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Research Article

Confronting the “knowledge-action gap” in invasive species prevention: A study of biosecurity behaviors among aquarium hobbyists in Illinois, USA

Elizabeth J. Golebie [a], Carena J. van Riper [a,*], Greg Hitzroth [b], North Joffe-Nelson [a]

[a] Department of Natural Resources and Environmental Sciences, University of Illinois Urbana-Champaign, 1102 S. Goodwin Ave, Urbana, IL, 61801, USA
[b] Illinois-Indiana Sea Grant, Illinois Natural History Survey, Prairie Research Institute, Glencoe, IL, 60022, USA

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ABSTRACT

Biological invasions threaten water resources worldwide owing to interrelated biological and anthropogenic drivers of change. Though the role of people in the (un)intentional spread of aquatic invasive species is increasingly recognized as a priority, there are widespread assumptions about the importance of public awareness in explaining biosecurity behaviors. A disconnect exists between what people think and what they do—as articulated by the simple but powerful “knowledge-action” gap—that warrants attention to clarify how environmental social science research can most effectively advance invasive species prevention. Using survey data collected from aquarium hobbyists in the U.S. state of Illinois, we investigated the role of belief systems in shaping intentions to engage in biosecurity behaviors, such as purchasing only native species as pets. We also examined how beliefs were rooted in multiple forms of knowledge. Self-efficacy was the strongest driver of intended biosecurity behavior, whereas both perceived benefits and risk perceptions were instrumental in explaining hobbyists’ decisions. Beliefs were informed by two types of reported knowledge, which in turn, were influenced by a range of information sources. Our results suggest that a more nuanced conceptualization of public awareness is urgently needed given its critical but often misunderstood role in the formation of beliefs that influence participation in biosecurity behaviors. Knowledge of both biological invasions and biosecurity behaviors, in addition to information sources, needs to be distinguished in future research. These multiple forms of knowledge serve as the foundation for belief systems that activate behavior change among aquarium hobbyists. We also argue that science communication and outreach campaigns that highlight the risks of invasive species while strengthening self-efficacy and perceived benefits of prevention will be the most effective pathways for fostering hobbyist engagement in biosecurity behaviors.

1. Introduction

Prevention of aquatic invasive species (AIS) transport is a key goal for aquatic ecosystem management. The impacts of biological invasions include decreases in native species abundance and diversity, as well as abiotic effects such as altering nutrient availability in waterbodies (Gallardo et al., 2016). Annual costs associated with such invasions have increased exponentially, exceeding $23 billion USD in 2020 (Cuthbert et al., 2021). Consequently, numerous national and international laws have been implemented to minimize the risk of species introductions (Doelle, 2003; Firestone and Corbett, 2005), and outreach programs have been developed to increase knowledge of the problem of AIS and the ways hobbyists can take action (Funnell et al., 2009; Golebie and van Riper, 2023; Seekamp et al., 2016). However, new invasive species continue to be detected every year in most regions of the world (Bailey et al., 2020).

The aquarium trade is a crucial pathway for invasive species transport (Barroso Magalhaes and Simoes Vitule, 2013) yet has been underrepresented in previous water biology research. Although policies have been implemented to minimize the spread of invasive species through the pet trade, many have ultimately been unsuccessful (Patoka et al., 2018). Aquarium species may comprise as much as one third of the most pressing invasive species threats (Padilla and Williams, 2004). Thousands of non-native aquarium species are traded internationally, meaning that aquarium hobbyists are at high risk of accidently causing a species invasion (Chapman et al., 1997; McDowall, 2004). Hobbyists often intentionally release fish, because of an array of factors such as fish growing too large, or the hobbyist moving or losing interest (Gertzen

* Corresponding author.
E-mail address: cvanripe@illinois.edu (C.J. van Riper).

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et al., 2008). For example, the number of aquarium fish released in Montreal in one year was estimated to be over 10,000 (Gertzen et al., 2008). Aquarium retailers often sell large fish at small sizes, which unintentionally increases the likelihood that hobbyists purchase a species they will be unable to care for in the long term (Holmberg et al., 2015), particularly given that size and longevity are the primary reasons hobbyists release their pets (Stringham and Lockwood, 2018). Aquarium hobbyists can prevent the spread of invasive species by engaging in biosecurity behaviors during species purchasing (e.g., selecting only native species) and disposal (e.g., rehoming or euthanizing unwanted pets).

Patterns in biosecurity behaviors among aquarium hobbyists have been investigated in previous research to provide guidance on the most effective prevention measures for reducing risks of environmental hazards (Banha et al., 2019; Wood et al., 2022). Although this body of work has provided insight on how to implement more targeted science communication (Gozlan et al., 2024; Hughes et al., 2023; Kemp et al., 2017) and establish pathways such as deliberation for strengthening knowledge systems (Henke et al., 2024), few studies have accounted for a theoretically informed range of psychological drivers of risk reduction behaviors. This is problematic because psychological theories can provide insight on the reasons why people may resist or even increase environmental impacts in response to management interventions (Heberlein, 2012). Moreover, there tends to be an underlying assumption in water biology research that raising awareness of invasive species is a panacea for behavior change (Simis et al., 2016). However, longstanding empirical evidence in the environmental social sciences indicates that knowledge does not directly lead to behavior change—a phenomenon known as the "knowledge-action gap" (Kollmuss and Agyeman, 2002; Nguyen et al., 2018). Research is therefore urgently needed to understand how psychological drivers beyond knowledge (Coon et al., 2020; McLeod et al., 2015), can help to explain biosecurity behaviors among key interest groups such as aquarium hobbyists.

A growing body of previous research on the psychology of decision-making has provided valuable insights into the reasons why interest groups engage in biosecurity behaviors (Golebie et al., 2022). Although there are many theoretical frameworks that can be used to explain environmental behavior (Heimlich and Ardoin, 2008), the Health Belief Model (Rosenstock, 1974) is particularly well-suited for understanding biosecurity behaviors given its focus on risk. Further, the model offers a parsimonious framework to fill the gap between knowledge and behavior given that it includes only direct predictors of behavior, in contrast to models such as the Value-Belief-Norm Theory (Stern et al., 1999) that includes a causal chain of multiple indirect predictors of behavior. Specifically, the Health Belief model posits that the most relevant drivers of behavior are risk perceptions and three key beliefs about prevention behaviors: self-efficacy, benefits of the behavior, and barriers to action. Risk perceptions, defined as the perceived severity of threats like species invasions, have been shown to have a strong influence on behaviors related to invasive species prevention (Estévez et al., 2015; Golebie et al., 2021), among other environmental behaviors (Kothe et al., 2019). Likewise, self-efficacy, defined as beliefs about one's ability to effectively complete a behavior (Bandura, 1977), has been found to have one of the strongest influences on invasive species prevention (Clarke et al., 2021; Golebie et al., 2023; Howell et al., 2015). This body of work suggests that perceived benefits that would result from completing a behavior are weighed alongside the barriers or constraints that might limit one's ability to act (Champion and Skinner, 2008). A meta-analysis of the Health Belief Model indicated that barriers and benefits were the strongest predictors of behavior (Carpenter, 2010); however, most of these studies have focused on health behaviors, which have direct personal benefits, in contrast to biosecurity behaviors, whose personal benefits may be more abstract. Thus, deeper knowledge of psychological factors such as risk, self-efficacy, benefits, and barriers can inform efforts to change behavior in the context of biosecurity.

Research guided by the Health Belief Model considers knowledge to be a modifying factor that influences belief systems (Champion and Skinner, 2008); however, this relationship is often assumed and not empirically tested. Past invasive species prevention research has focused a large degree of attention on understanding knowledge or awareness, possibly owing to the emphasis that resource management agencies place on educational outreach. The extant literature has broadly concluded that awareness of invasive species is high (Cole et al., 2016; Eiswerth et al., 2011), yet paradoxically, knowledge is often assumed to be minimally relevant to behavior and is thus omitted from models of behavior change (McLeod et al., 2015). There is recent evidence for knowledge serving as a precursor to beliefs such as the perceived risk of invasive species and self-efficacy of biosecurity behaviors (Moore et al., 2024). Indeed, it could be that there are different types of knowledges that affect beliefs and behaviors (Frick et al., 2004), as well as distinguishable concepts such as familiarity, awareness, knowledge, and information sources that have been conflated in previous research (van Riper et al., 2020). Further insights are needed on the different forms of knowledge that an individual holds, how that knowledge can be derived from informational campaigns, and its influence on beliefs and, ultimately, behavior.

The aim of this study was to evaluate how biosecurity behaviors among aquarium hobbyists in the U.S. state of Illinois were informed by various psychological factors, including information sources, knowledge, risk perceptions, benefits, self-efficacy, and barriers (Fig. 1). Specifically, we addressed the following two research questions: (1) How do beliefs influence Illinois aquarium hobbyists' intentions to prevent the spread of AIS through actions related to their hobby? (2) What are the direct and indirect effects of knowledge on the biosecurity behaviors of Illinois aquarium hobbyists? Understanding the combined effects of knowledge and belief systems on biosecurity behaviors will help to close the knowledge-action gap and enhance environmental communication from natural resource management agencies focused on encouraging aquarium hobbyists to reduce species invasions.

2. Materials and methods

2.1. Study context

This study took place in the U.S. state of Illinois, where Illinois-Indiana Sea Grant has developed outreach campaigns to promote biosecurity behaviors among aquarium hobbyists. These campaigns include *Be a Hero – Release Zero, Take AIM: Aquatic Invaders in the Marketplace, What's in your water garden?* and *What's in your aquarium*? Over the past two decades, these campaigns have been used in conjunction with national-level initiatives (e.g., *Habitattitude*) to raise awareness of aquatic invasive species and change the behaviors of relevant interest groups (Kemp et al., 2017; Lauber et al., 2015). In Illinois, though few studies have been conducted to understand aquarium hobbyists, empirical evidence has indicated that awareness and concern of AIS within this interest group is moderate to high (Seekamp et al., 2016; Mayer et al., 2015). However, fewer than half of these participants reported that they kept AIS prevention in mind when making species purchasing and disposal decisions, for instance by purchasing only non-invasive species.

2.2. Sampling methods

Data were conducted via an online survey that took place during October and November 2022. Respondents were recruited from a Qualtrics panel, which is a list of individuals who have volunteered to take part in survey research in exchange for compensation. For this survey, Qualtrics provided participants with approximately \$5–10 in value with reward options such as cash, airline miles, gift cards, redeemable points, charitable donations, sweepstakes entrance, or vouchers. To be eligible for this study, participants had to live in Illinois, be 18 years or older, and meet at least one of the following requirements: (a) Keep a fish bowl or small freshwater aquarium of five gallons or less; (b) Keep a large

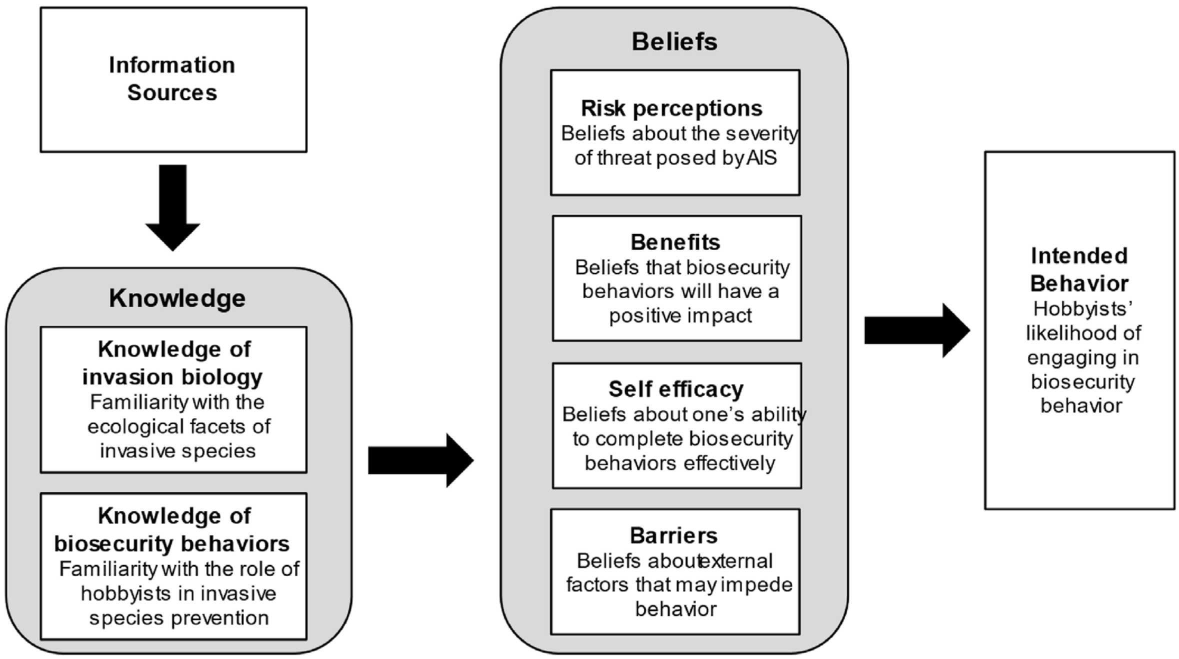

Fig. 1. Conceptual diagram illustrating the variables examined in our study and their definitions.

freshwater aquarium of five gallons or more; (c) Keep a saltwater aquarium; (d) Keep a koi pond or water garden; or (e) Keep indoor aquatic pets (e.g., turtles, frogs).

Responses were discarded and replaced when participants did not complete the entire survey, failed at least one of two attention check questions (Berinsky et al., 2014) or had response patterns that indicated extreme inattention or possible use of bots. This process continued until a final sample size of 219 was attained. All participants who had successfully completed the survey were compensated by Qualtrics. This study was approved by the University of Illinois Urbana Champaign Office for the Protection of Research Subjects (protocol #23131).

2.3. Survey measures

The survey instrument (see Appendix 1) included questions designed to collect information on hobby engagement to measure knowledge, beliefs, and behaviors related to aquatic invasive species. A suite of biosecurity behaviors was identified based on the key activities promoted by Illinois-Indiana Sea Grant's outreach programs: purchasing non-invasive species, quarantining species before introducing them to a pond or aquarium, and sterilizing water prior to disposal to avoid spreading microscopic organisms. The specific items were selected from past research (Seekamp et al., 2016).

Four constructs were hypothesized to directly predict behavior, in line with the Health Belief Model (Rosenstock, 1974). Three items measuring environmental risk perceptions were drawn from past research (Golebie et al., 2023a). This construct asked respondents to report the potential impacts AIS pose to different facets of the environment. Perceived benefits of biosecurity behaviors were measured with six items drawn from past research (Golebie et al., 2023a) and tailored to aquarium hobbyists. For instance, respondents were asked to report the extent to which they agreed or disagreed that biosecurity behaviors would contribute to "maintaining a healthy aquarium or water garden" and "teaching younger generations about the impact of our behavior on the environment." A three-item self-efficacy measure was drawn from past work (Bandura, 1977) and adapted to the context of biosecurity among aquarists. Finally, we defined barriers as external contextual factors that may impede behavior (i.e., "structural barriers" (Crawford and Godbey, 1987)). Three items were identified from informal interviews with experts in the aquarium and water gardening hobbies (Golebie et al., 2023b).

Three variables pertaining to knowledge were measured: (1) knowledge of invasion biology; (2) knowledge of biosecurity behaviors; and (3) information sources. The particular items were informed by past research in an invasive species context (Golebie et al., 2023a), and expert interviews pertaining to aquariums (Golebie et al., 2023b). Three items were used to measure the two knowledge dimensions (see Table 1). Information sources were defined as frequency of consulting sources for advice about the aquarium hobby and measured with five items.

2.4. Analysis

Hypothesized relationships were analyzed using latent variable modeling (Kline, 2015). Using the guidelines of kurtosis index $< |3|$ and skew index $< |10|$, no concerns related to normality were identified. The proportion of missing data was very low (0.07%) and handled with the full information maximum likelihood model. Survey scales were assessed using confirmatory factor analysis. Two items ("family members, friends, or neighbors" and "retailers") were dropped from the information sources scale given factor loadings <0.40 (Hair et al., 2011), which resulted in improved model fit ($\Delta\chi^2 = 79.303$; $\Delta df = 55$). Removing these items also resulted in an information sources scale that was focused on sources that are less accessible to novice hobbyists yet represent potential communication pathways that could be leveraged by agencies (Golebie et al., 2023). All other items had standardized factor loading scores above 0.40 and were therefore retained. Knowledge was measured as a second order factor given correlation >0.70 (Fig. 2). Three measures of internal consistency were used: Cronbach's Alpha (α) $\geq$ 0.70, MacDonald's Omega (Ω) $\geq$ 0.70, and average variance explained (*AVE*) $\geq$ 0.40. All scales met these three thresholds. Acceptable model fit was assumed given Root Mean Square Error Approximation (*RMSEA*) $\leq$ 0.08 (Steiger, 2007), Comparative Fit Index (*CFI*) $\geq$ 0.90 (Bentler, 1990), and Standardized Root Mean Square Residual (*SRMR*) $\leq$ 0.08 (Hu and Bentler, 1999). Acceptable model fit was observed for the final measurement model ($\chi^2 = 571.148$, $df = 327$, $\chi^2/df = 1.75$; $CFI = 0.930$; $TLI = 0.919$; $RMSEA = 0.058$, $SRMR = 0.064$).

After confirming acceptable model fit and scale validity, we estimated a structural regression model to test the predictive relationships among

Table 1
Means (*M*), standard deviations (*SD*), and factor loadings for the intended behaviors, beliefs, and knowledge reported by aquarium hobbyists in Illinois. Reliability metrics reported for each construct include Cronbach's Alpha (α), MacDonald's Omega (Ω), and average variance explained (*AVE*).

Survey Measures	Factor loading	M (SD)
***Intended behavior*[a] ($\alpha = 0.740$, $\Omega = 0.745$, *AVE* = 0.425)**		3.16 (1.00)
Purchase species based on scientific names	0.54	2.57 (1.34)
Purchase only native or non-invasive species	0.68	3.45 (1.26)
Quarantine species before introducing to pond or aquarium	0.75	3.60 (1.28)
Sterilize water (add bleach) used in an aquarium or water garden prior to disposal	0.63	3.01 (1.43)
***Risk Perceptions*[b] ($\alpha = 0.883$, $\Omega = 0.883$, *AVE* = 0.717)**		3.43 (0.82)
Quality of habitat and natural environments	0.85	3.45 (0.93)
Environmental processes (e.g., water cycle)	0.88	3.26 (0.93)
Survival of plants and animals	0.81	3.57 (0.98)
***Benefits*[c] ($\alpha = 0.885$, $\Omega = 0.884$, *AVE* = 0.561)**		4.18 (0.62)
Increasing my own knowledge and understanding of the ecosystem	0.81	4.22 (0.72)
Maintaining a healthy aquarium or water garden	0.83	4.31 (0.71)
Knowing that I have done the right thing to be a successful hobbyist	0.74	4.26 (0.74)
A sense of community among hobbyists	0.64	3.87 (0.85)
Teaching younger generations about the impact of our behaviors on the environment	0.73	4.21 (0.81)
Preserving aquatic resources for my community	0.77	4.19 (0.82)
***Self-efficacy*[c] ($\alpha = 0.843$, $\Omega = 0.847$, *AVE* = 0.649)**		3.80 (0.77)
I understand what I need to do in order to minimize the risk of AIS	0.75	3.62 (0.92)
I am capable of performing the tasks required to minimize the risk of AIS	0.84	3.95 (0.82)
I feel confident in performing the steps necessary to minimize the risk of AIS	0.84	3.84 (0.90)
***Barriers*[c] ($\alpha = 0.804$, $\Omega = 0.822$, *AVE* = 0.611)**		2.31 (0.88)
I lack the necessary resources or equipment	0.71	2.72 (1.09)
I do not have enough time to follow recommended guidelines	0.96	2.19 (1.01)
My health or physical abilities make following recommended guidelines difficult	0.66	2.02 (1.02)
Knowledge[d]		2.55 (1.04)
***Knowledge of invasion biology* ($\alpha = 0.855$, $\Omega = 0.858$, *AVE* = 0.671)**	***0.94***	2.54 (0.99)
The biological characteristics that make a species "invasive"	0.82	2.61 (1.14)
Names of species that are considered invasive	0.78	2.20 (1.03)
Ways that invasive species affect the environment	0.85	2.81 (1.20)
***Knowledge of biosecurity behaviors* ($\alpha = 0.925$, $\Omega = 0.927$, *AVE* = 0.810)**	***0.97***	2.57 (1.18)
How aquarium and garden hobbyists could spread invasive species	0.87	2.72 (1.31)
Types of actions you can take to prevent invasive species from spreading	0.93	2.57 (1.24)
How to complete recommended actions	0.90	2.42 (1.24)
***Information sources*[e] ($\alpha = 0.762$, $\Omega = 0.765$, *AVE* = 0.520)**		2.62 (1.08)
Other hobbyists	0.78	2.74 (1.26)
Breeders	0.76	2.26 (1.27)
Veterinarians	0.64	2.88 (1.42)

Fit statistics: $\chi^2 = 571.148$, df = 327, $\chi^2/df = 1.75$; CFI = 0.930; TLI = 0.919; RMSEA = 0.058.
SRMR = 0.064.
[a] Measured on a 5-pt scale from 1 (not at all likely) to 5 (extremely likely).
[b] Measured on a 5-pt scale from 1 (no impacts) to 5 (very severe impacts).
[c] Measured on a 5-pt scale from 1 (strongly disagree) to 5 (strongly agree).
[d] Measured on a 5-pt scale from 1 (not at all familiar) to 5 (extremely familiar).
[e] Measured on a 5-pt scale from 1 (never) to 5 (very often).

constructs (Fig. 3). We hypothesized that information sources positively predicted knowledge, a second order factor comprised of both knowledge of invasion biology and knowledge of biosecurity behaviors (H1). Next, we hypothesized that knowledge predicted risk perceptions, benefits, self-efficacy, and barriers (H2-H5), as well as behavior (H6). Finally, in line with the Health Belief Model, we hypothesized that beliefs positively predicted intensions to engage in biosecurity behaviors (H7–H9), whereas barriers negatively predicted such intentions (H10).

Using the same metrics referenced for the measurement model, fit was assessed using RMSEA, CFI, and SRMR. Missing data were accounted for with the full information maximum likelihood method (von Hippel, 2016). Analyses were conducted in R version 4.2.1 using lavaan and semTools packages.

3. Results

3.1. Sociodemographic characteristics and hobby experience

Participants were 74.9% female, with an average age of 38.19, and an average of 8.14 years of experience as a hobbyist (Table 2). Our sample was younger ($\chi^2 = 50.725$, $p < 0.001$; $\chi^2 = 35.120$, p < 0.001) and more female ($\chi^2 = 84.435$, $p < 0.001$; $\chi^2 = 74.646$, $p < 0.001$) than two prior studies of aquarium hobbyists in the U.S. Midwest, in which the proportion of women was 37–38%, and the proportion of those aged 50 or above was 51–54% (Fitzgerald et al., 2021; Seekamp et al., 2016). Given that women tend to report stronger environmental attitudes and commitment to pro-environmental behavior (Blankenberg and Alhusen, 2019; Lynn and Longhi, 2011), respondents in our study may have reported higher levels of beliefs and behavior than other comparable populations.

3.2. Modeling results

3.2.1. Direct predictors of behavior

The structural regression model demonstrated good model fit ($\chi^2 = 584.154$, $df = 332$, $\chi^2/df = 1.76$; $CFI = 0.928$; $TLI = 0.918$; $RMSEA = 0.059$, $SRMR = 0.068$) and accounted for approximately 53% of the variation in intended biosecurity behaviors (Fig. 4). In line with our hypotheses informed by the Health Belief Model (Rosenstock, 1974), significant positive paths were observed from risk perceptions ($\beta = 0.179$, $p = 0.015$), benefits ($\beta = 0.182$, $p = 0.020$), and self-efficacy ($\beta = 0.470$, $p < 0.001$) to intended behavior. The relationship between barriers and behavior was non-significant ($p = 0.369$).

3.2.2. Relationships between knowledge and behavior

Observed relationships among knowledge and beliefs partially supported our hypotheses (Table 3). Knowledge positively predicted risk perceptions ($\beta = 0.307$, $p < 0.001$), though with a low effect size ($R^2 = 0.094$). Knowledge also positively predicted self-efficacy ($\beta = 0.566$, $p < 0.001$, $R^2 = 0.320$) but negatively predicted barriers to completing the behaviors ($\beta = -0.271$, $p < 0.001$, $R^2 = 0.073$).

Although the direct relationship between knowledge and behavior was non-significant, knowledge had significant indirect effects through risk perceptions ($\beta = 0.055$, $p = 0.035$) and self-efficacy ($\beta = 0.266$, $p < 0.001$), in line with our hypotheses (Table 4). Accounting for both direct and indirect effects, knowledge was central in shaping beliefs that inform behavior ($\beta = 0.495$, $p < 0.001$).

4. Discussion

This research engaged the underrepresented interest group of aquarium hobbyists across the U.S. state of Illinois to generate information for aquatic ecosystem management about how best to prevent AIS transport. Drawing on the Health Belief Model (Rosenstock, 1974), we provided theoretical insights on how to close the knowledge-action gap. Specifically, a more nuanced conceptualization of public awareness is provided to explain the relationships among beliefs about AIS, and in turn, intentions to engage in biosecurity behaviors. Our results showed that self-efficacy, benefits, and risk perceptions were prominent, whereas barriers were a non-significant predictor of behavior for aquarium

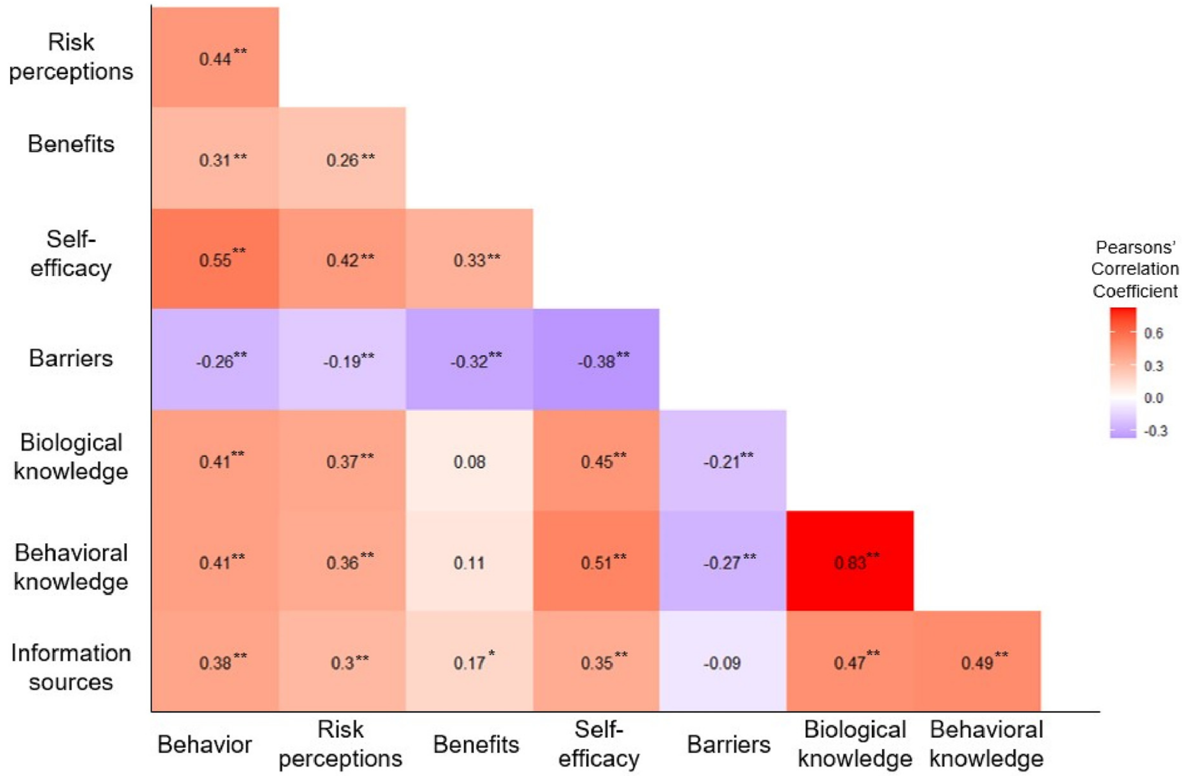

Fig. 2. Pearson's correlation coefficents between constructs included in the structural equation model. Significance is indicated by asterisks $*p < 0.05$ and $**p < 0.01$.

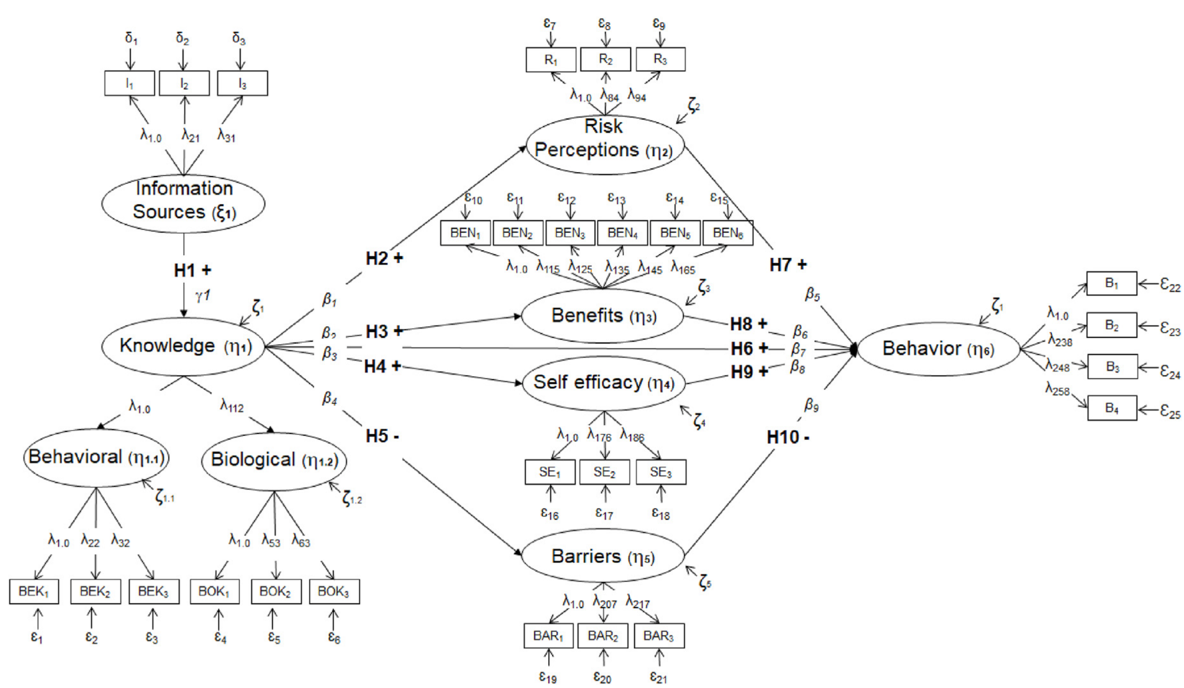

Fig. 3. Hypothesized structural regression model illustrating relationships among constructs.

hobbyists. Additionally, multiple forms of knowledge indirectly influenced behavior and were mediated by self-efficacy and risk. These results provide guidance on the type of information that will most likely catalyze behavior change among aquarium hobbyists. Science communication and outreach campaigns that highlight the risks of invasive species while activating self-efficacy and strengthening the perceived benefits of prevention strategies will be the most effective pathways for fostering hobbyist engagement in biosecurity behaviors.

4.1. Relationship between beliefs and behavior

We found that self-efficacy was the strongest psychological factor that explained the intended biosecurity behaviors of aquarium hobbyists. That is, as confidence in one's abilities increased, so did their intended

Table 2
Characteristics of Illinois aquarium hobbyists engaged in this research.

Variables	N (%)
Gender	
Male	53 (24.2)
Female	164 (74.9)
Other	2 (0.9)
Education	
Some high school	8 (3.7)
High school graduate or GED	95 (43.4)
Associate's degree	44 (20.1)
Bachelor's degree	56 (25.6)
Graduate degree (MA, MS, PhD, JD, MD, etc.)	16 (7.3)
Income	
Less than $24,999	32 (14.6)
$25,000 to $49,999	55 (25.1)
$50,000 to $99,999	85 (38.8)
$100,000 and over	44 (15.6)
Prefer not to answer	13 (5.9)
Race & Ethnicity[a]	
American Indian	14 (6.4)
Asian	9 (4.1)
Black or African American	21 (9.6)
Hispanic or Latino	22 (10.0)
Native Hawaiian or other Pacific Islander	1 (0.5)
White	171 (78.1)
Other	5 (2.3)
Age [M, SD]	[38.19, 15.60]
Total number of years having maintained an aquarium or water garden [M, SD]	[8.14, 8.67]
Number of aquarium tanks maintained [M, SD]	[2.86, 16.93]
Level of expertise compared to other hobbyists[b] [M, SD]	[2.98, 0.88]

[a] Respondents could check all that applied so column totals may not equal 100%.
[b] Measured on a 5-point Likert scale ranging from 1 (Much lower than average) to 5 (Much higher than average).

Table 3
Estimates of the structural regression model.

Dependent Variable	Predictor variable	β	p	R^2
Behavior	Risk perceptions	0.179	0.015	0.533
	Benefits	0.182	0.020	
	Self-efficacy	0.470	<0.001	
	Barriers	0.028	0.369	
	Knowledge	0.159	0.071	
Risk perceptions	Knowledge	0.307	<0.001	0.094
Benefits	Knowledge	0.123	0.103	0.015
Self-efficacy	Knowledge	0.566	<0.001	0.320
Barriers	Knowledge	−0.271	<0.001	0.073
Knowledge	Information Sources	0.595	<0.001	0.355

Table 4
Direct and indirect effects of knowledge on behavior.

	β	p
Total effects	**0.495**	**< 0.001**
Direct effect of knowledge on behavior	0.159	0.071
Indirect effects		
Mediated by risk	0.055	0.035
Mediated by benefits	0.022	0.177
Mediated by self-efficacy	0.266	<0.001
Mediated by barriers	−0.007	0.714

actions. The strong role of self-efficacy in predicting behavior echoes past research related to invasive species prevention (Golebie et al., 2023a; Howell et al., 2015), as well as other conservation-oriented actions (Pradhananga and Davenport, 2022). This finding highlights the importance of tailoring resources to specific interest groups like hobbyists to support their ability to act. Such resources may include lists of native species for use in aquariums and water gardens, as well as access to support networks that can help rehome unwanted animals. Support networks will help to ensure that knowledge is attainable even for those who are new to the hobby and may lack connections with other hobbyists or relevant experts such as breeders and veterinarians.

Benefits positively influenced behavior. The more hobbyists believed that biosecurity behaviors would yield personal and social benefits, the more likely they were to engage in these behaviors. Although a large body of previous work guided by the Health Belief Model has indicated that benefits are one of the most important predictors of behavior (Carpenter, 2010), research in the context of AIS has shown that benefits are only relevant when barriers to action are low (Golebie et al., 2023a). It could be that within the aquarium hobby, the connection between biosecurity behaviors and personal benefits is more salient, making benefits a more fruitful avenue for behavior change among this group. To

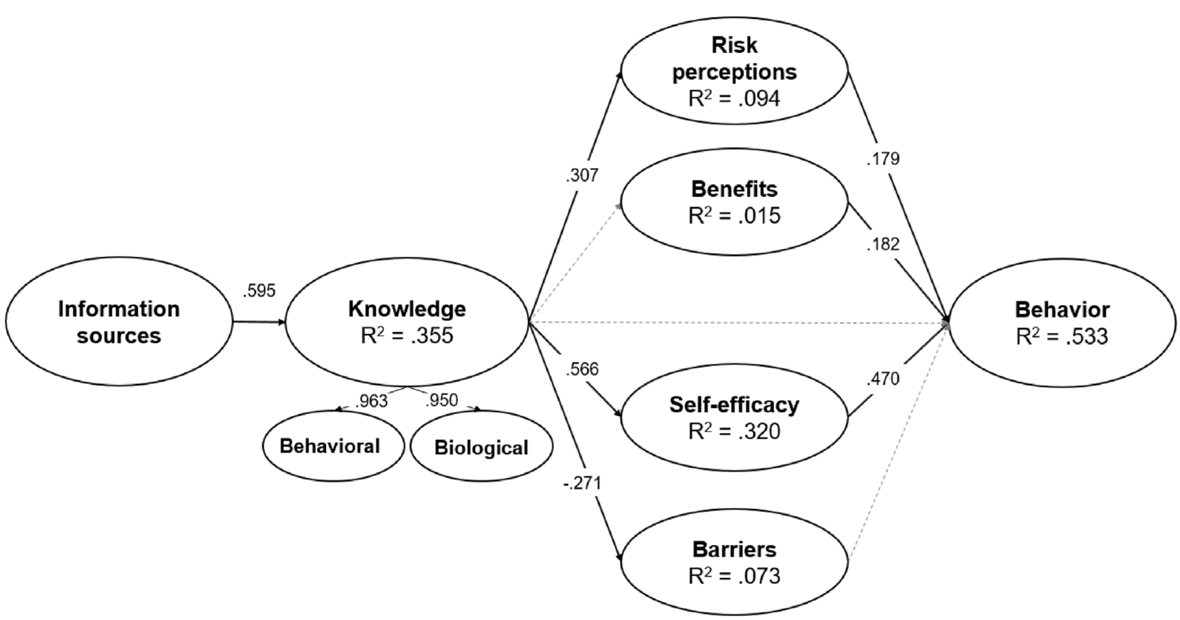

Fig. 4. Knowledge and beliefs as predictors of biosecurity behaviors of aquarium hobbyists in Illinois. Fit statistics are: $\chi^2 = 584.154$, $df = 332$, $\chi^2/df = 1.76$; $CFI = 0.928$; $TLI = 0.918$; $RMSEA = 0.059$, $SRMR = 0.068$. Standardized path coefficients (β) are indicated for each path; significant paths are shown in solid lines and non-significant paths are shown as grey dashed lines.

leverage benefits in AIS outreach, campaigns should highlight a diverse array of outcomes from participation such as a sense of community among hobbyists, increasing one's knowledge of ecosystems, and teaching younger generations about the impact of human behavior on the environment. Emphasizing these perceived benefits will be more likely to increase biosecurity behavior.

Risk perceptions exhibited a moderate positive effect on behavior. That is, the more hobbyists believed that AIS threaten the environment, the more likely they were to follow AIS prevention guidelines. Past work has stressed the risks AIS pose to multiple facets of human wellbeing such as food security, health, and recreational activities (Gozlan et al., 2024), and the importance of highlighting such perceived risks to motivate action (Estévez et al., 2015). Indeed, risk perceptions have emerged as a determinant of biosecurity behavior and perceived risks to one's own daily life have been shown to be most important (Golebie et al., 2021). Water biology researchers should keep in mind that the perception of risks may differ based on an individual's values. In the present study, we considered only perceived risks to the environment, which may be more salient to individuals who are environmentally oriented (i.e., biospheric values) (Golebie and van Riper, 2023). Appealing to individuals who value helping other people (i.e., altruistic values) or achieving personal goals (i.e., egoistic values), will require emphasizing the risks to one's community and one's own hobby activity to heighten risk perceptions and thereby encourage behavior change.

Results from our structural equation model showed the relationship between barriers and behavior was non-significant. The zero-order correlation between barriers and behavior was significant, however it was weaker than the other belief-behavior relationships. It could be that perceived barriers are not as important in this context as the other beliefs considered (i.e., risk, benefits, and self-efficacy). Past work has suggested that barriers function as a moderator of belief-behavior relationships rather than a direct predictor (Golebie et al., 2023a). Outside of research guided by the Health Belief Model, more in-depth studies on constraints have suggested that different types of barriers influence behavior at different stages in the decision-making process (Crawford et al., 1991). In this study, we considered only the role of structural barriers that directly influence behavior (Godbey et al., 2010). These barriers may have played a larger role in influencing actual behavior, rather than intended behavior as measured in this study. Finally, we did not account for the role of negotiation or facilitators (Kim et al., 2011), which are concepts that may have better captured the way people responded to barriers when making behavioral decisions.

4.2. The role of knowledge in behavior change

Knowledge accounted for a substantial portion of the variance in biosecurity behavior, particularly through indirect relationships with self-efficacy and risk perceptions. This finding aligns with past research that has considered knowledge as a precursor to behavioral outcomes (Moore et al., 2024) and provides support for treating knowledge as a modifying factor, as suggested by the Health Belief Model (Champion and Skinner, 2008). Linkages between knowledge and self-efficacy are also supported by past work that has parceled these psychological factors into a single concept that (strongly) predicts biosecurity behavior (Howell et al., 2015). These results suggest that self-efficacy can be increased by providing clear, accessible information about the biosecurity behaviors in which hobbyists should engage and how to complete such behaviors. Although raising awareness that invasive species exist is unlikely to inspire behavior change (Kollmuss and Agyeman, 2002), providing instructions on what, exactly, hobbyists should do about the issue is likely to evoke change. Ultimately, building knowledge is the first step in building self-efficacy, which in turn enables people to engage in biosecurity behaviors.

These results deepen our understanding of the knowledge-action gap (Kollmuss and Agyeman, 2002) and suggest that knowledge plays a more nuanced role than critiques of the knowledge deficit model might suggest (Simis et al., 2016). That is, our findings indicate that knowledge does influence behavior, albeit indirectly. It could be that this conclusion is specific to an invasive species context, given that this issue tends to be less politicized and controversial than other environmental issues such as the climate crisis (McCright et al., 2016). In other words, knowledge may be more influential in contexts that are less contentious, rather than contexts where scientific knowledge is ignored or denied. Additionally, our study included a measure of knowledge that was directly aligned with behavior, measuring knowledge not just of invasive species, but of actions individuals can take in response to invasive species. General awareness of an environmental problem may be less linked with behavior than more specific knowledge of what can be done to mitigate that problem, echoing calls in past research to distinguish between knowledge types (Carmi et al., 2015; Casaló et al., 2019).

Indirect effects of knowledge via barriers and benefits were non-significant, thus supporting the notion of a knowledge-action gap (Nguyen et al., 2018). Although knowledge negatively influenced barriers, barriers did not affect behavior. In other words, the more knowledge someone had regarding biosecurity behavior, the less constrained they felt, but such constraints were not relevant in whether individuals intended to act. The role of knowledge in minimizing barriers is nevertheless important and may be a useful outreach tool in other contexts where barriers exert a stronger force on behavior. Additionally, although perceived benefits were a significant predictor of behavior, beliefs about these benefits were not derived from knowledge. That is, knowledge did not predict benefits, nor was there any significant correlation between these two concepts. This finding may indicate that there is an opportunity to complement information about what behaviors one should perform with details about the benefits one might experience within their hobby by doing so. Providing more information about the positive personal and social outcomes of biosecurity may help boost the perceptions of these benefits and ultimately increase engagement in biosecurity among hobbyists.

Information sources play a large role in determining the level of knowledge hobbyists have in both invasion biology and biosecurity behaviors. That is, a higher frequency of reaching out to other hobbyists, breeders, and veterinarians for information about the hobby was associated with higher knowledge. Thus, agencies may consider sharing information about invasive species with the goal of disseminating the information to hobbyists and ultimately increasing knowledge. Given the importance of knowledge transfer among individuals within the hobby, hobbyist clubs and groups are another key avenue for narrowing the knowledge-action gap (Nguyen et al., 2017). Management agencies should identify key actors within such groups that can facilitate knowledge exchange between scientists and hobbyists. It is important to note that novice hobbyists are less likely to be connected with hobbyist clubs, breeders, and veterinarians, and thus may be more difficult to reach with key information. Management agencies should consider how information can be disseminated to individuals who do not (yet) have access to networks of experienced hobbyists. For example, hobbyist and veterinarian support networks could be showcased via avenues that novice hobbyists are most likely to access, such as pamphlets and brochures at aquatic species retailers, and advertisements disseminated via social media (Golebie et al., 2023b). Focusing communication on these arenas may help to increase the uptake of knowledge, and in turn boost risk perceptions, self-efficacy, and ultimately biosecurity behavior.

4.3. Limitations

The results of this study should be considered in light of several limitations. Respondents were recruited from a Qualtrics panel, which is not a random sample of hobbyists but a convenience sample of individuals who are willing to take surveys. Thus, this study should not be understood as presenting the average beliefs and behaviors of Illinois hobbyists (Wardropper et al., 2021), but rather what the relationships among these beliefs are and how they are influenced by knowledge. For example, given the high rate of female respondents, the average environmental beliefs reported in this study likely exceed the average beliefs of the population (Blankenberg and Alhusen, 2019; Lynn and Longhi, 2011). The Qualtrics sample also enabled a younger and less experienced sample population, in contrast to studies that have recruited participants through on-site surveys at events (Seekamp et al., 2016) and through hobbyist forums and social media (Fitzgerald et al., 2021). Accessing less experienced segments of the population allowed for more variation in knowledge and information sources, which enabled us to examine relationships among the constructs of interest. However, it is important to note that the proportion of experienced versus unexperienced hobbyists in Illinois is unknown, and correspondingly, the proportion of those currently relying on hobbyist groups, for instance, cannot be determined from our study. An additional limitation of the study was focusing on behavioral intentions, rather than reported behavior. Though correlated, intentions typically exceed actual or reported behavior (Webb and Sheeran, 2006), and the relationship between beliefs and actual behavior may be weaker than the relationships we present in this study. Finally, our measure of knowledge was based on respondents' familiarity with general content areas. Future study could identify the specific information needed by asking about familiarity with recommended behaviors. Given the importance of social networks and information sources, we suggest future studies examine hobbyists' knowledge of these sources to better inform what steps are needed to help individuals access key resources.

5. Conclusions

Prevention of aquatic invasive species transport by aquarium hobbyists is an essential goal for aquatic ecosystem management. Drawing on the Health Belief Model, we suggest that self-efficacy is the strongest factor in determining whether hobbyists take steps to reduce the risk of species invasions, such as purchasing only native species, and should thus be the focus of future outreach campaigns aimed at engaging aquarium hobbyists. We also show that the benefits of acting, as well as the perceived risks of species invasions influence behavior, but to lesser degrees. Hobbyist beliefs are underpinned by multiple forms of knowledge, including the information sources that individuals rely on to build an understanding of aquatic invasive species. Our results therefore help to close the so-called “knowledge-action gap” by providing insight on the multiple intervening variables between information dissemination and actions, which is important to consider when forming behavior change strategies surrounding invasive species prevention. Ultimately, ecosystem management that responds specifically to the knowledge, beliefs, and behaviors of relevant user groups like aquarium hobbyists is most likely to succeed in reducing species invasions.

CRediT authorship contribution statement

Elizabeth J. Golebie: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carena J. van Riper:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Greg Hitzroth:** Writing – review & editing, Funding acquisition, Conceptualization. **North Joffe-Nelson:** Writing – review & editing, Conceptualization.

Ethical statement

This study was approved by the University of Illinois Urbana-Champaign Office for the Protection of Research Subjects (protocol #23131).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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