

*Perspective***Learning to Manage the Multirisk World****Jonathan B. Wiener***

Risk assessment, perception, and management tend to focus on one risk at a time. But we live in a multirisk world. This essay in honor of the 40th anniversary of the Society for Risk Analysis (SRA) and the journal *Risk Analysis* suggests that we can—and have already begun to—strengthen risk analysis and policy outcomes by moving from a focus on the single to the multiple—multiple stressors, multiple impacts, and multiple decisions. This evolution can improve our abilities to assess actual risks, to confront and weigh risk-risk trade-offs and innovate risk-superior moves, and to build learning into adaptive regulation that adjusts over time. Recognizing the multirisk reality can help us understand complex systems, foresee unintended consequences, design better policy solutions, and learn to improve.

KEY WORDS: Adaptive; multirisk; precaution; regulation; risk; risk-risk trade-off; stressor

1. INTRODUCTION

The field of risk analysis has progressed enormously over the past 40 years, and the 40th anniversary of the Society for Risk Analysis and the journal *Risk Analysis* is an apt time to reflect. This essay addresses the growth of risk analysis from a singular focus to the reality of multiplicity, and suggests directions for risk analysis to progress further in coming decades.

It is by now familiar to hear that modernity has created a “risk society” (Beck, 1992; Giddens, 1990). This period of modernity does coincide with the establishment of the Society for Risk Analysis and this journal. But risk is not a new phenomenon; humans have always had to deal with risk for survival, and the notion that risk is new may rest on a heuristic error of nostalgia for a pre-risk epoch that never was (Bernstein, 1996).

In any case, it would be more realistic to say that we live in a “multi-risk world” (Wiener, 2002). The challenge is not only risk and uncertainty, but also multiplicity. We are exposed to multiple risks, and our decisions affect multiple risks. Yet, we often tend to neglect the multirisk reality and focus on a single target—one hazard or risk at a time, one target outcome at a time, and one decision at a time. This narrow framing is evident in human perception focusing on a single threat to a single identified individual victim (Small, Loewenstein, & Slovic, 2007; Västfjäll, Slovic, Mayorga, & Peters, 2014), in risk assessment focusing on one hazard or risk at a time, and in risk management aimed at regulating a target risk or a “silo” mission (Anastas & Zimmerman, 2019, pp. 101–103; Baldwin, 2017; Graham & Wiener, 1995; Liu et al., 2015).

This essay highlights the evolution from single to multiple: in risk assessment, from single to multiple risks (multiple stressors); in risk management, from single to multiple impacts (including indirect or ancillary impacts, i.e., risk-risk trade-offs), and from a single decision to multiple sequential decisions (adaptive learning), potentially made by multiple decisionmakers.

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2. FROM SINGLE TO MULTIPLE RISKS: RISK ASSESSMENT

Our risk assessment methods tend to estimate the effect of one hazard or stressor at time, such as by conducting toxicology bioassays on one substance administered to animals, or by undertaking epidemiological studies to distinguish the effect of a single chemical or pathogen from myriad confounding factors. But the reality that we are exposed to multiple stressors is well recognized (Elliott, 1997). “[S]ingle-stressor risk assessments do not reflect the real world, where hazards do not exist independently of one another. Rather, in the real world, communities are simultaneously exposed to multiple stressors via multiple exposure pathways” (Knudsen, 2017, p. 2322, citing Gallagher et al., 2015). For example, people exposed to asbestos may also be exposed to tobacco smoking. Amphibians may be exposed simultaneously to a complex mix of chemicals, pathogens, habitat loss, climate change, and ultraviolet radiation (Beebe & Griffiths, 2005; Hayes, Falso, Gallipeau, & Stice, 2010; McMenamin, Hadly, & Wright, 2008; Scheele et al., 2019). Natural disaster hazards may interact with technological hazards, such as tsunamis damaging nuclear power stations or hog farm waste lagoons (Kappes, Keiler, von Elverfeldt, & Glade, 2012). Wildfires may result from a combination of factors including a warming and drying climate, accumulated fuel material, forest management practices, and ignition sources (Cullen, Axe, & Podschwit, 2020). This year, researchers are trying to assess how infectious diseases such as Covid-19 may be exacerbated by combined exposure to air pollution and other health comorbidities (Fattorini & Regoli, 2020; Goldstein, 2020; Ogen, 2020; Zhu, Xie, Huang, & Cao, 2020).

Pioneers in the field addressing how to assess multiple stressors developed techniques for disentangling joint effects into attribution of the partial contributions by each stressor (Cox, 1984, 1985). Over time, US EPA has developed guidelines on cumulative risk assessment (US EPA, 2003, 2008), and scholars have developed updated analytic frameworks for cumulative risk assessment of exposure to multiple stressors (e.g., Fox, Brewer, & Martin, 2017; Gallagher et al., 2015; Kappes et al., 2012; McHale et al., 2018; Morreto et al., 2017; Sexton & Hattis, 2007) and associated strategies for risk management (Knudsen, 2017).

But as this work recognizes, assessing the joint effects of exposures to multiple stressors is difficult,

because the joint or cumulative effects are not necessarily the sum of their separate partial effects (as Kappes et al., 2012, p. 1927, observe, “multi-hazard risk analyses are not just the sum of single-hazard risk examinations”). The joint effects of multiple stressors may be synergistic or offsetting (Knudsen, 2017, p. 2325). As we move from assessing one risk to multiple risks, the verisimilitude of our assessments may improve but the complexities of our models may also increase. Any model is an approximation; trying to match the full complexity of reality would risk losing its utility as a tractable model. Still, we can improve our models and analyses to build more realism into our risk assessments. A challenge to the field of risk analysis is to develop better methods to represent and assess complex multirisk conditions and interactions. This effort will benefit from work on complex systems analysis (e.g., Anastas & Zimmerman, 2019; Liu et al., 2015) and from the development of better ways to depict the synthesis of multiple complex factors such as in graphical models (Calder et al., 2020). Progress may also come from applying artificial intelligence and related advanced methods to make sense of “open-world” indeterminacies in risk assessment (Cox, 2020).

3. FROM SINGLE TO MULTIPLE RISKS: RISK MANAGEMENT

In the book *Risk vs. Risk*, published 25 years ago, we critiqued the single-risk focus of decision makers (from individuals to regulatory bodies) and called for a more holistic analysis of risk-risk trade-offs in policy analysis (Graham & Wiener, 1995). The problem persists: scholars lament that “[u]nfortunately, institutions and regulations have traditionally focused on single issues and often do not have the mandate or infrastructure to address the organizational connections and detrimental spillovers” (Liu et al., 2015, 1258832-7). Baldwin (2017, p. 126) observes that regulation often “focus[es] attention on individual ‘silos of risk’ so that systemic or cumulative risks are neglected.”

Risk-risk trade-offs are pervasive and the need to address them finds antecedents in many walks of life. Over 2,000 years ago, Odysseus had to navigate between Scylla and Charybdis, minimizing the loss of his crew from these conflicting risks. Hippocrates warned of the side effect risks of medical care (“first, do no harm”), a challenge taken up in the 19th century by Ignaz Semmelweis and Joseph Lister

seeking to make hospitals safe for patients (Wiener, 1998)—a problem we still face today (Miller, 2011). Benjamin Franklin advised that good judgment required weighing the good and harm of each decision (Franklin, 1772; see Wiener, 2013). The understanding of interconnectedness in ecology goes back at least to John Muir, who wrote on July 27, 1869, that “when we try to pick out anything by itself, we find it hitched to everything else in the universe” (Muir, 1988: p. 110). Barbara Tuchman observed the folly of neglecting collateral damage in war (Tuchman, 1984). Lester Lave catalogued types of risk-benefit and risk-risk trade-offs (Lave, 1981).

In *Risk vs. Risk* (Graham & Wiener, 1995), we sought explanatory factors for the tendency by regulators to focus on one risk at a time and neglect side effects. These include mission-driven agencies, sometimes with narrow legal authority; fragmented institutions, with separate specialized domains; narrow or bounded thinking, driven in part by heuristic errors and in part by decision costs; and the omitted voices of those affected.

We proposed that overcoming these limitations should include at least the following measures (Graham & Wiener, 1995): First, confront: see the multirisk reality, think broadly and holistically; exercise foresight to illuminate the multiple potential consequences of each regulatory alternative. Second, compare: weigh the trade-offs among multiple risks, with the objective to reduce *overall* risk (rather than only the target risk). We recognized the challenges in comparing risks with diverse attributes on which people may have different perspectives (and perceptions), including probability, severity, population, uncertainty, type of impact, timing, and distributional equity. We noted that the full impact analysis should include both countervailing harms and co-benefits (Graham & Wiener, 1995, pp. 1–2, 37), a point later emphasized in greater detail by Revesz and Livermore (2008, 2020) and our own papers (Graham, Wiener, & Robinson, 2020; Stern & Wiener, 2008). We borrowed the phrase “treat the whole patient” from the analogous problem of side effects in medical specialties, and the need for comprehensive approaches that internalize full impacts in the regulatory system. Third, innovate: seek “risk-superior moves”—better options that reduce multiple risks in concert. Risk-superior moves can turn countervailing harms into added benefits. (One example: overcoming the risk-risk tragedy that automobile airbags were saving adults but killing children, by requiring children to ride in the safer rear seat and introduc-

ing smarter airbags that adjust deployment to correspond to the occupant, see Graham et al., 1998.)

And we encouraged a suite of improvements in laws and institutions (Graham & Wiener, 1995). Key measures we suggested include requiring impact assessment of full impacts—currently practiced in both environmental impact assessment (EIA) and regulatory impact assessment (RIA), and expressly required in the section of OMB Circular A-4 (2003) on “ancillary impacts” (see Wiener & Ribeiro, 2016); assuring that agencies have the legal authority to consider full impacts (as provided, for example, in the Safe Drinking Water Act amendments of 1996); executive review through oversight bodies such as OMB/OIRA, as well as a new body we suggested to scan ahead and to resolve interagency risk trade-offs, a “council of risk analysts” (later cited by the World Bank (2014, pp. 278–279) in its recommendation to establish “national risk boards”); coordination and notification across regulatory agencies when their regulations pose spillover effects in other agencies’ domains (a function that OIRA has fostered, Sunstein, 2013); and judicial review for arbitrariness and unreasonableness if agencies neglect important multirisk impacts (which is now on the rise, see Masur & Posner, 2018; Sunstein, 2017).

The problem is not government regulation versus markets, the problem is narrowness—neglect of important impacts (Stewart, 2014; Wiener, 2021). Nor are risk-risk trade-offs limited to health and environmental policy. They occur pervasively across domains, notably in medical care (Miller, 2011; Wiener, 1998), transportation (Graham et al., 1998; Thompson, Segui-Gomez, & Graham, 2002), and in military and national security policies (Stern & Wiener, 2008; Tuchman, 1984; Vermeule, 2012). As noted above, the risk of Covid-19 may interact with multiple stressors such as air pollution and comorbidities; in turn, the responses to remedy Covid-19 may affect multiple risks, including triage of other ailments such as heart disease; countervailing risks of social distancing and shutdowns such as depression and hunger due to isolation, and co-benefits such as reduced air pollution; and the benefits and risks of vaccines.

The core point is that we live in a multirisk world, so our decisions to address one risk may affect other risks. The real world is not a series of separate risks, but a web of multiple causally interconnected risks and opportunities; we face multiple nodes, and each move to manage one involves potential slopes toward or away from others. This *n*-dimensional web or network of risks is daunting, and the slopes among

nodes reflect marginal rates of substitution or trade-off among risks. To be sure, not every side effect is important enough to warrant attention and action; when considering how many “ripples” of impact one should address (Graham & Wiener, 1995, pp. 20–22, 228; Hofstetter, Bare, Hammitt, Murphy, & Rice, 2002, p. 836), we can avoid paralysis by applying a kind of value of information (VOI) approach to assessing the relative importance of each *n*th risk effect, the potential improvement from addressing it and the costs (including delay) of doing so (Graham et al., 2020). Risk-superior moves are, in a sense, ways of rising above the current web of risks to see a new paradigm that overcomes the trade-offs and reduces multiple risks in concert.

4. FROM SINGLE TO MULTIPLE DECISIONS: ADAPTIVE POLICY LEARNING

Much risk regulation focuses on a single one-time decision, such as adopting an agency rule. The more this decision is seen as the only opportunity—or battleground—to address a problem, the more it warrants intensive *ex ante* policy analysis and sparks intense disputes. But a single regulatory decision faces the difficulty that the world changes—science, technology, economics, demographics, and public values may all evolve. Even if it was initially estimated to have net benefits at the time of adoption, a static policy may become increasingly out of step with the changing world, yielding worsening outcomes and increasing frustration (Bennear & Wiener, 2019). Moreover, the *ex ante* estimates of net benefits may prove inaccurate in retrospective analyses and as implementation unfolds (Cropper, Fraas, & Morgenstern, 2017; Greenstone, 2009).

The challenge is to find ways for risk regulation to adapt as the world changes. This entails a shift from single to multiple decisions—sequential, learning, adaptive regulation. Rather than blaming past decisions, we should learn from experience—including near-misses—to improve risk management (Paté-Cornell & Cox, 2014). One approach is to learn by comparing horizontally across jurisdictions (Clahsen et al., 2019; Hammitt, Wiener, Swedlow, Kall, & Zhou, 2005). We can also learn longitudinally and design regulatory systems that are planned to adapt—built to learn from experience and experimentation (Bennear & Wiener, 2019; Craig & Ruhl, 2014; Greenstone, 2009; Pidot, 2015). Some U.S. risk regulation already incorporates versions of this adaptive approach, such as periodic reviews every 5 or 10

years of key regulatory science and standards (McCray, Oye, & Petersen, 2010). Additional mechanisms can include monitoring of key variables, *ex post* retrospective review (Cropper et al., 2017), ongoing periodic review (every set period of time), safety boards to learn from crises (Balleisen et al., 2017), adaptive licensing (learning from phases of experience, such as with new drugs or vehicles, before expanding eligible populations), and discretionary reviews or automated adjustments (Bennear & Wiener, 2019).

Planned adaptive regulation poses pros and cons, so it may not be ideal for every risk regulatory issue. It offers the potential to improve policy outcomes in a changing world, so it may be best applied where significant change or resolution of prior uncertainty is likely—that is, where the gains from learning appear to be high, where the policy can increase net benefits by adjusting to new conditions and new understanding. On the other hand, it involves costs, including data collection (monitoring) and analysis, and periodic decisions whether to revise past policy, as well as the costs of policy instability for actors who rely and invest based on the rules (Bennear & Wiener, 2019). Importantly, the multirisk perspective discussed above should be reflected in planned adaptive regulation: the ongoing monitoring, analysis, and periodic reviews should account not only for costs and intended benefits, but also for unintended ancillary impacts. If the policy is yielding serious countervailing harms, that can be an important reason for revision.

There are, however, limits to learning as a strategy for risk regulation. Beyond the costs of monitoring and policy revision, there are some risks for which adaptive learning itself may be a risky strategy: extreme global catastrophic risks—existential risks—which might end all life or civilization. (More modest “catastrophes,” such as at the regional or local level, can still be addressed through combinations of preventive measures and adaptive learning to do better over time, see Balleisen et al., 2017; Bier, 2018; Haimes, 2012.) These extreme existential risks would be too rare to afford a learning experience for regulators or the public (Wiener, 2016), too massive to motivate empathetic public concern (which tends to focus on an individual victim, see Small et al., 2007; Slovic et al., 2013; Västfjäll et al., 2014), and too devastating or annihilating to wait to experience and hope to learn (Garrick, 2008; Wiener, 2016). These truly extreme existential risks pose the strongest case for judicious *ex ante* precautions (Bostrom, 2013;

Paté-Cornell, 2012; Posner, 2004; Sunstein, 2007; Wiener, 2016), keeping in mind that the potential risk-risk trade-offs flowing from such precautions—i.e., catastrophe–catastrophe trade-offs—must still be assessed and addressed (Sunstein, 2007; Wiener, 2016).

5. CONCLUSIONS

These multiple evolutions from a single risk to a multirisk world—addressing multiple stressors, multiple impacts, and multiple decisions—are already underway, and as this essay has indicated, the community of risk analysts has contributed important insights. There are, to be sure, additional dimensions of moving from single to multiple, such as moving from one actor to multiple actors—multiple decision-makers, perhaps representing multiple stakeholders with heterogeneous preferences—and the prospect of strategic behavior in addressing risks such as terrorism (Cox, 2009; Ezell, Bennett, Von Winterfeldt, Sokolowski, & Collins, 2010) or climate change and geoengineering (Abatayo, Bosettia, Casarid, Ghidonif, & Tavoni, 2020; Grieger, Felgenhauer, Renn, Wiener, & Borsuk, 2019; Sandler, 2018). This essay embodies the hope and confidence that as we improve our ability to understand and address the complex reality of a multirisk world, the science and profession of risk analysis can offer societies substantial progress in reducing overall risks and enhancing well-being.

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REFERENCES

- Abatayo, A. L., Bosettia, V., Casarid, M., Ghidonif, R., & Tavoni, M. (2020). Solar geoengineering may lead to excessive cooling and high strategic uncertainty. *Proceedings of the National Academy of Science (PNAS)*, 117, 13393–13398.
- Anastas, P. T., & Zimmerman, J. B. (2019). Environmental protection through systems design, decision-making, and thinking. In D. C. Esty (Ed.), *Better planet*. Pittsburgh, PA: Yale University Press.
- Baldwin, R. (2017). Regulatory excellence and lucidity. In C. Coglianese (Ed.), *Achieving regulatory excellence*. Washington, DC: Brookings Press.
- Balleisen, E. J., Benneear, L. S., Krawiec, K. D., & Wiener, J. B. (Eds.). (2017). *Policy Shock: Recalibrating risk and regulation after oil spills, nuclear accidents, and financial crises*. Cambridge: Cambridge University Press.
- Beck, U. (1992). *Risk society: Towards a new modernity* (trans. Mark Ritter). London: Sage Publications.
- Beebee, T. J. C., & Griffiths, R. A. (2005). The amphibian decline crisis: A watershed for conservation biology? *Biological Conservation*, 125, 271–285.
- Benneear, L. S., & Wiener, J. B. (2019). Built to learn: From static to adaptive environmental policy. In D. C. Esty (Ed.), *Better planet* (pp. 353–360). Pittsburgh, PA: Yale University Press.
- Bernstein, P. (1996). *Against the Gods: The remarkable story of risk*. Somerset: John Wiley & Sons.
- Bier, V. M. (Ed.). (2018). *Risk in extreme environments: Preparing, avoiding, mitigating, and managing*. New York, NY: Routledge.
- Bostrom, N. (2013). Existential Risk Prevention as Global Priority. *Global Policy*, 4, 15–31. <https://doi.org/10.1111/1758-5899.12002>
- Calder, R. S. D., Alatorre, A., Marx, R. S., Mallampalli, V., Mason, S. A., Olander, L. P., ... Borsuk, M. E. (2020). Graphical models and the challenge of evidence-based practice in development and sustainability. *Environmental Modelling and Software*, 130, 104734.
- Clahsen, S. C. S., van Kamp, I., Hakkert, B. C., Vermeire, T. G., Piersma, A. H., & Lebre, E. (2019). Why do countries regulate environmental health risks differently? A theoretical perspective. *Risk Analysis*, 39, 439–461.
- Cox, L. A. Jr. (1984). Probability of causation and the attributable proportion risk. *Risk Analysis*, 4, 221–230. <https://doi.org/10.1111/j.1539-6924.1984.tb00142.x>, and <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.1984.tb00142.x>.
- Cox, L. A. Jr. (1985). A new measure of attributable risk for public health applications. *Management Science*, 31, 800–813.
- Cox, L. A. Jr. (2009). Game theory and risk analysis. *Risk Analysis*, 29, 1062–1069. <https://doi.org/10.1111/j.1539-6924.2009.01247.x>
- Cox, L. A. Jr. (Tony). (2020). Answerable and unanswerable questions in risk analysis with open-world novelty. *Risk Analysis*, Retrieved from <https://onlinelibrary.wiley.com/doi/abs/10.1111/risa.13553>
- Craig, R., & Ruhl, J. B. (2014). Designing administrative law for adaptive management. *Vanderbilt Law Review*, 67, 1–87.
- Cropper, M., Fraas, A., & Morgenstern, R. (2017). Looking backward to move regulations forward: Rigorous ex post analyses can improve regulatory policies. *Science*, 355, 1375–1376.
- Cullen, A. C., Axe, T., & Podschwilt, H. (2020). High-severity wildfire potential – Associating meteorology, climate, resource demand and wildfire activity with preparedness levels. *International Journal of Wildland Fire*, <https://doi.org/10.1071/WF20066>, and <https://www.publish.csiro.au/WF/WF20066>.
- Elliott, E. D. (1997). Toward ecological law and policy. In M. R. Chertow & D. C. Esty (Eds.), *Thinking ecologically*. New Haven, CT: Yale University Press.
- Ezell, B. C., Bennett, S. P., Von Winterfeldt, D., Sokolowski, J., & Collins, A. J. (2010). Probabilistic risk analysis and terrorism risk. *Risk Analysis*, 30, 575–598. <https://doi.org/10.1111/j.1539-6924.2010.01401.x>
- Fattorini, D., & Regoli, F. (2020). Role of the chronic air pollution levels in the Covid-19 outbreak risk in Italy. *Environmental Pollution*, 264. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0269749120332115>
- Fox, M. A., Brewer, L. E., & Martin, L. (2017). An overview of literature topics related to current concepts, methods, tools, and applications for cumulative risk assessment (2007–2016). *International Journal of Environmental Research and Public Health*, 14(4), 389. Retrieved from <http://www.mdpi.com/1660-4601/14/4/389/pdf>
- Franklin, B. (1772). Letter to Joseph Priestley, September 19. Reprinted In F. L. Mott & C. E. Jorgenson (Eds.), *Benjamin Franklin: Representative selections, with introduction*,

- bibliography and notes* (pp. 348–349). New York: American Book Company.
- Gallagher, S., Rice, G. E., Scarano, L. J., Teuschler, L. K., Bollweg, G., & Martin, L. (2015). Cumulative risk assessment lessons learned: A review of case studies and issue papers. *Chemosphere*, 120, 697–705. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0045653514012144>
- Garrick, B. J. (2008). *Quantifying and controlling catastrophic risks*. Amsterdam; Boston, MA: Elsevier/Academic Press.
- Giddens, A. (1990). *Consequences of modernity*. Cambridge, England: Polity Press.
- Goldstein, B. D. (2020). EPA must consider COVID-19 when setting air pollutant standards. The Hill (June 28). Retrieved from <https://thehill.com/opinion/energy-environment/504908-epa-must-consider-covid-19-when-setting-air-pollutant-standards>
- Graham, J. D., Goldie, S. J., Segui-Gomez, M., Thompson, K. M., Nelson, T., Glass, R., ... Woerner, L. G. (1998). Reducing risks to children in vehicles with passenger airbags. *Pediatrics*, 102(1), e3. <https://doi.org/10.1542/peds.102.1.e3>, <https://pediatrics.aappublications.org/content/102/1/e3.short>
- Graham, J. D., & Wiener J. B. (Eds.) (1995). *Risk vs risk: Trade-offs in protecting health and the environment*. Cambridge, MA: Harvard University Press.
- Graham, J. D., Wiener, J. B., & Robinson, L. A. (2020). Co-benefits, countervailing risks and cost-benefit analysis. In D. Paustenbach (Ed.), *Human and ecological risk assessment*. New York: John Wiley & Sons, forthcoming.
- Greenstone, M. (2009). Toward a culture of persistent regulatory experimentation and evaluation. In D. Moss & J. Cisternino (Eds.), *New perspectives on regulation*. Cambridge: Tobin Project.
- Grieger, K., Felgenhauer, T., Renn, O., Wiener, J., & Borsuk, M. (2019). Emerging risk governance for stratospheric aerosol injection as a climate management technology. *Environmental System and Decisions*, 39(4), 371–382. Retrieved from <http://link.springer.com/article/10.1007/s10669-019-09730-6>
- Haimes, Y. Y. (2012). Strategic preparedness for recovery from catastrophic risks to communities and infrastructure systems of systems. *Risk Analysis*, 32, 1834–1845.
- Hammitt, J. K., Wiener, J. B., Swedlow, B., Kall, D., & Zhou, Z. (2005). Precautionary regulation in Europe and the United States: A quantitative comparison. *Risk Analysis*, 25(5), 1215–1228.
- Hayes, T. B., Falso, P., Gallipeau, S., & Stice, M. (2010). The cause of global amphibian declines: A developmental endocrinologist's perspective. *Journal of Experimental Biology*, 213(6), 921–933. <https://doi.org/10.1242/jeb.040865>
- Hofstetter, P., Bare, J. C., Hammitt, J. K., Murphy, P. A., & Rice, G. E. (2002). Tools for comparative analysis of alternatives: Competing or complementary perspectives? *Risk Analysis*, 22, 833–851.
- Kappes, M. S., Keiler, M., von Elverfeldt, K., & Glade, T. (2012). Challenges of analyzing multi-hazard risk: A review. *Natural Hazards*, 64, 1925–1958. <https://doi.org/10.1007/s11069-012-0294-2>
- Knudsen, S. (2017). Regulating cumulative risk. *Minnesota Law Review*, 101, 2313–2396.
- Lave, L. B. (1981). *The strategy of social regulation: Decision frameworks for policy*. Washington DC: Brookings.
- Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., ... Li, S. (2015). Systems integration for global sustainability. *Science*, 347, 963. <https://doi.org/10.1126/science.1258832>
- Masur, J. S., & Posner, E. A. (2018). Cost-benefit analysis and the judicial role. *University of Chicago Law Review*, 85, 935–986.
- McCray, L. E., Oye, K. A., & Petersen, A. C. (2010). Planned adaptation in risk regulation. *Technological Forecasting & Social Change*, 77, 951–959.
- McHale, C., Osborne, G., Morello-Frosch, R., Salmon, A. G., Sandy, M. S., Solomon, G., ... Zeise, L. (2018). Assessing health risks from multiple environmental stressors: Moving from $G \times E$ to $I \times E$. *Mutation Research*, 775, 11–20. Retrieved from <https://www.sciencedirect.com/science/article/pii/S1383574217300698?via%3Dihub>
- McMenamin, S. K., Hadly, E. A., & Wright, C. K. (2008). Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. *Proceedings of the National Academy of Science (PNAS)*, 105, 16988–16993. <https://doi.org/10.1073/pnas.0809090105>
- Miller, F. (2011). Medical errors, new drug approval, and patient safety. In J. B. Wiener, M. D. Rogers, J. K. Hammitt, & P. H. Sand (Eds.), *The reality of precaution: Comparing risk regulation in the United States and Europe* (Chapter 11). Washington, DC: RFF/Routledge.
- Morroto, A., Bachman, A., Boobis, A., Solomon, K. R., Pastoor, T. P., Wilks, M. F., & Embry, M. R. (2017). A framework for cumulative risk assessment in the 21st century. *Critical Reviews in Toxicology*, 47(2), 85–97.
- Muir, J. (1988). *My first summer in the sierras*. San Francisco, CA: Sierra Club Books, John Muir Library.
- Ogen, Y. (2020). Assessing nitrogen dioxide (NO₂) levels as a contributing factor to coronavirus (COVID-19) fatality. *Science of Total Environment*, 726, Retrieved from <https://www.sciencedirect.com/science/article/pii/S0048969720321215>
- Paté-Cornell, E. (2012). On “Black Swans” and “Perfect Storms”: Risk analysis and management when statistics are not enough. *Risk Analysis*, 32, 1823–1833. <https://doi.org/10.1111/j.1539-6924.2011.01787.x>
- Paté-Cornell, E., & Cox, L. A. Jr. (2014). Improving risk management: From lame excuses to principled practice. *Risk Analysis*, 34, 1228–1239. <https://doi.org/10.1111/risa.12241>
- Pidot, J. R. (2015). Governance and uncertainty. *Cardozo Law Review*, 37, 112–184.
- Posner, Richard A. (2004). *Catastrophe: Risk and Response*. Oxford: Oxford University Press.
- Revesz, R. L., & Livermore, M. A. (2008). *Retaking rationality*. Oxford: Oxford University Press.
- Revesz, R. L., & Livermore, M. A. (2020). *Reviving rationality*. Oxford: Oxford University Press.
- Sandler, T. (2018). Collective action and geoengineering. *Review of International Organization*, 13, 105–125. <https://doi.org/10.1007/s11558-017-9282-3>
- Scheele, B. C., Pasmans, F., Skerratt, L. F., Berger, L., Martel, A., Beukema, W., ... Canessa, S. (2019). Amphibian fungal panzootic causes catastrophic and ongoing loss of biodiversity. *Science*, 363, 1459–1463. <https://doi.org/10.1126/science.aav0379>
- Sexton, K., & Hattis, D. (2007). Assessing cumulative health risks from exposure to environmental mixtures – Three fundamental questions. *Environmental Health Perspectives*, 115, 825–832. Retrieved from <https://pubmed.ncbi.nlm.nih.gov/17520074/>
- Slovic, P., Zions, D., Woods, A. K., Goodman, R., & Jinks, D. (2013). Psychic numbing and mass atrocity. In E. Shafir (Ed.), *The behavioral foundations of public policy* (Chapter 7, pp. 126–142). Princeton, NJ: Princeton University Press.
- Small, D. A., Loewenstein, G., & Slovic, P. (2007). Sympathy and callousness: The impact of deliberative thought on donations to identifiable and statistical victims. *Organizational Behavior and Human Decision Processes*, 102, 143–153.
- Sunstein, C. R. (2007). *Worst-case scenarios*. Cambridge, MA; London: Harvard University Press.
- Sunstein, C. R. (2013). The office of information and regulatory affairs: Myths and realities. *Harvard Law Review*, 126, 1838–1878.
- Sunstein, C. R. (2017). Cost-benefit analysis and arbitrariness review. *Harvard Environmental Law Review*, 41, 1–41.
- Stern, J., & Wiener, J. B. (2008). Precaution against terrorism. In P. Bracken, D. Gordon, & I. Bremmer (Eds.), *Managing strategic surprise: Lessons from risk management and risk assessment* (Chapter 5). Cambridge: Cambridge University Press.

- Stewart, R. B. (2014). Remedying disregard in global regulatory governance. *American Journal of International Law*, 108, 211–270.
- Thompson, K. M., Segui-Gomez, M., & Graham, J. D. (2002). Validating benefit and cost estimates: The case of airbag regulation. *Risk Analysis*, 22, 803–811. <https://doi.org/10.1111/0272-4332.00070>
- Tuchman, B. W. (1984). *The March of folly: From Troy to Vietnam*. New York: Ballantine Books.
- U.S. EPA. Framework for Cumulative Risk Assessment (U.S. EPA). (2003). Retrieved from https://www.epa.gov/sites/production/files/2014-11/documents/frmwrk_cum_risk_assmnt.pdf
- U.S. EPA. (2008). *Concepts, methods, and data sources for cumulative health risk assessment of multiple chemicals, exposures and effects: A resource document*. Final Report EPA/600/R-06/013F, U.S. Environmental Protection Agency, Washington, DC. Retrieved from <https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=190187>
- Västfjäll, D., Slovic, P., Mayorga, M., & Peters, E. (2014). Compassion fade: Affect and charity are greatest for a single child in need. *PLoS One*, 9, <https://doi.org/10.1371/journal.pone.0100115> and <https://journals.plos.org/plosone/article?id=https://doi.org/10.1371/journal.pone.0100115>
- Vermeule, A. (2012). Precautionary principles in constitutional law. *Journal of Legal Analysis*, 4, 181–222.
- Wiener, J. B. (1998). Managing the iatrogenic risks of risk management. *Risk: Health Safety and Environment*, 9, 39–82.
- Wiener, J. B. (2002). Precaution in a multi-risk world. In D. D. Paustenbach (Ed.), *Human and ecological risk assessment: Theory and practice*, pp. 1509–1531. New York: John Wiley & Sons.
- Wiener, J. B. (2013). The diffusion of regulatory oversight. In M. A. Livermore & R. L. Revesz (Eds.), *Globalization of cost-benefit analysis in environmental policy* (pp. 123–141). New York, NY; Oxford: Oxford University Press.
- Wiener, J. B. (2016). The tragedy of the uncommons. *Global Policy*, 75(Supp1), 67–80.
- Wiener, J. B. (2021). Disregard and due regard. *NYU Environmental Law Journal*, forthcoming.
- Wiener, J. B., & Ribeiro, D. L. (2016). Impact assessment: Diffusion and integration. In F. Bignami & D. Zaring (Eds.), *In Comparative law and regulation* (pp. 159–189). Cheltenham, UK: Edward Elgar.
- World Bank. (2014). Risk and opportunity—Managing risk for development. World Development Report, 2014. Retrieved from <https://openknowledge.worldbank.org/handle/10986/16092>
- Zhu, Y., Xie, J., Huang, F., & Cao, L. (2020). Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China. *Science of Total Environment*, 717, Retrieved from <https://www.sciencedirect.com/science/article/pii/S004896972032221X>