SOCIAL SCIENCES

Does the U.S. public support using gene drives in agriculture? And what do they want to know?

Michael S. Jones[1,2], Jason A. Delborne[2,3], Johanna Elsensohn[2,4], Paul D. Mitchell[5], Zachary S. Brown[1,2]*

Gene drive development is progressing more rapidly than our understanding of public values toward these technologies. We analyze a statistically representative survey ($n = 1018$) of U.S. adult attitudes toward agricultural gene drives. When informed about potential risks, benefits, and two previously researched applications, respondents' support/opposition depends heavily (+22%/−19%) on whether spread of drives can be limited, non-native versus native species are targeted (+12%/−9%), or the drive replaces versus suppresses target species (±2%). The one-fifth of respondents seeking out non–GMO–labeled food are more likely to oppose drives, although their support exceeds opposition for limited applications. Over 62% trust U.S. universities and the Department of Agriculture to research gene drives, with the private sector and Department of Defense viewed as more untrustworthy. Uncertain human health and ecological effects are the public's most important concerns to resolve. These findings can inform responsible innovation in gene drive development and risk assessment.

INTRODUCTION

Rapidly advancing research in gene drives, with proposed applications for human health (*1*, *2*), environmental management (*3*, *4*), and agriculture (*5*), has sparked intense debate among scientists, regulators, and nongovernmental organizations. In some scenarios, gene drives might alleviate a pest or disease by using preferential inheritance to generate self-sustaining spread of genetic traits that either suppress a species population or render the organism less harmful (*6*, *7*). Experts currently disagree on the feasibility of gene drives to accomplish these goals and on the mix of potential benefits and adverse outcomes that might result (*3*, *4*, *6*, *8*).

While much publicity and social debate has highlighted the opportunities and risks of gene drive pursuits for vector-borne human disease control (*1*, *2*) and biodiversity protection (*3*, *4*), potential agricultural applications are also under development. An early attempt was to control Huanglongbing or citrus greening, a bacterial disease (*Candidatus liberibacter* spp.) vectored by the Asian citrus psyllid (*Diaphorina citri*) and other psyllid species, which is devastating the citrus industry globally (*9*). A proposal funded by the U.S. Department of Agriculture (USDA) attempted to develop a population replacement drive—the self-sustaining spread of an insect strain incapable of transmitting the disease to replace the existing population (Citrus Research and Development Foundation, https://citrusrdf.org/wp-content/uploads/2019/04/Annual-REEport-August-2017-Final.pdf). Similarly, spotted wing *Drosophila* (*Drosophila suzukii*), an invasive fruit fly from eastern Asia, has established in Europe and the Americas, where it causes extensive damage to ripening berry and stone fruits and markedly increases control costs (*10*). Research funded by the USDA and grower associations is seeking a population suppression drive (*11*, *12*), a system that causes population collapse by spreading a trait that inhibits normal reproduction (*7*).

[1]Department of Agricultural and Resource Economics, North Carolina State University, Raleigh, NC, USA. [2]Genetic Engineering and Society Center, North Carolina State University, Raleigh, NC, USA. [3]Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, USA. [4]Department of Entomology and Plant Pathology, North Carolina State University, Raleigh, NC, USA. [5]Department of Agricultural and Applied Economics, University of Wisconsin–Madison, Madison, WI, USA.
*Corresponding author. Email: zack_brown@ncsu.edu

Acknowledging potentially substantial benefits and risks of gene drive technologies, and the diverse array of stakeholders, the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) recommended in 2016 that gene drive research continue in concert with ecological risk assessment and early-stage engagement with communities, stakeholders, and the public (*6*). In response, several sponsors of drive research have committed to ethical principles based on NASEM recommendations, including two-way public engagement and to ensuring "the perspectives of those most affected are taken into account" in research and development (*13*). However, to date, almost no published research systematically assesses public views and questions about the application of gene drives in any domain despite calls for such information (*6*, *14*, *15*).

Assessing public views toward gene drives is warranted at this time because of the pace of innovation and the potential for more permanent, widespread consequences as compared to previous forms of genetically engineered pests (described at the end of this article). The distinct challenges posed by many gene drive designs with super-Mendelian inheritance and difficult containment have led researchers to call this a "postnormal," multilayered scientific issue (*16*). Brossard *et al.* (*16*) argue that specific evaluation of public attitudes and perceptions toward these technologies are necessary, because "facts are uncertain, values are in dispute, stakes are high, and decisions are urgent," as researchers and policy-makers evaluate diverse strategies for potential drive deployment, which vary in terms of efficacy and controllability. Attitudes specifically about agricultural applications of gene drives are important to study because of the economic motives in these applications (somewhat in contrast to human disease vector control and biodiversity protection) and because of consumer controversies about genetically modified organisms (GMOs) in food supplies (*17*, *18*).

This article fills a significant gap in evidence on public attitudes for genetically modified agricultural insect pests in general and gene drives in particular. Analyzing original data from a web-based questionnaire administered to a population-based sample of the U.S. general public, we investigate the importance to the public of specific factors with extant variation in proposed gene drive systems: the controllability of the system (*3*, *4*, *6*, *19*), its application to non-native or native pests (*1*, *12*), and whether it is designed to alter or eliminate the pest (*6*, *12*). We also explore the types of information sought by the public and measure prioritization of future research endeavors. We further examine how the public views gene drive insect interactions with specialized grower systems such as certified organic production.

Our research expands on limited information about public awareness and attitudes toward the use of genetically modified insects in any context, and even more limited anecdotes on attitudes toward agricultural applications. In the context of controlling Zika spread in late 2016, one study found that 62.1% of Floridians and 57.6% of U.S. non-Floridian adults favored releases of modified (nondrive) mosquitoes (*20*). The Pew Research Center also provides survey evidence from 2018 that 70% of U.S. adults viewed genetic engineering of mosquitoes for disease control as "an appropriate use of technology," while 29% said it is "taking technology too far" (*21*). Kohl *et al.* (*22*) investigate U.S. public attitudes toward the use of gene-editing tools, including in gene drives, in wildlife conservation and find that majorities perceive both risks and benefits of using these technologies in conservation. In terms of actual proposed releases of engineered insects, the Florida Keys Mosquito Control District conducted a nonbinding referendum in 2016 among residents of Monroe County, Florida, as part of a proposed trial release of a genetically engineered, nondrive *Aedes aegypti* mosquito developed by the company Oxitec. While 57% of the county as a whole voted in favor of the trial, 65% of residents in the suburb where the release was to occur opposed it (*23*). In agriculture, Cornell University's request for a field release in New York of a genetically engineered, nondrive strain of diamondback moth (*Plutella xylostella*), also developed in collaboration with Oxitec, was discussed in public hearings and open comment periods and received some opposition from organically certified producer groups (*24*). However, to our knowledge, no quantitative measures of public support or opposition were published from this experience.

Our web survey questionnaire was based on three exploratory focus group discussions and survey pretesting (see Materials and Methods). The revised, final survey was fielded to a sample obtained from the GfK Knowledge Panel, which has been validated in other peer-reviewed academic research (*25*). A primary challenge with using a survey to elicit ex ante attitudes toward gene drives is the public's current unfamiliarity with these technologies (confirmed by our data). Following social science literature that seeks informed values about public goods (*26*), our objective was to characterize the views from an otherwise average member of the public who happened to be reasonably informed about the basic purpose, function, feasibility, and risks of gene drives in specific agricultural applications. We devoted significant effort in each focus group discussion and survey pretesting in explaining the technology to participants, using the citrus psyllid and spotted wing applications described above as concrete examples to identify points of engagement and confusion. Although it is impossible to judge an information frame as perfectly "balanced" or "objective," we intentionally provided content detailing the risky and uncertain nature of the drive technology and its potential to replace traditional control measures that are not working well or economically for the specific pest examples. On the basis of focus groups and pretests, we committed an extensive portion of the survey—a median of 27% of total questionnaire time—interactively providing information about gene drives. All respondents first received a basic explanation of the technology and illustrations of the two proposed applications, including discussion about the inadequacies of many current control strategies for these invasive species and their economic impact on the respective industries and growers. Respondents then had the option of selecting any or all of seven frequently asked questions (FAQs) about drive functions and risks, which were identified in focus groups and pretesting.

Following this description of the technology, example applications, and FAQ provision, respondents then indicated their extent of support for or opposition to $8 = 2^3$ types of gene drives for agricultural pest control, which varied according to three binary factors: (i) whether the drive would suppress or replace the target pest population, (ii) whether spread of the drive would be limited, and (iii) whether or not the species to be controlled was native to an area. These factors were identified in focus groups and survey pretesting as potentially important determinants of public support. Control of drive spread is particularly important, as "spread" may be explicitly desired in some contexts and biomathematical models have suggested difficulty in controlling potential invasiveness of some drive systems (*8*, *19*, *27*). Respondents also reported support or opposition for whether gene drive pest residue could be allowed on organically certified food.

Respondents further indicated the relative importance that they attributed to each of 10 scientific and policy uncertainties surrounding the use of gene drives in agriculture. The items on this list (described below) were adapted from the uncertainties the NASEM report (*6*) recommended be resolved before gene drive deployment, aggregated and simplified on the basis of focus groups and survey pretests. Last, respondents reported the trust that they placed in different entities to responsibly conduct research into agricultural applications of gene drives. The survey also elicited a variety of respondent characteristics (for example, whether they purchased or sought out organically certified or non-GMO food). We examine these characteristics vis à vis the above attitudinal indicators.

RESULTS

We first describe survey results on support for the different types of gene drives considered and for whether to allow gene drive pest residues in organic certification. We then analyze the selection of different FAQs and the levels of importance attributed to different uncertainties. Last, we analyze who the public trusts to responsibly handle research into these uncertainties.

Our data indicate that a majority of the U.S. public, when provided information about potential benefits and risks, would currently support use of an agricultural gene drive targeting non-native species damaging crops with failing and costly conventional control options, if mechanisms limit drive spread. As Fig. 1 illustrates, this result holds for population suppression (61% support, 14% oppose) and replacement (57% support, 16% oppose). However, even in non-native species, drives that spread freely have considerably less support, whether for suppression (33% support, 34% oppose) or replacement (37% support, 34% oppose). The distinction between unlimited and self-limiting drives is the most important factor analyzed, reducing the likelihood of public support by 22.1 percentage points ($P < 0.001$). Drives targeting native versus non-native species have less support (11.5 percentage point reduction, $P < 0.001$), as do drives suppressing rather than replacing pest populations (1.9 percentage point reduction, $P = 0.010$) (tables S2 and S3). These statistics are essentially equivalent when controlling for respondent covariates (Table 1).

Statistical analysis also shows that attitudes toward agricultural gene drive insects vary significantly between respondent subgroups and their level of awareness about existing pest control practices and regulations. As hypothesized, respondents regularly seeking non-GMO (or "GMO-free")–labeled products are statistically significantly less

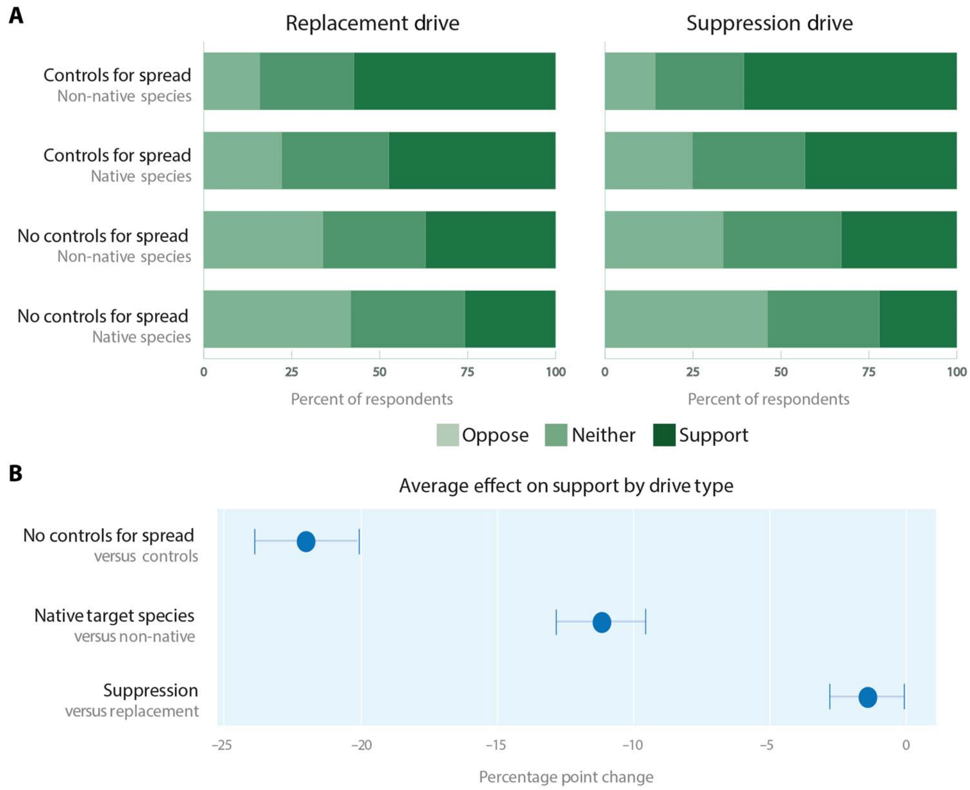

Fig. 1. Support for gene drive use in agriculture. Note: Respondents were asked whether they support or oppose the use of gene drives to control agricultural insect pests in each of eight applications. (**A**) Condensed Likert response frequencies varying (i) whether the drive would reduce populations or alter populations to not carry a crop disease, (ii) whether controls are in place to limit the extent of drive spread, and (iii) whether the target species was native to an area. (**B**) 95% confidence intervals (CIs) shown for average marginal effects of estimates from a pooled ordered logit model with SEs clustered by respondent (full model tables 2 and 3, inclusion of respondent covariates in Table 1).

supportive of gene drive insects in agriculture, with a 7.6 percentage point increase in opposition (Table 1). However, as shown in Fig. 2, a substantial portion of those seeking non-GMO food still support some types of gene drive insect use in the contexts described. Of the roughly one-fifth of the U.S. population who search for non-GMO–labeled foods, 52.8% [95% confidence interval (CI), 47.6 to 58.2%] supports gene drive applications in non-native species with controls for drive spread. Respondents regularly buying certified organic foods are not statistically significantly less likely to support drives. More educated respondents are more likely to take a supporting or opposing position, with undergraduate and graduate degree holders about 18 percentage points less likely to select a neutral or "Don't Know" position than respondents with no college exposure. While the survey questions about drive support were not specifically framed in terms any specific pest species, the spotted wing and psyllid applications described in the information frame likely increased the salience of the technology for consumers of the associated citrus and berry crops. Enhanced salience may have increased or decreased support, depending on whether perceived benefits from reduced crop damage (ensuring availability of affordable produce) outweigh perceived risks. We find that blueberry consumers are 4.4 percentage points more likely to support gene drives (Table 1). Similarly, given the citrus psyllid case description, orange juice consumers are 4.2 percentage points more likely to support drive use.

Around one in five respondents also report "regularly" purchasing USDA organically certified food (regular organic purchase exhibits a 0.485 correlation with seeking non-GMO–labeled food). When asked whether USDA organic certification standards should allow gene drive insects (without specifying adventitious or intentional presence), 43% of these consumers agree that farmers should be able to retain certification when drive insects are present "in the growing area" (Fig. 3). Agreement drops to 35% when gene drive insect material is "in or on crops," a reasonable expectation given current organic regulations. Focus groups suggested that organic consumers may have different views depending on awareness that certification standards permit some insecticide use. In the nationwide survey, only 57% of those regularly purchasing certified organic foods are aware that "certain types of insecticides" are allowed by organic certification standards. Among these "aware" individuals, 50% agree that certification should allow for drive insects "in the growing area" (Fig. 3). Those unaware of standard guidelines are 18 percentage points more likely to disagree that standards should permit modified insect material "in or on crops" ($P = 0.012$).

To understand what additional information different groups want to know about these technologies, we analyze respondents' voluntary selection of seven FAQs about agricultural gene drives (Fig. 4A). While more than 85% had never heard of gene drives before the survey, respondents appeared highly engaged with learning about the technology and more than 89% selected at least one FAQ. The most popular—"What are some possible risks of gene drives?"—was selected by 70%, suggesting widespread concern over unintended consequences. Women, nonwhites, household primary shoppers, and bachelor degree holders more frequently sought additional FAQ items (Table 1).

Respondents also selected what they believed to be the most and least important uncertainties to resolve "before deciding whether gene drive insects should be used to control pest damage to crops" (see note S4 for uncertainty item construction and exact phrasing). This survey exercise is known as best-worst scaling (BWS) (*28*, *29*) and was implemented in the survey by presenting each respondent

Table 1. Average marginal effects of gene drive attributes and respondent characteristics on support and FAQ selection. Note: Drive support estimated using a partial proportional odds (PPO)–ordered logit regression model and the *margins* command in Stata with compressed ordinal scale of oppose, neutral, or support and SEs clustered by respondent in parentheses. FAQ selection estimated using ordinary least squares. Additional regression specifications for these dependent variables in tables S3 to S5. McFadden's R^2 reported for the PPO-ordered logit regression and standard R^2 for least squares. Includes survey sampling weights. ***P < 1%, **P < 5%, and *P < 10%.

	Marginal effect on probability of drive use position			Number of FAQs selected
	Oppose	Neither	Support	
Gene drive attributes				
No controls for spread (versus controls)	0.190*** (0.010)	0.030*** (0.005)	−0.220*** (0.011)	–
Native species (versus non-native)	0.089*** (0.009)	0.032*** (0.007)	−0.121*** (0.010)	–
Suppression (versus replacement)	0.016** (0.007)	0.003** (0.001)	−0.019** (0.008)	–
Demographic variables				
Female	0.034* (0.018)	0.005* (0.003)	−0.040* (0.021)	0.427*** (0.149)
Age	−0.0004 (0.0005)	-6.82×10^{-05} (8.41×10^{-05})	0.0005 (0.0006)	0.003 (0.004)
White	0.044* (0.024)	−0.059** (0.026)	0.015 (0.026)	−0.554*** (0.163)
Income	−0.003 (0.002)	−0.0005 (0.0004)	0.003 (0.003)	0.013 (0.019)
Lives in "metro" area	−0.012 (0.033)	−0.002 (0.005)	0.014 (0.037)	0.060 (0.230)
Highest postsecondary education				
No college (base level)	–	–	–	–
Some college or associate degree	0.029 (0.027)	−0.112*** (0.031)	0.083*** (0.030)	0.356* (0.182)
Bachelor degree	0.094*** (0.032)	−0.183*** (0.031)	0.089*** (0.033)	0.518** (0.210)
Graduate degree	0.098*** (0.034)	−0.182*** (0.033)	0.085** (0.036)	0.323 (0.228)
Religiosity scale	−0.003 (0.002)	−0.0005 (0.0004)	0.003 (0.003)	0.018 (0.020)
Consumption variables				
Primary shopper	−0.046** (0.022)	−0.007* (0.004)	0.054** (0.025)	0.354** (0.175)
Buys blueberries	−0.038** (0.019)	−0.006* (0.003)	0.044** (0.022)	0.279 (0.154)
Buys orange juice	−0.037** (0.018)	−0.006** (0.003)	0.042** (0.021)	0.064* (0.155)
Buys "local" foods	0.054** (0.022)	−0.061*** (0.022)	0.007 (0.023)	0.238 (0.147)
Buys "USDA-organic" foods	0.020 (0.023)	0.003 (0.004)	−0.024 (0.027)	0.372* (0.202)
Seeks "non-GMO"–labeled foods	0.076*** (0.025)	0.012*** (0.004)	−0.088*** (0.029)	0.372* (0.203)
Constant	–	–	–	1.826*** (0.432)
Respondents		1000		1001
Observations		7997		1001
(McFadden's) R^2		0.0723		0.092
Wald test P value for joint significance				
Drive attributes		P < 0.0001		–
Demographic variables		P < 0.0001		P = 0.0007
Consumption variables		P < 0.0001		P < 0.0001

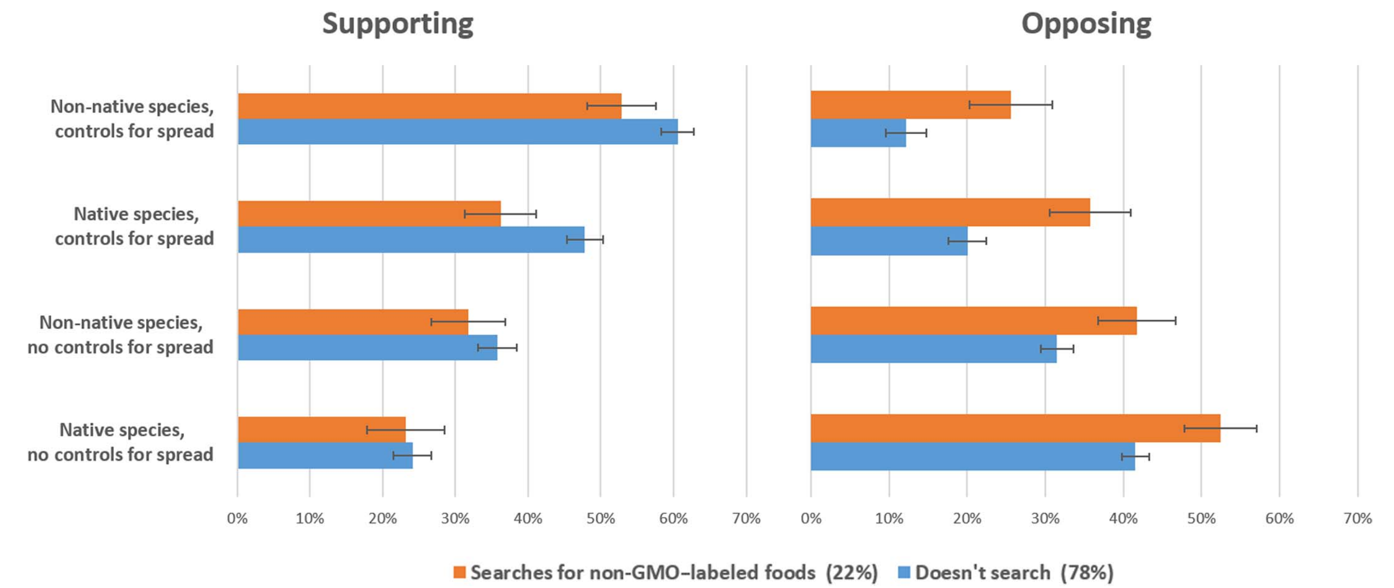

Fig. 2. Drive support and opposition by whether seeking non-GMO food. Note: Level of support and opposition to gene drive insect applications for seekers and nonseekers non-GMO–labeled food [95% CIs shown; suppression and replacement applications combined (see table S6)]. While those searching for non-GMO–labeled food are relatively less supportive and more likely to explicitly oppose drive applications (Table 1), a slight majority (53%) still support applications in non-native species with controls for drive spread with 26% opposing.

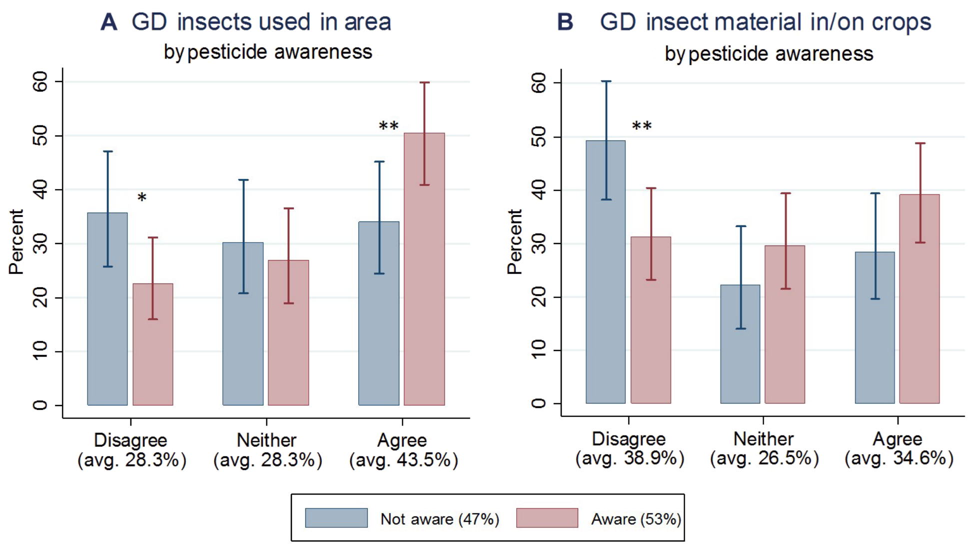

Fig. 3. Organic certification attitudes when drive insects present. Note: Level of agreement (with 95% CI) that a farmer should be able to retain organic certification in the presence of gene drive insects, among affirmed regular purchasers of certified organic food products (n = 228), by whether the respondent is aware that some types of insecticides are allowed under organic regulations (57% of regular organic consumers aware). Questions are asked separately by whether (**A**) gene drive insects are used in the area to control a damaging insect species or (**B**) that use of drive insects in results in genetically modified insect material "getting in or on crops." **P < 5% and *P < 10% for adjusted Wald tests of equivalent response means.

with five subsets of the 10 uncertainties shown in Fig. 4B, from which respondents selected the most and least important items in each subset. The subsets are experimentally controlled and randomized across respondents so that the frequency an item is selected as most (or least) important provides an unbiased statistical estimator of that item's (un)importance within the population (see Materials and Methods). Analysis of these data implies that potential human health impacts and ecological consequences of species removal are most frequently viewed as the highest priorities (Fig. 4B). Although NASEM recommends human health risk assessment only on drives for human disease vectors, this result suggesting the question of human health remains important to the public in any application (*6*). Uncertainty about the ecological consequences of species removal emerged as more important than economic impact and technical feasibility (P < 0.001; table S7), suggesting that the NASEM report's recommendations for ecological risk assessments (*6*) align with public concerns. These results are in line with a recent Pew Research Center study showing both high public acceptance of genetically engineered mosquitos for vector control and high

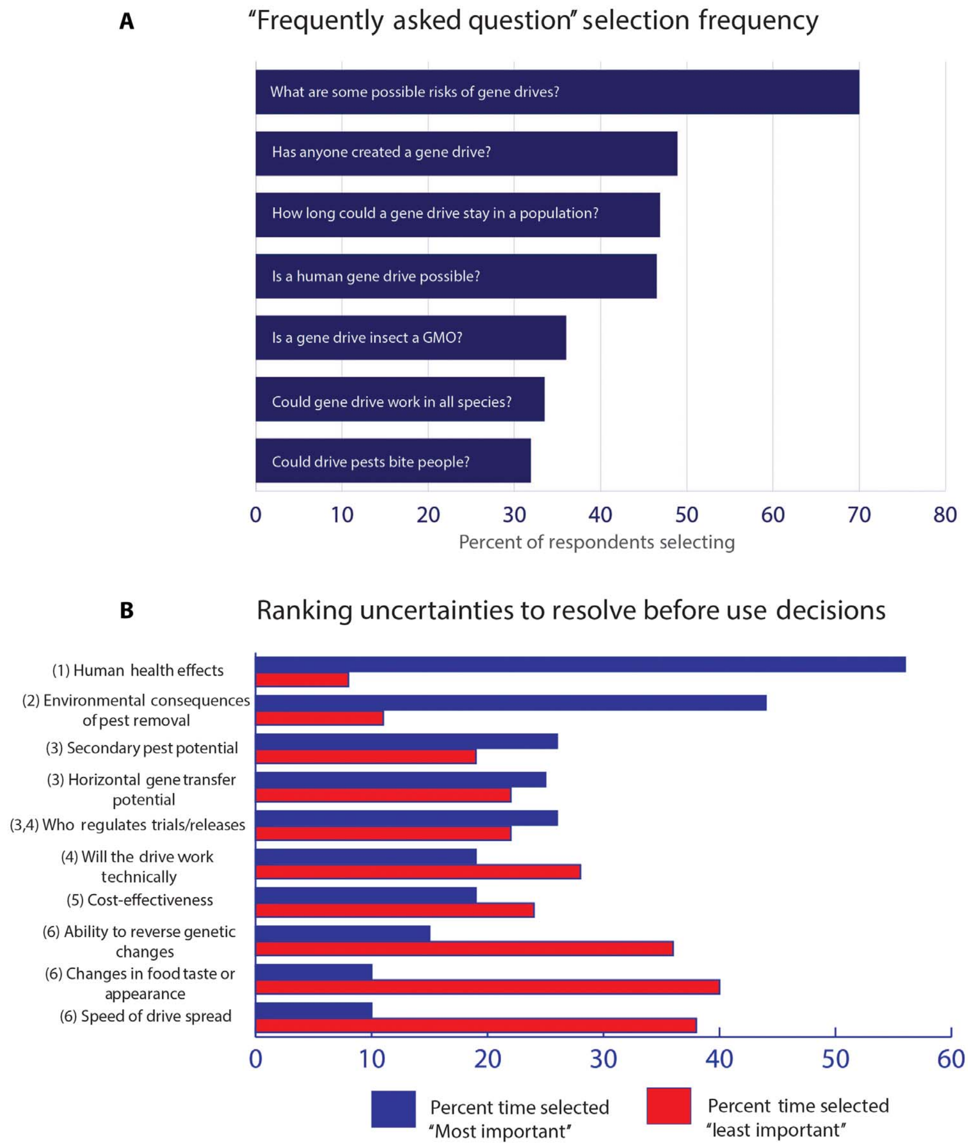

Fig. 4. What does the public want to know about agricultural gene drives? Note: (**A**) FAQ selection. Voluntary respondent selection frequency from the seven-item FAQ list. Question wording is abbreviated for exposition; see the Supplementary Materials for the complete survey text. (**B**) Ranking uncertainties to resolve before use decisions. Respondents selected the "most important" and "least important" among iterative four-item subsets of the 10 alternatives to resolve "before deciding whether gene drive insects should be used to control pest damage to crops" (numbers denote statistical ranking via weighted least-squares regression and Wald tests of linear hypotheses; full item wording is found in note S4, WLS model results are found in table S7, and an example choice scenario is found in fig. S1).

concern about risks to the environment and ecosystem impact among dissenters (*21*). "Reversal drives," or the possibility of releasing a second gene drive to overwrite and reverse unintended effects of a previous drive, have received much attention in debates (*6*, *30*). However, reversibility was among the lowest ranked priorities. Taken with our evidence of public support for self-limiting drives (Fig. 1), this result suggests that the public tends to prefer avoiding the need for reversal drives.

The U.S. public will also likely scrutinize who develops and assesses the risks for agricultural gene drive applications. Our data indicate that 62% regard both U.S. universities and the USDA as "somewhat" or "very" trustworthy to conduct "research on gene drive insects to control agricultural pests," compared to 9 and 15% responding "somewhat not" or "not at all" trustworthy, respectively (Fig. 5). However, only 16% view large private companies as trustworthy drive insect researchers, and 46% view them somewhat not or not at all trustworthy. Similarly, there is more public distrust in the U.S. Department of Defense (DOD) to conduct this research (18% "somewhat not" and 15% "not at all" trustworthy). However, this study does not explicitly measure differences between "conducting" versus "funding" research.

DISCUSSION

This survey analysis provides an ex ante portrait of U.S. public attitudes toward gene drives at an important point in time, well before any field release and with sparse popular press coverage about these technologies in agricultural contexts. Our analysis suggests that developers are most likely to have strongest public support for gene drive applications, with controlled spread for invasive agricultural pests with costly and/or

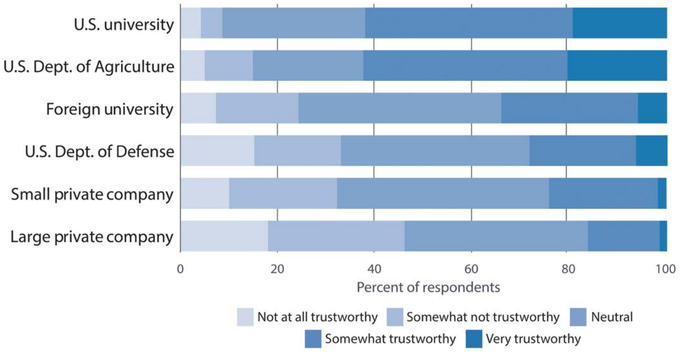

Fig. 5. Trust in institutions to conduct research on gene drive agricultural pests. Note: Respondents indicated "how trustworthy [they] feel each type of institution would be conducting research on gene drive insects to control agricultural pests" (full question wording and raw data is found in table S8).

failing conventional control options. Biological models have shown that gene drive invasion efficiency is potentially very high for first-generation, population-altering gene drives designed for uncontrolled spread (*8*). Theoretical models of newer gene drive designs using engineered underdominance have suggested that these alternate approaches may afford more spatial control of spread but in so doing would require a higher threshold initial release ratio of gene drive versus wild-type insects for traits to persist (*19*). High release ratios for established, high-density pests (like both of the pests considered here) would increase the cost of rearing sufficient numbers of gene drive pests to achieve persistence. However, our finding that survey respondents placed a relatively lower priority on resolving uncertain cost-effectiveness, compared to other uncertainties about the technology (Fig. 4B), suggests that the public would be willing to sacrifice some degree of cost-effectiveness for more controllability.

We also find that while seekers of non-GMO food are relatively less supportive of pursuing gene drives, roughly half of this subpopulation still supports pursuit for controllable applications to non-native species (Fig. 2A). This result suggests that a significant portion of this subpopulation does not uniformly transfer their revealed preferences regarding GMO food to other genetic engineering technologies. This finding could be an artifact of the specific information that we provided to survey respondents about gene drives (a possible limitation discussed below). Yet, even if this were the case, this study highlights that these individuals may be more sensitive to information about the benefits and risks of agricultural gene drives than recent research on the "absolute moral opposition to genetically modified food" would suggest (*31*).

The type and trustworthiness of the information about gene drive insects—and about the problems they are intended to solve—are also important to the public in forming their views. Our analysis of voluntary engagement with FAQs shows strong demand for further information about gene drive risks. Our analysis also suggests that, in some cases, respondents carefully weigh information about the benefits of gene drives relative to alternative pest control options. For example, we find that organic food consumers' knowledge of whether pesticides are used in organic agriculture is a significant determinant of their permissiveness of gene drive insect residue in organic certification.

This finding has important policy implications for how to handle agricultural gene drives in certification standards for organic products, which accounted for U.S. food sales of $43.4 billion USD in 2016 (*32*). Release of gene drive pests in nonorganic farms would spread to organic farms in the same area, providing nonchemical pest control benefits but also potentially resulting in genetically modified pest residue on organic produce. How current organic standards would handle such a situation is unclear. For example, the USDA's organic certification standards do not directly address presence of genetically modified insect material, and some researchers have asserted that direct or indirect support from grower groups in release programs may complicate farmer claims of "adventitious" presence (*33*). Our analysis shows how organic food consumers' knowledge about pest control practices currently allowed within organic certification may be pivotal in determining support for USDA revisions to organic standards.

Last, the relatively greater trust the U.S. public places in universities and the USDA to conduct research on agricultural gene drives is important to consider as development progresses. While not currently directly funding agricultural gene drives, the DOD is funding development of gene drives for biodiversity protection and measures for controlling and reversing the effects of gene drives (*34*). The DOD is also funding other genetic pest management (GPM) techniques for agricultural applications, for example, "insect-delivered horizontal genetic alteration" of crops to increase resistance to environmental stressors and disease (*35*, *36*). The DOD's support of horizontal genetic alteration technologies has raised concerns about possible dual use (*36*). Private industry is also developing nondrive, self-limiting GPM techniques for area-wide pest control and crop protection (*37*), including development of engineered *Aedes aegytpi* mosquitos and diamondback moth. However, one of the primary firms active in this area, Oxitec, has so far steered away from producing gene drives (*38*). Further, the Broad Institute, a holder of a key molecular biology patent for gene drive development, has prohibited its use for this purpose in licensing agreements with private firms (*39*). Our data suggest that this Broad Institute policy aligns with prevailing public attitudes.

Our survey methods and results have several layers of uncertainty and limitations that raise possible questions for future research. As a new, generally unfamiliar technology, a large contingent of respondents (between 25 and 35%) reported neither "support" nor "opposition" to the eight applications of gene drives. This percentage is somewhat higher than response patterns in other surveys of novel technologies such as human-genome editing (*40*; about 10 to 15%) and genetically modified (nondrive) mosquitoes (*41*; about 18%). Certain applications of gene drives could see overall majority public acceptance or opposition hinging on whether uncertain or neutral contingents gravitate toward either direction. Thus, our finding of significant undecided portions of the population constitutes important information on its own. While we find that respondents with more postsecondary education are less likely to fall into this undecided category (Table 1), our findings recommend more deeply investigating why individuals are or more or less likely to express a neutral position on biotechnologies.

Further, similar to challenges noted by researchers eliciting ex ante public attitudes toward nanotechnology (*42*), the process of eliciting attitudes on new, unfamiliar technologies can induce the formation of respondents' preferences (*43*). As we were aware in designing our survey, this can make results heavily dependent on the way information is provided about the technology's risks and benefits in the questionnaire. For example, we separated the information provided to respondents into base text that described the function of gene drives in terms of their intended benefits and then addressed risks and public concerns in the set of voluntarily selected FAQs. We adopted this approach because we judged it essential to understand the intended function of the technology to develop an informed attitude. In contrast, the risks and concerns raised in focus groups and the NASEM report (see note S4) were so disparate that addressing all of them with every respondent would have gone well beyond our available survey resources. We were concerned that this design may overly influence elicited attitudes, which is why we exposed every respondent to each unselected FAQ with one-third probability (see Materials and Methods). This enables a statistical check of whether the informational variation in the survey affected attitudes. As we describe in the "Statistical analysis" section within Materials and Methods, we do not find any evidence for these effects. However, more survey resources allocated to this check could have increased its statistical power. In addition, because we did not randomize the base text on intended functionality of the technology, we do not know how the overall information frame may or may not have nudged respondents' attitudes. We suggest that future research more specifically investigates the potential effects of information provision on attitudes toward unfamiliar biotechnologies.

In addition, the choice of example applications—spotted wing *Drosophila* and Asian citrus psyllid—in the base information text may also have limited the generalizability of our findings. The survey included specific examples to minimize the potential bias that can arise from overly hypothetical scenarios, and we selected these pests because of their economic relevance and because gene drives approaches have actually been pursued in both cases. However, these examples likely influence subsequent reported attitudes on gene drive applications. In particular, our results would not be appropriate for making inferences about levels of support or opposition in applications to agricultural pests of less economic significance. Nevertheless, since many drive proposals will likely focus on intractable, invasive pests that are highly destructive, results may thus still be useful to consider for a large relevant pool of future candidate species.

Our study was also designed to compare gene drives only against the status quo of conventional (primarily chemical-based) pest control and did not compare the technology to other (nondrive) forms of engineered insects or other insect control technologies exhibiting self-sustaining spread. Strategies involving mass release of modified insects for area-wide pest management have a long history and extend well beyond gene drives (*37*, *44*, *45*). Some of these technologies have historically been deployed in agriculture without much public attention. For example, mass release of radiation-sterilized insects has occurred for over 60 years to disrupt mating and suppress certain pest populations (*44*, *46*). Analogous approaches using genetic engineering include self-limiting conditional, dominant lethal systems such as RIDL (*37*, *44*), or, more recently, the demonstration of a CRISPR-based precision-guided sexing and sterility system (*47*). Modern biological control methods are also being pursued, notably the use of *Wolbachia* bacterial infections to bias reproduction in suppression or replacement strategies. Like gene drives, *Wolbachia*-based approaches have the potential for self-sustaining spread (at least within a local area) but, unlike gene drives, do not use genetic engineering (*6*, *45*). This latter feature has been portrayed as an advantage by proponents, who have described it as a "natural" method for insect control (*48*). *Wolbachia*-based approaches have predominantly focused on public health applications, although there have been early-stage laboratory trials with spotted wing *Drosophila* (*49*).

We did not elicit attitudes on these alternative technologies because of limited survey resources and concerns about respondent fatigue in assessing multiple unfamiliar technologies. So, we can only hypothesize, for future investigations, how public views toward them might differ. In the context of nondrive methods using genetic engineering, we hypothesize on the basis of our findings that a comparable survey sample might view these technologies at least as favorably as any of the types of gene drives considered in our survey. Our results suggest this support because nondrive approaches are highly controllable, in the sense that engineered insects will disappear after releases cease, and our evidence identifies controllability as the most important technological factor determining support/opposition among respondents. Furthermore, although one of the possible advantages of gene drives is their cost-effectiveness relative to nondrive approaches (due precisely to the gene drives' finite versus continual releases required to sustain impact), we refer again to our finding that cost-effectiveness is a relatively low-priority concern among the U.S. public (Fig. 4B).

Our results are more ambiguous for hypothesizing support/opposition toward *Wolbachia*-based control of an agricultural pest: On one hand, prior food marketing research has reinforced the value of "natural" claims to consumers (*50*), which could be invoked to increase *Wolbachia* favorability in food production. On the other hand, the self-sustaining spread of *Wolbachia*, like a gene drive, is likely to raise concerns about its controllability. In addition, because relatively more research is underway to enhance the controllability of gene drives (described above), it is unclear whether a similar set of respondents—assuming they were appraised of all of this information—would view *Wolbachia*-based control more or less favorably. Effectively evaluating these hypotheses would require a more interactive, deliberative social science research tool, such as a large-scale focus group or stakeholder workshop series, in addition to further surveys. Similar interactive social science methods may also be necessary to gain more insight on distinct subpopulations [e.g., Native Americans (*51*)], as concerns about cultural equity are addressed for drive deployments.

To uphold public trust while investigating gene drive technologies, researchers and policy-makers should weigh the evidence presented here when deciding whether and what type of application to deploy, the extent and prioritization of risk assessments and stakeholder engagement, and the organizations conducting this work. Furthermore, noting the high portion of undecided respondents in our survey, public attitudes toward gene drives can change as events occur to increase the salience of perceived risks, as was allegedly seen, for example, with GMOs in Europe in the 1990s (*52*). Potential movement of drive species and agricultural trade will require discussions among international publics with heterogeneous values and market environments, ultimately necessitating continued public engagement both over time and beyond immediate release areas.

MATERIALS AND METHODS

Data collection

Results were based on a nationally representative survey of 1018 of U.S. adults (18 and older), conducted by the survey firm GfK from 17 October to 14 November 2017. Respondents were drawn from GfK's KnowledgePanel, a widely used national probability-based online panel validated in other peer-reviewed research (*25*). This sampling frame is unique compared to other web-based survey panels, in that GfK combines address-based sampling and random digit dialing, and both laptops and internet access are provided to active members when necessary.

A total of 2269 panel members were sampled, of which 1356 entered the Qualtrics-based online survey instrument and 1189 consented to complete the survey. For recruitment, after emailing initial invitations at survey launch, email reminders were sent by GfK to nonresponders on day 3 of the field period. Additional email reminders to nonresponders were sent on day 7 of the field period. The response rate was 45%, and the completion rate was 75%. Median response time among qualified completes was 23 min. Of those consenting, 77 had incomplete responses at survey close. A total of 90 respondents were excluded via real-time quality control metrics. Metrics included excessive speeding in the four-panel information frame, with a threshold set at 10 times an assumed average reading speed of 200 words per minute and assessed at total time on four information panels (full information frame wording in the Supplementary Materials) or failure of >1 (of 2) trap questions. Trap questions included failure to follow an embedded directive to select "disagree" in an early question and indicating household purchase of "fresh ackee fruit" from a fruit product list, as this is illegal to import in the United States. Four additional respondents were excluded ex post because of total completion times less than 25% of the survey-wide median. This resulted in 1018 qualified completes used for analysis.

Poststratification statistical weights were prepared by GfK as standard and used for all reporting of results here. The following benchmark distributions of 18+ U.S. general population from the most recent March 2017 Current Population Survey were used for the adjustment of weights:

1 Gender (male and female) by age (18 to 29, 30 to 44, 45 to 59, and 60+).
2 Race/ethnicity (white/non-Hispanic, black/non-Hispanic, other/non-Hispanic, Hispanic, and 2+ races/non-Hispanic).
3 Census region (northeast, midwest, south, and west).
4 Metropolitan status (metro/nonmetro).
5 Education (less than high school, high school, some college, and bachelor or higher).
6 Household income (under $25,000, $25,000 to $49,999, $50,000 to $74,999, $75,000 to $99,999, $100,000 to $149,999, and $150,000 and over).

The breakdown of benchmark distributions for demographic covariates used in regression models, in raw qualified completes versus adjustment with survey weights, is detailed in table S1.

Focus groups and survey questionnaire

Design of the survey questionnaire consisted of the following steps: (i) Three 2.5-hour exploratory focus group discussions about public attitudes and comprehension of agricultural applications of gene drive insects were conducted with a total of 21 primary grocery shoppers recruited at grocery stores in Durham, Raleigh, and Dunn, North Carolina in spring 2017 [note S5; *53*)]; (ii) using analysis of the focus groups, we drafted the survey instrument in Qualtrics and initially pretested with students and colleagues in North Carolina State's Genetic Engineering and Society Center (which encompasses many social and natural science disciplines and includes a broad range of opinion on novel biotechnologies); (iii) we revised the Qualtrics instrument and further pretested it with Amazon Mechanical Turk ($n = 300$) to gather qualitative feedback on information frame presentation, comprehension, and design; (iv) we further revised the Qualtrics instrument to address open-ended feedback in pretests, adhere to KnowledgePanel requirements and reduce median completion time to 25 min or less, and implement a final experimental design of BWS subsets; and (v) we launched the finalized the survey instrument with a KnowledgePanel sample.

After a brief introduction and informed consent, the survey instrument contained the following sections analyzed in this paper (presented in this order): (i) respondent consumer characteristics; (ii) general textual and visual information about how gene drives work, followed by description of the potential applications of a spotted wing *Drosophila* repression drive and a Asian citrus psyllid replacement drive; (iii) FAQs; (iv) BWS exercise on gene drive uncertainties; (v) respondent knowledge of current organic certification requirements; (vi) views on allowing gene drives within organic certification; (vii) elicit support/opposition to the eight types of gene drives in Fig. 1; and (viii) religiosity, elicited at the end to avoid any impacts (e.g., due to saliency or availability bias) of this question on preceding responses.

Part (i) included relevant respondent characteristics not automatically collected in the KnowledgePanel, described below. The information provision in (ii) began with the following consequentiality statement, to retain attention and to reduce hypothetical bias (*54*): "Your responses to questions about this information will inform policy decisions at the US Department of Agriculture." The full informational text and illustrations for (ii) are in note S1. Wording of the FAQs in (iii) is in note S2; these FAQs were crafted on the basis of focus group findings, open-ended feedback on survey pretests, and a previous FAQ webpage published by the Wyss Institute at Harvard (https://wyss.harvard.edu/faqs-gene-drives/). Respondents could select as many as they wished to view (including none), with presentation order randomized to avoid order effects. Each unselected FAQ was still shown to respondents with one-third probability. In table S10, we used an instrumental variable (IV) linear regression model with random forced assignments to view each FAQ as IVs to verify that viewing specific FAQ items did not significantly impact subsequent attitudes on gene drives ($P = 0.37$ for joint test of all FAQ items, process described further in the "Statistical Analysis" section).

The BWS exercise in (iv) followed methods in (*28*, *29*); this survey methodology was selected because of its lower cognitive demand and faster completion than elicitation of a full rank order, and as compared to a set of Likert scales, it avoids between-respondent scale differences and higher likelihood of ties. The exercise was preceded by the following instructions (further details in note S4 and example question in fig. S1):

> "Many questions remain to be answered before deciding whether gene drive insects should be used to control agricultural pests. Policy makers want to know how the public feels about these issues and which research questions are most important to answer. We need your help to inform these decisions.
> Here, we will show you a short series of questions. We would like to know which you feel is the 'most important' and which is the 'least important' to answer."

The selection and wording of the uncertainties included in the BWS exercise were based on the 2016 NASEM report conclusions (*6*) combined with focus group and survey pretest feedback; note S4 describes this in detail. The experimental design of the BWS exercise followed a Balanced Incomplete Block Design to guide choice set construction (*29*). With 10 items to rank, the full design contained 15 sets of 4 items each, with each item occurring six times and co-occurring two times with each other item. The SAS software package (version 9.4, with macro %mktbibd) was used to identify a statistically efficient three-block design limited to five sets for each respondent to reduce survey fatigue and completion time. Respondents were randomly assigned to a block, and every respondent saw each item at least once. Choice set order, as well as item order within each choice set, was randomized to avoid order effects.

Knowledge of organic certification in (v) consisted of the single question, "Please indicate the extent to which you believe the following statement is true or false: *Food that is certified 'USDA organic' can be produced applying certain types of insecticides* [Image of USDA organic label shown]." Responses consisted of a scale ranging from "Definitely False," "Probably False," "Probably True," to "Definitely True" and included a "Don't Know" option. We defined "awareness" of pesticide allowances within organic certification, as used in Fig. 3, as selection of "Probably True" or "Definitely True." In (vi), two questions on support for organic certification allowing gene drive insects ("in the area" for one question and "on or in the crops" for the second) were elicited on a five-point Likert scale ranging from "Strongly Disagree" to "Strongly Agree."

Part (vii) elicited respondents' levels of support or opposition to the eight possible combinations of three binary factors for gene drive insect applications: intended for suppression/replacement, self-limiting/unlimited spread, and native/non-native target species. These factors were chosen on the basis of the 2016 NASEM report recommendations (*6*) and related feedback from focus group participants. Particularly motivating was report recommendation 9-3: "The distinguishing characteristics of gene drives—including their intentional spread and the potential irreversibility of their environmental effects—should be used to frame the societal appraisal of the technology, and they should be considered in ecological risk assessment, public engagement, regulatory reform, and decision making" (*6*). The terminology for these factors was simplified to aid comprehension by respondents about these unfamiliar technologies. The description of these factors preceding this set of questions read as follows (emphases in instrument):

> "After reading about gene drives for agricultural uses, we would like to hear how you feel.
> Specifically, we want to know how you feel about gene drives **to reduce** populations of pests vs. **to alter** pests to prevent them from carrying a crop disease.
> We also want to know how you feel about gene drives used on insects which are **native** to an area vs. insects which are **not native** to an area. (Note: both the berry and citrus pest examples are invasive species not native to the United States).
> Finally, some scientists have proposed trying to control how far a gene drive can spread. We would like to know how you feel about gene drives when scientists try to **limit how far a gene drive can spread** vs. gene drives which are **allowed to potentially spread to the global population** of the insect species."

Following this preamble, respondents were then asked for each of the eight applications: "Overall, to what extent would you personally **support or oppose** the use of gene drives to control agricultural insect pests in the following applications: …" [emphasis in instrument]. Support or opposition to each of the eight applications (randomizing their order) was assessed for every respondent, on a five-point scale from 1 = "Strongly Oppose" to 5 = "Strongly Support," and including both a "Neither Support nor Oppose" and a "Don't Know" option (aggregated together here, but tested in robustness).

Demographic and consumer characteristics

We included in our statistical analysis standard demographic variables that may relate to public opinion of agricultural gene drive applications. The following variables were provided by GfK (not asked in survey instrument): Female is coded 1 = "female" and 0 = "male" (51.8% female). Age is measured in years (M = 50.7, SD = 16.2, and weighted mean = 47.3). For race, White is coded 1 = "white" and 0 = "otherwise" (64.0% white). GfK provides up to 21 levels for income, coded 1 = "less than \$5,000," 2 = "\$5,000 to \$7,499," 3 = "\$7,500 to \$9,999," 4 = "\$10,000 to \$12,499," 5 = "\$12,500 to \$14,999," 6 = "\$15,000 to \$19,999," 7 = "\$20,000 to \$24,999," 8 = "\$25,000 to \$29,999," 9 = "\$30,000 to \$34,999," 10 = "\$35,000 to \$39,999," 11 = "\$40,000 to \$49,999," 12 = "\$50,000 to \$59,999," 13 = "\$60,000 to \$74,999," 14 = "\$75,000 to \$84,999," 15 = "\$85,000 to \$99,999," 16 = "\$100,000 to \$124,999," 17 = "\$125,000 to \$149,999," 18 = "\$150,000 to \$174,999," 19 = "\$175,000 to \$199,999," 20 = "200,000 to \$249,000," and 21 = "\$250,000 or more" (median = 13).

We collected additional education information at a more granular level than the standard GfK-provided indicators to examine the potential importance of an undergraduate and graduate education with a topic as potentially complex as gene drives. The base level was "no college" (40.0%). Next, separate variables were coded for *Some college* as 1 = "some college" and 0 = "otherwise" (28.6% some college), *Bachelor Degree* as 1 = "bachelors" and 0 = otherwise (17.8% bachelor), and *Graduate Degree* as 1 = "masters" or "PhD" and 0 = otherwise (13.7% graduate). While not part of the GfK-supplied demographic information, *Religiosity*, or "how much guidance does religion provide in your everyday life?", has been shown to affect U.S. public opinion on some human genome–editing applications (*40*). This variable was measured on an 11-point scale from 0 = "No guidance at all" to 10 = "A great deal of guidance" (M = 6.32, SD = 3.68, and weighted mean = 6.41).

As gene drive insect applications in agriculture are inherently focused on commercial food products, consumer characteristics are a key focus for public opinion research. In the explanation of potential drive applications, both a major soft berry pest (spotted wing *Drosophila*) and a major citrus pest (Asian citrus psyllid) were discussed. Therefore, consumers of berries and citrus may have viewed a gene drive insect as more personally beneficial to reduce damage to consumed products, or, perhaps, more threatening since the gene drive insect may interact with their food. We ask respondents whether their household purchased several fruit and juice products in the last 6 months, including fresh blueberries and orange juice. *Household buys blueberries* and *Household buys O.J.* are each coded 1 = "yes" and 0 = "no" (blueberries, 56.8% yes; O.J., 70.4% yes). *Primary Shopper* is coded 1 = yes and 0 = no (79.1% yes). Last, specialty consumers who purchase USDA-Organic–labeled, non-GMO–labeled, or locally grown products may have distinct values about food production, which affect their support for the use of gene drive insects in agriculture. Buyers of certified organic and non-GMO–labeled foods may be particularly sensitive to the use of any genetic engineering in the food supply (*17*). Respondents were asked "the extent they agree or disagree with the following statements about food shopping", including questions "I regularly purchase food labeled 'USDA-Organic'," "I regularly search for food labeled 'non-GMO' or 'GMO-free'," and "I regularly purchase locally grown food." Responses were reported on a five-point scale, from 1 = "Strongly Disagree" to 5 = "Strongly Agree." Each variable *Buys USDA-Organic foods*, *Buys non-GMO/GMO-free labeled foods*, and *Buys "local" foods* is coded 1 for "buys" if responding "Strongly Agree" or "Agree" and 0 otherwise (Organic, 22.7% buys; non-GMO, 21.7% searches; and local, 43.4% buys).

Statistical analysis

The survey responses analyzed by design as dependent variables in this study were as follows: support for agricultural gene drive applications (five-point Likert scale responses), support for gene drive inclusion in organic certification (five-point Likert scale), FAQ selection, and perceived relative importance of gene drive uncertainties (BWS indicators for most/least important). For concise interpretation, in Figs. 1 to 3 and Table 1, we aggregated in the main text the five-point Likert scales for support (with a "don't know" option), into a three-point "agree" [Strongly Agree + Agree], "neutral" [Neither + Don't Know], and "disagree" [Strongly Disagree + Disagree] scale [following condensing in (*40*)]. Our statistical analysis used Wald tests of differences in subgroup means of these responses and generalized linear regression models to estimate the marginal effects of different gene drive factors and respondent characteristics on these outcomes.

Ordered logit regression models were used to obtain statistical estimates for the ordinal, Likert-scale responses in Fig. 1 and Table 1. Given concerns about violations of the proportional odds assumption in ordered logit models, which are common in empirical work (*55*, *56*), partial proportional odds (PPO)–ordered logit models were used where appropriate with the *gologit2* command in Stata. In a PPO-ordered logit model, some β-coefficients may be constrained to be the same across dependent variable levels (as in a standard ordered logit model), while others may be allowed to vary if the proportional odds assumption is rejected at the 0.05 confidence level. In an example from (*55*), with j-dependent variable levels, βs for X_1 and X_2 may be constrained, while βs for X_3 vary

$$P(Y_i > j) = \frac{\exp(\alpha_j + X_{1i}\beta_1 + X_{2i}\beta_2 + X_{3i}\beta_{3j})}{1 + (\exp(\alpha_j + X_{1i}\beta_1 + X_{2i}\beta_2 + X_{3i}\beta_{3j}))},$$
$$j = 1, 2, \ldots, M - 1$$

Ordinary least squares (OLS) models were used as robustness checks against the ordered logit models (table S8). OLS was also used to estimate marginal effects on the count of selected FAQs (Table 1), with a Tobit model used in robustness checks (table S5).

All estimation was done in Stata version 14. SEs for all regression coefficients (in Table 1 and used to estimate statistical precision in Figs. 1 to 3) accounted for GfK-provided survey weights and within-respondent clustering. Marginal effects for ordered logit regressions were obtained with Stata's *margins* command, which estimates SEs using the delta method.

The exposure of every respondent to the complete factorial of the three binary gene drive factors in eliciting general support ensured that these factors are not correlated with observed or unobserved respondent characteristics, reducing statistical bias and imprecision in estimates of these effects. The experimental design of the BWS exercise, and random assignment of respondents to the three blocks in this exercise, ensured that the subsamples presented with each block are statistically indistinguishable. The random ordering of different drive types and the BWS sets protected against bias from order effects in these measurements. Weighted least-squares regression was used to statistically rank uncertainty items (*29*). For this estimation procedure, the dependent variable was the total (sample level) log frequency of the 10* (10 − 1) = 90 possible most-least important pairs (i.e., "best-worst" pairs). The log selection frequency for each pair is a linear function of the difference in utility (*29*). Independent variables were 10 − 1 = 9 items (cost-effectiveness used as reference), which are coded 1 for the pair's "most important" item and "−1" for the pair's least important item. The regression weights were the frequencies each pair appears in the balanced incomplete block design.

In examining the impact of viewing the FAQs on gene drive attitudes, we approximated this impact with an IV linear two-stage regression model via the *cmp* command in Stata 14. First stages were defined as linear probability models (OLS) for binary variables of viewing each (of seven) FAQs. All demographic and consumption covariates were included in first-stage models, along with IVs of the random "forced" viewing of each unselected FAQ with (independent) one-third probability. The second stage OLS-dependent variable is the three-level Likert for support, neutrality, or opposition to gene drive applications and included as regressors all demographic and consumption variables in Table 1 and seven binary variables for ultimately seeing (voluntary or otherwise) each FAQ. A joint Wald test of significance of all seven second-stage covariates for seeing the FAQs was insignificant ($P = 0.37$). These results are presented in table S10. Specifying the second stage as a multinomial probit model produced nearly identical results (joint test of FAQ covariates at $P = 0.32$).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/9/eaau8462/DC1

Note S1. Full informational text and illustration materials
Note S2. Full FAQ wording
Note S3. Support or opposition to organic certification with gene drive insects
Note S4. Ranking gene drive uncertainties to resolve before use decisions—Question construction
Note S5. Focus group guide
Table S1. Sample details.
Table S2. Raw data from general Likert responses.
Table S3. Regression analysis of general gene drive Likert responses: Three-level Likert aggregation, PPO-ordered logit model.
Table S4. Regression analysis of general gene drive Likert responses: Five-level Likert aggregation, PPO-ordered logit model.
Table S5. Demographic and consumption correlates with number of FAQs selected.
Table S6. Tests for combining suppression and replacement in subgroup analysis.
Table S7. Ranking most important gene drive questions.
Table S8. Trust in institutions to conduct research on gene drive agricultural pests.
Table S9. OLS robustness check for three- and five-level gene drive attitude Likert questions.
Table S10. Estimates with and without endogenous FAQ selection, verify if specific FAQ info influenced gene drive attitudes.
Fig. S1. BWS question example.

REFERENCES AND NOTES

1. S. P. Sinkins, F. Gould, Gene drive systems for insect disease vectors. *Nat. Rev. Genet.* **7**, 427–435 (2006).
2. E. Pennisi, Gene drive turns mosquitoes into malaria fighters. *Science* **350**, 1014 (2015).
3. B. L. Webber, S. Raghu, O. R. Edwards, Opinion: Is CRISPR-based gene drive a biocontrol silver bullet or global conservation threat? *Proc. Natl. Acad. Sci. U.S.A.* **112**, 10565–10567 (2015).
4. K. M. Esvelt, N. J. Gemmell, Conservation demands safe gene drive. *PLOS Biol.* **15**, e2003850 (2017).
5. K. M. Esvelt, A. L. Smidler, F. Catteruccia, G. M. Church, Concerning RNA-guided gene drives for the alteration of wild populations. *eLife* **3**, e03401 (2014).
6. NASEM, *Gene Drives on the Horizon: Advancing Science, Navigating Uncertainty, and Aligning Research with Public Values* (The National Academies Press, 2016).
7. A. Burt, Site-specific selfish genes as tools for the control and genetic engineering of natural populations. *Proc. Biol. Sci.* **270**, 921–928 (2003).
8. C. Noble, B. Adlam, G. M. Church, K. M. Esvelt, M. A. Nowak, Current CRISPR gene drive systems are likely to be highly invasive in wild populations. *eLife* **7**, e33423 (2018).
9. J. V. da Graça, G. W. Douhan, S. E. Halbert, M. L. Keremane, R. F. Lee, G. Vidalakis, H. Zhao, Huanglongbing: An overview of a complex pathosystem ravaging the world's citrus. *J. Integr. Plant Biol.* **58**, 373–387 (2016).
10. M. K. Asplen, G. Anfora, A. Biondi, D. S. Choi, D. Chu, K. M. Daane, P. Gibert, A. P. Gutierrez, K. A. Hoelmer, W. D. Hutchison, R. Isaacs, Z. L. Jiang, Z. Kárpáti, M. T. Kimura, M. Pascual, C. R. Philips, C. Plantamp, L. Ponti, G. Vétek, H. Vogt, V. M. Walton, Y. Yu, L. Zappalà, N. Desneux, Invasion biology of spotted wing Drosophila (*Drosophila suzukii*): A global perspective and future priorities. *J Pest Sci.* **88**, 469–494 (2015).
11. F. Li, M. J. Scott, CRISPR/Cas9-mediated mutagenesis of the *white* and *Sex lethal* loci in the invasive pest, *Drosophila suzukii*. *Biochem. Biophys. Res. Commun.* **469**, 911–916 (2016).

12. A. Buchman, J. M. Marshall, D. Ostrovski, T. Yang, O. S. Akbari, Synthetically engineered *Medea* gene drive system in the worldwide crop pest *Drosophila suzukii*. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 4725–4730 (2018).
13. C. Emerson, S. James, K. Littler, F. Randazzo, Principles for gene drive research. *Science* **358**, 1135–1136 (2017).
14. P. D. Mitchell, Z. Brown, N. McRoberts, Economic issues to consider for gene drives. *J. Responsible Innov.* **5**, S180–S202 (2018).
15. J. Delborne, J. Kuzma, F. Gould, E. Frow, C. Leitschuh, J. Sudweeks, Mapping research and governance needs for gene drives. *J. Responsible Innov.* **5**, S4–S12 (2018).
16. D. Brossard, P. Belluck, F. Gould, C. D. Wirz, Promises and perils of gene drives: Navigating the communication of complex, post-normal science. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 7692–7697 (2019).
17. M. Costa-Font, J. M. Gil, W. B. Traill, Consumer acceptance, valuation of and attitudes towards genetically modified food: Review and implications for food policy. *Food Policy* **33**, 99–111 (2008).
18. J. Kolodinsky, J. L. Lusk, Mandatory labels can improve attitudes toward genetically engineered food. *Sci. Adv.* **4**, eaaq1413 (2018).
19. S. Dhole, M. R. Vella, A. L. Lloyd, F. Gould, Invasion and migration of spatially self-limiting gene drives: A comparative analysis. *Evol. Appl.* **11**, 794–808 (2018).
20. K. M. Winneg, J. E. Stryker, D. Romer, K. H. Jamieson, Differences between Florida and the rest of the United States in response to local transmission of the Zika Virus: Implications for future communication campaigns. *Risk Anal.* **38**, 2546–2560 (2018).
21. C. Funk, M. Hefferon, "Most Americans Accept Genetic Engineering of Animals That Benefits Human Health, but Many Oppose Other Uses | Pew Research Center" (2018).
22. P. A. Kohl, D. Brossard, D. A. Scheufele, M. A. Xenos, Public views about editing genes in wildlife for conservation. *Conserv. Biol.* **2019**, 1–10 (2019).
23. K. Servick, Update: Florida voters split on releasing GM mosquitoes. *Science* **2016**, aal0350 (2016).
24. C. P. Neuhaus, A. L. Caplan, Ethical lessons from a tale of two genetically modified insects. *Nat. Biotechnol.* **35**, 713–716 (2017).
25. B. Powell, L. Schnabel, L. Apgar, Denial of service to same-sex and interracial couples: Evidence from a national survey experiment. *Sci. Adv.* **3**, eaao5834 (2017).
26. R. J. Johnston, K. J. Boyle, W. Adamowicz, J. Bennett, R. Brouwer, T. A. Cameron, W. M. Hanemann, N. Hanley, M. Ryan, R. Scarpa, R. Tourangeau, C. A. Vossler, Contemporary guidance for stated preference studies. *J. Assoc. Environ. Resource Econ.* **4**, 319–405 (2017).
27. J. M. Marshall, B. A. Hay, Confinement of gene drive systems to local populations: A comparative analysis. *J. Theor. Biol.* **294**, 153–171 (2012).
28. A. Finn, J. J. Louviere, Determining the appropriate response to evidence of public concern: The case of food safety. *J. Public Policy Mark.* **11**, 12–25 (1992).
29. T. N. Flynn, J. J. Louviere, T. J. Peters, J. Coast, Best–worst scaling: What it can do for health care research and how to do it. *J. Health Econ.* **26**, 171–189 (2007).
30. J. E. DiCarlo, A. Chavez, S. L. Dietz, K. M. Esvelt, G. M. Church, Safeguarding CRISPR-Cas9 gene drives in yeast. *Nat. Biotechnol.* **33**, 1250–1255 (2015).
31. S. E. Scott, Y. Inbar, P. Rozin, Evidence for absolute moral opposition to genetically modified food in the United States. *Perspect. Psychol. Sci.* **11**, 315–324 (2016).
32. H. Willer, J. Lernoud, "The World of Organic Agriculture. Statistics and Emerging Trends 2018" (Bonn, Germany, 2018).
33. R. G. Reeves, M. Phillipson, Mass releases of genetically modified insects in area-wide pest control programs and their impact on organic farmers. *Sustainability.* **9**, 59 (2017).
34. DARPA, Building the Safe Genes Toolkit; www.darpa.mil/news-events/2017-07-19.
35. DARPA, Insect Allies; www.darpa.mil/program/insect-allies.
36. R. G. Reeves, S. Voeneky, D. Caetano-Anollés, F. Beck, C. Boëte, Agricultural research, or a new bioweapon system? *Science* **362**, 35–37 (2018).
37. L. Jin, A. S. Walker, G. Fu, T. Harvey-Samuel, T. Dafa'alla, A. Miles, T. Marubbi, D. Granville, N. Humphrey-Jones, S. O'Connell, N. I. Morrison, L. Alphey, Engineered female-specific lethality for control of pest lepidoptera. *ACS Synth. Biol.* **2**, 160–166 (2013).
38. Intrexon, Oxitec supports the National Academies of Sciences, Engineering, and Medicine recommendations on gene-drive and highlights why Oxitec's self-limiting approach is the opposite of gene-drive method (2016); https://investors.dna.com/Oxitec-supports-the-National-Academies-of-Sciences-Engineering-and-Medicine-recommendations-on-gene-drive-and-highlights-why-Oxitec-s-self-limiting-approach-is-the-opposite-of-gene-drive-method.
39. C. J. Guerrini, M. A. Curnutte, J. S. Sherkow, C. T. Scott, The rise of the ethical license. *Nat. Biotechnol.* **35**, 22–24 (2017).
40. D. A. Scheufele, M. A. Xenos, E. L. Howell, K. M. Rose, D. Brossard, B. W. Hardy, U.S. attitudes on human genome editing. *Science* **357**, 553–554 (2017).
41. Annenberg Public Policy Center, Annenberg science knowledge survey: Zika and GMOs March 16–20, 2016 (week 6) appendix (2016); https://cdn.annenbergpublicpolicycenter.org/wp-content/uploads/2018/03/Zika-Week6_Appendix.pdf.
42. M. Siegrist, Predicting the future: Review of public perception studies of nanotechnology. *Hum. Ecol. Risk Assess. An Int. J.* **16**, 837–846 (2010).
43. P. Slovic, The construction of preference. *Am. Psychol.* **50**, 364–371 (1995).
44. L. Alphey, M. Benedict, R. Bellini, G. G. Clark, D. A. Dame, M. W. Service, S. L. Dobson, Sterile-insect methods for control of mosquito-borne diseases: An analysis. *Vector Borne Zoonotic Dis.* **10**, 295–311 (2010).
45. S. Zabalou, M. Riegler, M. Theodorakopoulou, C. Stauffer, C. Savakis, K. Bourtzis, *Wolbachia*-induced cytoplasmic incompatibility as a means for insect pest population control. *Proc. Natl. Acad. Sci. U.S.A.* **101**, 15042–15045 (2004).
46. E. F. Knipling, Possibilities of insect control or eradication through the use of sexually sterile Males. *J. Econ. Entomol.* **48**, 459–462 (1955).
47. N. P. Kandul, J. Liu, H. M. Sanchez C., S. L. Wu, J. M. Marshall, O. S. Akbari, Transforming insect population control with precision guided sterile males with demonstration in flies. *Nat. Commun.* **10**, 84 (2019).
48. World Mosquito Program, First mosquitoes with *Wolbachia* released in the Pacific | World Mosquito Program (2018); www.eliminatedengue.com/progress/index/view/news/1063.
49. J. Cattel, K. Nikolouli, T. Andrieux, J. Martinez, F. Jiggins, S. Charlat, F. Vavre, D. Lejon, P. Gibert, L. Mouton, Back and forth *Wolbachia* transfers reveal efficient strains to control spotted wing drosophila populations. *J. Appl. Ecol.* **55**, 2408–2418 (2018).
50. J. R. McFadden, W. E. Huffman, Willingness-to-pay for natural, organic, and conventional foods: The effects of information and meaningful labels. *Food Policy* **68**, 214–232 (2017).
51. S. K. Barnhill-Dilling, J. A. Delborne, The genetically engineered American chestnut tree as opportunity for reciprocal restoration in Haudenosaunee communities. *Biol. Conserv.* **232**, 1–7 (2019).
52. L. J. Frewer, S. Miles, R. Marsh, The media and genetically modified foods: Evidence in support of social amplification of risk. *Risk Anal.* **22**, 701–711 (2002).
53. E. F. Fern, *Advanced Focus Group Research* (Sage, 2001).
54. J. Herriges, C. Kling, C.-C. Liu, J. Tobias, What are the consequences of consequentiality? *J. Environ. Econ. Manage.* **59**, 67–81 (2010).
55. R. Williams, Understanding and interpreting generalized ordered logit models. *J. Math. Sociol.* **40**, 7–20 (2016).
56. J. S. Long, J. Freese, *Regression Models for Categorical Dependent Variables Using Stata* (Stata press, College Station, TX, ed. 3, 2014).

Acknowledgments: We thank F. Gould, R. M. Rejesus, and faculty and student affiliates of the NC State Genetic Engineering and Society Center for helpful comments, which improved survey design, statistical analysis, and writing of this manuscript. **Funding:** This research was funded by the U.S. National Institute of Food and Agriculture grant number 2017-67030-26778 and HATCH project NC0250 and by the National Science Foundation award numbers 1068676 and 1533990. **Author contributions:** Z.S.B. and P.D.M. conceived the study with assistance from J.A.D. and M.S.J. M.S.J. and Z.S.B. designed the survey and focus group discussions with assistance from all coauthors. M.S.J. and J.E. conducted focus group discussions with assistance from Z.S.B. and J.A.D. M.S.J. analyzed the data, with assistance from Z.S.B. and J.E. M.S.J. and Z.S.B. led the drafting of the manuscript, with assistance from all coauthors. All authors read and approved the final manuscript. **Competing interests:** The authors declare that they have no competing interests. **Human subjects approval:** The human participant components of this research were classified as Exempt by the North Carolina State University Institutional Review Board on 6 February 2017 under protocol no. 9344. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 20 July 2018
Accepted 9 August 2019
Published 11 September 2019
10.1126/sciadv.aau8462

Citation: M. S. Jones, J. A. Delborne, J. Elsensohn, P. D. Mitchell, Z. S. Brown, Does the U.S. public support using gene drives in agriculture? And what do they want to know? *Sci. Adv.* **5**, eaau8462 (2019).

Science Advances

Does the U.S. public support using gene drives in agriculture? And what do they want to know?

Michael S. Jones, Jason A. Delborne, Johanna Elsensohn, Paul D. Mitchell and Zachary S. Brown

Sci Adv **5** (9), eaau8462.
DOI: 10.1126/sciadv.aau8462