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RESEARCH ARTICLE

Anticipating risks, governance needs, and public perceptions of de-extinction

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ABSTRACT
Advances in biotechnology may allow for de-extinction. Potential impacts of de-extinct species remain uncertain; they may improve ecosystem function, or hinder conservation efforts and damage socio-ecological systems. To better anticipate de-extinction's outcomes, ethical dilemmas, and governance needs, we surveyed experts from multiple disciplinary backgrounds. We applied a mixed-method approach to our analysis, integrating quantitative responses of perceived outcomes with qualitative responses, to clarify and provide context. Overall, respondents indicated de-extinction was more likely to induce hazards, not benefits. Reasons for this viewpoint included a 'moral hazard' argument, suggesting conservation policies could be undermined if society perceives that species need less protection because they can be revived later. Pessimistic views of de-extinction were linked to concerns about unclear development paths. Experts believed the public might be skeptical about de-extinction. Our results suggest future de-extinction efforts may benefit from collaborative efforts to clarify hazards and explore salient concerns among the engaged public.

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De-extinction; governance; environmental risk; moral risk; technological pessimism

Introduction

Advances in biotechnology may allow for the de-extinction of species. De-extinction is the re-creation of extinct species using methods from synthetic biology, cloning, genetic engineering, reproduction technologies, and stem cell research. Numerous species are currently being considered as candidates for de-extinction, notably the passenger pigeon and woolly mammoth. De-extinction research on passenger pigeons includes genome sequencing (Hung et al. 2014), with plans to integrate DNA from preserved passenger pigeons into the genome of band-tailed pigeons (Novak 2013). Similarly, research on the woolly mammoth includes genome sequencing (Palkopoulou et al. 2015) with plans to gradually add mammoth genes into Asian elephant embryos, creating hybrids with progressively more mammoth traits (Devlin 2017).

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Arguments in-favor of de-extinction suggest that de-extinct species will improve ecosystem function, satisfy a moral obligation to revive extinct species, and re-invigorate efforts for conserve biodiversity. The ecological benefits of reintroducing de-extinct species may be the most significant potential outcome of de-extinction (Shapiro 2015; Iacona et al. 2017; McCauley et al. 2017). Potential ecological benefits of de-extinction are purportedly similar to restoring locally extirpated species (Jørgensen 2013; Seddon, Moehrenschlager, and Ewen 2014). For example, reintroduction of musk oxen, hares, and marmots to Pleistocene Park in Siberia altered plant distributions, facilitating grassland restoration, and ultimately increasing biodiversity (Zimov 2005). Some researchers believe returning the woolly mammoth to the Siberian tundra might yield similar results (Shapiro 2015). As an act of restorative justice, reviving species driven to extinction by humans, such as the passenger pigeon, yields a moral good (Cohen 2014). This restorative act aligns with the goals of conservation biology, namely restoring ecological components and processes previously removed or damaged by human activities (Thorpe and Stanley 2011). Additionally, restoring animals like woolly mammoths may inspire great awe (Sherkow and Greely 2013) and lead to additional support for conservation.

In contrast, arguments against de-extinction suggest that the process may be detrimental to conservation efforts and ecological systems, and rife with ethical dilemmas. Re-creation of extinct species may weaken conservation policies by providing a riskier alternative solution to preventing extinction (Pimm 2013). This moral hazard, or alternative solution, enables riskier behavior (Lin 2013), which is compounded by ecological change. Returning a re-created animal to its former ecosystem could be detrimental to the current, often different, ecosystem or to the de-extinct animal. For example, forests have been fragmented and degraded, and farms and urban systems have expanded in the historic passenger pigeon range (Greenberg 2014). If re-introduced, the bird may exhibit tendencies similar to invasive species (Sherkow and Greely 2013). Alternatively, a passenger pigeon may be unable to adapt to contemporary ecosystems. Would the creators of a de-extinct animal then be obligated to care for the de-extinct population in perpetuity?

Ethical questions such as these extend beyond those considered during wildlife reintroductions (McCoy and Berry 2008) and include ownership responsibilities for de-extinct animals (Carlin, Wurman, and Zakim 2013). In most contexts, wildlife are considered common property until captured in some way (Blumm and Ritchie 2005), but de-extinction challenges these norms. Products of de-extinction may be eligible for patents based on their novelty or the technical processes used to create them (Carlin, Wurman, and Zakim 2013; Swedlow 2015). The potential commercial value could be derived from exclusive rights to exhibit, or by creating pet markets. Institutions that exhibit animals such as zoos typically require permitting under the Convention on International Trade in Endangered Species of Wild Fauna and Flora, and, in the United States, most zoos are regulated by the Animal Welfare Act (Grech 2004). There is considerable uncertainty regarding whether de-extinct animals should be considered endangered, native, exotic, or native and whether they would receive the corresponding protection or management (Camacho 2015; Okuno 2017). Further, attempts to reconstitute genomes and create hybrids, may be viewed as hubristic or similar to playing god (Sandler 2014). Playing god connotes individuals transgressing fixed limits on human behavior often linked to creation, and the pejorative label has been levied at biotechnology since its inception (Dabrock 2009). Although humans have a cultural duty to maximize positive impacts and minimize negative impacts on the world, accusations of playing god may have moral weight when they refer to technologies used to alter the biology of living organisms with unacceptable or unpredictable consequences or violate duties towards moral agents (Dabrock 2009). Animal rights and welfare concerns further complicate de-extinction. Animals such as the woolly mammoth are presumably social animals (Shapiro 2015), and rearing them in isolation may be cruel.

Other potential de-extinction efforts (e.g. gastric-breeding frog or the Xerces butterfly) may require fewer physical accommodations (Seddon, Moehrenschlager, and Ewen 2014), but would still require navigating issues of public support and outdated biotechnology policies (Kuzma and Tanji 2010; Kuzma 2016). In the United States, federal regulation of biotechnology has not adapted to advancing biotechnological methods and novel products; for example, a de-extinct animal may be regulated following protocol originally intended for animal drugs (FDA 2009). Guiding principles have been suggested for selecting de-extinction candidates, by considering efficiency and feasibility (IUCN SSC 2016) and incorporating the 2013 IUCN Guidelines for Reintroduction and Other Conservation Translocations (Seddon, Moehrenschlager, and Ewen 2014). While these guidelines address many of the ecological risks involved in wildlife reintroduction efforts, such as ecological and socioeconomic impacts, disease risk, and feasibility, they assume opposition based on ethical principles will not matter, and that conservation policy will not inhibit de-extinction efforts. Further, these guidelines do not fully address issues associated with unique biotechnologies, higher uncertainty related to environmental risks, and more conflict between stakeholder groups compared to decision-making groups in traditional wildlife reintroduction efforts.

A more systematic assessment of de-extinction seems necessary to anticipate risk and improve governance. In situations of high complexity and uncertainty, like de-extinction, it is especially important to anticipate risks so that appropriate governance systems are in place before technological deployment (Karinen and Guston 2009). Anticipatory governance suggests building capacities in foresight, engagement, and integration between experts (natural scientists, social scientists, and humanities scholars) and organizations (government agencies, technology developers, publics) may lead to better decisions and increased public good (Barben et al. 2007). In the absence of data on risks and benefits, expert elicitation provides a method for engaging the mental models of experts (Morgan, Henrion, and Small 1990) in order to begin the process of identifying potential risks and responding to them upstream in innovation and governance systems (Stilgoe, Owen, and Macnaghten 2013; Barben et al. 2007).

As a first step in anticipatory governance, this paper presents the first analysis of the potential environmental impacts of de-extinction, ethical dilemmas, and governance needs by eliciting experts' opinions from multiple disciplines. We surveyed experts in the natural sciences, social sciences, and the humanities, who have been involved in technologies and policies associated with genetic engineering and synthetic biology. Experts on biotechnology issues are well suited to assess potential de-extinction impacts, dilemmas, and governance needs because of their experiences with biotechnology development and governance. The science of biotechnology continues to develop, but at least in the United States, biotechnology policy has not explicitly addressed new genetic engineering technologies like gene editing, gene drives, or de-extinction (Kuzma 2016). International frameworks may cover genetically engineered animals, such as the Convention on

Biological Diversity and the Cartagena Protocol on Biosafety, but these have not been ratified by all nations with active de-extinction research programs (Vàzquez-Salat et al. 2012; Kuzma 2016). Public opposition to genetically engineered foods is highly political, varies internationally, and is potentially becoming more controversial over time (Frewer et al. 2013). Controversies also brew within the biotechnology field as some products and companies fail to live up to their own hype (Borup et al. 2006). Biotechnology experts working within these contexts have unique experiences and can provide valuable assessments for the nascent field of de-extinction. To better anticipate the environmental impacts, ethical dilemmas, and governance needs for de-extinction, we applied a mixed-method approach to analyze quantitative responses regarding perceived risks and benefits with qualitative responses used to clarify and provide context. We compare participants' perceptions of potential risks and benefits, highlight salient environmental and societal concerns, identify research and risk assessment needs for managing potential risks, and provide recommendations for de-extinction governance. This is the first study to our knowledge formally eliciting expert opinions about the governance of de-extinction. By conducting this study before viable, self-reproducing de-extinct species are developed, we hope to provide guidance to innovation and governance, promote environmental stewardship, and minimize unintended consequences.

Methods

Expert elicitation

Expert elicitation is commonly used in emerging fields where data and information is limited, and uncertainty is high (Fiorese et al. 2013). We used expert elicitation because this approach is ideal for studies seeking to identify a range of opinions, evaluate scientific evidence or risks, and examine governance options (Morgan, Henrion, and Small 1990). We conducted purposive sampling to recruit experts from multiple disciplinary fields. We compiled an initial list of potential participants by reviewing speakers who attended the following three conferences: Biobricks Foundation SB6.0: The Sixth International Meeting on Synthetic Biology, SynBio-Beta Conference for Synthetic Biology Startup Companies, Georgia Tech Frontier in Systems and Synthetic Biology. Subsequently, additional potential participants were drawn from the editorial board of the peer-reviewed journal, *Bioengineering and Biotechnology*. Invitations were sent to 234 experts, and forty-eight individuals agreed to participate. These participants are actively involved in biotechnology innovation or study the socio-political, ethical, economic, cultural, policy, or regulatory contexts of biotechnology (Kuzma 2016; Frewer et al. 2013; Vàzquez-Salat et al. 2012; Borup et al. 2006) and are thus well suited for anticipating the future impacts, dilemmas, and governance needs of de-extinction.

An online questionnaire was designed to elicit the opinions of experts regarding de-extinction risk and governance, and 35 experts completed the questionnaire. In studies using purposive sampling, large sample sizes and representativeness are not the primary goals of sampling (Teddlie and Yu 2007). Instead, sampling units are selected to address research objectives (Teddlie and Yu 2007), and we aimed to recruit a sample that included individuals from a broad range of backgrounds related to biotechnology innovation. These experts were able to assess environmental impacts, ethical dilemmas, and governance needs for de-extinction. Our sample size exceeded the typical threshold for purposive sampling studies (Teddlie and Yu 2007), and met the theoretical expectations for adequate sample size in qualitative research. The latter threshold is based on theoretical saturation, the point where additional interviews cease to generate new concepts (Guba and Lincoln 1994; Lee Jenni et al. 2015). Most ($n = 29$) self-identified their disciplines, with 16 social science, humanities, and law experts (hereafter identified as social scientists) and 13 natural science experts (hereafter natural scientists). Many experts identified with multiple disciplines. There were 10 experts with expertise in policy or governance, 7 with expertise in science, technology, and society (STS), 6 with another social science or humanities related expertise, 9 with expertise in chemical, molecular, or biological engineering, and 6 with expertise in ecology or environmental science. Because de-extinction is novel and developing, participants were provided a short description (available in Supplemental Materials) prior to the beginning of the study. This online questionnaire was self-administered using Qualtrics. The North Carolina State University Internal Review Board (IRB # 3574) reviewed this study.

Questionnaire development

We developed a questionnaire that allowed respondents to prioritize and then expand on their perceptions of issues related to de-extinction-risks, benefits, future areas of research, and governance needs. A Societal and Risk Evaluation Scheme (SRES), consisting of multiple 10-point Likert scale questions, measured perceived certainty of potential hazards, benefits, and societal outcomes related to de-extinction (Cummings and Kuzma 2017). This scheme was developed to assess biosecurity risks by evaluating potential risks, epidemic potential, ability to contain hazards, and overall consequences (Latxague et al. 2007; Suffert, Latxague, and Sache 2009). Given the novelty and uncertainty regarding de-extinction, we adapted the SRES to survey environmental and human health risk and added assessments of potential public concern and potential benefit. We used 10-point scale questions to assess potential benefits and hazards for human health and the environment. A similar question was used to ask participants how much public concern de-extinction might generate (Cummings and Kuzma 2017). Using a previous review of biotechnology oversight (Kuzma and Tanji 2010), we listed 16 areas of potential risk reduction research, and participants ranked them from highest to lowest priority. Participants were then asked to expand on their perceptions of de-extinction risks, potential areas for research, and public perceptions with open-ended questions. We also asked the participants which agency, group, or specific organization should have the most central authority for governing de-extinction (Questionnaire available in supplemental materials).

Data analysis

We applied a mixed-method approach to data analysis, integrating quantitative responses regarding perceived likelihood of risks and benefits with qualitative responses to provide context. Risk reduction priority mean scores were grouped using a Tukey-HSD test. We compared quantitative responses between social science and natural science experts, with a Student's t test, to identify potential differences in benefit and risk perceptions between these groups. Given the sample size ($n = 35$) and exploratory nature of this study we report differences significant at an alpha level of .10. We reported effect sizes, measured with Cohen's *d*, as weak (<0.5) moderate (> 0.5) and or strong (> 0.8) (Cohen 1988). To identify salient issues related to risk, research, and governance, we performed a qualitative thematic content analysis of responses to open-ended questions (Shellabarger, Peterson, and Sills 2012). Participants were asked about potential impacts to human health, the environment, and society, research needs for assessing potential hazards, what existing research areas may inform assessment, and what novel research areas may generate information to assess hazards. Major themes were identified and synthesized to clarify and provide meaning to quantitative results. Categorization criteria for qualitative results were developed to maintain consistency throughout analysis (Questions and criteria in supplemental materials). We report the frequency of major themes and direct quotes from participants. When quoted, participants are identified with a unique number and are identified as social scientists (ss), natural scientists (ns), or unidentified (un).

Results

Risks versus benefits

Participants perceived de-extinction as more likely to harm, not benefit, human health and the environment. They strongly perceived de-extinction as more hazardous than beneficial to the environment ($t = 4.70$, $p < 0.001$, Cohen's $d = 1.41$) (Figure 1). The experts suggested numerous potentially negative environmental impacts: de-extinct animals may exhibit characteristics similar to invasive species (e.g. ecological disruptions, outcompeting native wildlife species), broadly impact ecosystems, and increase wildlife disease risks (Table 1). One participant raised these issues when describing the potential for reviving a passenger pigeon, '*How* [passenger pigeons] *would impact modern agricultural settings which have replaced much of the prairie which formed the 'natural' habitat of these is a huge unknown. Where are the predators to keep the flocks under control? What disease might they carry to other occupants of their habitats?*' (ss4). Participants also strongly perceived de-extinction to be more hazardous rather than beneficial, to human health ($t = 3.378$, $p = 0.002$, Cohen's $d = 0.80$) (Figure 1). Almost half of the participants indicated

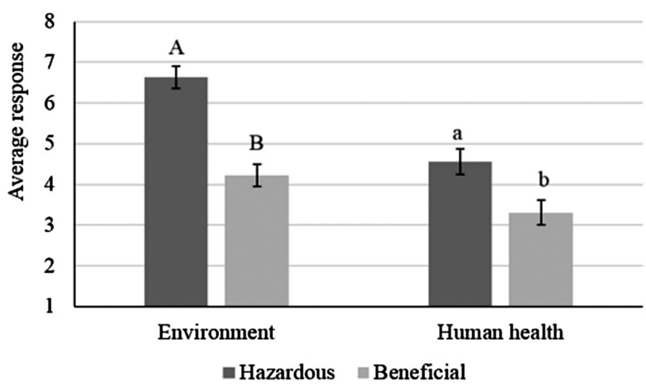

Figure 1. Average responses (Likert scale responses 1–10) and standard error bars of participant responses to potential environmental and human health hazards and benefits from de-extinction. Significant differences indicated by different letters.

Table 1. Participant response frequency and percentage regarding potential de-extinction impacts to the environment, human health, and society.

	n	%
Potential impacts to the environment		
Exhibit invasive characteristics	12	39
Ecosystem interactions (neutral)	9	29
Ecosystem impacts (negative)	6	19
Disease	6	19
Revived species ecosystem compatibility	6	19
Revived species health and rearing	3	10
Socio-ecological impacts	2	6
Feasibility questions	2	6
Little to no impact	2	6
Change conservation	1	3
Harm surrogates	1	3
Dangerous Animals	1	3
Potential impacts to human health		
Disease	15	52
None or Limited	8	28
Socio-ecological impacts	6	21
Case specific	4	14
Lead to human genome engineering	2	7
Physical harm	1	3
Don't know	1	3
Potential impacts to society		
Threatens conservation efforts	13	43
Hubris and Techno-optimism	6	20
Ethics of reviving	6	20
Socio-ecological impacts	5	17
Animal rights	4	13
Public engagement	4	13
Regulation	3	10
Questionable benefits	2	7
Ethics of human cloning, gene editing	2	7
Encourage conservation	2	7
Public concern	2	7
Encourage science	2	7
Ethical obligation	2	7
Conserving de-extinct animal	2	7
Irreversible	1	3
Biodiversity issues	1	3
No moral obligation	1	3

that disease emerging from de-extinct animals may impact human health (Table 1), with concern typically stemming from two causes, '*Rebooting of encoded viruses that are harmful to humans*' (ns29) or '*Difficult to assess the potential problems of a reintroduced species acting as a vector for a human disease*' (ns24). Participant responses indicating low potential benefits may be partially explained by those who were uncertain about what the actual benefits might be. As one participant indicated, '*A key issue here concerns the benefits of these technologies. Other than being interesting, it seems that much of what is driving the effort to de-extinct is commercial interest. The 'whys' and 'what for' have not been clearly addressed*' (ss3). At the time of this survey, de-extinction was being advocated by Revive & Restore, a non-governmental organization (NGO) coordinating de-extinction information and research, and a small group of researchers. These advocates lacked support from governments or other NGOs, likely adding to concerns about motives for de-extinction research.

Although all expert views trended toward skepticism of benefits, social scientists held less favorable views than natural scientists. Compared to natural scientists, social scientists perceived de-extinction to potentially be more environmentally hazardous ($t = 1.397$, $p = .087$, Cohen's $d = 0.538$) and less beneficial to the environment ($t = 1.384$, $p = .088$, Cohen's $d = 0.538$). Social scientists also perceived de-extinction to be less beneficial to human health ($t = 1.60$, $p = .06$, Cohen's $d = 0.628$). Perception of potential hazards to human health was similar between these groups.

Some participants were concerned that de-extinct animals might have poor health or be unable to survive in contemporary ecosystems (Table 1). One respondent asked, '*How will the species compete with other species for food, water, etc. Why did t. species become extinct in the first place?*' (ss14). Almost a third of the participants indicated that de-extinction may alter ecosystem interactions but did not explicitly describe these impacts as positive or negative (Table 1). For example, one participant contextualized the potential impacts of de-extinction as system dependent, '*Community dynamics will certainly be altered if these forms of hybrids are successfully established in any environment. Whether that is good or bad depends on the system*' (un25).

Research needs

Participants indicated that both ecosystem and social science research might help assess hazards but were uncertain if any novel research fields could aid risk assessment. Participant ranking of natural science research topics, 'ecological system effects', 'competitiveness with other organisms', 'biopersistence', and 'genetic stability' were the highest priority research topics for managing potential de-extinction risk (Figure 2). Research topics related to tradeoffs with other technologies and regulation were viewed as less important for managing de-extinction risk (Figure 2). Compared to natural scientists, social scientists ranked two research topics as higher priorities, 'horizontal gene transfer' ($t = 2.081$, $p = .047$, Cohen's $d = 0.823$) and 'competitiveness with other organisms' ($t = 1.783$, $p = .086$, Cohen's $d = 0.707$). Horizontal gene transfer was not raised in subsequent open-ended responses. Variance for ranking 'competitiveness with other organisms' may be explained by a few natural scientists who ranked this as a low priority research topic.

Subsequent open-ended responses re-affirmed these risk prioritizations, as participants were most likely to suggest general ecology research as a discipline for assessing hazards and reducing risks (Table 2). General ecological research was alluded to in this response, '*Broad studies of animal population dynamics and broader ecosystem function are needed for any study of revived species, prior to and after individuals have been revived*' (ss27). Occasionally, participants identified more specific questions and types of ecological research, restoration ecology or invasive species biology, to assess hazards and reduce risk (Table 2). One respondent suggested studies may, '*Compare to reintroduction of extant species into formerly-occupied regions. Similarly, how do invasive species affect disease dynamics?*' (ns8).

Natural and social scientists both suggested social science research comparing different approaches to conservation, such as cost–benefit analysis or decision analysis, (Table 2). As an example, one participant indicated a need for, '*Research to understand tradeoffs in de-extinction vs conservation and restoration of existing ecosystems and their ecosystem services*' (R14; natural scientist). Many suggestions for social science research did not provide a

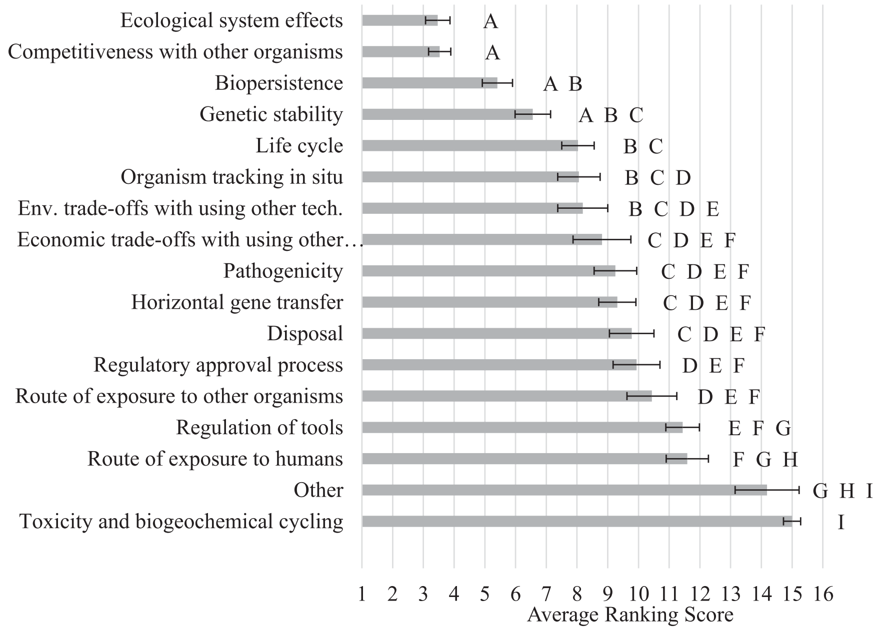

Figure 2. Average ranking scores (1–16) for research topics to manage de-extinction risks. Topics were ranked by perceived priority (low rank = high priority). Significant groupings are indicated by letters and were calculated using a Tukey-HSD test for comparing multiple means.

specific research area and instead provided questions that might drive research agendas. Participants posed questions such as, '*What about the ownership and possible monopolization of the technology?*' (ss19), and '*Which species should be reconstructed (and who should decide on this)?*' (ns5). Another question raises the potential for a moral hazard, '*Whether the attempt to revive species will overshadow ongoing conservation efforts?*' (ss7).

Table 2. Frequencies and percentages of responses regarding potential research needs for assessing de-extinction hazards, research areas for reducing de-extinction hazard, and potential novel research areas for reducing risk.

Assessing hazard	*n*	%	Reduce risk	*n*	%	Novel research	*n*	%
General ecology	9	31	General ecology	8	30	Don't know	4	18
General social science	5	17	Invasive species biology	6	22	Molecular and synthetic biology	4	18
Restoration ecology	4	14	Restoration ecology	4	15	Genomics	3	14
Molecular and synthetic biology	4	14	Disease and Immunology	4	15	Disease ecology/Ancient DNA	3	14
Cost-benefit or decision analysis	4	14	Conservation biology	3	11	No novel research	3	14
Population genetics	3	10	Paleontology	2	7	General ecology	3	14
Invasive species biology	3	10	Molecular and synthetic biology	2	7	Ecology/Big data	1	5
Policy & Regulation	3	10	Bioethics	2	7	Cost-benefit analysis	1	5
Ethics	2	7	Historical ecology	2	7	Evolutionary genetics	1	5
Biosafety	1	3	Systems biology	2	7	Reproductive studies	1	5
Public engagement	1	3	Physiology	1	4	Restoration ecology	1	5
Difficult to assess	1	3	Evolution	1	4	Bioethics	1	5
			Economic	1	4	Science fiction	1	5
			Don't know	1	4	Safety	1	5

Many participants were uncertain or did not respond regarding novel research programs that could reduce de-extinction risk (Table 2). This uncertainty is exemplified by the following responses, '*Not sure*' (ss7), '*None*' (ns11), '*Unknown*' (ss14). More social scientists ($n = 4$) explicitly stated these uncertainties compared to natural scientists ($n = 1$). Among participants that did offer a response, molecular studies, such as synthetic biology and genomics, were most commonly mentioned as areas that may inform hazard assessment and risk reduction, followed by ecology and disease research (Table 2). Responses for molecular and synthetic biology, genomics, and disease ecology/ancient DNA research all came from natural scientists (Table 2). One respondent suggested a basic science research goal for achieving de-extinction, '*Understanding of the function of the genome as the orchestration of all genes and its modifications, which we don't understand yet*' (ns23). Another respondent suggested how further research might improve perceptions of de-extinction, '*Perhaps there are ways to predict susceptibility of a species to human pathogens/diseases from their genomic information … If the risk of an organism acting as a vector for known disease could be predicted, it might allay concerns*' (ns24). Most responses suggested already developed or emerging research areas, but *novel* approaches were also mentioned, including a suggestion from a social scientist to incorporate big data methodologies with ecological modeling, '*Perhaps this is an interesting case for exploring computational simulation methods in ecosystem analysis*' (ss3). Further research on molecular mechanisms as a sub-discipline of systems biology was mentioned as a way to reduce risk, '*Genome editing CRISPR/Cas systems coupled with advanced prediction of function from cryptic elements to screen out hazards and or build in controls*' (ns29).

Technological optimism: a threat to conservation?

Participants also believed that de-extinction may threaten traditional conservation efforts by increasing techno-optimism and reducing fear of extinction. Half of participants indicated de-extinction's most important societal impact could be threatening and undermining traditional conservation efforts (Table 1). This concern was shared by social ($n = 4$) and natural scientists ($n = 5$). One participant suggested that de-extinction may result in, '*Less focus on habitat conservation. You may be able to synthesize DNA, but not the rainforest*' (ss17), another participant similarly suggested de-extinction may lead to, '*Less public support to protect at-risk species due to the belief that they can easily be "de-extincted"*' (ns26). Along those lines, some participants worried that de-extinction would result in scientific hubris or techno-optimism (Table 1). Some respondents succinctly responded, '*Hubris*', '*Techno-optimism*' (ss10), '*Moral issues, playing god, hubris*' (ns5), and one respondent further explained, '*This is a HUGE distraction from saving the habitats of animals that are very endangered today. It tempts humans to think that our technology is the solution*' (ss12).

Social impacts

Participants also suggested de-extinction may negatively impact natural resources and raise ethical concerns. Socio-ecological impacts focused on economic damage to agricultural or water resources (Table 1). Participants also raised ethical concerns, including, '*Whether people will agree with the concept of bringing back extinct species, playing god*' (ss7), animal rights, '*Harm to animals caused by the cloning process*' (ss12), and public engagement, '*Who will decide W. species to restore and where to put them?*' (R12) (Table 1). Other issues were raised, such as this 'slippery slope' argument, '*The need t. develop cloning techniques to bring to term any extinct mammal raises questions about whether clones of humans would be next.*' (ss12).

Although experts perceived de-extinction's greatest societal impact to be the challenge it poses to traditional conservation, they believed the public would be more concerned about the uncontrollable nature of the technology as portrayed in science fiction interpretations of biotechnology in the popular media. The participants indicated public concern regarding the risks of de-extinction might be high ($\bar{x} = 6.8$ based on a 1–10 scale, $SE = 0.3$) and were most likely to reference the science fiction series *Jurassic Park*, when describing what might elicit concern from the public (Table 3). The *Jurassic Park* science fiction series includes speculative biotechnology and moral lessons for re-creating extinct dinosaurs. Science fiction can offer stances to forecast ethical dilemmas (Berne, 2008), but many of the *Jurassic Park* responses were vague, '*Jurassic Park*' (ns8), '*Jurassic Park scenario*' (ss10), '*Jurassic Park syndrome*' (ss17), making it difficult to determine what lessons or ideas might be most salient when comparing *Jurassic Park* to potential real-life de-extinction. Concerns about de-extinction stemming from *Jurassic Park* may include ethics of reviving, hubris, animal rights, ownership questions, regulation, or fear of uncontrollable animals run amok. One participant suggested a better understanding of science and technology might alleviate public concerns about de-extinction, explaining, '*Education, as in when the obvious parallels are drawn to an infamous movie, wherein the scientists didn't do so well*' (ns28).

Many participants also indicated that the public may question the value of de-extinction. They noted that the public may see de-extinction as, '*Wasteful*' (ns8), and ask '*Is a sentimentally fun project of scientific or societal merit?*' (ss33). They also suggested that the public may be concerned about ecosystem impacts, '*Impacts on local natural resources management and public property*' (un25). Only one participant expressed the concern that the public might link de-extinction to competition with traditional conservation efforts

Table 3. Participant response frequency and percentage of responses regarding characteristics that may most concern the public.

Potential public concerns	*n*	%
Jurassic Park (scenario)	9	29
Ecosystem *impacts*	7	23
Ethics of reviving	5	16
Ethics (General)	3	10
Hubris and techno-optimism	3	10
Animal welfare	2	6
Uncertainty	2	6
Other science fiction references	2	6
Awe	1	3
Governance concerns	1	3
Economic damages	1	3
Lead to human genome engineering	1	3
Ignore conservation	1	3
Depends on the organism	1	3
Don't know	1	3

stating the public may wonder, '*Why reintroduce new species when we are not doing enough to protect existing ones*' (un15) (Table 3). It may be that participants believe that the public will be able to identify potential direct impacts of de-extinction, ecosystem impacts and management and containment concerns, but may not be able to identify the potential indirect impacts to conservation efforts. Few participants suggested that de-extinction might positively encourage scientific or conservation initiatives, for example, '*The benefits might be in capturing the public's imagination and providing a beneficial view concerning applications of the synthetic biology*' (un25).

Regulation and governance

Participants raised questions about adequacy of current oversight systems and split over who should govern de-extinction. One participant raised several governance questions, '*Do new regulations, or do regulations in existence, need to be developed/modified for de-extincted organisms. Role of Cartagena and or Nagoya protocols?*' (ns28) (Table 1). Almost a quarter of the participants indicated that an environmental risk assessment agency such as the EPA should be a central governing authority (Table 4). An equal number of respondents indicated that a government agency should be a central authority but did not name a specific agency (Table 4). A fifth of the respondents suggested the US Department of the Interior (DOI) or the FWS (Table 4) as the governing body. Less common responses included federal agencies and departments governing agricultural products and pharmaceuticals (e.g. USDA, FDA), and other organizations with more voluntary authorities for governance including non-governmental organizations, researchers, and universities (Table 4).

Discussion

New biotechnology ventures often generate optimism, yet de-extinction presents a novel case in which the technology faces pronounced pessimism. The sociology of expectations suggests biotechnology innovators often advance the benefits of speculative technologies to pre-establish value and build socio-political networks (Borup et al. 2006; Fortun 2001). For example, Fortun (2001) suggests optimistic media statements made by a gene bank company in the midst of a litigation scandal were created to ease and encourage

Table 4. Frequency and percentage of responses regarding who should have the most central authority for the governance of de-extinction.

Governance authority	*n*	%
Environmental Protection Agency (EPA)	7	23
Government (General)	7	23
Natural resources agency (Fish and Wildlife Service, Department of the Interior)	6	20
US Department of Agriculture (USDA)	4	13
Human health agency (Federal Drug Administration (FDA), National Institute of Health (NIH), Health & Human Services (HHS))	4	13
International Organizations (International Union for the Conservation of Nature (IUCN)), United Nations Environment Programme (UNEP), Conservation of Biological Diversity (CBD)	2	7
Non-Governmental Organizations & Non-profits	2	7
Universities	2	7
Industry	2	7
Other (each of the following had a single response: National Science Foundation, research experts, public, none)	1	3

corporate alliances. Historically, researchers have promised grandiose benefits of biotechnology (Turney 1998) and technological optimism remains high among many biotechnology experts (Hamdouch and Depret 2010; Kerschner and Ehlers 2016). Although some de-extinction advocates have promoted the speculative benefits of de-extinction (Brand 2013), that optimism was not apparent among the experts in this study. We might have expected experts in the natural sciences, including some biotechnology developers, to be more optimistic about de-extinction, compared to scholars from the social sciences and humanities, who often criticized the hype surrounding biotechnology development (Fortun 2001; Nightingale and Martin 2004). We found that both groups doubted the potential benefits, and perceived hazards to be more likely than benefits, although some differences in magnitude were seen between the groups. Future research with larger sample sizes are needed to establish these relationships among the broader community of natural and social scientists engaged in conservation biology.

Experts were concerned that de-extinction may perversely lead to environmental degradation, by creating a moral hazard, thus detracting from current efforts to conserve species. Experts aligned de-extinction with pessimism about environmental restoration, which associates technological advancement with environmental destruction (Marx 1994; Tutton 2011).

Critics of biotechnology hype have called for increased attention to the social context of innovation (Nightingale and Martin 2004). In this case, de-extinction may critically disrupt conservation efforts. We might have expected natural science experts to promote potential benefits by drawing on technological optimism or ecological modernism. Ecological modernism is a theory suggesting technology promotes both economic growth and ecological stability (Cohen 1997). Current de-extinction plans may lack the clarity needed to promote 'buy-in' among experts.

Uncertainties associated with technology development and the processes for creating a viable population of de-extinct animals may inhibit experts' ability to envision potential ecological benefits. Instead, experts expanded on a number of risks. A number of factors may impact the success of biotechnology products, including risks revealed during development processes, forming collaborative relationships, market acceptance, regulation, and the regulatory approval processes (Tutton 2011). Experts' concerns about the well-being of individual de-extinct animals seem well founded. Efforts to clone an extinct wild goat, the bucardo (Spanish Ibex), resulted in a single birth (Folch et al. 2009). But the bucardo died 11 min later because of a birth defect. The literature on cloning cites high rates of miscarriages, stillbirths, genetic abnormalities, and chronic diseases (Fiester 2005). Without further development in cloning techniques the early death of the bucardo may represent the norm, not the exception. Additionally, different techniques will likely be required for reviving species of different taxa (Shapiro 2017) and the efficacy of various approaches is likely to differ.

The process of sustaining a population in a natural environment may be even more challenging because estimating a population size that is viable and large enough to create desired ecosystem impacts, but small enough not to cause undesired effects is nearly impossible without significant trial and error (McCauley et al. 2017). Following experts' suggestions for increased ecological research and modeling may help identify places with adequate habitat for some de-extinction efforts. Advancements in ecosystem modeling and restoration ecology (Thorpe and Stanley 2011) may provide useful insights prior to de-extinction re-introductions, although ecologists' limited ability to predict invasive species impacts (Ricciardi and Cohen 2007; Hayes and Barry 2008) suggests that this may be a challenging endeavor.

Experts affirmed the importance of social and political contexts to the development and success of biotechnology (Nightingale and Martin 2004). At the broader societal level, concern regarding ownership, moral hazards and opportunity costs contributed to expert's pessimism. Some experts cited issues of power and control over technology; similar issues influenced public reactions to genetically engineered food crops (Finucane and Holup 2005). An opportunity cost is the loss of potential benefits when one alternative is chosen over others (Naidoo et al. 2006). When experts worried that attention or funds for traditional conservation efforts might be re-directed towards de-extinction projects, they were describing the opportunity costs that de-extinction might impose. As suggested by experts, this issue may be partially resolved if de-extinction projects undergo cost–benefit or decision analysis during early planning stages. A challenge for these types of analyses will be incorporating cultural and ethical concerns (Satterfield et al. 2013). Moral hazards are more commonly associated with financial and insurance risks-reckless behavior may become more likely if consequences fall to others. Geoengineering technologies to mitigate climate change may present a moral risk if these technologies convince people to abandon other climate change mitigation efforts because they believe geoengineering will resolve climate change impacts (Lin 2013). The moral hazard for de-extinction is that risky behaviors for increasing the likelihood of a species extinction may seem less problematic today because the responsibility for reviving them through de-extinction can now be given to people in the future (Delord 2014). Our respondents believed this undesirable outcome could be catastrophic when combined with de-extinction, which fails to address the causes of extinction and applies to few species. De-extinction fails to address the major cause of wildlife extinctions, habitat degradation and destruction (Pimm and Raven 2000). To minimize potential moral hazards, de-extinction advocates may consider lobbying for stronger conservation policies, such as enhancing the Endangered Species Act in the United States.

The perception that non-experts will rely more on fictional representations of science when considering de-extinction may relate in part to growing stereotypes of the public as less rational and more likely to evaluate science based on personal ideology and heuristics. While experts express dismay over public doubt about science associated with climate change and vaccinations, mismatched perceptions between experts and publics may be partially blamed on failures to acknowledge public concerns (Kahan 2010). This failure appears to extend to biotechnology. Scientists have described non-expert concerns regarding biotechnology and genetic engineering as more emotional compared to their own 'rational' concerns (Cook, Pieri, and Robbins 2004). Furthermore, public concerns regarding biotechnology have been dismissed by comparing their concerns to science fiction, not science (Turney 1998). Experts may have been following similar patterns when describing public concerns as likely to be related to *Jurassic Park*. The *Jurassic Park* series exhibits common science fiction tropes of science experiments gone awry (Turney 1998), and raises ethical dilemmas and ownership concerns. Interestingly, experts raised some of these issues themselves, but the references to science fiction emerged only when describing public concerns. Public concerns and experts' concerns may be more similar than suggested by participant responses. References to *Jurassic Park* in biodiversity conservation have previously emerged. *Jurassic Park* was mentioned in five out of eight stakeholder focus group meetings regarding the potential application of gene drive systems for controlling invasive fish species in the Great Lakes, USA (Sharpe 2014). Clearly, this movie series resonates among various populations. De-extinction advocates may prefer to avoid unwanted comparisons to science fiction in order to protect their professional image. However, avoiding the comparison may not be possible. The fictional representations that precede de-extinction are likely to impact public perceptions and dismissing these perceptions as simply science fiction will likely exasperate conflicts between experts and non-experts (Turney 1998). Future deliberations might acknowledge how de-extinction is like *Jurassic Park*, and more importantly, how de-extinction differs in ways that limit problems presented in the science fiction series.

Government agencies and policies have been slow to adapt to development of biotechnology in recent years, likely contributing to the respondents' confusion over who should govern de-extinction. In the United States, genetic engineering (GE) is federally regulated by the Environmental Protection Agency, Department of Agriculture, and the Federal Drug Administration, under the Coordinated Framework for Regulation of Biotechnology (OSTP 1986). This framework has not been updated to adequately cover contemporary biotechnology products (Kuzma 2016). Further, state and local governments also regulate specific GE products (Bratspies 2004). Consequently, genetically engineered pet GloFish® are largely unregulated but restricted from California (Knight 2003), and genetically engineered salmon have waited years for regulatory approval to enter the United States market (Vàzquez-Salat et al. 2012). Regulatory changes appear pressing amid growing concerns about genetic engineering, synthetic biology, and gene drive systems (Oye et al. 2014). Unlike previous genetic technologies, gene drive systems, which could be incorporated into de-extinct populations, may be able to transform entire populations or species, not just individuals, presenting larger regulatory challenges (Esvelt et al. 2014). The lack of agreement about who should govern de-extinction identified in this study may relate to the division of responsibility currently in place, and the lack of updates in the face of advancing biotechnology. Experts infrequently mentioned international governance institutions, which may reflect the fact that the United States is not party to the Convention on Biological Diversity (CBD) or the Cartagena Protocol on Biosafety (CPB; Kuzma 2016). This represents a critical future governance need, especially as the U.S. may take the lead on de-extinction. Conservation experts have already cited the lack of a shared international framework for genetic engineering as a potential limiting factor in future conservation applications (Sutherland et al. 2017). The CBD-CPB requires Advance Informed Agreements in transporting living modified organisms (LMO) across borders for countries that have signed and ratified the treaty (CBD 2000). It also hosts a clearinghouse of risk analysis information and protocols for LMOs (CBD 2000). It could be used to develop sub-protocols and guidelines for de-extinction, but if one of the key developers of de-extinction, the U.S., remains outside of its jurisdiction, it will not be effective. Thus, without an international governance framework for de-extinction that includes all countries developing and deploying LMOs, as well as their neighbors (i.e. in case of unintentional movement outside desired areas), de-extinct animals may cause transnational conflicts (Okuno 2017). Their deployment could lead to disputes under trade and transport agreements associated with the World Trade Organization or other multi-lateral frameworks. Deployment without assurance of agreed upon governance frameworks could result in political disagreements or onerous financial penalties.

De-extinction also has characteristics that make it different from previous GE applications, including development of hybrid species, releases into wild or natural places, and ethics of revival. As suggested by experts, DOI/FWS may provide expertise with ecological restoration, invasive species control, and species re-introductions needed for governing de-extinction implementation (Jeschke, Keesing, and Ostfeld 2013). Some standards from the International Union of Conservation of Nature's guidelines for de-extinct proxies (IUCN SSC 2016) may be useful, but at present, inadequately address ethical or governance concerns. As noted by Camacho (2015), governance of de-extinct species, at least in the United States, will depend on whether these species are designated as native, hybrids, or invasive species. Furthermore, the de-extinction of plants will also require careful risk assessment and governance considerations. De-extinct plants could be used to develop new medicines or act as 'trophy plants' in gardens and greenhouses (Sherkow and Greely 2013; Martinelli, Oksanen, and Siipi 2014) but may also present human health concerns or biological invasion risks. There are projects to revive plants, including the cloning of the plant *Silene stenophylla* from fossilized immature fruit (Yashina et al. 2012). Plant de-extinctions have not received as much attention as animals from scholars or the news media, and were not discussed by experts in this study. This may represent a pressing research and governance need because de-extinct plants have been developed (Yashina et al. 2012).

Responses infrequently discussed public lands and natural resource laws and regulation, which potentially represents either a gap in expertise among our participants or a subject that is not yet salient because de-extinction is in early development. In countries such as the United States, public lands, regulated by the National Park Service Organic Act, the National Wildlife Refuge System Improvement Act, and the Wilderness Act among others, are typically managed to preserve native wildlife within public lands and exclude protections for non-native species (Camacho 2015). Considerable uncertainty exists regarding how de-extinction species would be regulated under these public lands laws. For example, if a de-extinct animal is a 'new, non-obvious, and useful' product that is patentable (Swedlow 2015, 195), could it also be managed on public lands that aim for 'historical preservation' (Camacho 2015, 878)? There is also uncertainty regarding whether a de-extinct animal would be considered threatened, native, or nonnative (Camacho 2015), and these labels define how the animals would be governed under natural resource laws. Natural resource and public land law related questions may gain more attention after de-extinction becomes more prevalent.

De-extinction reflects a vision of integrating science, technology, environmental management, and conservation policy, re-defining what can be done and forcing us to reconsider what should be done. Collaboration with stakeholders may help reconcile experts emphasizing environmental risks and the disruption of current conservation methods, with concerns about the public viewing de-extinction through lenses of science fiction stories of 'science run amok'. Decreasing ambiguity in definitions of de-extinction risk does not guarantee that perceptions of de-extinction risk will subside (Kahan et al. 2009). Collaborative, anticipatory, decision-making between governmental agencies, experts from multiple disciplines, and stakeholders from the public represent one avenue for de-extinction governance (Davies, Bryce, and Redpath 2013; Barben et al. 2007). Other governance strategies include the use of citizens' juries (Dunkerley and Glasner 1998), allowing for the broad inclusion of stakeholders' considerations regarding the implementation of de-extinction in specific contexts. There is still time for these processes to begin, before viable, self-reproducing de-extinction species are developed. Such processes may help determine contexts where de-extinction might be appropriate, if at all.

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