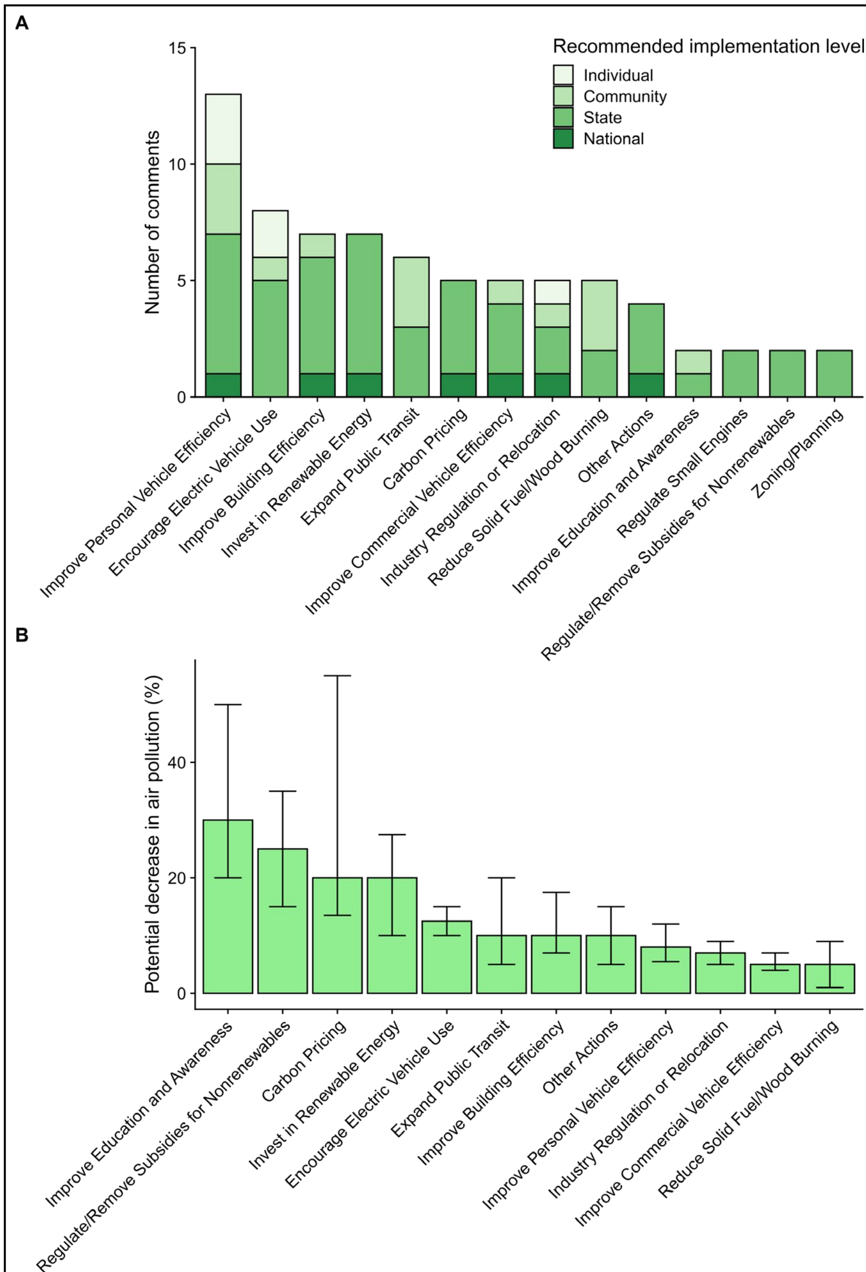


Figure 3. Recommendations to improve air quality. (**A**) Actions and the most effective scale of implementation. (**B**) Potential decrease in air pollution possible for various actions. Bars show the count (**A**) or median and 95% confidence range (**B**) from 13 experts.

different pollutants dominating the overall impacts in different regions[31]. These regional differences are associated with the type and degree of business, domestic, and industrial activity in those areas as well as natural environmental differences[9,30,41].

There is widespread support among Utahns to improve air quality. Utahns ranked air quality as the 3rd most important issue in the state, after only water and education, and 80% of Utahns said they would accept additional taxes and legislation to improve air quality[9,12]. Recent, state-sponsored reports and this study (for example, Fig. 3) have outlined concrete changes that could reduce pollution and enhance the health and economy of Utah[9,31]. These recommendations align with proven measures taken in communities around the U.S. and the world, some of which we briefly outline in the next section.

Immediate and long-term opportunities of improving air quality: Cities, states, and countries that have invested in reducing air pollution have universally seen immediate and long-lasting economic and health benefits. The most comprehensive summary to date on the effects of improving air quality concluded the following, based on a synthesis of 95 large-scale studies[11]:

> *Reducing pollution at its source can have a rapid and substantial impact on health. Within a few weeks, respiratory and irritation symptoms, such as shortness of breath, cough, phlegm, and sore throat, disappear; school absenteeism, clinic visits, hospitalizations, premature births, cardiovascular illness and death, and all-cause mortality decrease significantly. The interventions are cost-effective. Reducing factors causing air pollution and climate change have strong co-benefits. Although regions with high air pollution have the greatest potential for health benefits, health improvements continue to be associated with pollution decreases even below international standards. The large response to and short time needed for benefits of these interventions emphasize the urgency of improving global air quality and the importance of increasing efforts to reduce pollution at local levels.*

Economic analysis confirms that improving air quality substantially stimulates economic growth across sectors while also addressing other environmental issues such as climate change[2,37,42]. For example, the Clean Air Act of 1970 was followed by a decrease of 68% in common air pollutants while the U.S. Gross Domestic Product grew by 212%[39]. More recently, the direct and indirect benefits of the 1990 Clean Air Act Amendment have added at least $2 trillion to the U.S. economy (an average of $65 billion each year), representing a return on investment of $32 for every $1 of cost[2,11,39]. Cleaning Utah's air would increase property values, stimulate tourism, and encourage business investment[9]. Increasing state and federal investment in clean air could result in billions of dollars of economic growth in Utah and reduce billions of dollars of expenses currently associated with health, education, and the economy[37].

In addition to decreasing ambient (outdoor) air pollution, short-term interventions to improve indoor conditions have been highly effective. For example, installing commercially available filters in elementary school classrooms improved student performance by the same amount as more costly measures[43]. Additionally, cleaner indoor air has been found to enhance performance of employees doing a broad range of cognitive and physical activities[44].

Expert assessment methods: When management decisions are urgent but uncertainty is high, *expert assessment* (combining multiple expert opinions) has long been used to estimate possible system responses and risk of dangerous

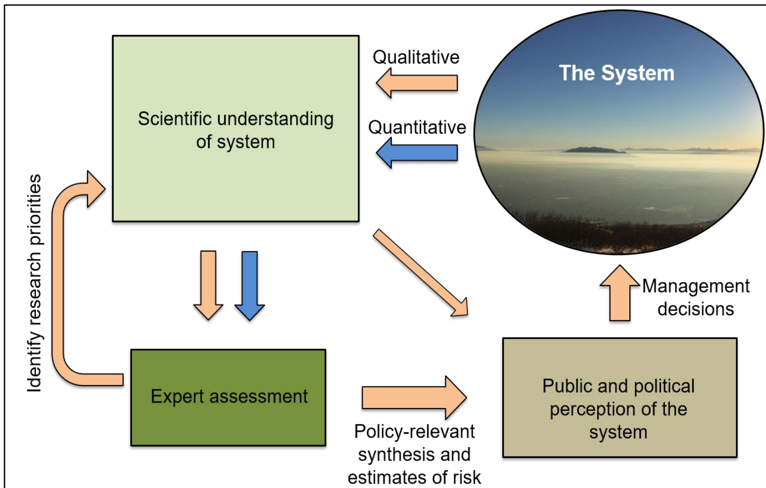


Figure 4. Conceptual diagram of the role of expert assessment in generating and communicating scientific understanding (modified from Abbott *et al.* 2016).

or undesired outcomes[45–48]. Expert assessment complements modeling and empirical approaches by allowing the synthesis of formal and informal knowledge about the system to inform decision makers and researchers[49–51] (Fig. 4). The approach is based on evidence that multiple estimates built on different assumptions and data provide more robust and reliable numbers[52]. Because the experimental unit in an expert assessment is an individual researcher, each data point integrates multiple types of knowledge available to that person, providing a holistic and integrative estimate of all available information.

This study consisted of 4 stages, during which we:

1. Compiled a list of 85 subject matter experts with expertise in air quality, human health, and economics in Utah by searching the scientific literature, asking for referrals from local to national agencies, and querying university websites.
2. Developed the questionnaire, which consisted of 7 questions and a summary of recent health and economic studies.
3. Distributed the questionnaire and received 14 completed responses, with an average of 10 responses per question (participants only answered questions for which they had pertinent expertise).
4. Analyzed the responses and produced this report with input from all contributors (7 additional experts provided feedback during this stage). 19 of the 21 contributors are listed at the beginning of this report as co-authors (two participants wished to remain anonymous until submission of the report for review). We are now preparing these results for submission to a peer-reviewed journal.

Study questions (number of respondents in parentheses):

1. What is the number of disability-adjusted life years (DALYs) lost to air pollution in Utah each year? (9)
2. What percentage of Utahans experience the following shortening of life because of air pollution? (10)
3. What pollutants contribute most to your health burden estimates from Questions 1 and 2? (11)
4. What health conditions contribute most to your health burden estimates from Questions 1 and 2? (9)
5. What is the direct cost of air pollution to Utah's economy? (8)
6. What is the indirect cost of air pollution to Utah's economy? (8)
7. What actions would you recommend to reduce air pollution in Utah and how much could they reduce the health and economic costs estimated above? (13)

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Air pollution has degraded our health and economy for decades now. We made huge improvements in the 1980s and 1990s, when the overall air pollution index dropped by half (Utah Department of Air Quality 2019). These gains were thanks to national and local regulations, which removed sulfur and lead from fuels, as well as technological and behavioral changes. However, since the year 2000, improvements in Utah's air quality have slowed or stopped due to increased automobile use, area sources (businesses and homes), and power plants. We urge you to support the air-quality legislation listed below to help kick things back into gear. **Cleaning up Utah's air is an enormous opportunity to improve our quality of life and stimulate our economy**. To provide you with the most complete and recent information available, we have compiled peer-reviewed findings about links between air quality, human health, and economic growth.

Utah voters want decisive action now

- Utahans ranked air quality as the 3rd most important issue in the state, after only water and education (Envision Utah 2019)
- **80%** of Utahans said they would accept additional taxes and legislation to improve air quality (Envision Utah 2019)

Bills to Consider, Given the Following Information on Utah's Air Quality

- HB0098: Freight Switcher Emissions Mitigation, sponsored by Representative Handy
- HB0139: Motor Vehicle Emissions Amendments, sponsored by Representative Romero
- HB0148: Vehicle Idling Revisions, sponsored by Representative Arent
- HCR002: Concurrent Resolution Supporting Rural Development of Wind, Solar, Hydrogen Hydroelectric, and Geothermal Energy, sponsored by Representative Arent
- HCR003: Concurrent Resolution Urging the Environmental Protection Agency to Update Switcher Locomotive Emission Standards, sponsored by Representative Handy
- Vehicle Emissions Reduction Program, sponsored by Representative Stenquist
- Concurrent Resolution Urging Policies that Reduce Damage from Wildfires, sponsored by Representative Ward
- Air Quality Amendments, sponsored by Representative Briscoe

Personal and family health depend on clean air

- Air pollution directly impacts the daily lives of Utahans
  - Air pollution kills more Utahans annually than traffic accidents (Chu 2013).
  - On bad air quality days, visits to the emergency room for respiratory and upper respiratory problems increase by 35-40%; visits to the emergency room for Chronic Obstructive Pulmonary Disease increase by 90% (Penrod 2017).
  - There is a 16% increase of spontaneous pregnancy loss associated with 10 ppb increase of nitrogen dioxide (Leiser et al, 2018).
  - Between 1985-1990, there were 77% more school absences due to illness during winter-time inversions in Utah (Ransom & Pope 1991).
- Air pollution affects more than just your lungs (Landrigan *et al.* 2017). It is associated with:
  - Diseases of the central nervous system (autism, dementia, mental retardation)
  - Cardiovascular diseases (strokes, acute respiratory infections, bronchitis, asthma attacks, upper respiratory irritation, and chronic respiratory issues)
  - Psychological and metabolic conditions (suicide, depression, obesity, diabetes)
  - Reproductive health (spontaneous pregnancy loss, low sperm count)

Solving air pollution is an economic opportunity

- Cleaning Utah's air would increase property values, stimulate tourism, and encourage business investment.
- Every dollar invested in air quality in the USA is estimated to yield $30 in benefits (Landrigan *et al.* 2017). This suggests that the $100 million invested this year in Utah can result in a return of $3 billion for Utah's economy (Penrod 2017).
- Clean air is an economic good that people want and demand. It improves our well-being and can't be produced without a cost. The environmental and social cost of pollution should be compared to the production cost of clean air.
- Reducing pollution caused medical conditions could save Utah billions of dollars. For example, Chronic Obstructive Pulmonary Disease alone costs an estimated $5,020 per capita in the state of Utah (Ford *et al.* 2015).

We thank you for all you do to make Utah a better place. We love this state and we hope and pray that we can work together to improve the quality of Utah's air and increase the wellbeing and economic strength of Utah and its citizens.

Sincerely,

Isabella Errigo, Rebecca Frei, Sam Bratsman, Leslie Lange, Allie Tutte, and Audrey Stacey

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