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Critical Perspectives

The Atrazine Saga and its Importance to the Future of Toxicology, Science, and Environmental and Human Health

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Abstract: The herbicide atrazine is one of the most commonly used, well studied, and controversial pesticides on the planet. Much of the controversy involves the effects of atrazine on wildlife, particularly amphibians, and the ethically questionable decision making of members of industry, government, the legal system, and institutions of higher education, in most cases in an effort to "bend science," defined as manipulating research to advance economic, political, or ideological ends. In this Critical Perspective I provide a timeline of the most salient events in the history of the atrazine saga, which includes a multimillion-dollar smear campaign, lawsuits, investigative reporting, accusation of impropriety against the US Environmental Protection Agency, and a multibillion-dollar transaction. I argue that the atrazine controversy must be more than just a true story of cover-ups, bias, and vengeance. It must be used as an example of how manufacturing uncertainty and bending science can be exploited to delay undesired regulatory decisions and how greed and conflicts of interest—situations where personal or organizational considerations have compromised or biased professional judgment and objectivity—can affect environmental and public health and erode trust in the discipline of toxicology, science in general, and the honorable functioning of societies. Most importantly, I offer several recommendations that should help to 1) prevent the history of atrazine from repeating itself, 2) enhance the credibility and integrity of science, and 3) enrich human and environmental health. *Environ Toxicol Chem* 2021;40:1544–1558. © 2021 SETAC

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INTRODUCTION

If one had to pick the most widely studied, commonly used, and controversial pesticide, it very well may be the herbicide atrazine. A search for the term "atrazine" in the search engine Web of Science (conducted on 11/26/2020) produced 13 651 studies. Although it is banned in Europe, atrazine is the second most commonly used pesticide in the United States (Grube et al. 2011). It was the most commonly used pesticide in the United States just before the advent of genetically modified crops, which facilitated the herbicide glyphosate (Roundup®) surpassing atrazine in use (Grube et al. 2011). The persistence, mobility, and heavy use of atrazine make it one of the most common chemical contaminants in drinking and surface water (Rohr et al. 2003; Knutson et al. 2004), and thus, there has been considerable interest in the effects of atrazine on humans and freshwater organisms (e.g. Solomon et al. 2008; Rohr and McCoy 2010b), particularly freshwater vertebrates, because of their physiological similarities to humans. A substantial amount of work has been conducted on amphibians, because of their global declines (Rohr et al. 2008a; Wake and Vredenburg 2008; Rohr and Raffel 2010; Liu et al. 2013; Raffel et al. 2013; Rohr et al. 2015) and early work suggesting that atrazine causes hermaphroditism in frogs (Hayes et al. 2002b).

Syngenta Crop Protection, the former producer of atrazine, made approximately 2.3 billion USD annually on its herbicides, of which atrazine is their leading product (Slater 2012). Unsurprisingly, Syngenta wanted to protect its top product, which resulted in a well-documented smear and intimidation campaign against researchers revealing adverse effects of atrazine and Syngenta adopting questionable activities to convince the public and the US Environmental Protection Agency (USEPA) of atrazine's safety. In this Critical Perspectives, I document this and related history surrounding atrazine, and submit that the story of atrazine represents a textbook example of manufacturing

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uncertainty and bending science to delay undesired regulatory decisions that must be widely familiar to both current and future toxicologists so that history does not repeat itself.

Bending science is the processes by which the culture of science, regulation, and other segments of society can interact to suppress unfavorable or enhance favorable scientific results, in many cases to advance economic, political, or ideological ends (McGarity and Wagner 2008). McGarity and Wagner (2008) describe 6 major tools for bending science, which I will highlight throughout my documentation of the history of atrazine (see Lane and Landis 2016 for similar example on fracking). The first tool is *shaping* science, which is the art of creating research to produce a desired outcome, often referred to as outcome-oriented research. When efforts to shape science fail, advocates will often attempt to *hide* science associated with unwelcome information or *attack* this science by launching illegitimate critiques in an effort to turn reliable science into "junk" (Huber 1991; Herrick and Jamieson 2001). To discourage future damaging research, advocates will also *harass* or bully scientists who produce damaging research. *Packaging* science is the art of assembling an expert group to advance a favored outcome, whereas *spinning* science is the art of manipulating public perception about credible science. Hence, the scientific pipeline can be contaminated by outside advocates at the point of devising and conducting research to the use and interpretation of science to affect legal, regulatory, and policy debates and decisions (McGarity and Wagner 2008). In some cases, academics with no associations to industry can corrupt the scientific process, such as cases when academic scientists fabricate data. However, many of the most well-documented cases of bending science involve industry or public officials that rely on industry support, likely because these entities have a larger financial stake and more financial resources to bend science than academics. For example, many of the 6 tools for bending science were used by fossil fuel companies and by the Bush and Trump administrations (in the United States) to prevent climate change regulations, big tobacco to generate uncertainty regarding the harm of cigarettes (Mooney 2005; Rohr and McCoy 2010a; Oreskes and Conway 2011), oil companies to reduce costly fines and clean up for the *Exxon Valdez* and *Deepwater Horizon* oil spills (McGarity and Wagner 2008; Bradshaw 2014), and pesticide companies to intimidate Rachel Carson and disparage the underlying science of *Silent Spring* (McGarity and Wagner 2008). Hence, the tactics I describe below associated with atrazine are not unique but represent a well-used playbook for many advocates.

Despite the USEPA concluding in 2016 that atrazine poses risks to aquatic plants, fish, amphibians, mammals, birds, and reptiles (Farruggia et al. 2016), and in 2018, that it poses reproductive and developmental risks to humans, particularly children (US Environmental Protection Agency 2018), in 2020, the USEPA renewed the registration of atrazine and relaxed regulations, allowing 50% more atrazine to enter water bodies (Erickson 2019; US Environmental Protection Agency 2020). Although the story of atrazine has been partially told (Rohr 2018), these recent regulatory events, the Trump administration's regular dismissal of science (Lin 2019), and the change in the United States presidency, underscore the importance of drawing new attention to this remarkable story in the history of toxicology that is unfamiliar to so many. Hence, I provide a more complete and updated account of the most salient moments in the history of the atrazine controversy, emphasizing bent science and how it might have impacted decision making with potential consequences for ecosystem and human health and public trust in science. Importantly, I do not only highlight how members of industry bent science, but I also place a spotlight on the questionable decision making of members of government, the legal system, the peer review system, and institutions of higher education. I end with a discussion of lessons learned from the history of atrazine and how these lessons can be used to improve toxicology and health. However, before I provide an updated timeline on the history of the atrazine controversy, I first briefly review the effects of atrazine on freshwater vertebrates to provide important context.

A BRIEF REVIEW OF THE EFFECTS OF ATRAZINE ON AMPHIBIANS

The effects of atrazine on freshwater organisms, including fish and amphibians, are well documented and diverse. I focus predominantly on the effects of atrazine on amphibians because most of the controversy surrounding atrazine has centered on amphibian studies. Atrazine is documented to affect amphibian growth and timing of metamorphosis, (Larson et al. 1998; Allran and Karasov 2000, 2001; Boone and James 2003; Rohr et al. 2004; Forson and Storfer 2006a, 2006b) behaviors crucial for foraging and avoiding predators, (Rohr et al. 2003, 2004, 2009) and desiccation (Rohr and Palmer 2005, 2013). Moreover, delayed or persistent effects of atrazine on behavior and physiology can increase mortality risk (Storrs and Kiesecker 2004; Rohr and McCoy 2010b; Rohr and Palmer 2005, 2013). There have been numerous studies on the effects of atrazine on physiology because of the role of physiology to vertebrate survival and conservation (Martin et al. 2010; Rohr et al. 2013b; Madliger et al. 2016). Several studies have explored the role of atrazine as an "infodisruptor," defined as a chemical contaminant that disrupts communication within or among organisms, including contaminants that breakdown or interfere with detection or production of chemical signals between senders and receivers or those that affect cell-to-cell communication within organisms (e.g., endocrine disruptors; Lürling and Scheffer 2007; Rohr et al. 2009). Atrazine has been shown to reduce chemical detection of cues from predators and mates (Moore and Waring 1998; Tierney et al. 2007; Ehrsam et al. 2016) and to affect cell-to-cell communication by altering hormones, such as stress hormones (Gabor et al. 2016; McMahon et al. 2017), thyroid hormones (Larson et al. 1998), and sex hormones (Hayes 2003; Hayes et al. 2003), the latter of which might alter sex ratios and the development of reproductive organs (Langlois et al. 2010; Trachantong et al. 2013; Hoskins and Boone 2018; Rimayi et al. 2018; Sai et al. 2018, 2019). More details on the effects of atrazine on amphibian sex hormones and gonadal development are provided in the section *A History of the Atrazine Controversy*.

Recent detection of hump- or U-shaped dose responses of contaminants is of particular concern because these dose responses are often associated with endocrine disruption and indicate that low doses of a chemical can have greater adverse effects than some higher doses (Welshons et al. 2003; McMahon et al. 2011, 2013; Vandenberg et al. 2012). Hump- or U-shaped atrazine dose responses have been revealed for several amphibian hormones, including corticosterone, thyroid hormone, and sex hormones (Larson et al. 1998; Hayes 2003; Hayes et al. 2003; Fan et al. 2007; McMahon et al. 2017). Atrazine also regularly has nonlinear effects on the timing of metamorphosis (Rohr and McCoy 2010b; Brodeur et al. 2013). Other endpoints have regularly produced nonlinear, logarithmic dose responses, where the greatest change in response occurs at low exposure concentrations (Rohr et al. 2004, 2006b, 2013c; McMahon et al. 2013), supporting the potency of low concentrations of atrazine.

Although atrazine generally does not directly cause mortality of freshwater vertebrates at ecologically relevant concentrations (Solomon et al. 2008; Rohr and McCoy 2010b), some studies suggest that it might increase mortality through indirect effects, such as by increasing infectious diseases, some of which are associated with amphibian declines (Li et al. 2013; Liu et al. 2013; Rohr et al. 2013b; McMahon et al. 2014; Venesky et al. 2014). In 2002, atrazine exposure was revealed to be associated with reduced amphibian immunity, elevated trematode infections, and limb malformations caused by these infections (Kiesecker 2002). Rohr and colleagues offered additional support for the immunosuppressive effects of atrazine and increases in trematode infections (Rohr et al. 2008b, 2008c, 2015; Raffel et al. 2009; Schotthoefer et al. 2011). In addition, they showed that atrazine increases both amphibian and human exposure to trematodes by reducing phytoplankton, which, in turn, reduces shading and increases the abundance of periphyton, the food source for snails, which are the intermediate host of trematodes (Rohr et al. 2008c, 2019; Raffel et al. 2010; Staley et al. 2010, 2011; Halstead et al. 2014, 2017; Rumschlag et al. 2019; Hoover et al. 2020). Syngenta-funded authors also found support for atrazine increasing snail abundance (Herman et al. 1986; Baxter et al. 2011), as documented by Rohr et al. (2012) and Rohr (2018). Atrazine exposure has also been associated with reduced immunity and increased amphibian viral and roundworm infections (Gendron et al. 1997; Forson and Storfer 2006a, 2006b; Hayes et al. 2006; Kerby and Storfer 2009; Koprivnikar 2010; Sifkarovski et al. 2014). In addition, atrazine exposure has been shown to reduce tolerance (the ability of hosts to reduce damage caused by parasites; Rohr et al. 2010c; Sears et al. 2013, 2015) of chytrid fungal infections that are associated with worldwide amphibian declines (Rohr et al. 2013c). In a 2010 meta-analysis (Rohr and McCoy 2010b), atrazine exposure was associated with a reduction in 33 of 43 immune function endpoints and with an increase in 13 of 16 infection endpoints, numbers that have increased since then (e.g. Koprivnikar 2010; Rohr et al. 2013c; Sifkarovski et al. 2014; Wang et al. 2018; Neamat-Allah et al. 2020).

Several researchers have also studied the effects of atrazine on freshwater communities containing freshwater vertebrates, rather than isolated amphibian species (Boone and James 2003; Rohr and Crumrine 2005; Rohr et al. 2008c; Halstead et al. 2014; Rumschlag et al. 2019, 2020). This work was at least partially motivated by positive relationships between biodiversity and ecosystem services, such as primary production, clean water, and pest and disease control (McMahon et al. 2012; Staley et al. 2014; Civitello et al. 2015; Cohen et al. 2016; De Laender et al. 2016; Halliday et al. 2020; Rohr et al. 2020), and the importance of indirect effects of chemicals mediated by species interactions (Rohr et al. 2006a; Clements and Rohr 2009; Halstead et al. 2014; Douglas et al. 2015). Many of these studies document alterations to amphibian growth and abundance associated with atrazine-induced changes to photosynthetic organisms. Ecologically relevant concentrations of atrazine are expected to have numerous indirect effects by altering the abundance of phytoplankton and macrophytes (Herman et al. 1986) and photosynthetic and nonphotosynthetic organisms in periphyton (Staley et al. 2010, 2011, 2012, 2015), the food source for most tadpoles.

Of particular concern is that freshwater vertebrate exposure to atrazine can exacerbate the effects of other stressors commonly experienced by these organisms. For example, abiotic factors, such as drying (Rohr et al. 2004; Rohr and Palmer 2005, 2013) and other common agrochemicals (Rohr et al. 2008c; Halstead et al. 2014), and biotic factors, such as parasitism (Rohr and McCoy 2010b) and predation risk (Rohr and Crumrine 2005; Ehrsam et al. 2016), can be exacerbated by atrazine. The exception is that global warming is expected to accelerate amphibian development, reducing aquatic exposure to atrazine (Rohr et al. 2011). There is a clear need to understand how climate change and other abiotic and biotic factors will affect exposure and toxicity of atrazine and other chemical contaminants (Rohr et al. 2013a; Landis et al. 2014), interactions that are rarely considered in most ecological risk assessments of chemicals (Rohr et al. 2016, 2017).

A HISTORY OF THE ATRAZINE CONTROVERSY

The beginning

The seed of the atrazine controversy was planted in 1998, when a biology professor from the University of California Berkeley, Dr. Tyrone Hayes, was hired by EcoRisk, the consulting company that hired academic scientists to study atrazine on behalf of Syngenta Crop Protection, (Box 1). Hayes initially conducted atrazine research under a contract between EcoRisk and his wife's company, which then subcontracted with the University of California Berkeley for the research (Blumenstyk 2003). Importantly, Dr. Hayes' contract, like that of many of the other scientists Syngenta and EcoRisk hired, restricted Hayes from publishing any Syngenta-funded research without Syngenta's permission. While working for Syngenta, Hayes claims to have discovered that atrazine levels below 3 ppb, the USEPA maximum allowable level in drinking water, induced hermaphroditism (having both male and female sex organs) and reduced larynx size in male frogs. Syngenta and

BOX 1 Atrazine controversy timeline

1994: Tyrone Hayes is hired by UC Berkeley, CA, USA.
1998: Hayes is hired by EcoRisk, the consulting company funded by Syngenta, the company that produces atrazine.
November 2000: Hayes quits EcoRisk and Syngenta allegedly tries to buy his silence.
2000: Hayes claims that Syngenta tried to block his tenure at UC Berkeley.
2002: The head of EcoRisk ends his membership on the main scientific advisory board of the USEPA that was involved in making the reregistration decision for atrazine.
February 2002: Rohr is hired as a postdoc at University of Kentucky to study atrazine.
April 2002: Hayes publishes research in *PNAS* showing that levels of atrazine below US federal limits for drinking water cause hermaphroditism in male frogs.
October 2002: Hayes publishes a paper in *Nature* on associations between atrazine and hermaphroditism in field-caught male frogs.
November 2002: Syngenta-funded groups successfully petition the USEPA to ignore Hayes' studies based on the 2001 Data Quality Act.
2003: Syngenta interferes with Hayes' job offer at Duke University.
October 2003: The USEPA approves the continued use of atrazine, the same month that the European Union bans atrazine because of ubiquitous and unpreventable water contamination.
October 2003: The *Chronicle of Higher Education* publishes an article on Hayes, Syngenta, and atrazine.
November 2003: Hayes presents only emails at a national meeting that ostensibly incriminated the USEPA and Syngenta of colluding to ensure the reregistration of atrazine.
December 2004: Hayes et al. publish a paper in *BioScience* demonstrating that the single best predictor of whether or not atrazine had a significant effect in a study was whether Syngenta was the funding source.
2005: The Natural Resources Defense Council obtained documents revealing that USEPA officials met privately with Syngenta >40 times while evaluating atrazine's toxicity.
2005: Syngenta begins a multimillion dollar campaign to discredit Hayes.
October 2008: Rohr et al. publish a paper in *Nature* showing that atrazine increases disease risk in a declining amphibian species.
November 2008: Solomon et al. publish a review paper on the effects of atrazine on fish, amphibians, and aquatic reptiles.
August 2009: A *New York Times* investigation found that 33 million Americans are exposed to atrazine through drinking water, in many cases exceeding the federal limit.
2010: Stephen Tillery visits Rohr to recruit him to testify in the class action lawsuit against Syngenta, but Rohr declines.
January 2010: Hayes et al. publish a paper in *PNAS* showing that low levels of atrazine both demasculinized (chemically castrated) and completely feminized genetically male frogs and some of these males even developed into functional females that copulated with unexposed males and produced viable eggs.
January 2010: Rohr and McCoy publish a meta-analysis in *Environmental Health Perspectives* showing that atrazine has highly consistent adverse effects on amphibians, contradicting the results of Solomon et al. (2008).
March 2010: Rohr and McCoy publish an article in *Conservation Letters* documenting the extreme bias and misrepresentation of the primary literature in the Syngenta funded review by Solomon et al. (2008).
July 2010: The *Huffington Post* Investigative Fund reports that >80% of the papers that the USEPA relied upon in past reregistration decisions for atrazine were not peer reviewed and at least half were conducted by scientists with a financial stake in the product.
August 2010: The *New York Times* and *Nature* write articles on the 102 page document released by Syngenta documenting the offensive and potentially harassing emails sent by Hayes to Syngenta representatives.
August 2010: Based on the 102 pages of emails sent by Hayes, Syngenta issues a formal ethics complaint filed at UC Berkeley, but UC Berkeley ruled that no ethics violation occurred.
November 2010: Syngenta sends an attorney to take copious notes at Rohr's seminar at Illinois State University, after doing the same the previous year for Hayes' seminar there.
2011: The director of the University of Florida's satellite campus, the husband of a Syngenta employee, removes Rohr from the property and outlaws faculty at the campus from collaborating with Rohr or conducting toxicological research on pesticides.
2012: The USEPA again concludes that atrazine does not adversely affect amphibians.

(*Continued*)

May 2012: Attorney Stephen Tillery negotiates with Syngenta to pay $105 million to settle a class-action lawsuit from Midwestern water utilities over atrazine levels in the water supply, but Syngenta denies all wrongdoing.
June 2013: Clare Howard publishes a groundbreaking article in *100Reporters* on the unethical tactics of Syngenta, including a multimillion dollar campaign to discredit Hayes, that is based on >1000 pages of subpoenaed documents from the settled Syngenta lawsuit.
February 2014: *The New Yorker* publishes an article on the Syngenta-Hayes atrazine controversy.
April 2014: Rohr, Hayes, Solomon, and the atrazine controversy receive primetime billing on the Canadian National Television show *16 × 9*.
October 2014: Boone et al. publish a paper in *BioScience* denouncing the USEPA's use of a single Syngenta funded study to evaluate the safety of atrazine.
June 2015: The USEPA announces that it will analyze the effects of atrazine and several other pesticides on 1500 endangered plants and animals.
April 2016: The USEPA changes it's tune on the safety of atrazine suddenly arguing that ecologically relevant concentrations of the pesticide are now dangerous *to fish, amphibians, aquatic invertebrates, and mammals.*
2017: Chinese state owned ChemChina purchases Syngenta.
2018: The USEPA concludes that exposure to atrazine from food, drinking water, and residential uses poses reproductive and developmental risks to humans, particularly children.
2020: The USEPA renewed the registration of atrazine and relaxed regulations, allowing for 50% more atrazine to enter water bodies.

Ecorisk blocked him from publishing these results (*hiding* science). EcoRisk panelists highlighted that "results from the contracts are jointly owned by the company and the scientist". "Therefore, publication is upon mutual consent" and Hayes "should be reminded of…the confidentiality of these results" (Blumenstyk 2003; Lee 2003). In addition, Syngenta and EcoRisk allegedly offered Hayes $2 million USD in research support, under the auspices of a start-up company owned by his wife, to continue to quietly and privately study atrazine (Blumenstyk 2003). In November of 2000, Hayes refused the offer and cut his ties with Syngenta and EcoRisk. Soon after, Hayes claims that Syngenta threatened to rescind all of the University of California Berkeley's pharmaceutical and medical funding provided by Syngenta's sister company Novartis if the University of California Berkeley tenured Hayes (*harassing* scientists; Rohr 2018). The University of California Berkeley tenured Hayes despite the alleged threat.

With independent funding, Hayes successfully replicated his Syngenta-funded studies at the University of California Berkeley. In April of 2002, Hayes published these findings in the *Proceedings of the National Academy of Sciences of the United States of the America* (*PNAS*; Hayes et al. 2002b). Hayes published follow-up articles on the associations between atrazine and amphibian gonadal abnormalities in the field (Rohr 2018) in *Nature* (Hayes et al. 2002a) and *Environmental Health Perspectives* (Hayes et al. 2003). A Syngenta funded study that had more amphibians per tank than the Hayes et al. study (2002b), and thus less atrazine per frog (*shaping* science), also found an association between atrazine and hermaphroditism in frogs, but at a higher atrazine concentration (Carr et al. 2003). The author of this study stated, "I don't think it contradicts Hayes…I think it shows that we weren't able to find a low-dose effect." (Blumenstyk 2003). Syngenta interpreted this study as providing evidence that atrazine does not cause hermaphroditism at ecologically relevant concentrations (*spinning* science; Blumenstyk 2003).

Soon after Hayes' research was published, attorneys associated with the Center for Regulatory Effectiveness, the Kansas Corn Growers Association, and the Triazine Network, which receive financial support from Syngenta, took quick action to neutralize Hayes' studies (Blumenstyk 2003). In November of 2002, these attorneys successfully blocked the USEPA from considering Hayes' work in the ongoing atrazine reregistration process by arguing that Hayes' studies did not conform with the 2001 Data Quality Act (Blumenstyk 2003; Aviv 2014), which prohibits federal agencies from using scientific findings for which there are no established standards (*hiding*, *packaging*, and *spinning* science), a tactic used commonly by industries attempting to block or delay unwanted regulation and as a broader assault on academic freedoms (Michaels and Monforton 2005; McGarity and Wagner 2008; Rohr and McCoy 2010a). The work of these attorneys forced the USEPA to revise its Environmental Risk Assessment policies, preventing hormone disruption from being considered as a legitimate reason for restricting the use of a chemical until "appropriate testing protocols have been established" (Sass and Devine 2004). In October of 2003, atrazine was reregistered for use in the United States, the same month that the European Union banned atrazine because of ubiquitous and unpreventable water contamination (Sass and Colangelo 2006). Interestingly, the head of the EcoRisk panel coordinating the investigation of atrazine for Syngenta was also a member of the USEPA's main scientific advisory board (until 2002) involved in making the reregistration decision for atrazine (Blumenstyk 2003).

The relationship between Hayes and Syngenta becomes further strained

Since leaving EcoRisk and Syngenta in 2000, the relationship between Hayes and Syngenta representatives became further strained. In 2003, Hayes received a job offer from Duke University, which is close to both Syngenta Crop Protection headquarters in Greensboro, North Carolina and to Syngenta's research facility in Research Triangle Park, North Carolina. Soon after making the job offer to Hayes, Syngenta contacted administrators at Duke University and then Duke withdrew their offer (Box 1). According to subpoenaed documents revealed in a lawsuit (see below), Syngenta interfered with Hayes' job offer to protect their reputation in the local community and among their employees (*harassing* scientists; Howard 2013). In October of 2003, an article in *The Chronicle of Higher Education* described the price Hayes had to pay to publish his research because of his damaged relationship with Syngenta (Blumenstyk 2003).

In November of 2003, Hayes, several USEPA representatives, Syngenta- and EcoRisk-funded scientists, and I attended an organized oral session on the effects of atrazine on amphibians at the North American Society for Environmental Toxicology and Chemistry meetings in Austin, Texas, USA. The room was over capacity, with attendees forced to stand along the margins of the room. Rather than present data, Hayes dropped a bombshell. He only presented emails incriminating the USEPA and Syngenta associates of colluding to ensure the reregistration of atrazine, walking the packed aisles handing out hard copies of his documentation. Armed with this email documentation and additional evidence, the Natural Resources Defense Council revealed in a lawsuit against the USEPA that their officials met privately with Syngenta more than 40 times while evaluating the toxicity of atrazine (Slater 2012). Hayes' strikes at Syngenta continued in 2004 when he published an article reporting that the single best predictor of whether or not atrazine had a significant effect in a study was whether Syngenta funded it (evidence of *shaping* science; Hayes 2004).

In 2005, in response to Hayes and colleagues' assaults, Syngenta began spending millions on a "smear campaign" aimed at Hayes. They bought the internet search results for his name so they could control what the public read about him and atrazine and employed a long list of methods for discrediting him (*attacking*, *harassing*, and *spinning* science; Howard 2013; Aviv 2014). Hayes claims that Syngenta representatives threatened him and his family. Hayes lived with anxiety and accusations of paranoia until this smear campaign became public in 2012 when thousands of Syngenta documents were subpoenaed in a lawsuit (Howard 2013; see below).

By 2008, there was an accumulation of papers on the effects of atrazine on amphibians. An important example was a paper in *Nature* in 2008 that demonstrated that atrazine increased infectious disease risk in a declining amphibian species by reducing immunity and increasing exposure to the pathogen (Rohr et al. 2008c). In an effort to discount this mounting literature, Syngenta provided financial support (documented in the Acknowledgements section of the publication) to several academics to publish a paper in *Critical Reviews in Toxicology* entitled "Effects of atrazine on fish, amphibians, and aquatic reptiles: A critical review" (*packaging* science; Solomon et al. 2008). I did not recall the primary literature on the effects of atrazine on fish, amphibians, and aquatic reptiles the same way as it was described in this paper (Solomon et al. 2008). Hence, my postdoc Krista McCoy and I began a multi-year effort to quantify any inaccurate representations of the primary literature by the Solomon et al. (2008) article and to set the record straight. Our efforts became even more important in August of 2009, when a *The New York Times* investigation found that 33 million Americans were exposed to atrazine through drinking water and that this contamination exceeded the federal limit in 9 of 10 Midwestern states. Moreover, for several of these states, levels were 9 to 18 times more than the federal limit, levels linked to birth defects, premature births, and low birth weight (Slater 2012).

Tensions further rise in 2010

In 2010, McCoy and I finished our assessment of the Solomon et al. (2008) article (Box 1), revealing that the Syngenta-funded review misrepresented over 50 studies and casted doubt on the validity of 94% of the 63 cases where atrazine had adverse effects on freshwater vertebrates, but almost never criticized the 70 cases where atrazine had no reported significant effects at environmentally relevant concentrations (Rohr and McCoy 2010a). The Solomon et al. (2008) review also had 122 inaccurate and 22 misleading statements, of which 96.5% were beneficial to Syngenta in that they supported the safety of the chemical (Rohr and McCoy 2010a). Our meta-analysis of the same data analyzed by Solomon et al. (2008) revealed that atrazine regularly disrupted the timing of amphibian metamorphosis, reduced size at or near metamorphosis, altered amphibian motor activity and antipredator behaviors, reduced olfactory abilities, diminished immune function, increased infection end points, and altered aspects of gonadal morphology and function and sex hormone concentrations, but did not directly affect amphibian survival (Rohr and McCoy 2010b).

The 2 Rohr and McCoy studies were submitted as companion papers to the journal *Environmental Health Perspectives*. Although the editor reviewed and accepted the meta-analysis, he had apprehension regarding the controversy surrounding atrazine and declined to send out for review the paper describing the conflicts of interest, inaccuracies, and biases in the Solomon et al. paper (2008). After 2 additional cases where editors from toxicological journals refused to send this paper out for review, mentioning concerns over adverse impacts on their journals, McCoy and I were compelled to publish this work in a nontoxicological journal (Rohr and McCoy 2010a). In subpoenaed documents, Syngenta referred to these Rohr and McCoy studies as "rigorous and comprehensive reviews." Subsequent Syngenta-funded reviews (*packaging* science) on the effects of atrazine on fish, amphibians, and reptiles were published in 2014 and 2019 (Van Der Kraak et al. 2014; Hanson et al. 2019). These papers had 1025- and 237-page supplements, respectively, which undoubtedly made it difficult to find scientists with the time or inclination to engage in a detailed and careful review of this work. One of the many Syngenta scientists that authored these papers had job responsibilities that included "atrazine defence" and "influencing EPA", according to a 2004 performance evaluation (Aviv 2014).

In 2010, I gave a seminar on atrazine at Illinois State University, which is not far from Syngenta's US headquarters in Illinois. After discovering the advertised seminar, Syngenta sent an attorney to take notes throughout my talk. This was not an uncommon tactic employed by Syngenta as they similarly sent 2 attorneys to Hayes' seminar at Illinois State University the year before. This led Illinois State University to hire security for my talk and to check for recording devices on the attorney. Syngenta representatives have stated repeatedly that it is in their best interest to attend talks from researchers studying atrazine to counter their claims (Slater 2012; Howard 2013; Aviv 2014).

After several papers published by my laboratory between 2008 and the beginning of 2011 on atrazine and chlorothalonil, 2 pesticides produced by Syngenta, I started receiving pushback from the director of the University of Florida's Gulf Coast Research and Education Center (GCREC) where I conducted my outdoor tank (mesocosm) experiments on agrochemicals. I collaborated with a faculty member at GCREC, which was just a short drive from the University of South Florida where I was employed. This collaboration allowed me to have my tank facility at GCREC. Unfortunately for both my collaborator and me, the wife of the director of GCREC worked for Syngenta. Once my collaborator and I began publishing our findings, my collaborator, an assistant professor at the time, surprisingly found himself forced out of GCREC, having to sell his home and move back to the main campus of the University of Florida in Gainesville. Given that my colleague was now at the University of Florida's main campus, the director of the GCREC told me that I also had to leave because my collaborator was no longer at the facility. I resourcefully looked for other collaborators at GCREC so I could continue my work there. I found 2 other assistant professors that expressed an interest in collaborating, but the director blocked both collaborations and eventually forbade all GCREC faculty from collaborating with me or conducting any pesticide-related toxicological research (*hiding* science), stifling their academic freedoms and postponing my planned toxicological research.

Also, in 2010, Hayes and colleagues published an experiment in *PNAS* (Hayes et al. 2010) where they exposed a laboratory population of all genetically male frogs to low levels of atrazine and showed that these males suffered from depressed testosterone, decreased breeding gland size, feminized laryngeal development, suppressed mating behavior, reduced spermatogenesis, and decreased fertility. In addition, 10% of these atrazine exposed males developed into functional females that copulated with unexposed males. I was a reviewer of this paper and advised both Hayes and the editor, who was from Hayes' own department, to reassign the article to a different editor at the journal to avoid any perceived conflict of interest, but both rejected this suggestion (i.e., academics bending science). Syngenta struck back against this Hayes study (Hayes et al. 2010) by issuing a formal ethics complaint filed at the University of California Berkeley over a 102-page document reporting offensive emails sent by Hayes to Syngenta representatives over the years. In these emails, Hayes regularly used profanities, sexual taunts, and aggressive, salacious, lewd, and insulting language (*harassing* Syngenta scientists). These embarrassing emails were covered in stories by *The New York Times* (Schor 2010; http://www.atrazine.com/amphibians/combined_large_pdf-r-opt.pdf) and *Nature* (Dalton 2010). In reference to these emails, D. Slater stated in her *Mother Jones* article, "His [Hayes] irreverence had always been an asset, attracting attention to atrazine just as Rachel Carson's impassioned lyricism drew attention to DDT. But now irreverence had tipped toward irrationality." (Slater 2012). The University of California Berkeley investigated, but the emails reportedly were sent from a personal computer and thus the University of California Berkeley ruled that no ethics violation had occurred (Slater 2012; Union of Concerned Scientists 2017).

Following Syngenta's email release, Hayes served as an expert witness in a class action lawsuit against Syngenta that gained momentum in 2010. The lawsuit, led by Stephen Tillery of the law firm Korein Tillery, eventually included more than 1000 community water systems in Illinois, Missouri, Kansas, Indiana, Iowa, and Ohio. The lawsuit was filed because these water treatment facilities often could not get atrazine concentrations in their drinking water below the USEPA maximum contaminant level deemed safe for human consumption (3 ppb; Howard 2013).

With Hayes already recruited to the lawsuit, Tillery and another lawyer from his firm flew from Illinois to Florida in 2010 to recruit me as an expert scientist for the same case. Before jumping at the opportunity, I asked Tillery whether the atrazine problem in the Midwestern United States was predominantly because of how much atrazine was applied there and because most water treatment plants lacked modern carbon filtration systems necessary to remove the atrazine. Tillery confirmed that these were indeed major sources of the problem. I then asked rhetorically whether Syngenta could control who buys their product, where they apply it, how much they apply, or whether water treatment plants have adequate carbon filtration systems. Tillery, of course, replied, no. I then emphasized that the atrazine problem in the Midwestern United States appeared to be a USEPA enforcement issue and that the USEPA, not Syngenta, should be the party that is sued. Tillery agreed with all the logic, but claimed that he could not sue the USEPA. I corrected Tillery and highlighted that he could sue the USEPA over policy enforcement, which the Natural Resource Defense Council does regularly. However, he could not sue the USEPA for money. Despite Tillery offering to pay me generously for my services and being dismayed by many of Syngenta's tactics, I politely declined the offer, because I was worried that the lawsuit was misdirected at the entity with the deepest pockets.

As the lawsuit continued, in 2011, Hayes and 21 other scientists published findings on the application of the well-respected Hill's criteria for identifying causal relationships to atrazine studies across different vertebrate classes (Hayes et al. 2011). They concluded that independent lines of evidence consistently showed that atrazine disrupts the reproductive development of frogs (Aviv 2014).

The lawsuit continued until 2012 when it was settled soon after illicit behaviors of a star witness for Korein Tillery (someone other than Hayes) were allegedly exposed. Syngenta paid $105 million USD to reimburse more than a thousand Midwestern water utilities for the cost of filtering atrazine from drinking water, but denied all wrongdoing and did not claim any liability. Once fees for Korein Tillery were collected, each water treatment plant received well under $100 000 USD to improve their facilities (Howard 2013; Aviv 2014).

Exposés from the lawsuit and the USEPA scientific advisory panel

The most important outcome of the lawsuit was almost certainly not the settlement but the investigative reporting that it triggered. Clare Howard of *100Reporters* submitted a Freedom of Information Act request associated with the lawsuit that was granted by the Madison County Circuit Court (Box 1). This decision "unsealed" approximately 1000 pages of Syngenta memos, notes, and emails, pulling back the curtain on Syngenta's tactics and efforts to conceal and discredit the science on atrazine (Howard 2013). Hayes finally had vindication that he was not paranoid after all (Howard 2013; Union of Concerned Scientists 2017). The subpoenaed documents revealed that Syngenta was indeed behind a campaign to smear him and his reputation and that their strategy was to "purchase 'Tyrone Hayes' as a search word on the internet, so that any time someone searches for Tyrone's material, the first thing they see is our material." They later also purchased the phrases "amphibian hayes," "atrazine frogs," and "frog feminization" (Howard 2013). For years, Syngenta had full control over the narrative because online searches for "Tyrone Hayes" brought up a top search result of "Tyrone Hayes Not Credible" (*attacking*, *harassing* science). Other tactics in the documents directed at Hayes included "commissioning a psychological profile," "have his work audited by 3rd party," "ask journals to retract," "set trap to entice him to sue," "investigate funding," "investigate wife," "tracking him at speaking engagements," "baiting him through emails," and interfering with Hayes' job offer at Duke (*attacking*, *harassing* science). Syngenta also would send representatives to Hayes' talks to question and embarrass him (Howard 2013). I had similar experiences when I presented at conferences or Universities (*attacking*, *harassing* science). The subpoenaed documents unveiled a multi-million dollar campaign, which not only included discrediting and distracting Hayes but also hiring detectives to investigate scientists on a federal advisory panel, looking into the personal life of a judge, and keeping a list of 130 people and groups it could recruit as experts, including academics, without disclosing ties to the company (*packaging* science; see https://www.documentcloud.org/documents/686401-100reporters-syngenta-clare-howard-investigation.html for the list; Howard 2013). In some cases, Syngenta or its public relations team wrote the op-ed pieces and then scanned its stakeholder database for a signer (Howard 2013). According to Jayne Thompson from Jayne Thompson & Associates, a public relations firm hired to work on the Syngenta campaign, paying these individuals to write op-eds and other articles supporting the safety of atrazine allows us to "get out some of our messages from someone who comes off sounding like an unbiased expert. Another strength is that the messages do not sound like they came from Syngenta" (*packaging*, *spinning* science). Clare Howard's ground-breaking article on this exposé was published in June of 2013 in *100Reporters* (Howard 2013). *The New Yorker* magazine released their own story in 2014 later acknowledging Howard's seminal investigative work (Aviv 2014).

In April of 2014, Hayes, Solomon, and I appeared on *16 × 9*, a Canadian National Television primetime news show similar to 60 Minutes, 20/20, and Dateline in the United States (Shochat 2014). The story was produced by G. Shochat and summarizes the story of the amphibian-atrazine controversy. Importantly, it also offers an interview with a former Syngenta staffer who describes Syngenta's internal strategies for discrediting scientists.

As the class-action lawsuit and exposé were being completed, so too were the policy decisions on the safety of atrazine. I was originally asked to be a member of the scientific advisory panel convened by the USEPA to assess the effects of atrazine on amphibians. However, this offer was rescinded because the USEPA was concerned that my work would serve too prominently in panel discussions. Dr. Michelle Boone was recruited to take my place. After convening this panel, the USEPA concluded that "exposure to atrazine at concentrations ranging from 0.01 to 100 [milligrams per liter] had no effect on *Xenopus laevis* [an amphibian species] development (which included survival, growth, metamorphosis, and sexual development)" (p. 60) and that the "level of concern for effects on aquatic plant communities… was lower than the atrazine concentration observed to produce significant direct or indirect effects on invertebrates, fish, and amphibians" (US Environmental Protection Agency 2012), which would eliminate further assessments of atrazine's impacts on amphibians, despite significant effects at these concentrations in other studies. Importantly, the USEPA's conclusion that atrazine does not adversely affect amphibians was based on a single published study funded by Syngenta (*shaping* science), claiming that this was the only reliable study (*attacking* science). This decision was despite several members of the scientific advisory panel imploring the USEPA to consider other studies, of which there are hundreds. Frustrated after her experience on the scientific advisory panel, Boone collaborated with me and other colleagues to write articles denouncing the use of a single study to evaluate the safety of any chemical (*hiding* science), especially a study funded by the company with a financial stake in the product (Boone et al. 2014; Boone and Rohr 2015).

This is not the only time that the USEPA has ignored the majority of peer reviewed literature on atrazine. Danielle Ivory of the *Huffington Post* Investigative Fund reported that fewer than 20% of the papers that the USEPA used in its past decision making on atrazine were peer reviewed and at least half were conducted by scientists with a financial stake in atrazine (Ivory 2009, 2010). The USEPA also has overlooked important peer reviewed studies on atrazine and human health, such as statistically significant associations between atrazine's presence in drinking water and preterm births based on 130 000 birth records in 4 Midwestern states (Stayner et al. 2017), restricted fetal growth and small head circumference in babies whose mothers drank atrazine-contaminated tap water during the first trimester of pregnancy (Chevrier et al. 2011), and an elevated risk of genital malformations among male children born to mothers who lived in counties with frequent atrazine spraying (Agopian et al. 2013). According to other investigative reporting, the agency dismissed or ignored >10 human epidemiological studies showing human health harm from atrazine in drinking water, and data showing that atrazine can change brain function and behavior, can affect child development, and poses a cancer risk (Naidenko 2018).

The final chapter?

In 2016, after the damaging press of the unsealed court documents, Syngenta announced that it was set to be acquired by Chinese state owned ChemChina (China National Chemical Corporation). After dealing with various antitrust concerns that required divestments, the deal was finalized with ChemChina acquiring Syngenta in 2017 for $43 billion USD (Shields 2017). At approximately the same time, the entire agrichemical and seed industry saw market consolidation, with mergers between Dow Chemical and DuPont and between Bayer and Monsanto (Shields 2017). For the ChemChina-Syngenta merger, ChemChina only paid $5 billion USD of its own capital, cobbling together loans from banks and other institutions to make up the rest. ChemChina's borrowing continued even after the merger, reaching debt in excess of $63 billion USD by mid-2020 (Fickling 2020). With income barely covering the interest due on these loans, ChemChina has not made a profit since the takeover, and the lion's share of the debt could wind up back on Syngenta's shoulders (Fickling 2020). To address these debts, ChemChina is now working to merge with China's other giant state-owned, unlisted chemical company, Sinochem Group. This newly merged company would then be listed on mainland stock exchanges to garner additional revenue (Fickling 2020). The US Department of Defense, however, recently added both Sinochem and ChemChina to its list of entities it considers "Communist Chinese military companies." This allows the White House to impose crippling sanctions on any company doing business with them, which would be very harmful given that 97% of Syngenta's business is outside China (Fickling 2020). What happens with this newly proposed merger and the considerable debt of ChemChina and how this influences policies and regulations surrounding atrazine and other agrichemicals produced by the company remains to be seen. However, since the merger, all indications are that day-to-day operations and strategic management was left to the existing management teams and employees of Syngenta.

As a result of a court order, the President Obama-led USEPA re-evaluated atrazine and, apparently in error, released a reassessment report online in April of 2016 (Polansek 2016). In this "inadvertently" released reassessment of atrazine, the USEPA completely reversed its position. Despite the USEPA concluding that atrazine was safe for over 4 decades, the new and refined risk assessment (Farruggia et al. 2016) stated the following:

> "Based on the results from hundreds of toxicity studies on the effects of atrazine on plants and animals, over 20 years of surface water monitoring data, and higher tier aquatic exposure models, this risk assessment concludes that aquatic plant communities are impacted in many areas where atrazine use is heaviest, and there is potential chronic risk to fish, amphibians, and aquatic invertebrates in these same locations. In the terrestrial environment, there are risk concerns for mammals, birds, reptiles, plants and plant communities across the country for many of the atrazine uses. EPA levels of concern for chronic risk are exceeded by as much as 22, 198, and 62 times for birds, mammals, and fish, respectively. For aquatic phase amphibians, a weight of evidence analysis concluded there is potential for chronic risks to amphibians based on multiple effects endpoint concentrations compared to measured and predicted surface water concentrations… average atrazine concentrations in water at or above 5 μg/L for several weeks are predicted to lead to reproductive effects in fish, while a 60-day average of 3.4 μg/L has a high probability of impacting aquatic plant community primary productivity, structure and function."

In addition, in a 2018 draft assessment, the USEPA concluded that exposure to atrazine from food, drinking water, and residential uses poses reproductive and developmental risks to humans, particularly children (US Environmental Protection Agency 2018). Despite these 2016 and 2018 conclusions that atrazine poses risks to aquatic wildlife and humans, the President Trump-led USEPA renewed the registration of atrazine in 2020 and relaxed regulations, allowing for 50% more atrazine to enter water bodies (Erickson 2019; US Environmental Protection Agency 2020).

Lessons learned

The story surrounding atrazine is filled with members of industry, government, the legal system, and institutions of higher education—the cornerstones of modern day societies—making decisions based on questionable ethics, decisions than can erode the trust that the public has in these institutions, the discipline of toxicology, and more broadly, science in general. Thus, the story of atrazine must be more than just a true dramatic account of cover-ups, bias, deception, greed, and vengeance. It must represent an example of how our pillars of modern-day societies can disgracefully deteriorate into corruption in the absence of effective transparency, policing, and checks and balances. It must serve as a beacon for how conflicts of interest and bending science can compromise not only science and ecosystem and human health, but also the just and honorable functioning of societies.

To reduce the adverse effects of bent science, all people must be able to identify the tools for bending science highlighted throughout this piece, as well as its many other guises. One of its most common guises is manufactured uncertainty to avert undesirable decisions (Michaels and Monforton 2005; McGarity and Wagner 2008; Oreskes and Conway 2011). Uncertainty can make a decision seem premature, stonewalling and sometimes even preventing decision making (Michaels and Monforton 2005; McGarity and Wagner 2008; Rohr et al. 2012). Opponents of regulations and judicial decisions can engender uncertainty by disparaging science that opposes their interests, regardless of its quality, which is often referred to as the "junk science" movement (Huber 1991; Herrick and Jamieson 2001). This is often done by suppressing, ridiculing, distorting, and misrepresenting scientific research that threatens their interests (*attacking*, *harassing*), by releasing competing or misleading science (*shaping*), and by intentionally suppressing undesired information (*hiding*; Huber 1991; Herrick and Jamieson 2001). These tactics and influencing public perception of published science so that it is portrayed in the light most favorable to the sponsor (*spinning*) are often facilitated by hiring various experts, including scientists, public relations and product defense firms, and ghostwriters (*packaging*). This playbook has been used by company after company since this strategy was proven effective by big tobacco (Michaels and Monforton 2005; Mooney 2005; McGarity and Wagner 2008; Rohr and McCoy 2010a; Oreskes and Conway 2011). These tactics continue to be employed because the benefits often outweigh the costs (McGarity and Wagner 2008). For example, Syngenta's herbicide portfolio, of which atrazine is their leading product, is valued at nearly $2.3 billion USD annually (Slater 2012), making every year that Syngenta was able to delay any undesirable regulation on atrazine worth billions.

Although individuals and organizations have the right to defend their science, products, and actions, "greenwashing" or misleading the public to believe that an organization's products or actions are safer for humans and the environment than they actually are can damage trust and environmental and human health (Koh et al. 2010; Delmas and Burbano 2011). Alternatively, "blackwashing," when environmental or public health groups mislead the public into believing that a corporation's actions will result in greater environmental or human harm than is likely to occur, can also be harmful and undermine public support (McGarity and Wagner 2008; Koh et al. 2010). Both greenwashing and blackwashing almost certainly occurred with atrazine.

Fault in the atrazine story does not lie solely with companies or researchers misrepresenting science, or environmental or public health interest groups sensationalizing the science. In the case of atrazine, appreciable damage also came from governmental, legal, and scientific review processes failing to prevent or correct these conflicts of interest. For instance, the USEPA repeatedly favored industry funded studies and regularly vacillated between atrazine being safe and unsafe, contributing to the uncertainty surrounding atrazine, which helped to further justify delayed action. The legal system imposed no penalty on Syngenta for misleading the public on the safety of atrazine or disparaging scientists. And, the scientific review process allowed for Syngenta to misrepresent the primary literature, did not force a retraction of the Syngenta-funded review after the extreme errors and biases were revealed and indirectly acknowledged by Syngenta in subpoenaed documents (Rohr and McCoy 2010a, 2010b), and allowed for both of Hayes' *PNAS* studies (Hayes et al. 2002b, 2010) to be handled by an editor within his own department (see also Forbes et al. 2016). Although the peer review system is not infallible, fortunately there is little indication that it is widely corrupted as it generally serves to minimize misinformation and promote credibility (Burton and Wenning 2017).

Part of the reason that bending science persists is because the legal, regulatory, and academic systems ignore or even incentivize it (McGarity and Wagner 2008), which needs correction. Many scientists intentionally avoid policy or regulatory relevant science because they do not want their science continuously scrutinized or to be harassed by advocates. In addition, this type of science is often perceived as not cutting edge, lacking theoretical underpinnings, and poorly funded by federal agencies. Simply put, policy or regulatory relevant science is typically perceived as not tenure-granting research (McGarity and Wagner 2008). Moreover, academics generally just ignore science that they know is unreliable and are certainly reluctant to spend their valuable time refuting or attempting to replicate studies that their peers are already ignoring, even when there are potential implications for public and environmental health (McGarity and Wagner 2008). To make matters worse, many second- and third-tier journals are desperate for submissions, and thus will accept articles with minimal peer scrutiny. This all plays into the hands of advocates, reducing competition and scrutiny of their own outcome-oriented science. In turn, this simultaneously gives the perception that the scientific pipeline is not contaminated by outcome-oriented science, allowing advocates to control the flow of science through the pipeline often unnoticed (McGarity and Wagner 2008). Collaborative scientific efforts among unbiased scientists that challenge outcome-oriented research can help because advocates might not know who to harass or have the time and resources to harass all the authors. Moreover, greater weight is often given to consensus statements. Courts and agencies should also make use of the judgement of scientific advisory committees rather than ignore their expertise. Importantly, unbiased scientists must work together and be incentivized to challenge bent science, and whistleblowers must be thoroughly protected.

However, self-governance of science is simply not enough, and thus several improvements to education and review processes must also occur to prevent the history related to atrazine from repeating itself (also see final chapters of McGarity and Wagner 2008; Michaels 2008). First and foremost, the adverse consequences of conflicts of interest and bending science cannot be addressed until the public can readily recognize their subtleties, which requires education in general, especially that which highlights the detection of manufactured uncertainty. All journals and regulatory agencies should require and publish information on funding sources and potential conflicts of interest of authors, editors, and reviewers, penalize authors that do not disclose conflicts of interest, and add permanent notes to scientific papers about undisclosed conflicts that are discovered after the fact, much like corrections are appended to the front end of scientific papers. Importantly, the public must understand that disclosing a conflict of interest does not remove it. Finally, all journals should prohibit editors from handling submissions from their own institutions.

Changes to how product safety is assessed would also be helpful. For example, all governments must prevent parties with a vested interest in scientific, judicial, or regulatory outcomes from using uncertainty as a tool to forestall judicial and regulatory decisions or to fulfill personal agendas. Governments should also enact policies so that federal safety decisions are not based on safety research conducted by any institution or individual with a financial stake in the product. Rather, companies should provide funds to the regulatory agency and the agency should release an open request for proposals to study the product (Rohr and McCoy 2010a). The agency should then only fund qualified, impartial laboratories that remain anonymous until the safety research is completed (Rohr and McCoy 2010a). Governmental agencies and judicial systems should also mandate information on who paid for private scientific research and whether the sponsors controlled or influenced what research was publicly released. Even better, when private science is used to assess public health, safety, or environmental threats; supports product licenses or pollution permits; or is supposed to support industry's regulatory compliance, it should face the highest level of transparency and scrutiny, with all of the funding, data, and quality controls and checks made public (Shrader-Frechette and Oreskes 2011). Industry requests to protect proprietary data should be granted only when public health and safety are not at stake (Shrader-Frechette and Oreskes 2011). However, it must also be understood that transparency does not mean that the experimental design and implementation were not outcome-oriented–working backwards from a preordained, desired result.

Importantly, actions should also be taken to limit the abuse of national policies that serve to slow undesired science or stall or prevent important regulatory or judicial decisions. There are several subtle examples of these national policies. For example, the Daubert Rule allows judicial officials in the United States to set admissibility standards for scientific evidence or expert witnesses that exceed realistic certainty, precluding credible science from the courts (Michaels and Monforton 2005). Another example is the US Data Quality Act, which is widely described as being slipped into legislation to obviate science that can lead to "costly" regulations (Michaels and Monforton 2005) and was actively used to prevent regulations on atrazine. The US Data Access Act, also known as the Shelby Amendment, makes all data produced through publicly but not privately funded research openly available. This act has been used by advocates to make excessive data requests to slow and distract scientists producing research damaging to their interests (Shrader-Frechette and Oreskes 2011). Finally, the United States must revise their adverse effects reporting rules for private research to require more rigorous reporting. In summary, the use of the Daubert Act should be limited so that credible science can be used in the courts, the Data Quality and Data Access Acts should be amended to apply equitably to public and private science and establish criteria for when data requests constitute an unreasonable burden, and adverse effects reporting rules should be revised to err on the side of overreporting to reduce the suppression of undesired product safety data.

Finally, changes must be made so that the costs of bending science begin to exceed the benefits. As seen with the case of atrazine, the lack of cultural or institutional mechanisms to punish abuses, such as shaping, hiding, attacking, and spinning science and harassing scientists, provides few disincentives to counter the major financial incentives to bend science. There needs to be greater consequences for attacks on scientists, bending science, and more generally, knowingly misguiding the public on product safety. Changes must be made to legal systems and investments made to enforcement systems to help tip the balance toward the costs of bending science exceeding the benefits. As McGarity and Wagner (2008) so eloquently stated, "When the current legal regime is prepared to penalize harassment, encourage balanced and representative scientific advisory boards, and create beneficial outlets for diverse set of skeptics to engage in scientific oversight, it will be in much better position to deter bent science." In conclusion, I hope that the story of atrazine and the associated lessons learned arm readers with the knowledge necessary to identify and minimize the adverse effects of bent science—the credibility and integrity of science and the health of our families and environment might depend on it.

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