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INTRODUCTION

'Mapping research and governance needs for gene drives'

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What is a gene drive?

A gene drive is a mechanism that biases inheritance of a trait in a sexually reproducing species of organisms. In this context, 'bias' means to increase the odds of a parent passing on a portion of their DNA to above 50%, or what is historically understood as Mendelian inheritance (remember the wrinkled pea experiments?). In fact, under laboratory conditions, some gene drives have been shown to function at 95% efficiency or higher, meaning that a parent carrying a genetic sequence associated with a gene drive will pass on that sequence nearly every time that they reproduce. While a number of papers in this volume expand on this definition, the key takeaway is that designed gene drives could theoretically allow humans to 'drive' a desired trait into a population of organisms. Importantly, this population could be wild – neither its habitat nor its breeding behavior need be under human control – and the desired trait might *reduce* the fitness of the organism even while increasing in frequency throughout the population. At a crude level, gene drives thus disrupt Mendelian and Darwinian assumptions about how to predict inheritance and measure evolutionary fitness.

Why all the attention to gene drives?

While it has not quite become a household term, there has been significant attention to this emerging field of research in the popular and scientific media. On one hand, this should come as no surprise given the anticipated potential for gene drives to address intractable problems in public health, agriculture, and conservation. The close association between recent advances in gene editing (e.g. CRISPR) and gene drives likely also contributes to its newsworthiness. And perhaps there is some additional excitement seeing biotechnology cautiously embraced by public health advocates and biodiversity

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conservation NGOs – a significant leap in the locus of innovation from the laboratories of multinational life science corporations seeking global profits in pharmaceuticals and high-tech agriculture. On the other hand, gene drives are not exactly *new* – 'selfish genetic elements' have been recognized by population geneticists for decades; in other words, some gene drives exist and function in nature without deliberate human intervention. Of equal importance, while laboratory proofs of concept are accumulating slowly – increasing confidence that humans can construct gene drives with a purpose – no one yet knows if they really work. As of the close of 2017, no gene drive modified organism has been released outside of the laboratory. We note the irony of publishing in a field where credible experts disagree – that is, some warn of the unstoppable power of gene drives to transform our shared environment while others suggest that gene drives will fail when they confront the complexity of actual ecosystems and genetically diverse populations.

What is behind this special issue?

In January 2015, even before the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) formed their ad-hoc committee to study gene drives, faculty from North Carolina State University's Genetic Engineering and Society Center submitted a workshop proposal to the National Science Foundation's Science, Technology, and Society (STS) program entitled, 'Gene Drives: A Deliberative Workshop to Develop Frameworks for Research and Governance.' The proposal noted that

> [r]ecent legal and policy scholarship has focused on the need for governance to 'keep pace' with technological innovation in multiple domains, including biotechnology. However, we currently lack a broad evaluation of the potential ecological, political economy, ethical, and other issues to guide research and development of gene drives.

The workshop was envisioned to contribute to filling this gap, and its February 2016 agenda included presentations from diverse experts, ranging from molecular biologists to public policy scholars. Those experts and other attendees were invited to submit papers to this special issue, which were peer reviewed by a mixture of workshop attendees and other scholars. The authors of this introduction served as the editorial team who managed the review process with the assistance and advice of the *Journal of Responsible Innovation's* editor-in-chief, Erik Fisher, and *JRI*'s editorial staff at Taylor and Francis.

What is inside this special issue?

This special issue represents both deep and broad thinking about gene drives. The papers were first drafted nearly two years ago, and since then have been reviewed and revised to flesh out key arguments and take account of ongoing developments in the field. This field has moved very fast indeed! Technical research publications have increased in number; NASEM released a major report in June 2016; and workshops have proliferated. This special issue does not capture or summarize all of this activity. Instead, we offer a collection of diverse, thoughtful papers that outline a kind of roadmap for the research and governance needs of the still emerging field of gene drives. While we would encourage a front-to-back read of this special issue, the remainder of this introduction provides brief summaries to give readers the broadest perspective on this volume as well as guiding them to articles of personal interest.

Kuzma et al. (2017) report on the workshop described above, funded by the National Science Foundation (SES-1533990), the Genetic Engineering and Society Center at North Carolina State University, and the Center for Nanotechnology in Society at Arizona State University, to explore the research and governance needs for the emerging field of gene drives. The authors, who also represent the steering committee for planning the workshop, describe the use of systems thinking and concept-mapping tools to help workshop participants make sense of the ways that social, policy, economic, and ecological variables inform research agendas, regulatory oversight, and the pursuit of responsible innovation around gene drives. They describe the structure of the workshop, which included discussions of case studies and ethical issues, systems mapping, and research information needs for risk governance; analyze the workshop's emergent themes; and engage the Institutional Analysis and Development (IAD) framework to categorize substantive variables in a manner that respects the complexity of the socio-ecological system for gene drives. The article thus both represents a report of the workshop discussions, as well as a framework for generating hypotheses and assessment criteria for future research surrounding gene drives.

Min et al. (2017) clarify for readers that not all gene drives are created equal. Drawing on a mix of innovations at various stages of development, they offer a classification system that accounts for key differences in gene drive function, such as the potential for spread (standard vs. local), the mechanism of limiting spread (self-exhausting vs. threshold dependent), and the ability to reverse the drive at the trait or DNA sequence level. The authors offer historical perspective on gene drive research, especially the impact of RNA-guided systems based on CRISPR endonucleases, and describe potential applications in public health, agriculture, and conservation. Paired with such optimism, however, are sets of technical challenges and social constraints, for which the authors offer potential solutions. In addition, and in line with this journal's mission, Min et al. wrestle with the moral responsibility that scientists bear when their work has the potential to alter the shared environment. They acknowledge the moral hazard of an accidental gene drive release – and the ensuing loss of public trust – and describe confinement strategies key to responsible research. But careful experiments are not sufficient. The authors make the case for scientific reform – starting within the gene drive research field – that emphasizes transparency, community-responsiveness, pre-registered research, and the incentives needed to realign scientific practices with such goals.

Burt et al. (2017) examine what has become, arguably, the poster child for the development and eventual release of gene drive modified organisms: using gene drives to reduce malaria transmission in sub-Saharan Africa. After providing a snapshot of the impact of malaria globally, including nearly 300,000 deaths in Africa of children under 5 years of age in 2015, the authors make the case that genetic approaches to malaria control have a role to play. Specifically, they describe various molecular mechanisms underlying the two primary strategies for deploying gene drives: (1) suppressing the mosquito population – or at least biasing the population toward males, which do not bite; and (2) spreading a genetic characteristic that interferes with the transmission of the Plasmodium parasite between mosquitoes and humans. As active researchers in this field, the authors go on to describe the challenge of resistance evolving against a driving construct, methods to counteract resistance, and potential strategies to reverse or counteract a released gene drive, if warranted. Finally, demonstrating the ways that responsible innovation spans the technical, biological, ecological, political, and social, the authors provide example questions to ask prior to releasing a driving construct for mosquito population suppression or changing vector competence.

Baltzegar et al. (2017) embrace Gould's (2008) call for an interdisciplinary approach to considering the suitability of gene drives specifically to control agricultural pests. They focus on economic and socio-cultural concerns, anticipating and describing a number of complexities made visible through a multidisciplinary lens: identification of relevant stakeholders (made challenging by the potential for gene drive modified insects to spread across boundaries); distribution of costs and benefits (which vary across scales of production and may require new payment structures); impacts on specialized agricultural producers (including organic, pesticide-free, or genetically modified [GM]-free farms where certification regimes, deeply rooted consumer values, and uncertain public perceptions alter the cost–benefit calculus); interactions with traditional pest management strategies (which complicate population, ecological, and legal dynamics); trade patterns and regulations (including sanitary and phytosanitary regulations and certification programs that impact global markets); and dynamics of public engagement and approval (which can be understood in terms of having a 'social license to operate' and implicitly trigger questions of trust). Throughout, the authors helpfully reference historical case studies of GM crops, releases of sterile insects, and classical biological control to provide insights into how gene drive modified insects may be understood, governed, and deployed in a responsible manner.

Scott et al. (2017) continue the focus on gene drives in agriculture by drilling down into the realms of population biology and genetics for key pest targets for population-suppressing gene drives. They draw upon the experience of deploying the 'sterile insect technique' (SIT), which eradicated the New World screwworm fly from all of North and Central America through the mass rearing and release of irradiated flies. In particular, reviewing the pest cases of the screwworm fly (an obligate parasite of livestock), spotted wing *Drosophila* (an invasive pest of soft skinned fruits), the diamondback moth (which feeds on plants in the mustard family, causing $4–5 billion in global damages per year), the red flour beetle (a worldwide pest of stored grain), and Hemiptera (plant sucking insects that vector diseases such as citrus greening disease), the authors describe the particular ecological and molecular challenges of constructing gene drive modified insects and deploying them effectively – often to bias sex ratios of insect offspring or introduce lethal mutations that crash local populations. While not every reader of *JRI* will follow all of the technical detail, the key insight is that gene drives make possible new strategies that mirror the goals of SIT, offering greater efficiencies than the mass rearing and releases of SIT and alternatives to pesticides that are less damaging to ecosystems. The authors note, however, that gene drives are no panacea; design issues must incorporate safety and efficacy from the earliest stages, and deployments may breed resistance that undermines a particular intervention's effectiveness.

Leitschuh et al. (2017) focus attention on a specific potential application of gene drive technology – eradicating invasive rodents on islands to protect biodiversity. As scientists active in the genetic biocontrol of invasive rodents (GBIRd) program and participants in the Genetic Pest Management NSF-IGERT program, they describe the potential to harness a naturally-occurring gene drive system in mice in order to skew the sex ratio of a wild breeding population to virtually all-male, making the population reproductively unviable. Such a strategy may offer fewer off-target environmental effects and a safer, scalable, more humane eradication process than current approaches to rodent eradication that rely upon the spread of hemorrhage-inducing toxicants. The authors review the multiple and complex technical issues central to the innovation of a gene drive modified rodent, offer perspectives on the need for a phased-testing pathway, discuss the importance and challenges of conducting an ecological risk assessment, and address the benefits of engaging communities, stakeholders, and regulators during the early stages of innovation.

Hayes et al. (2017) delve deeply into the methods to identify hazards and detect potentially adverse ecological outcomes as gene drive modified organisms progress through a phased test and release pathway. They first discuss checklist approaches, which have the advantage of building on analogous technologies but the disadvantage of missing novel risks. Second, they describe structured hazard analysis techniques, which rely upon understanding causal pathways that link events at the molecular level to organismal, population, community, and ecosystem outcomes. They emphasize the research challenges at each phase of a pathway that begins with laboratory testing and ends with monitoring that follows open field release of gene drive modified organisms. Building upon the World Health Organization (WHO) framework, they advocate for 'entry' and 'exit' strategies at the beginning of the phased testing and release pathway; entry strategies bring diverse stakeholders together to develop a shared understanding of the problem to be solved and set evaluation criteria prior to a formal risk analysis, while exit strategies define the point at which interested parties would agree to discontinue monitoring programs after a period of no apparent adverse effects. Readers of this journal will appreciate the way that these authors defend the integrity and rigor of highly formalized and quantitative risk analysis as foundational – but not sufficient – to responsible innovation in the field of gene drives.

Thompson (2017) brings multiple domains of ethics to bear on the research and development of gene drive technology. These domains overlap but offer complementary insights into the values, norms, oversight procedures, and governance institutions that surround gene drives. Specifically, Thompson addresses (1) standard research ethics (e.g. informed consent, research integrity); (2) identification and interpretation of risk; (3) fiduciary responsibility; (4) democratizing technology; (5) epistemology and power; and (6) procedural ethics. In so doing, he explicitly builds upon perspectives outlined in *Gene Drives on the Horizon* (NASEM 2016) and also reveals shortcomings of that report. What is perhaps most valuable is Thompson's careful attention to the way that ethics infuses the entirety of research, development, and governance in ways that oppose the tendency to relegate ethics to the margins of innovation as a discrete box to check at certain sensitive moments of deployment.

Mitchell, Brown, and McRoberts (2017) consider the specialized insights provided by an economic analysis of potential pathways of research and development of gene drive technology. For example, they point out that the types of gene drives pursued (i.e. self-sustaining vs. self-limiting) will strongly affect the kinds of organizations and firms willing and able to invest in technological development. Relatedly, they describe how public perception and formal regulations may combine to influence the costs of bringing a gene drive product to market. These costs, which also will invariably include unintended negative social impacts (as all technologies do), affect the classic economic calculation of social welfare. Their model, presented with limited disciplinary jargon in the article and additional technical detail in a supplement, posits the existence of multiple equilibria for the production of gene drives, given high degrees of uncertainty. In other words, rather than following smooth functions of supply and demand, non-linear components of gene drive technology may create a degree of path-dependence that reduces future adjustments in the supply of technology – making regulatory flexibility and ongoing research paramount in striving for responsible innovation in this field.

Acknowledging the significant uncertainties that surround how the U.S. regulatory system will govern field trials and potential environmental releases of gene drive modified organisms, Meghani and Kuzma (2017) analyze the Food and Drug Administration's (FDA) oversight of Oxitec's genetically engineered (GE) mosquito – an organism that does not contain a gene drive but raises a similar set of issues for risk assessment. They illustrate multiple instances in which the FDA's decisions and practices show favor to corporate interests over the public interest, including problematic assumptions about the ability of GE mosquitoes to spread and persist in the environment, and a failure to take seriously the possibility of harm to non-target species. Meghani and Kuzma make sense of such governance shortcomings neither as simple mistakes nor a conspiracy, but rather as reflecting the increasingly 'neoliberal' orientation of the FDA toward its oversight of biotechnology. From this perspective, they call for major reform in the U.S. regulatory approach toward GE organisms broadly, and gene drive modified organisms in particular.

Evans and Palmer (2017) use the lens of 'anomaly handling' to tease apart diverse views on how gene drives should be governed. They notice that various actors make claims about how gene drives fit within, or challenge, existing regulatory frameworks, and they explore the kinds of adjustments (to regulations or to gene drive technology itself) that are required to maintain social and political order. After reviewing the motivations for *Gene Drives on the Horizon* (NASEM 2016), and recent shifts in the current landscape of biotechnology governance in the U.S. and globally, Evans and Palmer draw upon a rich history of scholarship in anomaly-handling to make sense of the governance landscape for gene drives. They identify substantive arguments that surround several key questions: (1) To what degree do gene drives represent truly novel (i.e. anomalous) technologies that possess attributes unlike existing technologies? (2) Can the current regulatory oversight system adjust to and manage the anomalous characteristics of gene drives? (3) Can technical design choices within gene drive development reduce or eliminate the novel characteristics predicted to strain regulatory practice? (4) Do gene drives signal a need to overhaul the existing biotechnology governance framework? Answering such questions, they explain, is an inherently political process of figuring out visions for technology that maintain social order. To illustrate, Evans and Palmer apply their framework to recent public debates over gene drives, ranging from calls for a research moratorium at the UN Convention on Biological Diversity, to the NASEM committee's recommendations for conducting ecological risk assessments. Such analysis offers insight by providing language to understand the intersection of technological innovation, politics, and regulatory oversight of gene drives.

With permission from the National Academies Press, we include a reprint of the executive summary of the book-length report, *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values* (NASEM 2016). This report, written by an ad-hoc committee of diverse experts (including guest editor of the present special issue, J. Delborne) was convened in July 2015. The committee reviewed the state of the science of gene drives, examined oversight mechanisms (including risk assessment) for gene drive research and development, and engaged deeply with relevant legal, ethical, and social considerations. One major finding stated that

> [t]here is insufficient evidence available at this time to support the release of gene-drive modified organisms into the environment. However, the potential benefits of gene drives for basic and applied research are significant and justify proceeding with laboratory research and highly controlled field trials (10).

Report recommendations address many audiences, including scientists, regulators, policy-makers, and university biosafety committees. Of particular note, the NASEM report emphasizes the importance of an interdisciplinary perspective on gene drive research by attending explicitly to complex human values and the necessity of community, stake-holder, and public engagement to accompany technical research and development.

Finally, in a shorter perspective piece, Medina (2017) explores the potential for gene drives to join the arsenal of tools used to control agricultural pests. He describes important differences between strategies of pest eradication through gene drives and the modification of pest populations, for example, to reintroduce pesticide susceptibility. He also points to the key distinction between global drives, which are meant to spread widely, and local drives, which offer greater promise for experimentation and learning without the risks of global eradication of a species. He calls for an interdisciplinary approach to governing the development and potential release of gene drives in agriculture – one that involves natural and social scientists; ecological and evolutionary considerations; a balance of regulatory oversight, stakeholder and public involvement; and a comparative approach that considers the unique risks of gene drives as well as the existing risks of conventional pest management such as pesticides.

In sum, this special issue provides a roadmap for gene drive research and governance. It is not a roadmap in a typical sense, such as a Google map, whose utility is marked by comprehensive integration of ground-truthed facts and perfect clarity in departure points and destinations. Instead, the articles provide signposts that encourage attention to diverse issues, remind readers of helpful frameworks and analogies, and foster interdisciplinary conversations about the pursuit of responsible innovation in gene drive research and development.

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Notes on contributors

Jason Delborne joined the Genetic Engineering and Society Center at North Carolina State University in 2013. His research focuses on emerging technologies, responsible innovation, and public engagement, drawing on the interdisciplinary field of Science, Technology, and Society (STS). He served on the National Academies of Sciences, Engineering, and Medicine's (NASEM) committee that produced the report, *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values* (2016) and was appointed in 2017 to the NASEM committee to investigate the potential for biotechnology to improve forest health.

Jennifer Kuzma is the Goodnight-NCGSK Foundation Distinguished Professor in Social Sciences and co-director of the Genetic Engineering and Society Center at North Carolina State University. Previously, she was a faculty member in science and technology policy at the Humphrey School of Public Affairs, University of Minnesota (2003–2013); study director at the National Academies of Science in Washington DC for genetic engineering and bioterrorism (1999–2003); and a AAAS Risk Policy Fellow at the US Dept. of Agriculture (1997–1999). She has over 100 scholarly publications on emerging technologies and governance; and has been studying genetic engineering and its societal aspects for over two decades.

Fred Gould works in the area of ecology and evolutionary biology. An elected member of the National Academy of Sciences, he conducts empirical and theoretical studies of insect pests to improve food production and human and environmental health. He chaired the NASEM committee that reviewed over twenty years of research and experience with genetically engineered crops to produce the comprehensive report, *Genetically Engineered Crops: Experiences and Prospects* (2016).

Emma Frow is an assistant professor with a joint appointment at the School for the Future of Innovation in Society and the School of Biological and Health Systems Engineering at Arizona State University. Her research focuses on standards and governance in contemporary life sciences, with a particular focus on synthetic biology.

Caroline Leitschuh is a doctoral candidate in zoology and a member of the Genetic Engineering and Society Center at North Carolina State University. She studies how rearing environment affects mouse anxiety-related and exploratory behavior, in the context of eradication of invasive mice from islands. She also is interested in facilitating communication between disparate scientific disciplines and between researchers and the public.

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References

Baltzegar, J., J. Cavin Barnes, J. E. Elsensohn, N. Gutzmann, M. S. Jones, S. King, and J. Sudweeks. 2017. "Anticipating Complexity in the Deployment of Gene Drive Insects in Agriculture." *Journal of Responsible Innovation* 4 (S1): 81–97.

Burt, A., M. Coulibaly, A. Crisanti, A. Diabate, and J. K. Kayondo. 2017. "Gene Drive to Reduce Malaria Transmission in Sub-Saharan Africa." *Journal of Responsible Innovation* 4 (S1): 66–80.

Evans, S. W., and M. J. Palmer. 2017. "Anomaly Handling and the Politics of Gene Drives." *Journal of Responsible Innovation* 4 (S1): 223–242.

Gould, F. 2008. "Broadening the Application of Evolutionarily Based Genetic Pest Management." *Evolution* 62 (2): 500–510. doi:10.1111/j.1558-5646.2007.00298.x

Hayes, K. R., G. R. Hosack, G. V. Dana, S. D. Foster, J. H. Ford, R. Thresher, A. Ickowicz, et al. 2017. "Identifying and Detecting Potentially Adverse Ecological Outcomes Associated with the Release of Gene Drive Modified Organisms." *Journal of Responsible Innovation* 4 (S1): 139–158.

Kuzma, J., F. Gould, Z. Brown, J. Collins, J. Delborne, E. Frow, K. Esvelt, et al. 2017. "A Roadmap for Gene Drives: Using Institutional Analysis and Development to Frame Research Needs and Governance in a Systems Context." *Journal of Responsible Innovation* 4 (S1): 13–39.

Leitschuh, C. M., D. Kanavy, G. A. Backus, R. X. Valdez, M. Serr, E. A. Pitts, D. Threadgill, and J. Godwin. 2017. "Developing Gene Drive Technologies to Eradicate Invasive Rodents From Islands." *Journal of Responsible Innovation* 4 (S1): 121–138.

Medina, R. F. 2017. "Gene Drives and the Management of Agricultural Pests." *Journal of Responsible Innovation* 4 (S1): 255–262.

Meghani, Z., and J. Kuzma. 2017. "Regulating Animals with Gene Drive Systems: Lessons From the Regulatory Assessment of a Genetically Engineered Mosquito." *Journal of Responsible Innovation* 4 (S1): 203–222.

Min, J., A. L. Smidler, D. Najjar, and K. M. Esvelt. 2017. "Harnessing Gene Drives." *Journal of Responsible Innovation* 4 (S1): 40–65.

Mitchell, P., Z. Brown, and N. McRoberts . 2017 "Economic Issues to Consider for Gene Drives." *Journal of Responsible Innovation* 4 (S1): 180–202.

National Academies of Sciences, Engineering, and Medicine (NASEM). 2016. *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values*. Washington, DC: National Academies Press. doi:10.17226/23405

Scott, M. J., F. Gould, M. D. Lorenzen, N. Grubbs, O. R. Edwards, and D. A. O'Brochta. 2017. "Agricultural Production: Assessment of the Potential Use of Cas9-Mediated Gene Drive Systems for Agricultural Pest Control." *Journal of Responsible Innovation*. 4 (S1): 98–120.

Thompson, P. 2017. "The Roles of Ethics in Gene Drive Research and Governance." *Journal of Responsible Innovation* 4 (S1): 159–179.