



Promises and perils of gene drives: Navigating the communication of complex, post-normal science

Dominique Brossard^{a,b,1}, Pam Belluck^c, Fred Gould^{d,e}, and Christopher D. Wirz^a

^aDepartment of Life Sciences Communication, University of Wisconsin–Madison, Madison, WI 53706; ^bMorgridge Institute for Research, Madison, WI 53715; ^cThe New York Times, New York, NY 10018; ^dDepartment of Entomology and Plant Pathology, North Carolina State University, Raleigh, NC 27695; and ^eGenetic Engineering and Society Center, North Carolina State University, Raleigh, NC 27695

Edited by Baruch Fischhoff, Carnegie Mellon University, Pittsburgh, PA, and approved November 9, 2018 (received for review June 13, 2018)

In November of 2017, an interdisciplinary panel discussed the complexities of gene drive applications as part of the third Sackler Colloquium on “The Science of Science Communication.” The panel brought together a social scientist, life scientist, and journalist to discuss the issue from each of their unique perspectives. This paper builds on the ideas and conversations from the session to provide a more nuanced discussion about the context surrounding responsible communication and decision-making for cases of post-normal science. Deciding to use gene drives to control and suppress pests will involve more than a technical assessment of the risks involved, and responsible decision-making regarding their use will require concerted efforts from multiple actors. We provide a review of gene drives and their potential applications, as well as the role of journalists in communicating the extent of uncertainties around specific projects. We also discuss the roles of public opinion and online environments in public engagement with scientific processes. We conclude with specific recommendations about how to address current challenges and foster more effective communication and decision-making for complex, post-normal issues, such as gene drives.

gene drives | science communication | public engagement

The idea that diseases such as malaria could be controlled by manipulating inherited traits of the organisms responsible for their spread has been around for decades (e.g., ref. 1). Technical barriers to the feasibility of the approach have remained numerous, but progress in genetic engineering techniques has made the scenario more viable. In 2003, a paper in the *Proceedings of the Royal Society B* suggested an innovative way to genetically modify naturally occurring “selfish genes,” which could be used to manipulate wild populations of various organisms (2). A decade later, the potential use of the ground-breaking tool CRISPR/Cas9 for these “gene drives” brought the idea closer to reality (3) and also ignited public debate about the idea. We might eventually succeed in genetically modifying species for the sake of public and environmental health, but how can that be done in an ethical way? What might be the unintended consequences of such an approach? And who should be involved in the conversation?

In November of 2017, an interdisciplinary panel discussed the complexities of gene drive applications as part of the third Sackler Colloquium on “The Science of Science Communication.” The panel brought together a social scientist, a life scientist, and a journalist to discuss the issue from each of their unique perspectives. This paper builds on the ideas and conversations from the Colloquium session to provide a more nuanced discussion about the context surrounding responsible communication and decision-making for cases of post-normal science. Deciding to use gene drives to control and suppress pests will involve more than a technical assessment of the risks involved, and responsible decision-making regarding their use will require concerted efforts from multiple actors. Gene drives represent a classic case of “post-normal science” (4) for which purely technical expertise is not enough to address the complexities surrounding a scientific issue that has not only technical but also social, ethical, and legal dimensions. Unlike “normal” scientific issues for which risk assessment can be

based for the most part on scientific inputs, post-normal science has to rely on a multitude of perspectives when assessing risks and benefits. Along the same lines, reflecting on communication about the post-normal science of gene drives can only benefit from multidisciplinary approaches. Our aim is therefore to use our collective experiences and knowledge to highlight how the current debate about gene drives could benefit from lessons learned from other contexts and sound communication approaches involving multiple actors.

Gene Drives: From Species Irradiation to Species Preservation

In 1950, a few years after Hermann Muller received the Nobel Prize for his work on radiation-induced genetic mutations, the entomologist, Edward Knipping wrote to him inquiring about whether pest insects that became genetically sterile when mutated by exposure to radiation could be used to eradicate damaging species. This led to development of the sterile insect technique that eliminated a major cattle pest from almost all of North and Central America, saving billions of US dollars and decreasing use of insecticides. The method required the rearing and release of hundreds of millions of irradiated insects (5). Because this method only worked on a few pest species (6) it led researchers to consider how it could be improved to broaden its reach. The key seemed to be developing a means by which genetically manipulated insects could be released with genetic traits that spread through a population even though they conferred no benefit to the insect (or actually decreased the insect’s fitness). Even in the 1940s researchers were examining how they could drive genes into a pest to cause demise of its natural populations (6).

Fast-forward to the age of genomics and we appear to be on the threshold of genetic methods that will enable us to spread genes that disrupt the ability of pests to transmit pathogens or bias their sex ratio so that virtually all offspring are male. Of course, a population with few females is bound for extinction. There are typically two components to these manipulations. First, there must be a way to alter or disable a gene to alter the individual pest’s biology. Then, there needs to be a way to link it to a gene or to genetic systems to drive it into the population.

Many approaches have been devised for driving the “effector” genes into pest populations, but the one that has garnered the greatest attention recently is the use of CRISPR/Cas9 gene drives. Such a gene drive could, theoretically, spread from its initial introduction into a fraction of the population to almost all

This paper results from the Arthur M. Sackler Colloquium of the National Academy of Sciences, “The Science of Science Communication III” held November 16–17, 2017, at the National Academy of Sciences in Washington, DC. The complete program and audio files of most presentations are available on the NAS Web site at www.nasonline.org/programs/sackler-colloquia/completed_colloquia/Science_Communication_III.html.

Author contributions: D.B., P.B., F.G., and C.D.W. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Published under the PNAS license.

¹To whom correspondence should be addressed. Email: dbrossard@wisc.edu.

Published online January 14, 2019.

individuals in that population and beyond it, which makes it both exciting and scary. If these CRISPR/Cas9 gene drives succeed, we could eliminate malaria, save endangered species, and control agricultural and household pests without insecticides. But, in the wrong hands it could harm ecosystems or our food supply by targeting populations of species that serve useful roles. Also of concern is that researchers with good intentions could cause harm because of unanticipated impacts of their manipulations (7).

In many countries, there are regulations in place to guard against unintended effects of releasing genetically engineered organisms into the environment. But these regulations were developed for crop plants and animals that typically don't spread on their own in the environment. The existing regulations for engineered organisms call for a step-by-step process where the first releases are in small isolated areas to ensure that there is no unexpected spread or persistence (8). With gene drives, the intention is for the engineered organism to spread in the environment, so the established regulations are not generally appropriate for testing them, even in somewhat isolated environments (8). Researchers, regulators, and communities have been trying to develop approaches for the responsible testing and control of gene drives for a number of years (e.g., refs. 9–11). No nation has regulations in place for gene drives and no case of release of an organism with a gene drive has been recorded, but there is a need to prepare for the eventual development of strains with a stable gene drive that could be released.

Most of the public discussions of gene drives relate to one theoretical type of gene drive where the release of a small number of individuals could cause the spread of the gene drive and linked effector genes to all or almost all populations of that species in the world. It is important to recognize that this is only one type of gene drive and that it will be very difficult to develop such a gene drive to function indefinitely without pests evolving resistance to it (12, 13). There are other types of gene drive that have been developed in laboratory populations of insects, some of which use CRISPR/Cas9, and others that use different approaches. One approach involves creation of a strain that reproduces well on its own, but when it mates with individuals from natural populations it produces many inviable offspring or grand-offspring. Models of this system show that it can spread and predominate in a population, but only if enough individuals are released so that the engineered individuals are initially more than 25% of the total population (14, 15). If the engineered individuals carry genes for not transmitting malaria and this method results in the engineered trait becoming predominant in a local population, malaria transmission is locally inhibited. If a few engineered pest individuals move to a new location, they would be rare and therefore unable to spread in that new location. There are a number of theoretical approaches with this characteristic. Some have been shown to work in small laboratory colonies (16–18).

Other approaches that aim at localization have the goal of searching for a specific gene that differs between the targeted population and other populations. With this approach, the gene drive can only function in individuals with the form of the gene found in the target population. Finally, there are approaches that are expected to drive genes into populations for only a limited period of time (19).

Clearly, the risks inherent in gene drives designed to spread indefinitely to all populations are likely to be greater than with those that are designed to have limits to spread. Concerns with unlimited gene drive approaches have resulted in researchers considering genetic manipulations that would make nontarget populations immune to these gene drives (3). This would make it unlikely that the gene drive could cause destruction of an entire species.

So, what if a single species were wiped off the face of the Earth? In many cases it would probably be hard to measure any ecosystem impact if the changes were small compared with changes caused by other factors. In other cases, if the species was

key to functioning of the ecosystem, there could be major disruption. Often people point to rats and mice; where invasive they cause harm, but they are important in their native habitats. Of course, one must balance risk and benefit. What would be considered acceptable risk if the benefit was ridding the planet of malaria? What would be acceptable risk if the benefit was saving one beautiful bird species? Here is where culture and diverse public values come into play.

The Role of Journalists in Communicating the Uncertainties

Journalism, especially science journalism, has an important role to play in helping the public understand complex and technical subjects, especially those that raise ethical issues (20). Journalism in various forms—in writing, video, or audio, or in iterations of these forms shared on Twitter, Facebook, or other social media, which we discuss in more detail below—is a major source of information for most of the lay public, especially for science-related information (20). Despite this prominence, journalism faces many key challenges as media environments and pressures change (21). And, to paraphrase a quote that is itself an example of popular misunderstanding because it has been falsely attributed to Mark Twain and others: a misconception can travel halfway around the world before the facts get their boots on.

Corralling and correcting misconceptions—and disseminating facts—is especially critical with a topic like gene drives because it is not only complicated, but untested. There are many unknowns, and unknowns can be viewed as carrying big risks (22). How researchers and practitioners use gene drives in their first attempts to manipulate the DNA of organisms could have a lasting, potentially permanent, impact on society's view of this technology.

Editing pernicious genes to make a disease-causing mosquito or a pathogen-carrying rodent less harmful sounds like an appealing idea. But there are serious questions about the ethics of engineering a wild species and about potential environmental consequences that might change ecosystem dynamics or spread well beyond the specific targeted location.

Good journalism communicates the scientific facts and ethical questions in a responsible and fair manner. It explains how gene drives operate in clear language, possibly supplemented with graphics that show how it compares to typical gene editing and how the genetic change could be designed to travel down through the germ line and ultimately alter genes in most or all individuals in a population (23). It says what is known and what is unknown about the science.

Journalism should communicate in ways that do not raise false hope or cause false alarm. That includes headlines, because a headline is usually the first, and sometimes the only, element of an article a person might read. Effective journalism might use analogies or describe historical examples of scientific advances that raised ethical questions and explain how those questions were approached and navigated (24).

It's important to include the views of credible researchers and thoughtful stakeholders on all sides of the issue. One way to find the diverse viewpoints is to simply ask the primary interviewee, "Who are your most credible critics and what would they say?" Very few watershed discoveries in science are implemented in the real world without first encountering criticism and caution from people who have studied the field or from those who might be affected by the change. So a journalist's job is to seek out and ask questions of proponents and opponents, and to accurately reflect the tensions and dissensions. Respected journalism is not promotional and it is not unsubstantiated; its purpose is to investigate, challenge, and explain (23).

As gene drive research advances, journalists should and will evaluate the roles of different constituencies and new developments. For example, the Defense Advanced Research Projects Agency, part of the United States military, has become a major funder of gene drive research (25, 26). Critics and groups that

are fearful of gene drive worry that the military will end up using the technology as a biological weapon (25, 26). Military officials say they are concerned that enemies might use the technology that way, so they want to develop ways to counteract nefarious uses of gene drive. Journalists should keep track of this military-funded research, ask questions about goals and results, and report significant findings to the public, whose tax dollars are footing the bill for the research.

There is also potential for commercial use. For example, as the *MIT Technology Review* reported in December 2017, the California Cherry Board is funding research by scientists who are experimenting by putting a gene drive in the spotted-wing *Drosophila*, an invasive fruit fly that ruins cherry crops, as a way to potentially eradicate the flies or stop their ability to damage cherries (27).

And it will be important to monitor the major public health projects being considered for gene drive. In hopes of attacking the scourge of malaria, the Gates Foundation has invested more than \$75 million in research at Imperial College in London aimed at engineering a gene drive to make female malarial mosquitoes sterile so that the species would essentially be extinguished. In April 2018, in an opinion piece in *The Telegraph*, Bill Gates wrote, “I’m particularly excited about the potential of gene drive, a method of mosquito control that can make mosquitoes infertile or prevent them from carrying the malaria parasite” (28). He added, “We have a long way to go before the technology is perfected, but it is the kind of breakthrough we need, while deploying other proven tools in the short run.”

Science journalists should also follow the innovative scientific efforts, some described in the previous section, to modulate or limit the effects of gene drive before it is ever deployed in the real world. Those include restricting the edited change to a specific location, like an island, or engineering it so that it would peter out after several generations. Will any of these approaches be feasible, acceptable, or effective?

Journalists are also reporting on the ways that scientists are engaging in debate, in expressions of caution, and in ways of making data and other information directly available to the public. The National Academies of Sciences, Engineering, and Medicine released a report in 2016 that examined the technical, social, and ethical issues surrounding gene drives (8). The report (8) concludes that “. . .there is broad agreement on the importance of engaging affected communities and broader publics in decision making about activities involving gene drives. The outcomes of engagement may be as crucial as the scientific outcomes to decisions about whether to release a gene-drive modified organism into the environment.” For a more in-depth review of public engagement models and mechanisms, see Rowe and Frewer (29). Concerns about the social and cultural acceptability of gene drives and the need for community engagement dates back before the discovery of CRISPR (e.g., refs. 30 and 31).

In one example of a gene drive discussion that has received considerable coverage, Kevin Esvelt, an evolutionary biologist at the Massachusetts Institute of Technology, held discussions with the communities of Nantucket and Martha’s Vineyard about eventually using gene drive to engineer white-footed mice with antibodies that would allow the mice to resist Lyme disease and other tick-borne illnesses. Esvelt’s unusually forthright way of communicating with residents of these islands was an interesting aspect of the gene drive story itself, as was the fact that the communities said no to gene drive (but might ultimately say yes to more conventional genetic engineering that does not automatically spread throughout an entire population).

In November 2017, Esvelt and Gemmell (32) published a perspective piece that was critical of New Zealand conservation biologists’ interest in potentially using gene drives for eradicating invasive species that are a threat to the country’s existing biodiversity. The concern was that the gene drives would move beyond New Zealand and alter ecosystems in places where the

targeted species occurred naturally. At the same time, Esvelt and coworkers (33) published a mathematical model, indicating that a gene drive can spread so rapidly to places where a species isn’t invasive that it could in essence create an invasive species itself. This critical call for researchers and conservationists to “be bold in our caution” (32) resulted in articles by journalists, some with strongly worded headlines expressing reservations about gene drive (34–36).

Some others doing gene drive research and assessment felt that their efforts and findings were not represented in those articles. They pointed out that the published mathematical model had not been peer reviewed (33) and only examined gene drives that did not cause reduction in the number of individuals in a population. These scientists felt that while this model was reasonable for examining dynamics of a gene drive that altered a mosquito species’ ability to transmit a pathogen without reducing the number of mosquitoes, the model was not appropriate for commenting on the gene drives designed to decrease or eradicate an invasive species population (2, 37, 38). Conservation biologists in New Zealand were caught by surprise because they thought they were already being very cautious in their deliberations about the possibility of using gene drives in the future. These case studies highlight the need for scientists to be trained in science communication to more effectively discuss and engage with various audiences, rather than for them to rely on their own intuition for communication (39). They underscore the responsibility of journalists to reflect the views of all relevant scientific voices. And they suggest that social science research should analyze these early case studies of applications of gene drives to better understand their complexities and dynamics, especially with respect to their communication aspects.

These days, journalism also offers many avenues for laypeople to respond and comment, and those should be considered part of the public engagement ecosystem as well. Allowing people to air their concerns and views may help build public trust in science; this should be evaluated empirically to determine its effectiveness. In 2016, when the National Academies endorsed continued research on gene drive but did not endorse any releases, the *New York Times* article about the recommendation generated a number of reader comments (40). “This will only have one outcome,” wrote a reader from Massachusetts (41). “And it’s not bad. It’ll be horrible beyond all belief.” A Minneapolis reader wrote: “The Academies suggested that more work must be done. What kind of illogical arguments must be used to stop this work? Only ones based on fear and ignorance of basic scientific principles. . . Let the experts experiment!” (41).

One reader referenced the Robert Burns line that “the best-laid schemes of mice an’ men often go awry” (41) and another warned against human beings playing “the Sorcerer’s Apprentice by making decisions about which species to wipe out. Let’s put away the magic broom and lock the closet door” (41). A reader from New York saw a welcome application: “Scientists: Please make cockroaches next on your ‘elimination list’” (41). And another reader jokingly made a point that might resonate in some way with people on all sides: “There is one species that truly needs management, and it’s not a mosquito” (41).

Public Opinion and Gene Drives

As mentioned above, most people find out about advances in science through media coverage. However, mainstream media attention to gene drives is still relatively low compared with coverage of other genetic engineering applications and levels of public awareness are most likely very low. Although to the best of our knowledge, data on public opinion and awareness about gene drives has yet to be published, some useful take-home messages can be extrapolated from what we know about public attitudes toward genetic engineering in general and gene editing in particular. In 2016, although 66% of Americans reported

having a fair (or higher) understanding of genetically engineered food (42), 46% reported not having heard or read anything at all about gene editing. An additional 48% had heard or read only a little (43).

This does not prevent Americans from having an opinion about gene editing. Despite having heard little about the topic, over half of American adults (53%) supported the use of gene-edited mosquitoes to help fight the Zika virus during the 2016 outbreak (44). However, when asked about editing genes in wildlife populations, the majority of respondents said it “messes with nature” (71.3%) and over half said it “allowed humans to play god” (59.7%) (45). Respondents are more divided regarding the morality of editing genes in wildlife to decrease or eliminate local populations of animals or plants that are causing environmental problems, 38.5% finding it morally unacceptable, 29.7% being unsure, and only 32% finding it acceptable (45).

These results are not surprising. Empirical social science research has long established that explaining the science behind a technology, such as gene drive, to lay audiences, does not automatically translate into more support for the technology (46). Indeed, only providing science-related information assumes there is a public “knowledge deficit” that, once corrected, will lead to a change in audiences’ attitudes and on better public understanding. The knowledge deficit approach has proven to be ineffective in meaningfully engaging public audiences in a wide range of scientific issues (47), including genetic engineering (48). In fact, different individuals can interpret the same information in different ways through motivated reasoning, by filtering and integrating information based on their preexisting values, experiences, and perceptions (49, 50). Value-based shortcuts used to make sense of complex science have included religiosity (51), deference to science (52), and values embedded within different cultures (53). The way issues are framed in media content can also resonate with some readers more than with others, and impact their attitudes (54).

Additionally, perceptions of the risks related to a technology are for the most part related to “subjective risks” rather than “objective risks” (55). Subjective risk is related to qualitative factors, such as the perceived magnitude of a technology’s negative impacts or the ethical dimensions associated with its use [to cite just two of these qualitative factors; see Covello (56) for a review], while objective risk can be measured through a purely technical assessment.

It is plausible to assume American attitudes toward gene drive will be influenced by extant attitudes toward genetic engineering and gene editing technologies as applied to food (57). Indeed, it has been established that individuals use their existing attitudes toward specific technologies to inform their views of unknown ones that seem similar. This phenomenon, known as the “spill-over effect,” is important to keep in mind when attempting to foster meaningful debate about gene drives. As discussed above, genetic engineering and gene editing in food have generated strong feelings in the United States (58).

Challenges Posed by Online Environments

Communication is not only about the content being delivered but is also largely influenced by the messenger and source of the content. Media consumers now rely less on content curated by professional editors in the form of newspapers and TV broadcasts and rely more on information that is tailored and delivered by algorithms (21). These algorithmic sources, such as social media platforms and online news aggregators, are now how news consumers get over half of their news (54%), as opposed to sources that rely on human news selection (59). Algorithmic editing enables media sources to target content directly to specific users, based on the preferences individuals set or by using data the sources collect about their audiences. This targeting makes it less likely individuals will be exposed to content outside

of their interests or in opposition to their beliefs (60). Additionally, news articles and other online content are very often accompanied by comments from other audience members that can affect readers’ perceptions of the trustworthiness of the news source (61). These factors make it harder to effectively deliver information to broad audiences online and engage them in meaningful discussions about scientific topics, like gene drives.

Individuals receive even more tailoring and filtering of information when they construct their own social networks and choose which platforms to use. As a result, these homogenous social networks act as “echo chambers” (62) and “filter bubbles” (63, 64) that further filter the information individuals are exposed to online, including information about scientific issues (65, 66). Selectivity processes and individuals’ homogenous social networks are especially concerning because of the challenges facing “traditional” science journalism.

Over the past decade, there has been a rapid decrease in the number of science journalists and amount of mediated content dedicated to scientific topics (20). These changes in the media ecosystem have allowed scientists to take on a new role as direct communicators with the public, rather than relying on journalists and specialists to facilitate these conversations. Some scientists have therefore begun communicating directly with the public through social media or blog posts or online forums. This can be beneficial to public understanding in some ways, but it can also be detrimental because, without the balance and objectivity of good journalism, communication directly from scientists who lack adequate experience or training can be one-sided or serve as a means to promote their own work or research area, rather than provide a discussion of many different perspectives of an issue.

Additionally, communicating directly online shifts editorial decisions from professional journalists to the scientists themselves, thus opening the door to discussing and circulating research publicly before it has been published in peer-reviewed outlets (67). In theory, social media platforms allow experts and lay audiences to engage and share information about scientific topics, but in practice it may be difficult to break out of the filter bubbles and encourage meaningful interactions (68, 69).

A Case of Post-normal Science in a Complex Communication Environment

As discussed above, deciding to use gene drives to control and suppress pests will obviously involve more than a technical assessment of the risks involved. A useful framework for this type of context is the concept of post-normal science: facts are uncertain, values are in dispute, stakes are high, and decisions are urgent. Although traditional (i.e., “normal”) science clearly has a role to play in this decision-making, it will also necessitate a broader strategy in which “the complexity and uncertainty of natural systems and the relevance of human commitments and values” are taken into account (70).

Gene drives are generally proposed or applied as examples of post-normal science problems, which are incredibly complex and may actually “have more than one plausible answer, and many have no well-defined scientific answer at all” (70). As discussed earlier, there are several approaches to gene drives being explored, with various levels of effectiveness and controllability.

Considering the widespread implications surrounding the applications of gene drives, the involvement of many stakeholders, regardless of their credentials or qualifications, in the decision-making process is essential (70). Engagement about gene drives should aim to foster open, substantive dialogue between all interested and affected individuals in areas where the technology may be used [see Rowe and Frewer (29) for more specific information about engagement]. This will necessitate a strong reliance on two-way communication between multiple stakeholders, an idea that has been advocated in the 2016 National Academies of Sciences, Engineering and Medicine report, which was pointedly titled *Gene*

Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values (8). This report defines public engagement as “seeking and facilitating the sharing and exchange of knowledge, perspectives, and preferences between or among groups who often have differences in expertise, power, and values” (8).

Motivations for public engagement about gene drives include learning from the communities and various stakeholders about the contexts in which the drives will happen and building trust through transparency and well-informed consent (8). Understanding the different contexts is especially important for gene drives because their applications are “already embroiled in important social debates and ethical discussions that reflect different values and priorities” (8). As discussed earlier and in line with the post-normal science framework, conclusions reached through public engagement exercises might be as important as the ones reached through scientific studies when deciding to use (or not) gene drives in the wild (8). In sum, plans for public engagement must be multidisciplinary and integrated into the decision process early on, rather than added on as an afterthought.

Challenges and Opportunities for Sound Science Communication

It is clear that the gene drives case is complex and that responsible decision-making regarding their use will require concerted efforts from multiple actors, including life scientists, social scientists, and journalists, particularly as far as science communication is concerned. The following conclusions and recommendations are the product of our collective experiences. We have reached consensus that these are crucial elements social scientists, life scientists, and journalists alike need to consider for communication about controversial science.

Scientists (the authors included) need to think carefully about what their goals are when communicating with journalists and lay audiences about complicated, multidimensional issues, such as gene drives, and must be transparent about these goals. Efforts should be made to disentangle advocating for a specific application

of a technology that we know particularly well from providing the necessary information for others to make decisions regarding the technology.

Trust is built through transparency and this includes declaring and addressing potential conflicts of interest. This is sometimes tricky, as relevant conflicts of interest can go beyond the financial ones and can include how the topic at hand relates to our worldviews, the success of our next grant proposal, or the positive views of our administrators and colleagues. Additionally, while scientists should directly communicate with lay audiences and their peers to promote productive discussions, they need to take into account evidence from social science research when doing so to avoid potential pitfalls.

Journalists covering issues such as gene drives should strive to provide nuance and balance and reflect a diverse range of views. Reporters should ask about and mention their sources’ potential conflicts of interest, refrain from alarming or oversimplifying, and explain how scientific efforts and evidence are evolving. Journalists who are not well versed on a particular scientific issue should also take advantage of the available resources and programs that work to support quality coverage of scientific topics, especially as more become available.

It is clear that commercial models for media incentivize narrowcasting and audiences are these days likely to find information that confirms their point of view. This is a reality that journalists need to take into account in their reporting, life scientists need to acknowledge when communicating, and social scientists need to address in their research.

Public desire for meaningful engagement in decision-making and governance of issues such as gene drives should be honored and will necessitate mechanisms to do so; social scientists will need to propose such mechanisms based on sound empirical data and will have to make sure their findings are communicated to audiences who can use them.

Interdisciplinary work engaging perspectives from various fields will be key in addressing complex, post-normal scientific issues.

- Craig GB, Jr, Hickey WA, Vandehey RC (1960) An inherited male-producing factor in *Aedes aegypti*. *Science* 132:1887–1889.
- Burt A (2003) Site-specific selfish genes as tools for the control and genetic engineering of natural populations. *Proc Biol Sci* 270:921–928.
- Esvelt KM, Smidler AL, Catteruccia F, Church GM (2014) Concerning RNA-guided gene drives for the alteration of wild populations. *eLife* 3:e03401.
- Ravetz I (1999) What is post-normal science. *Futures* 31:647–654.
- Krafsur ES, Townson H, Davidson G, Curtis CF (1986) Screwworm eradication is what it seems. *Nature* 323:495–496.
- Gould F, Schliekelman P (2004) Population genetics of autocidal control and strain replacement. *Annu Rev Entomol* 49:193–217.
- Fears R (2017) *Assessing the Security Implications of Genome Editing Technology: Report of an International Workshop* (InterAcademy Partnership, Herrenhausen, Germany), Report 1.
- National Academies of Sciences, Engineering, and Medicine (2016) *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values* (National Academies, Washington, DC).
- Benedict M, et al. (2014) *Guidance Framework for Testing of Genetically Modified Mosquitoes* (WHO, Geneva).
- James S, et al. (2018) Pathway to deployment of gene drive mosquitoes as a potential biocontrol tool for elimination of malaria in Sub-Saharan Africa: Recommendations of a scientific working group. *Am J Trop Med Hyg* 98(Suppl 6):1–49.
- Delborne J, et al. (2018) Mapping research and governance needs for gene drives. *J Responsible Innovat* 5(Suppl 1):S4–S12.
- Hammond AM, et al. (2017) The creation and selection of mutations resistant to a gene drive over multiple generations in the malaria mosquito. *PLoS Genet* 13:e1007039.
- Champer J, et al. (2018) Reducing resistance allele formation in CRISPR gene drive. *Proc Natl Acad Sci USA* 115:5522–5527.
- Davis S, Bax N, Grewe P (2001) Engineered underdominance allows efficient and economical introgression of traits into pest populations. *J Theor Biol* 212:83–98.
- Magori K, Gould F (2006) Genetically engineered underdominance for manipulation of pest populations: A deterministic model. *Genetics* 172:2613–2620.
- Buchman AB, Ivy T, Marshall JM, Akbari OS, Hay BA (2018) Engineered reciprocal chromosome translocations drive high threshold, reversible population replacement in *Drosophila*. *ACS Synth Biol* 7:1359–1370.
- Reeves RG, Bryk J, Altrock PM, Denton JA, Reed FA (2014) First steps towards underdominant genetic transformation of insect populations. *PLoS One* 9:e97557.
- Akbari OS, et al. (2013) A synthetic gene drive system for local, reversible modification and suppression of insect populations. *Curr Biol* 23:671–677.
- Noble C, et al. (June 7, 2016) Daisy-chain gene drives for the alteration of local populations. bioRxiv, 10.1101/057307.
- National Academies of Sciences, Engineering, and Medicine (2017) *Communicating Science Effectively: A Research Agenda* (National Academies of Sciences, Engineering, and Medicine, Washington, DC).
- Scheufele DA, Nisbet MC (2013) Commentary: Online news and the demise of political disagreement. *Ann Int Commun Assoc* 36:45–53.
- Khan U, Kupor DM (2017) Risk (mis) perception: When greater risk reduces risk valuation. *J Consum Res* 43:769–786.
- Nisbet MC, Fahy D (2017) New models of knowledge-based journalism. *The Oxford Handbook of the Science of Science Communication*, eds Jamieson KH, Kahan D, Scheufele DA (Oxford Univ Press, New York), pp 273–281.
- Schäfer MS (2017) How changing media structures are affecting science. *The Oxford Handbook of the Science of Science Communication*, eds Jamieson KH, Kahan D, Scheufele DA (Oxford Univ Press, New York), pp 51–59.
- Kuiken T (2017) DARPA’s synthetic biology initiatives could militarize the environment. *Slate*. Available at www.slate.com/articles/technology/future_tense/2017/05/what_happens_if_darpa_uses_synthetic_biology_to_manipulate_mother_nature.html. Accessed April 25, 2018.
- Brown KV (2017) Why DARPA is investing big in gene drives. *Gizmodo*. Available at <https://gizmodo.com/why-darpa-is-investing-big-in-gene-drives-1821028638>. Accessed April 25, 2018.
- Regalado A (2017) Farmers seek to deploy powerful gene drive. *MIT Technology Review*. Available at <https://www.technologyreview.com/s/609619/farmers-seek-to-deploy-powerful-gene-drive/>. Accessed April 25, 2018.
- Gates B (2018) Commonwealth countries are key in the global fight against malaria. *The Telegraph*. Available at <https://www.telegraph.co.uk/news/2018/04/18/commonwealth-countries-key-in-global-fight-against-malaria/>. Accessed April 25, 2018.
- Rowe G, Frewer LJ (2005) A typology of public engagement mechanisms. *Sci Technol Human Values* 30:251–290.
- Lavery JV, et al. (2010) Towards a framework for community engagement in global health research. *Trends Parasitol* 26:279–283.

31. Lavery JV, Harrington LC, Scott TW (2008) Ethical, social, and cultural considerations for site selection for research with genetically modified mosquitoes. *Am J Trop Med Hyg* 79:312–318.
32. Esvelt KM, Gemmill NJ (2017) Conservation demands safe gene drive. *PLoS Biol* 15: e2003850.
33. Noble C, Adlam B, Church GM, Esvelt KM, Nowak MA (November 16, 2017) Current CRISPR gene drive systems are likely to be highly invasive in wild populations. *bioRxiv*, 10.1101/219022.
34. Borel B (2017) New model warns about CRISPR gene drives in the wild. *Quanta Magazine*. Available at <https://www.quantamagazine.org/new-model-warns-about-crispr-gene-drives-in-the-wild-20171116/>. Accessed May 3, 2018.
35. Zimmer C (2017) 'Gene drives' are too risky for field trials, scientists say. *The New York Times*. Available at <https://nyti.ms/2jy9217>. Accessed April 25, 2018.
36. Yong E (2017) New Zealand's war on rats could change the world. *The Atlantic*. Available at <https://www.theatlantic.com/science/archive/2017/11/new-zealand-predator-free-2050-rats-gene-drive-ruh-roh/546011/>. Accessed April 25, 2018.
37. Vella MR, Gunning CE, Lloyd AL, Gould F (2017) Evaluating strategies for reversing CRISPR-Cas9 gene drives. *Sci Rep* 7:11038.
38. Eckhoff PA, Wenger EA, Godfray HJ, Burt A (2017) Impact of mosquito gene drive on malaria elimination in a computational model with explicit spatial and temporal dynamics. *Proc Natl Acad Sci USA* 114:E255–E264.
39. Yeo SK, Brossard D (2017) The (changing) nature of scientist–media interactions: A cross-national analysis. *The Oxford Handbook of the Science of Science Communication*, eds Jamieson KH, Kahan D, Scheufele DA (Oxford Univ Press, New York), pp 261–272.
40. Harmon A (2016) Panel endorses 'gene drive' technology that can alter entire species. *The New York Times*. Available at <https://nyti.ms/1WEMu48>. Accessed April 10, 2018.
41. Harmon A (2016) Panel endorses 'gene drive' technology that can alter entire species. *The New York Times*. Available at <https://www.nytimes.com/2016/06/09/science/national-academies-sciences-gene-drive-technology.html#commentsContainer&permid=18784703>. Accessed April 10, 2018.
42. Annenberg Public Policy Center (2016) Annenberg science knowledge survey: Zika and GMOs March 16–20, 2016 (week 6) appendix. Available at https://cdn.annenbergpublicpolicycenter.org/wp-content/uploads/2018/03/Zika-Week6_Appendix.pdf. Accessed May 16, 2018.
43. Funk C, Kennedy B, Podrebarac Sciapac E (2016) US Public Opinion on the Future Use of Gene Editing. Available at www.pewinternet.org/2016/07/26/u-s-public-opinion-on-the-future-use-of-gene-editing/. Accessed May 16, 2018.
44. Annenberg Public Policy Center (2016) Just Over Half of U.S. Public Favors Using GM Mosquitoes to Fight Zika. Available at <https://www.annenbergpublicpolicycenter.org/just-over-half-of-u-s-public-favors-using-gm-mosquitoes-to-fight-zika/>. Accessed May 16, 2018.
45. Science, Media, and the Public Research Group (SCIMEP) (2018) An Overview of Lay Audiences' Perceptions of Genome Editing Wildlife (University of Wisconsin-Madison, Department of Life Sciences Communication, Madison, WI). Available at <https://scimep.wisc.edu/projects/reports/>. Accessed May 16, 2018.
46. Scheufele DA (2013) Communicating science in social settings. *Proc Natl Acad Sci USA* 110:14040–14047.
47. Akin H, Scheufele DA (2017) Overview of the science of science communication. *The Oxford Handbook of the Science of Science Communication*, eds Jamieson KH, Kahan D, Scheufele DA (Oxford Univ Press, New York), pp 25–33.
48. National Academies of Sciences, Engineering, and Medicine (2016) *Genetically Engineered Crops: Experiences and Prospects* (National Academies of Science, Engineering, and Medicine, Washington, DC).
49. Kunda Z (1990) The case for motivated reasoning. *Psychol Bull* 108:480–498.
50. Yeo SK, Cacciatore MA, Scheufele DA (2015) News selectivity and beyond: Motivated reasoning in a changing media environment. *Publizistik und gesellschaftliche Verantwortung: Festschrift für Wolfgang Donsbach [Journalism and Social Responsibility: Festschrift for Wolfgang Donsbach]*, eds Jandura O, Mothes C, Petersen T, Schielicke A (Springer, Berlin), pp 83–104.
51. Brossard D, Scheufele DA, Kim E, Lewenstein BV (2008) Religiosity as a perceptual filter: Examining processes of opinion formation about nanotechnology. *Public Underst Sci* 18:546–558.
52. Brossard D, Nisbet MC (2007) Deference to scientific authority among a low information public: Understanding U.S. opinion on agricultural biotechnology. *Int J Public Opin Res* 19:24–52.
53. Kahan DM, Gastil J, Slovic P, Mertz C (2007) Culture and identity-protective cognition: Explaining the white-male effect in risk perception. *J Empir Leg Stud* 4: 465–505.
54. Scheufele DA, Tewksbury D (2007) Framing, agenda setting, and priming: The evolution of three media effects models. *J Commun* 57:9–20.
55. Hansson SO (2010) Risk: Objective or subjective, facts or values. *J Risk Res* 13:231–238.
56. Covello VT (2010) Risk communication. *Environmental Health: From Local to Global*, ed Frumkin H (Wiley, San Francisco), pp 1099–1140.
57. Akin H, et al. (2018) Are attitudes toward labeling nano products linked to attitudes toward GMO? Exploring a potential 'spillover' effect for attitudes toward controversial technologies. *J Responsible Innovat*, 10.1080/23299460.2018.1495026.
58. Scott SE, Inbar Y, Wirz CD, Brossard D, Rozin P (2018) An overview of attitudes toward genetically engineered food. *Annu Rev Nutr* 38:459–479.
59. Newman N, Fletcher R, Kalogeropoulos A, Levy DAL, Nielsen RK (2017) Reuters Institute Digital News Report 2017. Available at https://reutersinstitute.politics.ox.ac.uk/sites/default/files/Digital%20News%20Report%202017%20web_0.pdf?utm_source=digitalnewsreport.org&utm_medium=referral. Accessed November 29, 2018.
60. Bennett WL, Iyengar S (2008) A new era of minimal effects? The changing foundations of political communication. *J Commun* 58:707–731.
61. Anderson AA, Yeo SK, Brossard D, Scheufele DA, Xenos MA (2018) Toxic talk: How online incivility can undermine perceptions of media. *Int J Public Opin Res* 30: 156–168.
62. Sunstein CR (2007) *Republic.com 2.0* (Princeton Univ Press, Princeton, NJ).
63. Pariser E (2011) *The Filter Bubble: What the Internet Is Hiding from You* (Penguin, New York).
64. Flaxman S, Goel S, Rao JM (2016) Filter bubbles, echo chambers, and online news consumption. *Public Opin Q* 80:298–320.
65. Yeo SK, Xenos MA, Brossard D, Scheufele DA (2015) Selecting our own science: How communication contexts and individual traits shape information seeking. *Ann Am Acad Pol Soc Sci* 658:172–191.
66. Winter S, Krämer NC (2012) Selecting science information in web 2.0: How source cues, message sidedness, and need for cognition influence users' exposure to blog posts. *J Comput Mediat Commun* 18:80–96.
67. Thursby JG, Haeussler C, Thursby MC, Jiang L (2018) Prepublication disclosure of scientific results: Norms, competition, and commercial orientation. *Sci Adv* 4:eaar2133.
68. Southwell B (2017) Promoting popular understanding of science and health through social networks. *The Oxford Handbook of the Science of Science Communication*, eds Jamieson KH, Kahan DM, Scheufele DA (Oxford Univ Press, New York), pp 223–233.
69. Jia H, Wang D, Miao W, Zhu H (2017) Encountered but not engaged: Examining the use of social media for science communication by Chinese scientists. *Sci Commun* 39: 646–672.
70. Funtowicz S, Ravetz J (2003) Post-normal science. *Online Encyclopedia of Ecological Economics*, ed International Society for Ecological Economics. Available at <https://pdfs.semanticscholar.org/ce91/a2cf9b7e05411fb5b1b9276b9aaf565bffb2.pdf>. Accessed April 23, 2018.