Genetic Biocontrol and Aquatic Invasive Species Management in the Great Lakes Region: Perspectives of Resource Managers

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1.0 Introduction

Genetic biocontrol refers to the intentional release of genetically engineered organisms to control a population of those same organisms (Kapuscinski & Sharpe, 2014; Teem et al., 2020). This approach shows promise for managing and eradicating invasive species by precisely targeting unwanted species while minimizing impacts on non-target species. (Bajer, 2019; Teem et al., 2020). In the Great Lakes region, researchers are actively developing genetic biocontrol technologies to manage the spread of aquatic invasive species (AIS), such as invasive carp (Bajer, 2019), sea lamprey (Heath et al., 2014; Johnson et al., 2024; York et al., 2021), phragmites (Kowalski et al., 2015; Tao et al., 2023), and zebra mussels (Hernández Elizárraga et al., 2023; McCartney et al., 2022). Traditionally, chemical treatments (Marsden & Siefkes, 2019) and physical methods (Tsehaye et al., 2013; Zielinski et al., 2019) have dominated control strategies for these organisms. Although genetic biocontrol offers an attractive alternative method for AIS management, implementing such novel solutions will require integration into existing institutional and social systems (Jasanoff, 2007).

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Kuzma and Rawls (2016) argue that emerging technologies like genetic biocontrol often present considerable social, ecological, and regulatory complexities. For example, Schairer et al. (2019) report that the release of genetically engineered mosquitoes in the Florida Keys encountered significant social and regulatory challenges, including public opposition and jurisdictional conflicts between the U.S. Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA). After extensive deliberation involving technology developers, district partners, key stakeholders in the affected counties, and state and federal agencies, the EPA eventually approved field trials in 2016, followed by open-release approvals in 2021 and 2022. The approval process for releasing the modified mosquitoes spanned over a decade, reflecting the complexity of addressing social and regulatory obstacles for novel, genetically engineered organisms.

In light of the complexity and potential controversy surrounding genetic biocontrol strategies, the U.S. Fish and Wildlife Service has funded our team to engage with diverse stakeholders to explore the social, political, ecological, and governance systems that guide research and potential development of genetic biocontrol tools for AIS in the Great Lakes region. In this report, we provide results of the first phase of our landscape analysis: semi-structured interviews with resource managers in the Great Lakes region, conducted May-July 2023. The resource managers we interviewed for this study are state government employees from departments of natural resources (and similar institutions) with specialized expertise in managing aquatic invasive species (AIS). Their perspectives are essential in guiding the development, testing, and potential deployment of new technologies for AIS management.

This report begins with an overview of AIS and genetic biocontrol, followed by an explanation of the methods used to recruit resource managers and conduct and analyze interviews. Our results review participants' perspectives on the potential effectiveness and benefits of genetic biocontrol; concerns; likely regulatory pathways; and preferences for public engagement and building partnerships.

2.0 Aquatic Invasive Species and Genetic Biocontrol

The Great Lakes region is home to at least 184 non-native plants and animals, 34% of which are classified as invasive. Among these are several aquatic invasive species, such as sea lamprey, zebra and quagga mussels, phragmites, invasive watermilfoil, and invasive carp (Bartos, 2021; US EPA, 2022). These species are non-native and were likely introduced into the Great Lakes waters through human activities, such as transportation (Adebayo et al., 2014) and recreational water activities (O'Malia et al., 2018). Aquatic invasive species have significantly disrupted aquatic ecosystems and impacted the local economy by outcompeting native fish for essential food resources (Escobar et al., 2018), threatening commercial fishing output (Marsden & Siefkes, 2019), affecting freshwater supplies (Moorhouse & Macdonald, 2015), and clogging water intakes for power plants (Havel et al., 2015). For example, Marsden and Siefkes (2019) report that invasive sea lampreys have significantly contributed to the collapse of the fishing industry in the Great Lakes by reducing fish populations. Similarly, Chapman and Hoff (2011) note that the invasion of common carp, a highly efficient filter feeder, has disrupted aquatic food webs in the Great Lakes, decreased native fish diversity, and negatively impacted the $7 billion fishing industry. Aquatic invasive species also create substantial costs for major infrastructure in the Great Lakes. For example, Warziniack et al (2021) report that zebra mussels alone cause between $300 and $500 million in damages annually to power plants, water systems, and industrial water intake systems.

Current strategies for managing aquatic invasive species (AIS) in the Great Lakes region include a combination of techniques, such as chemical treatments (Ferreira-Martins et al., 2021) and physical removal methods (Tsehaye et al., 2013). These approaches often require repeated application and can potentially affect native species (Ferreira-Martins et al., 2021; Siefkes et al., 2021). For example, Kujawa et al (2017) review chemical treatments like lampricide, which target the larval stage of sea lampreys, and the physical removal of carp to manage the spread and establishment of invasive species. These strategies can impact non-target species (Teem et al., 2020). Likewise, Nault et al. (2014) describe how using chemicals in large quantities can significantly harm native plant biomass.

The potential precision of genetic biocontrol in targeting species without negatively impacting non-target species has sparked interest in developing and applying this technology. For instance, genetic biocontrol has been proposed to reduce mosquito populations to protect human health in the Florida Keys (Waltz, 2021), manage agriculture pests and diseases (Ram et al., 2018), conserve coral reefs in Australia against the Crown-of-thorns starfish (Hall et al., 2017), and eradicate invasive rodents on oceanic islands (Godwin et al., 2019). Additionally, Harvey-Samuel et al. (2021) reported that genetic biocontrol techniques have been implemented in the Hawaiian Islands to reduce invasive mosquito populations to protect native bird species.

Genetic biocontrol offers alternative strategies for reducing or suppressing invasive species populations by modifying an organism's genetic material. Employing techniques like CRISPR-Cas9 and other gene-editing strategies (Esvelt et al., 2014), these modifications can target traits that influence reproduction, survival, or behavior. Some methods (e.g., gene drive) ensure that a particular trait is passed on to the next generation up to 100% of the time, compared to the typical inheritance rate of 50% (Esvelt et al., 2014; Phelps et al., 2017; Zentner & Wade, 2017). Consequently, a desired trait can spread rapidly through the target population (Esvelt et al., 2014). Various other methods of genetic biocontrol include the sterile male technique (Johnson et al., 2024; Knipling, 1955; Smith, 1963), hormonal sex reversal (Gutierrez & Teem, 2006), and RNA interference (McCartney et al., 2022).

Researchers in the Great Lakes region are exploring various genetic biocontrol techniques for AIS management (see Table 1.0, below). This includes RNA interference for species like phragmites (Kowalski et al., 2015; Tao et al., 2023), sea lamprey (Heath et al., 2014), and zebra mussels (McCartney et al., 2022); sterile male techniques for sea lamprey (Johnson et al., 2024); and synthetic incompatibility for common carp (Bajer, 2019). RNA interference aims to break down specific RNA strands, disrupting protein formations and trait expressions that influence the reproduction of the target species (Bramlett et al., 2020; Heath et al., 2014). Johnson et al (2024) reported that the sterile male technique involves sterilizing adult male sea lampreys with a chemo-sterilant and releasing them to mate with female sea lampreys to produce nonviable embryos. Meanwhile, the synthetic incompatibility technique involves altering the genes of a particular species to produce offspring that are either infertile or incapable of reproducing effectively when they mate with wild individuals of the same species (Bajer, 2019), resulting in population reduction of the target species. To date, most genetic biocontrol research in the Great Lakes has been conducted at the laboratory scale. However, Johnson et al. (2024) have conducted some field testing of the sterile male technique for sea lampreys in three rivers (Sturgeon, Pigeon, and Maple) in the region. One or more of these approaches could advance to field trials within the next decade (Bajer, 2019).

Table 1.0: Targeted aquatic invasive species for genetic biocontrol in the Great Lakes region

Invasive Species	Impacts	Existing Management Method(s)	Genetic Biocontrol Technique(s)	Developing Institution	Project Stage
Invasive carp: Common carp (*Cyprinus carpio)*	Outcompetes other fish for food Reduces ecosystem biodiversity	Mechanical removal Electric barriers to block upstream adult carp migration	Synthetic incompatibility Daughterless carp	University of Minnesota	Laboratory testing
Sea lamprey *(Petromyzon marinus)*	Predates on native fish species Causes the collapse of native species such as lake trout	Lampricide to target larval stage. Physical and electric barriers to block upstream migration of adult lampreys	RNA interference	University of Michigan	Laboratory testing
			Sterile insect technique	US Geological Service	Testing in rivers
Zebra mussels *(Dreissena polymorpha)*	Clogs water intake pipes Filters algae that native plants need for food Impacts water quality.	Mechanical removal Chemical treatment	RNA interference	University of Minnesota	Laboratory testing
Common reed (*Phragmites australis)*	Crowd out native plants Block access to shoreline for fishing and swimming	Herbicide treatment Physical removal	RNA interference	US Geological Service - Great Lakes Science Center (Multi-agency collaboration) US Army Corps of Engineers Louisiana State University Wayne State University	Laboratory testing

3.0 Methods

This study aims to understand the perspectives of resource managers on the social, ecological, and governance factors surrounding the development and utilization of genetic biocontrol technologies to manage AIS in the Great Lakes region. The Great Lakes region comprises eight US states (Michigan, Ohio, Minnesota, Wisconsin, Illinois, Indiana, New York, and Pennsylvania) and two Canadian provinces (Ontario and Quebec) with interconnected waterbodies faced with similar AIS issues. We conducted qualitative semi-structured interviews with 13 resource managers across eight states and two provinces. These resource managers, employees of departments of natural resources and similar institutions, design and implement strategies to manage AIS. We chose resource managers because of their valuable knowledge and expertise in managing AIS. Their viewpoints and perspectives are crucial for decision-making on how and whether to develop genetic biocontrol tools to manage AIS, as they would likely play key roles in the practical deployment and implementation of these tools. We conducted confidential interviews with individual resource managers because it allowed them to express their views, concerns, and opinions on a potentially controversial, emerging issue. The North Carolina State University Institutional Review Board (IRB) approved and classified the study as exempt under protocol #25849.

To identify resource managers for our study, we conducted an online search for individuals who work with departments of natural resources and similar institutions and possess expertise in managing AIS. We also examined attendee lists from two workshops on carp genetic biocontrol, held at the University of Minnesota in 2019 and 2023. In addition, we included referrals from interviewed resource managers to expand our pool of potential participants. This process helped us identify 43 individuals, of which 24 were resource managers directly involved in AIS management. We invited the 24 resource managers to participate in our study; 9 did not respond, while 2 did not consider themselves the appropriate person to talk to. In total, we interviewed 13 resource managers across six US states and one Canadian province: Minnesota

(3), Michigan (3), Ohio (2), Illinois (2), Wisconsin (1), Indiana (1), and Ontario (1). Of the 13 resource managers we interviewed, 11 have a background in fisheries and conservation, one in social science, and one in molecular genetics and ecology.

We conducted interviews both in person (n=1) and via Zoom (n=12) May-July 2023. The interviews were structured around the following key questions:

1. What are resource managers' perceived understanding of genetic biocontrol tools?
2. What are the potential benefits and concerns of developing and implementing genetic biocontrol technologies for AIS management?
3. What are the likely risk assessments and regulatory pathways for genetic biocontrol technologies?
4. Which individuals should be engaged to understand their perspectives in developing and implementing these technologies?

During the interviews, we took notes and recorded audio to ensure accuracy. We then transcribed the recorded interviews using Otter.ai or generated transcripts via Zoom. We used Dedoose qualitative software (version 9.0.90) to initially code the responses based on the key questions above. After iterative coding, we organized and categorized emerging and overlapping themes together, ultimately generating the final themes that organize the presentation of our results below.

4.0 Results

This section summarizes the responses from resource managers about using genetic biocontrol for AIS management. The responses are organized into four main themes: potential effectiveness and benefits, challenges and concerns, regulatory considerations, and the importance of public engagement and building partnerships.

4.1 Potential Effectiveness and Benefits of Genetic Biocontrol

Resource managers highlighted several perceived benefits of genetic biocontrol for managing aquatic invasive species (AIS), as categorized below:

- Potential precision in targeting specific species
- Scalability for widespread implementation
- Cost-effectiveness in eradicating AIS

All resource managers highlighted the potential precision of genetic biocontrol as a significant advantage compared to current AIS control methods, such as pesticides and electric and physical barriers, which all affect non-target species. For example, lampricides used to control invasive sea lamprey can also kill native species like the American brook, northern brook, silver, and chestnut lampreys. These native species are valuable to the Great Lakes ecosystem, serving as prey for other species and helping to improve stream habitats. The resource managers stated that using genetic biocontrol instead of lampricides could allow for more targeted eradication of invasive sea lamprey without harming native lampreys in the ecosystem.

In regards to the potential scalability of genetic biocontrol, some resource managers referenced that genetic biocontrol can access and eradicate target species, such as common carp or sea lamprey, in other water bodies that current AIS control strategies cannot easily reach, resulting in more effective eradication of those species. For instance, pesticides used to manage invasive lampreys and phragmites are limited to the specific area of their application and do not reach other water bodies. The species can re-establish in those areas from nearby water bodies after the pesticide dissipates. They noted that utilizing genetic biocontrol to mitigate AIS could allow for broader implementation on a larger scale because introduced species are not confined to the area of introduction.

Many resource managers highlighted the potential cost-effectiveness of genetic biocontrol as a benefit in the context of implementation. Traditional strategies - installing and implementing electric barriers, applying pesticides, and physically removing species - are expensive. For instance, a resource manager mentioned that their state spends $600,000 annually on current control measures to control Eurasian watermilfoil and common carp. Some resource managers noted that genetic biocontrol for this invasive species could be relatively inexpensive, albeit with uncertainties..

4.2 Concerns of Genetic Biocontrol

Resource managers' concerns about genetic biocontrol include a range of issues:

- Development timelines
- Susceptibility of modified species to real-world conditions
- Consequences of species eradication on the ecosystem and AIS control infrastructure
- Cost of R&D and sustainability of funding
- Public support

Regarding concerns about the development timelines of genetic biocontrol, some resource managers pointed out that developing genetic biocontrol might take several decades to achieve feasible implementation. For example, one resource manager mentioned that scientists developing genetic biocontrol for common carp would have to conduct extensive research to properly modify these species to ensure their effectiveness, followed by controlled field trials, which will take several years. As a result, practical implementation of these tools is not expected anytime soon.

Some resource managers were concerned that successful genetic biocontrol results observed in controlled environments may not translate effectively to real-world conditions. For instance, one resource manager suggested that severe winter conditions, which are common in the Great Lakes region, could influence the gene expression of modified sea lampreys and common carp that are released into open waters. This impact may differ from what is observed in confined, controlled environments. Real-world conditions could affect the ability of modified species to feed or find mates, ultimately diminishing their effectiveness in controlling invasive populations.

Many resource managers stated that severe weather events, such as heavy rains, could inadvertently spread modified species to non-target locations. For instance, heavy rainfall and associated flooding could facilitate the movement of modified lamprey from targeted water bodies to the Mississippi River, the Chicago Shipping Canal, the Ohio River watershed, and even the Atlantic Ocean via the St. Lawrence Seaway. Consequently, the movement of modified species raises concerns about disproportionate social and geopolitical impacts across the region, such that the impacts of modified carp may vary across different areas.

Several resource managers expressed concerns about the availability of funding for implementing and monitoring genetic biocontrol after R&D. One resource manager expressed skepticism about the sustainability of funding for genetic biocontrol and asked whether state taxes would be utilized to support implementation. They mentioned that the cost of R&D for genetic biocontrol could reach millions of dollars to reach the stage of field trials. Following proof of feasibility, implementation costs and monitoring will both require ongoing investments. All resource managers expressed concerns regarding public support of genetic biocontrol. Resource managers pointed out that modifying invasive carp, considered important for recreation and food in some states, could create public anxiety. Another concern was whether the public would perceive the benefits to outweigh the risks - especially in comparison to current control methods with familiar benefits and costs. Additionally, one resource manager pointed out that due to the historical association with genetically modified organisms, the term “genetic” might trigger negative public perceptions and reactions, especially for targeted species that have personal and cultural value.

One resource manager expressed concerns about how public perception could hinder the use of a potentially effective new tool for managing AIS. Stating that "even though the tool's effectiveness has not been practically established, we are highly optimistic about its potential selectivity. I would hate to have a promising tool that works but not be able to use it because public perception killed it before it was ready." They added that unfavorable public reaction to the implementation of the tools may cause state governments to overreact and risk missing the opportunity to use these tools for effective AIS management. On the other hand, another resource manager expressed optimism about the evolution of public attitudes. They suggested that people's views on genetic biocontrol might change with time, drawing parallels to historical shifts in public attitudes towards pesticide use for sea lamprey control. They noted that when lampricide was initially used for sea lamprey control, it encountered some public reaction. However, after years of employing this method, public perceptions shifted. They surmised that genetic biocontrol might experience a similar phase of skepticism but will ultimately gain support once its safety and effectiveness are demonstrated.

4.3 Regulatory Considerations for Genetic Biocontrol

As professionals who interface with regulations for AIS management, resource managers shared their perspectives on likely regulation pathways for genetic biocontrol. Three themes emerged:

- Inadequacy of current regulations
- Lack of clarity on agency jurisdiction
- Impact of varying management priorities on AIS regulation

All resource managers emphasized the inadequacy of the current regulatory framework for genetic biocontrol, in comparsion to traditional control methods. For instance, existing state regulatory systems, such as Michigan's Natural Resources and Environmental Protection Act (NREPA) and Minnesota's Statute for AIS (Chapter 84D), issue necessary permits for pesticide applications and mechanical removal techniques, and they have procedures for monitoring impacts of those existing management strategies. The same permits and monitoring strategies may not translate easily to genetic biocontrol. Even at the research and development phase, state agencies responsible for overseeing current strategies, including Minnesota's Environmental Review (ER) and Environmental Quality Board (EQB), currently lack a regulatory framework for designing and issuing testing permits for genetic biocontrol, which eventually must consider issues such as targeted species selection, field trials, open release, and monitoring the escape of modified species into non-target locations. However, some resource managers noted that some state agencies, such as Minnesota's EQB, are making efforts to clarify and establish criteria for issuing permits. They emphasized the importance of intensifying discussions on governance pathways for genetic biocontrol through the six regional panels of the Aquatic Nuisance Species Task Force (ANSTF) and the Invasive Carp Coordinating Committee (ICCC).

Another significant regulatory concern raised by resource managers is the lack of clear agency jurisdiction on genetic biocontrol. This includes ambiguity regarding which federal agency will be responsible for enforcing guidelines and disseminating regulatory information to states and provinces. According to one resource manager, multiple state and federal agencies from across two countries will play crucial roles in issuing permits for field trials and implementing genetic biocontrol. However, because the tools may be used for both plants and fish species, it is unclear which agencies will take primary responsibility.

Many resource managers cited the varying regulatory approaches among states, due to differences in AIS management priorities, as a regulatory concern for genetic biocontrol. Regulations for invasive carp or sea lamprey may vary among states because of differing management priorities or regional differences in the cultural value of species. For example, Michigan and Ohio have different management priorities for invasive carp due to the immediate threat these species pose to their waterways. In contrast, Illinois regulation for invasive carp, known locally as "Copi," acknowledges growing patterns of human consumption and Copi’s associated market value. Similarly, states with strong commercial and recreational fishing industries, such as Wisconsin and Minnesota, enforce stricter control measures for mussels and sea lamprey than states with less reliance on fishing. The resource managers noted that these differences in management priorities for AIS may derail the potential for a unified regulatory framework for genetic biocontrol in the Great Lakes region.

4.4 Diverse Public Engagement and Building Partnerships

Responding to questions on stakeholder involvement, all resource managers strongly emphasized engaging diverse publics and building partnerships with Tribal communities and First Nations to understand insights and cultural values related to AIS management and genetic biocontrol.For example, they emphasized the importance of engaging lakefront property owners, anglers, tool developers, regulators, other resource managers, commercial fishing associations, watershed districts, and non-governmental organizations. They noted that these groups play crucial roles in managing water resources in the region and could have a mix of similar and differing perspectives on genetic biocontrol. All resource managers stressed the significance of engaging and forging partnerships with Tribal communities and First Nations to understand cultural perspectives regarding genetic biocontrol and AIS management. They noted that Tribal Nations have key insights into cultural practices, values, and livelihoods associated with native species and management. For example, the Anishinaabe have a deep connection to whitefish, which is considered central to their cultural heritage and an important food source for many generations.

5.0 Conclusion

The increasing interest in developing genetic biocontrol in the Great Lakes region for managing and possibly eradicating AIS necessitates understanding the perspectives of resource managers, who play a central role in overseeing the management of these species. The insights offered by resource managers in this study are essential for substantive and normative reasons (Fiorino, 1990; Sharpe, 2014).

Substantively, resource managers' insights will contribute vital information that can enrich the knowledge base of scientists, regulators, and other actors to help guide decision-making in developing and implementing these tools. For instance, resource managers identified several technical concerns, including development timelines and the potential vulnerability of modified species in real-world conditions. They also raised ecosystem concerns, particularly regarding the consequences of modified species in the ecosystem, and governance challenges related to the complexities of regulation.

Normatively, resource managers highlighted the importance of public support and the need to engage diverse stakeholders and Tribal nations, particularly those who may be directly affected by these tools. This approach aligns with principles of fairness and inclusivity, ensuring that affected individuals and groups have the right to participate in discussions about managing novel tools in our shared environment.

Appendix: Interview guide

Project Title: Testing the waters for genetic biocontrol technologies: Engaging resource managers and key stakeholders to understand decision landscapes, information needs, and diverse perspectives.

(I) Demographics

1. What is your name and affiliation?

2. Which State/county do you currently work in, and where?

3. Tell me briefly about your professional and educational background.

4. What has been the focus of your work and/or research in the past couple of years?

(II) Knowledge and Concerns of Aquatic Invasive Species (AIS) Management.

5. I'm really interested in AIS management. How has your work connected to this issue?
    1. Follow up: Which species?

6. Can you tell me the story of how these invasive species came to be a problem here? How are species identified as a problem and prioritized for management?

7. What are some current practices for managing these aquatic invasive species?

8. Who decides what management practices to implement in managing these aquatic invasive species? How are those decisions made? How are these management practices funded?

9. Tell me more about the successes and failures of these management practices.

10. Have some of these practices worked in other places?

11. Do you receive or provide any training and support on AIS management to/from other stakeholders (such as tribal and community members)?
    - What does that look like and how do you think it is received by the different people involved?

(III) Genetic Biocontrol Technology - Diverse perspectives, hopes and Concerns.

12. What do you know about genetic biocontrol technologies?

13. Can you tell me about the potential of using genetic biocontrol techniques to manage AIS?

14. What are the potential benefits of using genetic biocontrol technology in AIS management?

15. What are the concerns of using genetic biocontrol technology for AIS?

16. How might we integrate genetic biocontrol technologies with local management practices?
    - How do we start this conversation?
    - How would you want this technology to be applied or used?

(IV) Pathways for the Governance and Regulation of Genetic Biocontrol Technology.

17. What do you know about Federal and state regulations that will govern genetic biocontrol technology for AIS?
    1. How do state and federal agencies cooperate?
    2. How do state agencies first learn about a potential innovation?
    3. How do state agencies determine AIS of concern?
    4. What sort of risk analyses are conducted at the state level?
    5. What state agencies are involved?
    6. What kind of public input is there at the state level?
    7. How do state policies/practices manage Native American/Tribal/First Nation perspectives? What sort of consultation processes are there?
    8. What triggers state agency oversight? Will genetic biocontrol trigger different oversight than classical biocontrol?
    9. What kind of monitoring happens after an approved release?
    10. What are the decision criteria for approving a field trial or full release of a genetic biocontrol technology?

18. What are the processes of modifying and releasing these organisms in this State for managing AIS?
    - What species are you modifying?
    - Tell me about your modification techniques.
    - What are the decision criteria for releasing these modified species?

- Where are the released locations and who makes decisions on the release locations?
- What are the concerns with choosing a release location?
- What kind of local input is there for determining these release locations?
- What sort of risk analysis is conducted in these release locations?
- What kind of monitoring happens in these release locations?

(V) Inclusion: Other stakeholders.

19. Part of our project will be to talk to other groups and stakeholders such as tribal members, and industry, NGO's about this technology in the Great Lakes Region: What other individuals, and/or groups (stakeholders)would be interested in talking to about genetic biocontrol technology in the management of AIS?
    Follow up: Ask for names/contact information

20. Is there anything else you would like to share or anything you think I need to know that I didn't ask about concerning this interview?

Thank you for your time.

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