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# Priority research needs to inform amphibian conservation in the Anthropocene

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**Abstract**

The problem of global amphibian declines has prompted extensive research over the last three decades. Initially, the focus was on identifying and characterizing the extent of the problem, but more recently efforts have shifted to evidence-based research designed to identify best solutions and to improve conservation outcomes. Despite extensive accumulation of knowledge on amphibian declines, there remain knowledge gaps and disconnects between science and action that hamper our ability to advance conservation efforts. Using input from participants at the ninth World Congress of Herpetology, a U.S. Geological Survey Powell Center symposium, amphibian on-line forums for discussion, the International Union for Conservation of Nature Assisted Reproductive Technologies and Gamete Biobanking group, and respondents to a survey, we developed a list of 25 priority research questions for amphibian

For affiliations refer to page 14

conservation at this stage of the Anthropocene. We identified amphibian conservation research priorities while accounting for expected tradeoffs in geographic scope, costs, and the taxonomic breadth of research needs. We aimed to solicit views from individuals rather than organizations while acknowledging inequities in participation. Emerging research priorities (i.e., those under-represented in recently published amphibian conservation literature) were identified, and included the effects of climate change, community-level (rather than single species-level) drivers of declines, methodological improvements for research and monitoring, genomics, and effects of land-use change. Improved inclusion of under-represented members of the amphibian conservation community was also identified as a priority. These research needs represent critical knowledge gaps for amphibian conservation although filling these gaps may not be necessary for many conservation actions.

**KEYWORDS**

actions, amphibian decline, Anthropocene, conservation needs, priority research, threats

## 1 | INTRODUCTION

Since the recognition of amphibian declines as a global phenomenon more than three decades ago (e.g., Blaustein & Wake, 1990; Drost & Fellers, 1996; Wake, 1991), research has advanced our understanding of a handful of drivers implicated in the declines. Although globally common drivers have been identified (e.g., Collins & Crump, 2009; Heatwole, 2013; Hof et al., 2011; Stuart et al., 2004), the strength of their effects on amphibian populations are mediated by local and regional contexts (Cayuela et al., 2020; Grant et al., 2016, 2020; Miller et al., 2018; Ramírez-Arce et al., 2022). In addition, identifying common drivers falls short of globally mobilizing (sensu Muths & Fisher, 2017) the necessary response for large-scale conservation to stabilize populations, recover declining amphibian populations, and maintain amphibian biodiversity (Gratwicke et al., 2012; Mendelson et al., 2006).

Research into these drivers has led to new insights that can inform conservation. For example, disease has repeatedly been highlighted as an important driver of amphibian decline (Brannelly et al., 2021; Collins & Crump, 2009; Kolby & Daszak, 2016; Yap et al., 2017), and, arguably, the global response to the newly emerged *Batrachochytrium salamandrivorans* (Bsal) will be improved because of the knowledge gained by recent investigations into *B. dendrobatidis* (Bd), Frog-virus 3 (amphibian ranavirus), and other amphibian pathogens (Allain & Duffus, 2019; Gray et al., 2015; Thomas et al., 2019). The importance of habitat loss (Chanson et al., 2008; Cushman, 2006; Ficetola et al., 2015; Powers & Jetz, 2019) and metapopulation dynamics (Bailey & Muths, 2019; Griffiths et al., 2010; Heard et al., 2013; Marsh & Trenham, 2001; Mendelson III et al., 2019; Sjögren-Gulve, 1991) to amphibian persistence contributes to reserve design (Chen et al., 2017; D'Amen et al., 2011), habitat creation, and landscape restoration (Clauzel et al., 2015; Scroggie et al., 2019; Smith et al., 2015). Research on captive husbandry (Murphy & Gratwicke, 2017a, 2017b) contributes not only to repatriation efforts (Linhoff et al., 2021) but also to our understanding of life history traits, genetics, behavior, and disease management.

This groundwork, based on three decades of documenting, diagnosing, and identifying possible solutions to the amphibian decline crisis, provides context and insights for amphibian conservation (Collins & Crump, 2009; Lannoo, 2005; Shoo et al., 2011; Stuart et al., 2004). The investment in research, as represented by the published literature, improves planning and predictions about individual and community responses to environmental change (Gvoždík, 2012; Riddell et al., 2018), documents advances in knowledge and techniques, and provides a record of how the amphibian conservation community has viewed conservation needs. As we proceed deeper into the Anthropocene, with an increasing number, frequency, and severity of threats to ecosystems, it is important to take stock of our existing knowledge and recognize that an acceleration in amphibian conservation cannot rely on the research record and ongoing disparate (although valuable) research efforts. Increased momentum depends on the prioritization of research that has the potential to advance collaboration and the execution of conservation actions by directing scientific investigations toward the most important information gaps. The gap between scientific knowledge and understanding and the application of such information to management continues to challenge conservation (Cook et al., 2010). This problem spans taxonomic groups and locations but may be particularly problematic for amphibians that are typically understudied (2200 species are data deficient in determining conservation status; Gonzalez-Del-Pliego et al., 2019), underappreciated (Olson & Pilliod, 2022), and underfunded (Gratwicke et al., 2012).

Identifying commonalities in global amphibian declines and conservation concerns, and the degree to which research is addressing the most pressing needs to inform conservation, is challenging at many levels. One particularly vexing challenge is the inequalities that exist among researchers and practitioners (Lindsey et al., 2017; Meijaard et al., 2015; Wilson et al., 2016). This includes limited representation and diversity at professional meetings, restricted conservation and research funding, bias in the conservation literature, and geopolitical challenges to research and representation. International meetings such as the World Congress of Herpetology (WCH) provide an opportunity to begin to address this challenge. WCH is intentionally held on different continents to reduce travel costs for attendees from traditionally underrepresented (though not less committed; Lindsey et al., 2017) countries, associated workshops are open to all and not by invitation-only, and a diversity of local and international conservation issues can be showcased to meeting attendees. Other groups are also attempting to address these systemic inequalities. For example, the Societas Europaea Herpetologica similarly varies its meeting locations to be as inclusive as possible within Europe. The U.S. Geological Survey's (USGS) Powell Center (https://www.usgs.gov/centers/john-wesley-powell-center-for-analysis-and-synthesis/proposal-submission-instructions; accessed June 18, 2022) hosts workshops focusing on particular scientific problems while working specifically to address under-representation, requiring evidence that a proposed working group "contributes to strengthening the participation of less well-represented groups in the Earth and environmental sciences (women, underrepresented minorities, early career)". Additionally, online communities supported through professional herpetological societies and associations provide a space to maintain communication and share knowledge (e.g., Society for the Study of Amphibians and Reptiles [SSAR]; FrogLog of the International Union for Conservation of Nature (IUCN) Amphibian Specialist Group https://www.iucn-amphibians.org/resources/froglog; Red MesoHerp https://redmesoherp.wixsite.com/red-mesoherp; Amphibian Ark Newsletter [in Spanish and English] www.amphibianark.org/news/aark-newsletter/). Despite this progress, significant barriers to participation still challenge the development of an equitable global conservation community that is responsive to amphibian declines. Additionally, research networks are often insular and clustered in nature, limiting global partnerships (Hennemann et al., 2012; Newman, 2001).

With the intent of prioritizing amphibian conservation research needs to facilitate conservation decision-making, we engaged a cross-section of *individuals* from the amphibian conservation and research community across a variety of venues (an international meeting, workshops, and professional online forums for discussion; aka, listservs). We placed the results within the context of recent needs derived from the literature and from priority threats and conservation actions identified by a large and well-regarded international conservation organization: the IUCN. Our goals were to: (i) identify the most-pressing information and knowledge gaps for reducing amphibian decline and recovering amphibian biodiversity and (ii) encourage increased global dialogue and collaboration toward improving amphibian conservation.

## 2 | METHODS

We identified amphibian conservation research needs using community consensus approaches and assembling priorities drawn from global amphibian specialists (Figure 1). First, we queried the research community for their current priority research questions. Next, we categorized these research needs by topics expressed in the last half decade of the scientific literature and by the Priority Threats and Actions listed by the IUCN (IUCN-CMP, 2012). Finally, we surveyed individuals in the research community, asking them to assess these research needs based on criteria that we provided and to identify the most immediate priorities. Criteria were selected to capture the scope and applicability of the research needs (see below). We defined "Participants" as individuals who contributed a research question, "Recipients" as individuals who received the subsequent survey, and "Respondents" as individuals who participated in the survey but did not necessarily contribute research questions.

### 2.1 | Eliciting research needs and generating questions

At the ninth WCH in January 2020 in Aotearoa (Te Reo [Māori']; New Zealand [English]), four authors organized a symposium and workshop to discuss and identify

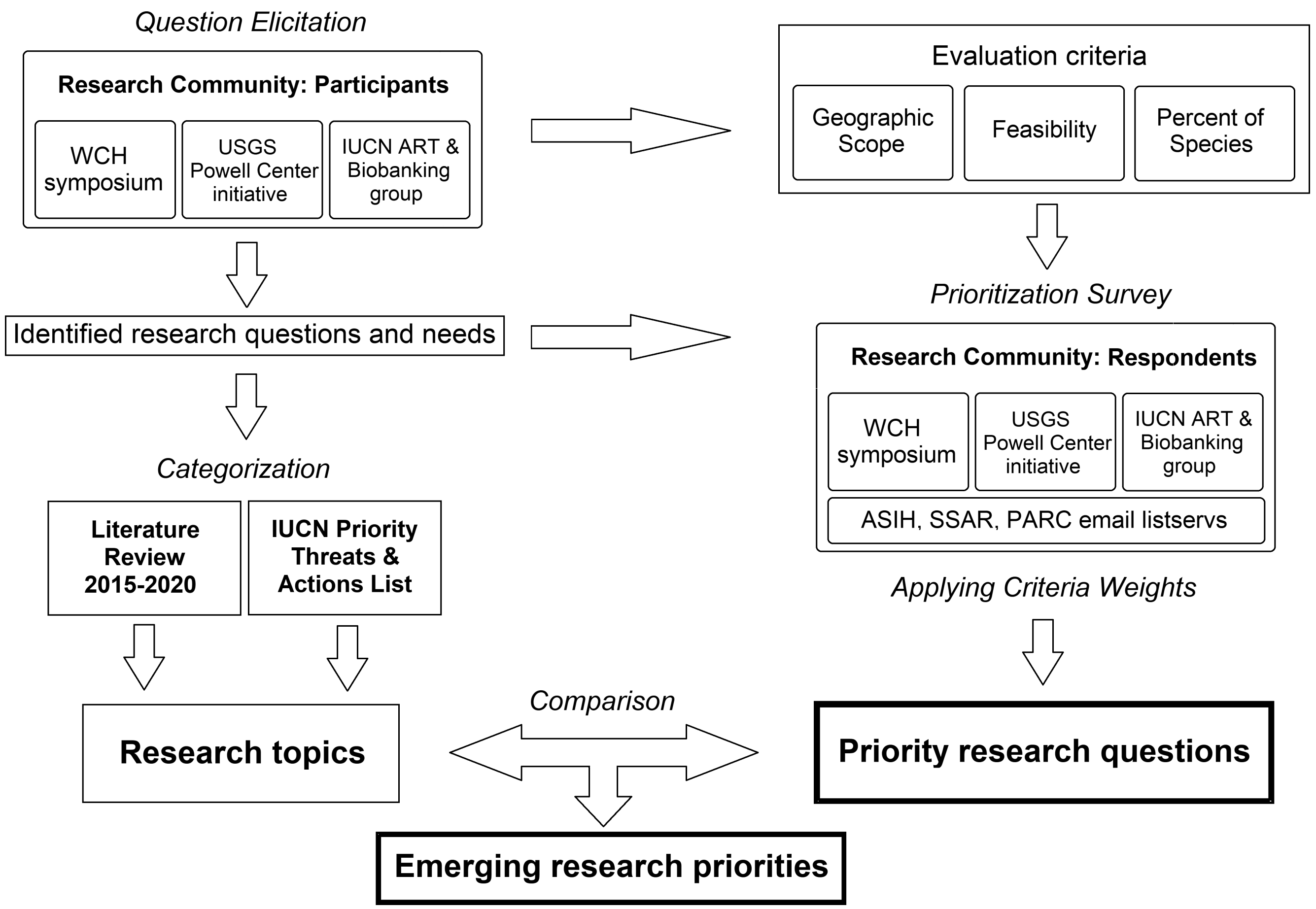


FIGURE 1 Conceptual diagram of the elicitation, categorization, evaluation, and prioritization process for determining priority research questions and emerging research priorities. Actions are indicated in italics. Actions initiated by a subset of the authors include *question elicitation*, *categorization*, *survey* submission, application of *criteria weights* to survey responses, and *comparison*. Actions performed by all authors include response to *question elicitation*, the development of *evaluation criteria*, and *survey* response. Bold boxes indicate the outcomes of this process: a list of priority research questions for amphibian research in the 21st century and a list of emerging research priorities, which are arising conservation concerns. ASIH, American Society for Ichthyology and Herpetology; IUCN ART, International Union for the Conservation of Nature, Assisted Reproductive Technology; PARC, Partners in Amphibian and Reptile Conservation; SSAR, Society for the Study of Amphibians and Reptiles; USGS, U.S. Geological Survey; WCH, World Congress of Herpetology.

amphibian conservation needs. After the invited talks, we divided the audience ($n = 32$ people) into five groups and gave instructions to identify research that would be directly relevant to amphibian conservation. Discussions were facilitated by the organizers and additional scientists familiar with decision science methods (Runge et al., 2011). Participants submitted their research questions on index cards with their names, home country, and contact information. During a Powell Center working group ("Elucidating mechanisms underlying amphibian declines in North America using hierarchical spatial models"; https://www.usgs.gov/centers/john-wesley-powell-center-for-analysis-and-synthesis/science/elucidating-mechanisms), we used membership lists of two professional herpetological societies (American Society of Ichthyologists and Herpetologists [ASIH] and SSAR) to identify global amphibian conservation researchers, identified within these societies and country contacts. We note that these societies include some representation from around the world although they are comprised predominantly of individuals from the United States and Europe. Reaching a broad international set of professional herpetologists in this way was not satisfactory (see discussion of further challenges to decrease geographical bias). To increase representation, we used a two-step process. First, we used the lists of country contacts from ASIH and JMIH and, second, we solicited additional contacts from these leaders within their regions. These contacts ($n = 229$) were then invited to contribute research questions. We also solicited questions from members ($n = 10$) of the Assisted Reproductive Technology (ART) and Biobanking working group, which is a part of the Amphibian Specialist Group of the Species Survival Commission of the IUCN.

Because of the potential expectation that broad and global priorities would be perceived to have the greatest importance (independent of the feasibility of conducting the research), we specified that priorities solicited from all groups should follow the guidance of Sutherland et al. (2009) that described criteria for useful research questions. According to Sutherland et al. (2009), a suitable question should be: (1) formulated specifically (i.e., more finely grained than a general topic area such as “disease” or “land-use”); (2) answerable using scientific methods; (3) applicable; (4) considered at a reasonable scale; (5) formulated clearly and answerable with more than a “yes,” “no,” or “it depends”; and (6) have a measurable outcome. To guide responses, we asked that the questions take the specific form of: “[What/Where/How/When] + [Topic/Knowledge gap], [Geographic scale], for [Species/Community], over [Timescale]?” where the elements in the brackets were filled in by the participants. By specifying a standardized format, we hoped to create questions that were easier for survey participants to evaluate and avoid receiving questions that were too difficult to implement and compare to others because of a lack of specificity. We reviewed submissions, removed redundant questions, and edited the remaining questions for clarity and consistency. The final list of 102 questions (Appendix S1) made up the survey that was sent to the broader amphibian conservation community to identify priority research needs.

## 2.2 | Creating evaluation criteria for the research questions

At the WCH workshop, we also requested that Participants contribute their opinion on how research questions should be evaluated for importance and priority. Participants were asked to write down two to three criteria to consider when assessing questions. They were told that the relative “value” of a research question would be determined using a combination of criteria. We summarized the criteria provided by Participants to identify values to assess the importance of research questions. For example, Participants often listed “Benefits multiple species simultaneously” and “Applicability to other species” as reasons why they would designate a research question as valuable and as a priority. We revised these statements into the category “Percent of species that a research question would impact.” We then enumerated the frequency at which each criterion was expressed by Participants. We selected the three criteria with the highest frequency: Geographic Scope, Feasibility, and Percent of Species affected (Table 1) to be used by survey Respondents in prioritizing the research questions (Figure 1).

**TABLE 1** Criteria for assessing the priority and importance of research questions.

| Criterion | Answer values |
|---|---|
| *Geographic scale*—What is the scale of the research question? | 1 = local population |
| | 2 = multiple populations |
| | 3 = single region |
| | 4 = multiple regions |
| | 5 = global |
| *Feasibility*—Considering cost and time, what is the feasibility of the research question? | 1 = low cost and short time |
| | 2 = low cost and moderate time OR moderate cost and short time |
| | 3 = moderate cost and moderate time |
| | 4 = moderate cost and long time OR high cost and moderate time |
| | 5 = high cost and long time |
| *Percent of species*—What percentage of amphibian species would the research affect? | 1 = none |
| | 2 = 1%–25% |
| | 3 = 26%–50% |
| | 4 = 51%–75% |
| | 5 = 76%–100% |

Surveys were sent by S.M. Amburgey (University of Washington) to Participants and to three herpetofaunal organization listservs (ASIH, SSAR, and Partners in Amphibian and Reptile Conservation [PARC]); these Recipients were asked to rank and score the research questions. The survey email included detailed instructions and a request to share the survey widely with the Recipient's networks. A single survey including all research questions had the potential to result in response fatigue (Savage & Waldman, 2008) and deter Respondents unable to commit substantial time (>40 min) to this task. To address this, a survey link with a simple randomizer to direct the Respondent to one of three randomized subsets of 50 questions was used. The Respondent then assigned a numeric score for the three criteria (Geographic Scope, Feasibility, and Percent of Species affected) to each of the 50 questions. Google Forms and the FormCreator add-in (Automagical Apps, 2020) was used to randomize the presentation of questions within each of the three surveys. Basic information about each Respondent was collected to contextualize their responses, such as their country of residence, the country(ies) in which they worked, their profession (e.g., federal, state, or provincial agency, academia, zoo or aquarium, non-governmental organization [NGO], or other), and how long they had worked in the field of amphibian conservation. Recipients were given 3 weeks to return completed surveys and were sent three reminders, except for those reached through professional listservs as these did not allow reminders. The survey concluded 2 weeks after the final reminder. Incomplete survey responses were not used.

## 2.3 | Applying criteria weights

We evaluated how sensitive the ranking of research questions was to the relative importance of each of the three criteria (Figure 1). We calculated a weighted average of the mean score for each question and considered three different weightings: (1) all criteria were assigned equal weight ($w_i = 0.33$); (2) one criterion was assigned a high weight ($w_i = 0.8$) while the others were assigned a low weight ($w_i = 0.1$); or (3) two criteria were assigned moderate weights ($w_i = 0.4$) with the other criterion assigned a low weight ($w_i = 0.2$). In all evaluations, the sum of $w_i = 1.0$. These different weighting schemes accounted for interactions among components of a particular project. For example, a project with high logistical costs (and thus less feasibility) would be more valuable if it affected a large number of species or had broad geographic applicability. We used this system to determine priority needs based on the Respondents' top-weighted survey questions. Priority research questions were considered those that remained in the top 25 when ranked across these alternative weighting schemes.

## 2.4 | Identifying recent research topics from the published literature

To contextualize the current direction of amphibian decline research and how it relates to research needs articulated by the amphibian conservation community in 2020, we summarized a subset of the published literature over the 5 years prior to the survey (i.e., 2015–2020; Figure 1). Three of the authors systematically searched the literature in five high-impact conservation science journals. Animal Conservation, Biological Conservation, Conservation Biology, Conservation Letters, and Journal of Applied Ecology are considered broad in scope but have a conservation focus. Within these journals we used two search engines (Google Scholar and Web of Science) to look for the key words "amphibian conservation." We limited journals to those with an international conservation focus, recognizing that the publication of research results may be biased to conservation issues of North America and Europe (e.g., Brito, 2008; Winter et al., 2016). However, these journals represent rigorous international conservation biology research (Christie et al., 2021). We checked the resulting publications for relevance (e.g., a publication needed to be focused on amphibian conservation rather than simply mentioning it as an example) and saved titles, keywords (where present), and abstracts (or the first paragraph of the introduction when an abstract was missing) as a text file (Appendix S2). We used the R package *tidyverse* (Wickham et al., 2019) in Program R (R Core Team, 2020) to extract and calculate the frequency with which words were used. We excluded common "stop" words (e.g., "the", "and", and "to") and did not enumerate use of the keywords "amphibian/amphibians" and "conservation" as those terms were included in our initial search. We also counted word combinations when we considered their combined use important for context (i.e., "climate change", "*Batrachochytrium dendrobatidis*", and "Red List"). We used this list of terms (i.e., words and word combinations) to identify the top 50 research topics most referenced in these publications and considered the frequency of usage as proportional to the importance in the amphibian conservation community early in the 21st century.

Four of the authors separately categorized each of the submitted research questions into the top 14 topics derived from the word frequency analysis (we note that the 15th ranked topic was "declines," which is the context for the present work). In cases where all elements of a question did not fit in existing topics, a new topic was added. A question was considered to fit in a topic if it was identified by any of the four authors (i.e., a single question could be categorized into multiple topics because we intended to capture the range in perspectives represented in the questions rather than to reach consensus). Thus, we did not recategorize questions that were assigned to multiple topics and present a total frequency for each research question across all topics.

## 2.5 | Categorization of research needs relative to IUCN threats and actions

The keyword frequency analysis clearly illustrated emerging topics, but they were too general to represent the identified threats and actions as articulated by the IUCN species status assessment experts. Therefore, a second analysis was conducted where the same four authors categorized each of the questions relative to the primary threats and conservation actions listed in the IUCN-CMP classification (IUCN-CMP, 2012; Figure 1).

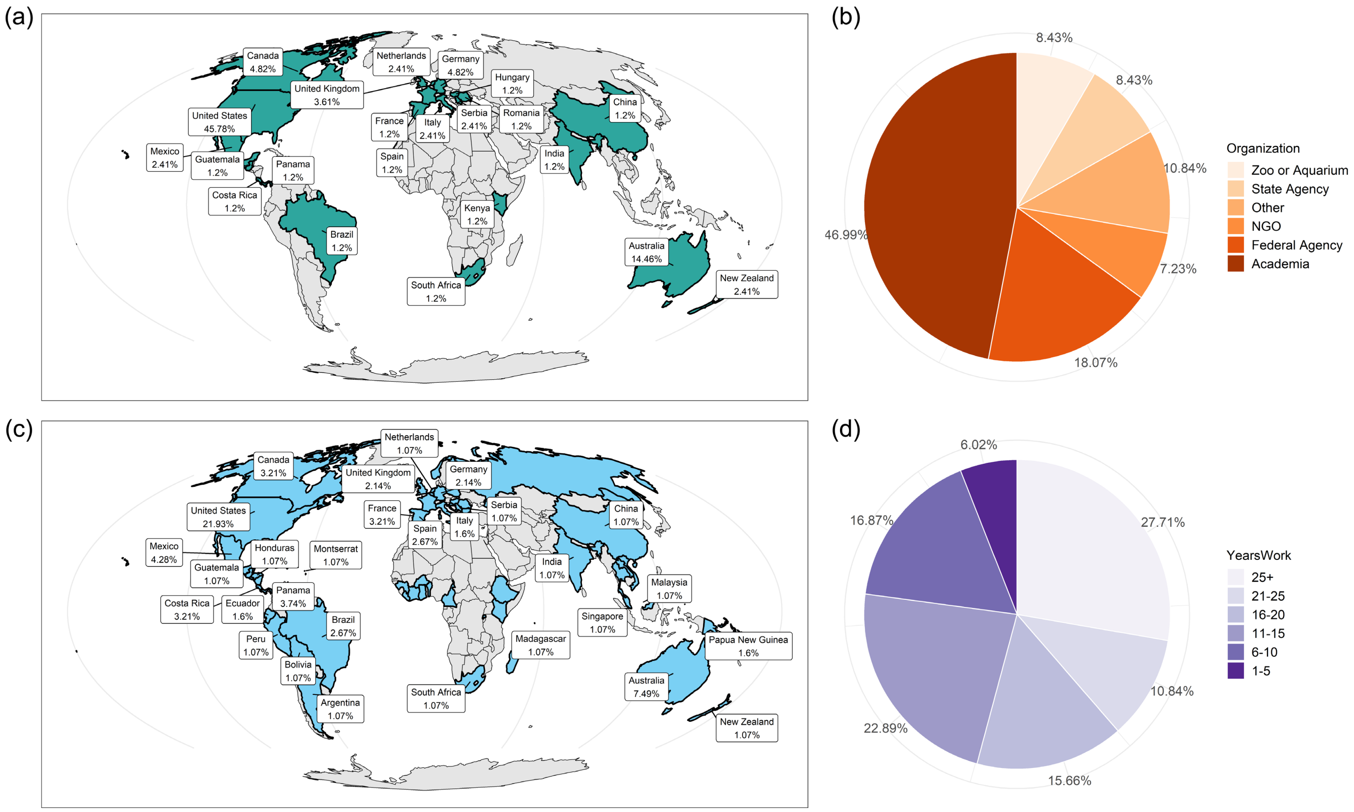


**FIGURE 2** Summary information on survey respondents. (a) Map of all countries in which respondents' organizations were based (green fill). The percentage of the total number of respondents' organizations located in each country is noted. (b) Pie chart summarizing the percentage of respondents working in each organization type. NGO stands for non-government organization. (c) Map of all countries in which respondents' work was or is currently being conducted (blue fill). The percentage of the total number of respondents with work that occurred or is occurring in each country is noted. Each respondent could conduct work in multiple countries. For ease of viewing, we only show those percentages greater than or equal to 1.07% (two people). (D) Pie chart summarizing the percentage of respondents with each category of years working in amphibian conservation.

## 3 | RESULTS

### 3.1 | Eliciting research needs, generating questions, and survey response

We received 102 research questions from Participants: 55 from the WCH workshop, 28 from the Powell Center group, and 19 from the ART and Biobanking group (Appendix S2). We received completed surveys from 83 Respondents but were unable to determine how many people were reached. We do not know how many Respondents came from each source because listserv membership is private information. Further, we asked Recipients to forward the survey to their research networks and do not know if, and to what extent, that occurred. There was fairly even representation across the three sets of randomized questions (23, 29, and 31 Respondents per survey subset). Respondents were based in 22 different countries, with minimal representation of the "Global South." Countries that were colonized or otherwise have a history of minimized geopolitical, socioeconomic, or military power due to historical or current power imbalances (e.g., Mesoamerica, Central America, and Africa) are oftentimes referred to as the "Global South," though we avoid these terms henceforth due to concerns related to this terminology (Haug, 2021). Australia, Canada, Germany, the United Kingdom, and the United States accounted for 73% of responses (Figure 2a). India and countries in Africa, West Asia, and Central and South America were notably under-represented among Respondents. Similarly, the countries where most Respondents worked were biased toward the United States and Europe (54%; Figure 2c), although many Respondents ($n = 69$) conducted work in other countries. Respondents were predominantly from academia (nearly 47%) followed by government agencies (nearly 18%; Figure 2b). NGOs were least represented (7.23%). Respondents represented a range of experience. Most indicated >25 years or between 11 and 15 years of work in the field of amphibian conservation, while only a

TABLE 2 Top 25 questions provided by participants (with equal weighting). Questions in bold type ($n = 12$) are those robust to emphasis of each metric (i.e., consistently ranked in the top priority questions across all alternative weighting scenarios).

| |
|---|
| **How can we optimize habitat and connectivity protections from increasing land-use effects, at landscape spatial scales, for multispecies amphibian assemblages, over multidecadal time scales?** |
| **How will land-use change and climate change necessitate assisted migrations at the global scale in the next 100 years?** |
| **What are the best methods for creating self-sustaining wild populations of Bd-susceptible amphibian species worldwide over the next 50 years?** |
| **How are pesticides linked to global decline of all amphibians in the last several decades?** |
| **How can we control the spread of novel, undescribed, and emerging diseases at the global scale that can impact amphibian communities over the next few years?** |
| **How can we optimize at-risk amphibian species protections given uncertain threats (including climate change, disease, and other context-specific risks) at landscape spatial scales over multidecadal time scales?** |
| **What is the genome-wide genetic architecture of Bd-resistance in Bd-susceptible and Bd-resistant amphibian species worldwide and can this information be used to increase Bd-resistance by improving captive breeding programs in the next 10 years?** |
| **What are effective ways of limiting global human-mediated cross-continental spread of amphibian infectious diseases from one amphibian community to another over the next 5 years?** |
| **How do we use long-term (10 years+) species and habitat monitoring to assess the effectiveness of global habitat restoration interventions and provide evidence for other similar projects?** |
| **What are the features or mechanisms that allow populations to recover from Bd outbreaks or persist in the presence of Bd, in Bd hotspots including Central America and the Western United States, for Bd-susceptible amphibians, over the last three decades (or more)?** |
| **What are the global effects of amphibian infectious diseases over the next 5 years on amphibian communities in areas with intensive agriculture?** |
| **How can the collection and cryo-storage of reconstitutable genomes protocols (gametes, gonadal tissue, and/or their stem cells) become incorporated into standard practices of global amphibian conservation and management procedures (through training and capacitation of ex situ management staff) in the next 20 or more years?** |
| How can amphibian populations in resource-poor countries be monitored effectively at a national level on an annual basis? |
| How do we identify at-risk or threatened amphibian populations (at a species or genera level), representative of key geographic areas, for genetic management and assisted geneflow using strategic biobanking and assisted reproductive technologies (ARTs) in the next 5 or more years? |
| What global strategies are being implemented to predict and manage ex situ populations of all amphibians into the future (10–100 years)? |
| How can we mitigate the increasing prevalence and intensity of wildfire, driven by climate change, on the world's forest-adapted amphibians over the coming two decades? |
| Can habitat manipulation or creation of environmental refuges mitigate the impacts of Bd on threatened anurans, particularly those likely to suffer substantial declines over the next decade? |
| What are the basic needs for global institutional and field partners to begin the implementation of bio-banking strategies in the next 5 or more years? |
| What is the role of genetic management in the establishment of captive breeding programs in the next 5 or more years for all amphibians globally? |
| How can we apply population monitoring strategies in underdeveloped countries, with budget constraints, for long-term ecological studies of all amphibians (10+ years)? |
| Where amphibians feature in traditional indigenous knowledge (globally), how should herpetologists respectfully go about integrating this knowledge with western science—to better conserve amphibians in the next 100 years? |
| Can captive-bred amphibian populations become more resilient to Bd infections through assisted evolution (e.g., selective breeding, genetic engineering, and genetic rescue) globally for species that have experienced massive declines or extinctions in the wild over the next decade? |
| How can an efficient global platform for following long-term dynamics of persistence and spatial organization of common amphibian species breeding sites be established and maintained? |
| What threatened amphibian species are currently found outside protected areas globally? |


**FIGURE 3** Results from a text analysis of recent (2015–2020) publications on amphibian conservation. Size and color of each point represent the frequency at which these terms occurred in relevant publications. The dotted line highlights the top 14, most-frequent topics in the recent literature. We show here the top 50 most frequent terms found in the published literature, which had a minimum of 55 mentions each across 234 articles.

few (~6%) indicated 1–5 years' work in this field (Figure 2d).

## 3.2 | Applying criteria weights to survey responses

Of the top 25 prioritized questions, 12 were robust (i.e., not sensitive) to variation in the relative importance of the three evaluation criteria (Table 2). These research questions emphasized topics such as disease, pesticide use, land-use and habitat change, climate change, and innovation of new conservation technologies or monitoring protocols. Collaboration with Indigenous knowledge holders and advancement of amphibian conservation in resource-limited countries were not widely identified topics but were highly ranked by Respondents when assessed via our three criteria. Whereas we asked Participants to identify research needs that were directly relevant to amphibian conservation, nearly all questions involved a global focus rather than a regional or local scale and were often generalized to amphibian communities or broad categories of amphibian species (e.g., "threatened" or "Bd-susceptible"). Most questions specified durations that were short- (>1 but ≤10 years) to mid-term (multi-decadal) with a few noting "long-term" or 100-year timespans.

## 3.3 | Identifying recent research topics from the published literature

Our search of five high-impact conservation journals yielded 234 articles. These article titles, keywords, and abstracts used 6214 terms, each one used from 1 to 375 times across all articles. Fifty terms were used at least 55 times (Figure 3). The top 14 of these terms were referenced at least 118 times across all 234 articles, and these 14 terms were the topics under which we categorized submitted research questions. These 14 topics ranged in focus from disease to habitat types and in scale from population-level to individual taxa-level (Figure 3). We identified 30 additional topics within the solicited research questions that were not included in these 14 high-frequency topics

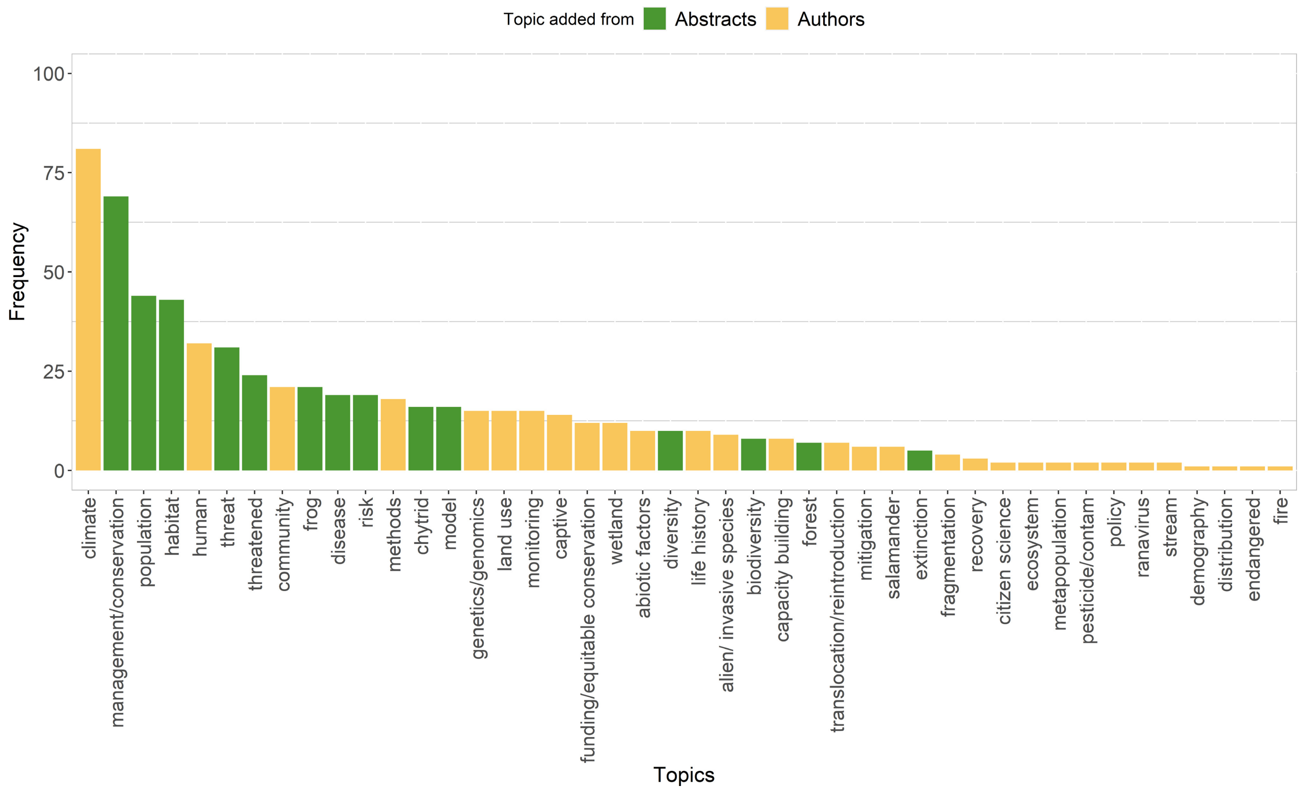


**FIGURE 4** Frequency distribution of topics addressed in research questions. Topics in dark green were drawn from published abstracts while those in yellow were added by four of the authors when a research question was not sufficiently described by abstract topics. Research questions were assigned to topics by all four authors and could be included in more than one topic.

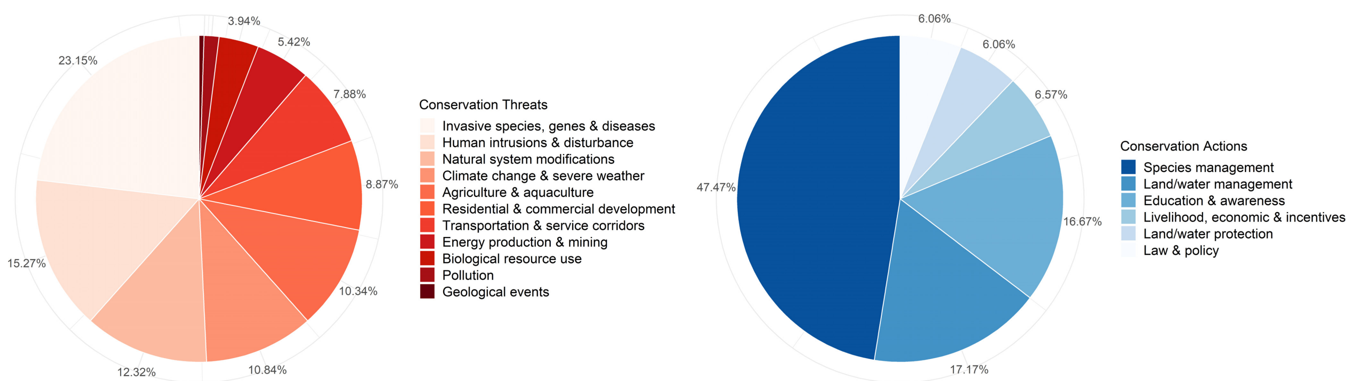


**FIGURE 5** Proportion of research questions ($n = 102$) that were categorized into each of the IUCN's Priority List of Threats (red) or Actions (blue). IUCN, International Union for the Conservation of Nature.

(e.g., "mitigation" and "genomics/genetics"; Figure 4). Each of the 102 research questions were categorized into one or more of these 44 topics.

## 3.4 | Categorization of research needs relative to IUCN threats and actions

Many (82) of the 102 research questions were categorized under a threat identified by the IUCN (Figure 5a), and about half (42 questions) were categorized under more than one threat. "Invasive and other Problematic Species, Genes and Disease" was the primary threat category (47 questions, Figure 5a). Nearly all (100) of the 102 research questions were categorized under at least one action identified by the IUCN (Figure 5b), with 86 questions categorized under more than one action. The primary identified action ($n = 94$) was "Species Management" and focused on recovery, reintroduction, and ex-situ conservation (Figure 5b). We categorized

80 questions as containing both IUCN threats and actions. One-fifth (20 of 102) of the questions did not relate to any direct threat but focused on methods of conservation and research (e.g., captive breeding or monitoring in resource-poor countries).

### 3.5 | Emerging research needs

Significantly, there was some mismatch between the research priorities identified by the Participants, literature, and IUCN. Additional (emerging) topics were highlighted by research questions (Table 2) but did not fall under existing topics from the literature or within the IUCN list. Three emergent topics predominated: (1) Genetics and genomics research—this topic was not mentioned frequently in the published literature, although the need for increased capability for this research was evident from top research questions, (2) Climate change—this topic was not among the top 14 identified in our literature search (though it was within the top 50, see Hakkinen et al., 2022; Figure 3) but was represented in several top research questions, and (3) Inclusion in science and the socioecological (human) aspect of amphibian conservation. This third topic, for example, encompassing community science and the braiding of Traditional Ecological Knowledge with Western scientific approaches (e.g., Abu et al., 2020), was recognized as key in developing and applying effective amphibian conservation management. Two of these emerging topics (inclusion and increased capacity in genomics research) could be considered more broadly as strategies to be applied to many of the research priorities.

## 4 | DISCUSSION

Conservation is limited by gaps in knowledge, disconnects between knowledge and action, and the challenges of scaling research results to regionally, nationally, or globally coordinated actions (e.g., Bertuol-Garcia et al., 2018; Grant et al., 2019; Reid et al., 2019). Additional challenges include competing interests, lack of political will, and funding limitations (e.g., Grant et al., 2019; Waldron et al., 2013). Overcoming each of these limitations is necessary for conserving global amphibian biodiversity and can be facilitated by the identification of priorities.

We present 12 research priorities (questions) among 102 research needs that were elicited from individuals in the global amphibian research community. We find that these 12 priorities are robust to variation in the perceived importance of assessment metrics (Table 1) and that most will likely require considerable collaboration and resources to implement. Although ambitious, if addressed, these priority questions are expected to yield benefits for conserving amphibians and maintaining diversity. We note that the top priorities address different aspects of amphibian decline and acknowledge that they may interact. Further, costs are not contextualized on an ecosystem scale. Addressing multiple priorities may be evaluated in a local context to find an optimal combination.

We found that "management" and "conservation of populations and habitats" were frequently referenced topics in the published literature. Despite this, research on the "effectiveness of alternate interventions" remains a high priority articulated by the amphibian conservation community. For example, research into the amphibian pathogen Bd was the second-most frequent topic in the literature. Even so, mitigation of Bd remains intractable in the field (Garner et al., 2016, but see Geiger et al., 2017; Lubick, 2010); identifying mitigation strategies for disease remains an important uncertainty as 6 of the 12 research priorities (Table 2) referenced disease (i.e., research on how disease affects populations; how to manage for resilience to disease threats). Beyond the obvious conservation issues elevating the disease topic, the prominence of disease in the literature may also stem from the ability of humans to observe sick and dead amphibians and relate to its threat. Increasing human ability to perceive and acknowledge other kinds of threats may be significant in advancing conservation (i.e., "social capital," sensu Olson & Pilliod, 2022), and community science is one strategy that could be applied to achieve advances in conservation (e.g., Lawson et al., 2015).

New and emerging priorities included understanding and mitigating the effects of climate change, and exploring human dimensions (e.g., Olson & Pilliod, 2022) of amphibian conservation, along with research on amphibian community assembly and responses to threats, research methods, genomic technologies, and the impacts of land-use (Figure 3). Though our directions were explicit and requested questions that were specific and had a measurable outcome (see *Eliciting research needs and generating questions*), several of the solicited priority research questions focused on population monitoring and research methods. That this focus emerged is not surprising as monitoring and research methods are critical for making management decisions and for implementing adaptive management programs (Williams, 2011). Putting information into action through processes such as active and adaptive management provides a potential path to move conservation forward.

Successful conservation requires implementation, and a lack of information may not be the impediment to action. In some cases, research that promised resolution of priority management uncertainties has been conducted for over a decade without resulting in defined implementation strategies (e.g., Frick et al., 2016; Grant et al., 2019).

The perception of these topics as continued research priorities may be due to: (1) failure to focus on critical uncertainties that meaningfully improve management (Bolam et al., 2019); (2) the impediment of management by factors other than ecological uncertainties (e.g., lack of funding, complexity in the scope of the problem; Converse et al., 2013, Converse & Grant, 2019, Walls et al., 2017); or (3) inadequate translation of research results to conservation action (Cook et al., 2013; Grant et al., 2019). The last point—inadequate translation of research to action—is frequently blamed for stalemate in implementing actions, and some view it as a general pattern in conservation biology (Godet & Devictor, 2018; Schmidt et al., 2020).

However, this perceived lack of translation of research into action is not universally true. For example, recovery of boreal toad (*Anaxyrus boreas*) populations in the western United States has been aided by integrating research on chytrid fungus infection dynamics (Gerber et al., 2018), and the removal of stocked fish facilitated recovery of the Sierra Nevada yellow-legged frog (*Rana sierrae*) even though it appeared to be most threatened by disease (Knapp et al., 2016). In Australia, dedicated programs, for which knowledge of Bd dynamics and impacts is fundamental, have stopped several species from extinction (Hunter et al., 2018; McFadden et al., 2018; Scheele et al., 2021; Scheele et al., 2022; Skerratt et al., 2016). Other species are managed based on the knowledge gained on Bd (Alford & Rowley, 2018; Hunter et al., 2018; McFadden et al., 2018), and experimental translocations for other species are being undertaken in habitat that would formerly have been viewed as unsuitable based on knowledge of environmental refuges (Hoskin & Puschendorf, 2014). These locally focused conservation efforts, supported by scientific research, are examples of evidence-based conservation, which seeks to assess which conservation strategy works best, and thus improve the connection between research and implementation (e.g., Petrovan & Schmidt, 2019; Schmidt et al., 2019). Methods like structured decision making can also improve the utility of science for specific management problems (Runge et al., 2011).

Topics derived from the published literature in high-impact conservation journals and from the IUCN aligned with priority research needs, but we identified additional emerging topics of importance to amphibian conservation from individuals in the global amphibian conservation community. These topics included climate change, pesticide use and other anthropogenic influences, and genetics and genomics. It is interesting that topics such as climate change and genetics/genomics are emerging topics which have been less-well represented in the recent literature. Climate change and genetics act on long-time scales; it is possible that the community's response to the amphibian conservation crisis has discounted these more "distant threats" while addressing more immediate stressors (Murray et al., 2014).

Additionally, participants highlighted the emerging need to improve inclusion of marginalized groups in conservation and to elevate grassroots participation. Inclusion is a particularly encouraging emergent topic because local conservation action is the key to addressing global amphibian decline (Grant et al., 2018). In a number of countries, community science supports multiple aspects of conservation research on amphibians, including initiating evidence-based conservation projects (Petrovan & Schmidt, 2019), collecting information on critical life stages (Johnson et al., 2011; Semlitsch, 2002), monitoring population trends (Mossman & Weir, 2005), and surveying for disease (Frías-Alvarez et al., 2010; Spitzen-van der Sluijs et al., 2013). Networking across several societal sectors (e.g., local communities and species and threat specialists, sensu Olson & Pilliod, 2022) can raise amphibians' "social capital" for conservation attention when managers are faced with competing conservation priorities among taxonomic groups (Olson & Pilliod, 2022). Furthermore, the emerging focus on biobanking may reflect new opportunities to integrate captive populations into conservation efforts, as has been done in the last decade by zoos and aquariums that maintain ex situ amphibian populations (Murphy & Gratwicke, 2017a). For example, biobanking efforts are being integrated in conservation actions worldwide (Naranjo et al., 2022) and are becoming an essential component of conservation (Silla et al., 2023). Importantly, local journals have limited impact on the field at large as they are likely not read widely by the global research community. This means that, while the work may be published and available in local journals, the wider research community may miss it. This also means that the answers to those research questions (and demonstration of the efficacy of attempted conservation actions) may not be widely available and, therefore, may be asked repeatedly. Additionally, an increasing number of amphibian conservation problems are framed and addressed using a formal decision-analytic approach (Converse & Grant, 2019; Wright et al., 2020). This process can identify priority information needs for specific population management goals using a value-of-information analysis (Canessa et al., 2018, 2020), which formally quantifies the relative importance of uncertainties relative to a particular decision. Further, decision analytic tools include methods to identify critical stakeholders (Reed et al., 2009) and thus improve inclusion.

The IUCN's first global amphibian assessment (Stuart et al., 2004) amplified the plight of amphibians and specifically laid out the need for capacity building and improved global coordination at a broad scale. "Global coordination" does not refer to prescriptive directives mandated by a global authority but rather collaborative efforts to identify overarching needs and leverage research capacity (e.g., Zimkus et al., 2018) and results (Gascon et al., 2007; Shoo et al., 2011). The Amphibian Conservation Action Plan (ACAP; Gascon et al., 2007) was inclusive for the times (early 2000s, with 78 scientists from 16 countries participating). The ACAP undertook a high level of organization and systematically laid out 11 thematic areas for action (Mendelson et al., 2006) but recognized that conservation priorities vary regionally (Gascon et al., 2012) and thus progress has been uneven (Catenazzi, 2015). Integration of these newly identified community-sourced amphibian conservation priorities warrant consideration for specific focus in the next phase of global amphibian conservation actions. This ACAP has been recently updated; the update is based on the 2015 online version (Wren et al., 2015) and includes many of the concerns addressed in this paper (IUCN SSC Amphibian Specialist Group, 2022), supporting the research needs we present here. Although climate change is a current ACAP theme, new themes could address inclusion and human dimensions of amphibian conservation, genetics and genomics, and biobanking.

Our efforts involved solicitation of research needs through multiple venues, with an aim to gather experiences from a broad section of the amphibian conservation and research community. We sought to create an open process through which any member of this community could contribute. However, there are clear shortcomings that are perhaps illustrative of the bias and lack of inclusivity that is pervasive in efforts to acquire a global perspective. We acknowledge that our sample is not representative of the global conservation community in herpetology and is limited in demographic and cultural representation, particularly from countries in Africa, Asia, South America, the Caribbean, and Mesoamerica. We have identified several areas of improvement, based on our experience here, highlighting barriers to greater inclusivity in these types of efforts. First, accessibility (i.e., knowledge of who is doing the work as well as the ability to reach those involved) may have reduced our ability to contact a segment of the amphibian conservation community. To remedy this, one approach is to allocate funding specifically directed at connecting conservation practitioners and cultivating global networks. Second, although we attempted to increase our network of contacts by identifying research leaders in under-represented areas of the globe, our responses were highly skewed from North America and Europe. A potential response to this disparity could be more personal engagement of professionals in these areas. Third, although we used multiple approaches (e.g., invitations to our symposium, personalized email summaries and reminders, listserv announcements, newsletter postings; sensu Trespalacios & Perkins, 2016), these approaches had a limited effect in increasing participation of Respondents beyond the listserv and professional society community. A more expansive effort to include national societies and herpetological listservs in under-represented areas could help. Fourth, while there is a strong international component to the herpetological societies we queried and membership includes scientists from countries outside North America and Europe, the number of representatives from these underrepresented countries is low (e.g., ∼20% of ASIH members are from outside the U.S.). This uneven representation is problematic because it skews responses, but the root of the problem may be similar even for more local societies. For example, there are numerous socio-economic barriers to inclusion in professional organizations that limit the participation of many contributors even at a local level. Fifth, conducting this solicitation and survey during the global pandemic (SARS-CoV-2) likely limited participation. Participation was certainly more difficult or impossible for those without adequate infrastructure or those struggling with economic, logistical, health and mental health issues, or other personal repercussions of the pandemic.

Although we did not receive equal responses from the entire global amphibian research community (we note that we had particularly limited representation of amphibian conservation biologists in amphibian diversity hotspots), we believe this to be the best available comprehensive effort to identify and prioritize amphibian conservation research needs. Importantly, we solicited responses from *individuals* rather than *organizations* for their opinions about conservation priorities for amphibians. We see this as an important step toward expanding our own conservation networks and recognizing the need for researchers and organizations to become more deliberate in how they address long-standing socioeconomic barriers and biases to collaborative conservation. To facilitate meaningful progress, we stress the need to increase investment and collaboration in informing conservation management in resource-limited regions. Significant economies of scale and opportunities to leverage information exist when commonalities are identified and pursued in a collaborative manner (e.g., Griffiths & Dos Santos, 2012). Finally, increased coordination of research initiatives, particularly those that test the effectiveness of conservation actions, is required to stem the loss of additional species and populations this century.

## 5 | CONCLUSION

Our goals were to (1) identify priority research aimed at reducing amphibian declines and recovering amphibian biodiversity, and (2) compare research needs from the early Anthropocene, as reflected in the literature and set forth by a global conservation organization (IUCN), to concerns articulated by individuals in the amphibian conservation community in 2020. Prioritizing critical research needs for applied conservation is especially necessary when resources are limited and time is short (Grant et al., 2019). Knowing if the research priorities of the conservation community align with "established" needs (as represented in the literature or determined by global entities) is useful for moving toward timely and relevant conservation action. The diversity of topics identified here demonstrates the presence of enduring uncertainties and supports the expectation of multiple drivers of amphibian decline (Grant et al., 2016), yet, despite these constraints, forward movement in implementing conservation actions can be achieved (sensu Semlitsch, 2002). From the research questions submitted, it was clear that the articulation of research needs is driven by local interests and that the amphibian research community continues to identify and highlight emerging priorities in amphibian conservation beyond issues addressed in the recent published literature. Our efforts in engaging the global amphibian community illustrates that greater attention to increase representation in these collaborative endeavors is needed, particularly inclusion of persons working in amphibian "hotspots" in Africa, Asia, South America, Mesoamerica, and the Caribbean. We hope that this list of priority questions will not only encourage increased dialogue about the path forward for amphibian conservation but provide information that can facilitate action.

## AUTHOR CONTRIBUTIONS

E.H.C. Grant, E. Muths and S.M. Amburgey conceived the idea, conceptualized, and wrote the initial and subsequent drafts of the manuscript. B. Gratwicke contributed to the conception of the manuscript and worked on early drafts. E.H.C. Grant, E. Muths, S.M. Amburgey and B. Gratwicke proposed and implemented the workshop. S.M. Amburgey conceived and implemented the survey, monitored and organized survey reminders and responses, and designed and implemented survey data analyses with technical input from E.H.C. Grant and E. Muths. S.M. Amburgey also created the figures summarizing the survey results. All authors anonymously submitted questions for, and responded to, the survey and provided comments on a draft of the manuscript.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

All data are presented in the manuscript and Supporting Information: appendices.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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