Cost-effectiveness of aquatic invasive species prevention techniques

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INTRODUCTION

Biological invasions are among the most impactful drivers of ecological change, with freshwater systems being particularly susceptible (Moorhouse and Macdonald 2015, Ricciardi and Rasmussen 1999). Upon introduction, aquatic invaders can outcompete native species, inducing ecosystem regime shifts, decreasing biodiversity, and altering natural habitat (Simberloff 2013). This in turn negatively impacts the economy by increasing management expenses and decreasing revenue sources (i.e., recreation, drinking water, irrigation) as waters cannot be used in the same ways post-invasion (Mida *et al.* 2010). Additionally, aquatic invaders impact human health by serving as direct infection sources and as disease vectors (Conn 2014). The scope and scale of invasive species impacts is large and is further exacerbated when coupled with anthropogenic influences (Kolar and Lodge 2000). As the breadth and magnitude of invasive species impacts continues to rise, management and control efforts are imperative for the preservation of vital water resources (Lodge *et al.* 2006). Aquatic invasive species introductions are one of the most difficult challenges we face in the 21st century as they are multifaceted with no one ‘correct’ pathway forward.

Aquatic invasive species (AIS) are geographically wide ranging and encompass several taxonomic groups including macrophytes, invertebrates, vertebrates, and microbes. Once introduced, invaders often lack natural predators and native organisms have few defenses against them, which can allow for quick proliferation and ecosystem domination (Weis 2011). Eradication efforts are controversial because they often fail and are expensive (Meyers *et al.* 2000); therefore, constant management and oversight are needed to contain and suppress an invading population. This makes prevention the best solution for AIS management because it stops invaders from being introduced in the first place, saving millions of dollars in maintenance and control costs later (Lovell *et al.* 2006).

Prevention is brought to the forefront of management activities because it is the most cost-effective form of AIS intervention and there are many prevention options for the wide range of AIS species and introduction pathways (Vander Zanden and Olden 2008). Aquatic invasive species introductions can be facilitated in many ways including natural water connections or intentional release by humans, but it is unintentional release via boater-mediated spread that is most ubiquitous (Johnson *et al.* 2001). Vessels of many shapes and sizes can spread AIS via residual water or physical attachment to a watercraft and its equipment, and invaders are often small or hidden facilitating easier translocation (Costello *et al.* 2022, Rothlisberger *et al.* 2010). Invaders of the Laurentian Great Lakes region are largely a result of ballast water introductions from other continents (Costello *et al.* 2022), and these initial invasions lead to secondary spread to inland lakes (Kelly *et al.* 2013). Small craft boaters often visit multiple lakes in a day and can transport AIS over long distances (Ashton *et al.* 2014). Limiting secondary spread by intercepting risky overland boat movement (i.e., boats moving from infested to uninfested waterbodies) is a popular prevention used across much of North America (Elwell and Phillips 2021, Minnesota Department of Natural Resources 2023g).

Three of the most popular prevention methods to limit the risk of AIS spread by overland boat movement are boater education, watercraft inspection, and hot water decontamination (Minnesota Department of Natural Resources 2023b, Minnesota Department of Natural Resources 2023g). Boater education involves teaching boaters' best management practices for reducing the likelihood of spread such as "Cleaning, Draining, and Drying" their watercraft and disposing of any unwanted bait in the trash (SAH! Campaign (n.d.)). Watercraft inspection involves a paid, trained inspector to visually examine and remove by hand any plants, debris, or organisms found on a watercraft. Hot water decontamination is a process that follows a watercraft inspection if an item is unable to be seen or removed by hand (i.e., residual water that won't drain or strongly attached AIS) or if it is suspected that there could be microscopic AIS attached to the watercraft. Hot water decontamination uses a hot-water and high-pressure unit to kill and/or remove potential AIS. While these three preventions are frequently used to prevent AIS spread, there is little known about their practical effectiveness (Mohit *et al.* 2023). Because there is limited quantitative data supporting the efficacy of these preventions, decisions on where and when to implement them are challenging (Kinsley *et al.* 2022). In addition to this, AIS managers have limited funding and labor; therefore, the cost-effectiveness of these preventions must be considered in prevention plans. There are currently few decision support tools that consider cost-effectiveness information, but such tools are clearly needed by AIS managers.

Managing and preventing the spread of aquatic invasive species is largely a collaborative effort involving federal and state agencies, tribes, local governments, lake associations, watershed districts and volunteers. Successful AIS prevention and management is at the mercy of adequate funding and workforce (Beaury *et al.* 2020). The state of Minnesota is a leader in this realm becuase the state prioritizes financing for AIS issues and appoints permanent, full-time positions focused solely on AIS management, prevention, and control. To put this in perspective, the state annually allocates $10 million dollars to counties to support AIS prevention programs in addition to funding their own prevention program and maintaining a grant program that smaller nonprofits and watershed districts can access (Minnesota Department of Revenue 2023, Minnesota Department of Natural Resources 2023a). Additionally, Minnesota lake associations contribute another $6.25 million dollars annually to lake improvement and AIS issues, and organize over 1.2 million volunteer hours (Minnesota Lakes and Rivers Advocates 2023).

The immense quantity of funding and labor put toward AIS prevention in Minnesota justifies the urgent need to better understand the impacts that result from those resources and effort. Thus, the purpose of this thesis is to quantify the effectiveness and costs of three common AIS prevention techniques implemented in Minnesota: boater education, watercraft inspection, and hot water decontamination. I outline my mixed methods approach to this question using empirical studies, qualitative and quantitative survey administration, and interviews with stakeholders to draw on realistic issues and acquire results informed by the many parties that are involved with AIS issues in Minnesota. Additionally, I will describe how collaborators and I will make these data operationally accessible by developing an online decision support tool for AIS prevention planning that incorporates my cost-effectiveness data. The tool allows AIS managers to compare and contrast their prevention options in light of their prevention goals (i.e., what reduction in risk they want to achieve), budget (i.e., what fiscal amount are they limited by), and variation across the landscape (i.e., infestation status, boater movement) to efficaciously limit new AIS infestations. Furthermore, I will also discuss the importance of using empirical data to inform real life decision making and the value of including stakeholders in natural resource management to achieve synergistic goals and produce collaborative, inclusive research. Results will ultimately aid in preserving and maintaining healthy, diverse, and robust aquatic ecosystems free of aquatic invasive species and their detrimental effects.

CHAPTER 1

Quantifying the effectiveness of three aquatic invasive species prevention methods

1.1 ABSTRACT

Efforts to prevent the spread of aquatic invasive species (AIS) have been widely implemented at many scales to mitigate economic and environmental harms. Boater education, watercraft inspection, and hot water decontamination are popular strategies for preventing AIS from spreading through recreational boating. However, few studies have quantified the effectiveness of these strategies under field conditions. We estimated the effectiveness of AIS preventions based on the performances of boaters, watercraft inspectors, and hot water decontaminators. Participants (n = 144) were recruited at 56 public water access sites in Minnesota and one in Wisconsin. Each participant was asked to inspect and remove AIS from a boat staged with macrophytes, adult zebra mussels, and spiny water fleas. The types and amounts of AIS removed were used to estimate the effectiveness of each prevention method. We observed that removal rates varied by type of AIS, with macrophytes being most commonly removed by all participant types. There were also regional (Twin Cities Metro versus outstate) differences for some species, specifically with spiny water flea being more removed in outstate regions perhaps due to differing awareness and education. Hot water decontamination was the most effective intervention (mean = 84.4% removal rate, SD = 10.2%) but was not significantly better than watercraft inspection (mean = 79.2% , SD = 9.80%). Our results suggest boaters are less effective (mean = 56.4%, SD = 17.0%) at removing AIS than trained professionals, but nevertheless play an important role in AIS prevention. Furthermore, we identified areas of the boat that were often overlooked (i.e., winch, bow line, transducer) by boaters and could be incorporated into future outreach campaigns. We observed high variability in the actions (i.e., time spent, places looked, methods used) taken by individuals from each participant group, revealing opportunities for standardizing outreach and professional training to maximize effectiveness. This was particularly evident among

paid hot-water decontaminators, who often made risk-based decisions to modify the protocol and relied on equipment that often failed to reach minimum temperature thresholds. These results can better inform AIS managers as they weigh the tradeoffs of each prevention strategy to meet their management objectives.

1.2 INTRODUCTION

Aquatic invasive species (AIS) have negatively impacted the economy, environment, and human health throughout the Laurentian Great Lakes region (Pimentel *et al.* 2005; Conn 2014). For example, invasions by sea lamprey (*Petromyzon marinus*) in 1835 and zebra mussel (*Dreissena polymorpha*) in 1988 via man-made canals and overseas transport, respectively, have created an estimated management burden of $320-520 million annually and have drastically altered ecosystem function (Lawrie 1970; Crooks 2002; Warziniack *et al.* 2021). Secondary spread to and among inland lakes exacerbates the problem, with local vectors (e.g., recreational boats) facilitating introductions between otherwise disconnected waterbodies (Vander Zanden and Olden 2008; Kelly *et al.* 2013).

Current recreational boat and trailer designs readily harbor invasive plants and invertebrates in hard-to-see and -reach places (Johnson *et al.* 2001). Eurasian watermilfoil (*Myriophyllum spicatum*) can become entangled on boat motors and trailers and then be transported to new lakes where it can proliferate quickly (Aiken *et al.* 1979), outcompete native aquatic vegetation (Madsen *et al.* 1991), and degrade fish populations by altering habitat (Lillie and Budd 1992). Juvenile zebra mussels (*Dreissena polymorpha)* can go undetected while attached to boats or in residual water (Campbell *et al.* 2016) and, when a new population develops, change nutrient dynamics and ecosystem function (Ludyanskiy *et al.* 1993; Vanderploeg *et al.* 2002; Hansen *et al.* 2020). Spiny water fleas (*Bythotrephes longimanus*) negatively alter aquatic food web structure (Hansen *et al.* 2020) and are a nuisance for anglers because they entangle on fishing lines and impair equipment use (Kerfoot *et al.* 2011; Branstrator 2021).

Prevention is the most cost-effective form of aquatic invasive species (AIS) intervention (Leung *et al.* 2002; Lovell *et al.* 2006) because there are few, if any, effective strategies to eradicate established AIS populations (Escobar *et al.* 2018). Common AIS spread prevention methods targeting recreational boating include boater education, watercraft inspection, and hot water decontamination (Elwell and Phillips 2021). Boater education programs aim to increase AIS awareness and teach best practices for preventing spread (e.g., inspecting and removing AIS from watercraft and trailers; Aquatic Nuisance Species Task Force 2011). However, evaluating these programs is difficult because this relies on observing boater behavior or capturing boaters' self-proclaimed intent (Fortin Consulting Inc 2020, Seekamp *et al.* 2016). Watercraft inspection and decontamination programs, often managed by state or local agencies, aim to prevent AIS spread by placing trained staff at public water access sites. Watercraft inspectors visually examine boats and remove AIS by hand, whereas watercraft decontaminators perform both visual inspections and use a decontamination unit producing hot water and/or high pressure to kill or remove AIS. In addition, new innovations for AIS prevention are being developed, including self-service AIS removal stations (Campbell *et al.* 2020), targeted boater education campaigns (Sharp *et al.* 2017), and canine detection of AIS (Sawchuk 2018).

While studies have examined boater intent (Seekamp *et al.* 2016), and the efficacy of watercraft inspection (Rothlisberger *et al.* 2010) and decontamination (Mohit *et al.* 2021; Morse 2009; Shannon 2018) under ideal or controlled settings, to our knowledge no research has assessed the effectiveness of realistic prevention scenarios using these techniques in real-mohitworld conditions. Rothlisberger *et al.* (2010) showed that visual inspection plus hand removal was 88% effective at removing macrophytes and 65% effective for small-bodied organisms. However, the study's participants were research personnel who may have had better knowledge of what to look for compared to the average boater. Rothlisberger *et al.* (2010) also administered a survey that indicated that 24-27% of boaters say they always clean their boat by rinsing, washing, or drying and 57-87% say they always remove aquatic weeds, though reported intentions and actual behaviors could differ (Ajzen 1985; Nguyen *et al.* 2019). Mohit *et al.* (2021) reviewed the literature to determine the threshold of hot water exposure needed to kill zebra mussels and aquatic vegetation under controlled laboratory conditions; their findings showed that many prior studies had tested water temperatures and contact durations inconsistent with standard decontamination protocols (Elwell and Phillips 2021; Blumer *et al.* 2009; Beyer *et al.* 2011; Branstrator *et al.* 2013; Anderson *et al.* 2015). In addition, no studies have tested if lethal temperatures and durations are reached by trained decontaminators under field conditions or if current equipment (i.e., mobile decontamination units) can achieve and maintain those levels. Quantifying the effectiveness of these common AIS prevention practices under realistic conditions with more 'real world' participants would help natural resource managers implement and improve AIS prevention strategies that offer the most prevention benefit for their available funding and resources.

Our study objective was to quantify the effectiveness of three popular AIS prevention strategies – boater education, watercraft inspection, and hot water decontamination – by assessing the effectiveness of the boating public, inspectors, and decontaminators respectively under field conditions. We conducted experimental AIS removal trials by having participants remove dead or surrogate AIS from a staged watercraft at public water access sites in Minnesota and Wisconsin. By providing a boat contaminated with dead or surrogate AIS and recording how well each individual performed at removing and/or killing the AIS, we were able to quantify the effectiveness of these AIS spread prevention techniques.

1.3 METHODS

1.3.1 Site selection and participant recruitment

Public water access sites and centrally located decontamination stations (e.g., at a town hall) within Minnesota or close to its borders were selected based on the targeted participant type (boating public, trained inspectors, or trained hot water decontaminators). Criteria used to determine site selection for the boating public ("boaters") were access site popularity (as reported by AIS managers) and size of the parking lot. Popular accesses gave us opportunities to recruit more participants, and we needed an expansive parking area to complete the trials without impeding water access and traffic. Site selection for inspectors and decontaminators involved using work schedules obtained from county and state managers as well as targeting overlap between inspectors and decontaminators. Access sites with inspectors and decontaminators overlapping or close by were preferentially chosen to efficiently increase sample size. Eiswerth *et al.* (2011) and Cole *et al.* (2016) suggested there may be regional differences between AIS education and prevention actions. Therefore, each selected access site was classified as being “metro” (within the Minneapolis/Saint Paul metro area) or “outstate” (within Minnesota but outside of the Minneapolis/Saint Paul metro area) to facilitate regional comparisons of participant performance (Figure 1.1). One additional site was included near the Minnesota border in Wisconsin and grouped for analysis with the outstate locations. The only centrally located decontamination site visited was grouped for analysis with outstate public water access sites.

Participant recruitment and data management followed the University of Minnesota Institutional Review Board protocol #00013846. Participants were verbally recruited at public water access sites or centrally located decontamination stations using a standardized script stating expectations and instructions (Angell *et al.* 2023). Boaters were identified as anyone launching or trailering a boat at the lake during the onsite experiment period, and study participants included no more than one individual from a group, preferably the boat owner/operator. All inspectors and decontaminators were employed by the Minnesota Department of Natural Resources (MNDNR) or the county in which they were operating. All inspectors and decontaminators had received formal training using the Uniform Minimum Protocols and Standards for Watercraft Inspection and Decontamination Programs (UMPS IV; Elwell and Phillips 2021) or the University of Wisconsin Stevens Point Extension Lakes Program Clean Boats Clean Waters Program (CBCW; UW-SP n.d.). Both training programs are comparable, with similar goals and expectations. A nominal reward was provided to each boater participant following the completion of each experimental trial.

1.3.2 Experimental AIS removal trials

Two similar Lund fishing boats were used for experimental AIS removal trials: a 16.5' Rebel XL (used for trials in the metro region) and an 18' Alaskan SSV (used for trials in the outstate region). Both are similar v-hull aluminum watercraft with a tiller steer outboard motor and interior compartments. This style is a common watercraft in the Upper Midwest and representative of many other boat designs. Three species of AIS known to move through the recreational boating pathway (Buchan and Padilla 2000; Johnson *et al.* 2001; Branstrator *et al.* 2021) were selected for evaluation following consultation with AIS managers to identify high-priority species. The species were Eurasian watermilfoil, zebra mussel, and spiny water flea. To eliminate the risk of spreading AIS during the experiment, surrogate, dead, or preserved specimens were used. This included a fresh, native look-alike to Eurasian watermilfoil, Coontail (*Ceratophyllum demersum*), dried zebra mussel shells, and spiny water fleas preserved in ethanol. In addition to the three AIS, a bait bucket with residual water was placed in the boat to represent the known risk factor of microscopic AIS (e.g., zebra mussel veligers) and aquatic pathogens (e.g., viral hemorrhagic septicemia virus; Campbell *et al.* 2016; McEachran *et al.* 2021).

The AIS were placed at ten high-risk locations on the boat based on expert opinion and a literature review. The locations and amounts of AIS were standardized across all trials to facilitate comparisons. AIS placement types and locations included: six locations containing Coontail (trailer frame, amount = ~40 g; motor propeller, amount = ~40 g; motor intake valve, amount = ~0.2 g; anchor, amount = ~40 g; boat hull, amount = ~2 g; trailer rollers, amount = ~40 g), two locations containing zebra mussels (motor mount, amount = 3 shells; boat hull, amount = 3 shells), one location containing spiny water fleas (last eyelet of a fishing rod, amount = clump of 10), and one location containing residual water (bait bucket, amount = 500 ml; Figure 1.2).

Following boat preparation, participants were verbally recruited at public water access sites. We acknowledge the limitations of recruiting volunteer participants for this type of experimental trial, however efforts were made to emphasize the need for their behavior to reflect a real world scenario. Participants were read a realistic and standardized scenario to help guide their inspection, including knowledge that the boat had been in a lake with AIS, and told that they should do what they would normally do in that situation as the boat was leaving the access site.

For hot water decontaminators, the scenario stated the boat had previously been in a lake with AIS for at least 48 hours (long enough for zebra mussel veligers to attach; Peyer *et al.* 2009) and was traveling to another lake without AIS that same day. All three participant types (boaters, inspectors, and decontaminators) had an opportunity to conduct a visual inspection of the boat and to hand-remove any AIS, while only the decontaminators had the additional opportunity to use a hot water decontamination unit. No additional tools were made available to any participants. There were no restrictions on time or guidance provided by the evaluators during the trial.

Two evaluators simultaneously observed each experimental trial. One recorded the removed quantity of each AIS by the participant. The other recorded where the participant was looking and touching the boat and trailer as they searched, even if an AIS had not been placed there. The date, location, duration of the trial, etc. were also recorded (Angell *et al.* 2023).

During a hot water decontamination, one evaluator recorded the steps the decontaminator took (i.e., use of low-flow hot water spray, performing a motor flush, using a high-pressure rinse, etc.) The other evaluator used a thermal imager (FLIR E75 Thermal Imager) to record the temperature and duration of water applied to the boat and its accessories. The boat was partitioned into 40 sections (Figure 1.3) for post-decontamination analysis.

When analyzing the thermal imagery, the hottest temperature and duration of water being sprayed on each of the 40 boat sections was determined by reviewing the recording using the manufacturer's software (FLIR Thermal Studio Standard Version). We used the UMPS IV standard protocol recommendations to set a baseline threshold needed to kill 100% of adult zebra mussels using hot water decontamination (Elwell and Phillips 2021). We deemed a sufficient decontamination of all exterior boat sections and equipment (sections 1-36 and 38, respectively; Figure 1.3) to be one that reached a minimum of 60°C for 10 seconds. For example, if a decontaminator sprayed hot water on a section for 17 seconds and the water temperature reached 61°C then that section was deemed sufficiently decontaminated; if the temperature only reached 52°C for the 17 seconds then the section was deemed not sufficiently decontaminated. We deemed a sufficient decontamination of sensitive locations and equipment (motor flush, section 40) to be one that reached a minimum of 48.9°C for 130 seconds. A standardized threshold for decontaminating a fishing rod or bait bucket (sections 37 and 39 respectively) was not explicitly stated in the UMPS IV protocol, so we categorized it as "regular equipment" and its decontamination sufficiency threshold was deemed to be a minimum of 60°C for 10 seconds (Figure 1.3).

The standardized scenario scripts read to each participant group and all data entry forms are available on the University of Minnesota Data Repository (Angell *et al.* 2023).

1.3.3 Statistical analyses

To determine the effectiveness of each removal strategy, each AIS removed accounted for a 10% removal rate across the ten locations on the boat. For example, if a participant removed AIS from six of the ten locations, they were considered 60% effective in their AIS removal. To determine the effectiveness of a hot water decontamination, each of the 40 boat sections was given a binary sufficiency rating (pass/fail), and each passed section accounted for 2.5% towards a removal/kill score. For example, if a decontaminator successfully met the threshold for effective decontamination (according to UMPS IV) on 18 sections of the boat, they were deemed 45% effective in their hot water decontamination process.

We built and ran a binomial mixed-effects regression model, including random intercepts for each participant to account for potential pseudoreplication. The response variable, percent AIS removed, was regressed against six categorical fixed effects (three main effects and three two-way interactions). The three main effects were participant type (boater, inspector, or decontaminator), AIS type (plants, zebra mussel, spiny water flea, or residual water), and region (metro or outstate). Boater, plants, and metro, respectively, were coded as zeroes to be the default levels for comparisons. The three interaction terms were participant typexAIS type, participant typexregion, and regionxAIS type. We initially included the three-way interaction terms between these three variables in the model, but all associated terms were not significant (all p values > 0.83), so we removed them to simplify our analysis. We report only final model results. A post hoc Tukey's test was conducted to evaluate the differences among levels of a factor if a significant interaction or main effect was detected. Statistical significance was assessed using an alpha of 0.05.

We used the model's estimates and standard errors for its parameters to calculate the predicted probabilities of successful AIS removal for any hypothetical combination of our fixed effects (e.g., the probability a metro-area boater would remove zebra mussels successfully from a specific location on the boat). We did this via a randomization process by first drawing a random value from a Normal distribution for each parameter using its estimate and standard error. For the random intercept, 0 was instead used as the mean. We then used the regression model equation to calculate a log-odds of success for a given scenario, which we converted to a probability using an inverse logit function. We repeated this process 1,000 times for each possible scenario, determining that scenario's mean success probability and 95% Confidence Interval (CI) from the corresponding 1,000 estimates.

1.3.4 Post-experimental AIS removal trial survey

A post-trial survey was administered via Qualtrics on an iPad tablet (Model A2152, Apple Inc.). Surveys administered to boaters were slightly different from those for inspectors and decontaminators. Within the survey given to boaters, data on demographics (age, gender, and education level), boating experience, boating frequency, and type of boat most often used were obtained. With the survey given to inspectors and decontaminations, data on demographics (age, gender, and education level), inspecting experience (years and number of lakes), and affiliation were obtained. Additional questions were included in both the boater and inspector/decontaminator surveys as part of a complementary study focused on the connections between participants' ability to remove AIS, their AIS awareness or training, and their self-reported intentions, attitudes, and behaviors (Campbell *et al.*, in prep).

1.4 RESULTS

1.4.1 Effectiveness of AIS removal trials

The boater group was the largest of the three interventions tested; however, only ~33% of invited boaters agreed to participate. Public water access sites were split relatively evenly between metro (n = 32) and outstate (n = 40) for all participant types and were almost entirely within Minnesota, with only one public water access site located in neighboring Wisconsin (Table 1.1; Figure 1.1). Boaters were the quickest with their AIS removal efforts and also the least effective, whereas decontaminators removed the most AIS on average but were slowest in doing so and were not significantly better at removing AIS when compared to inspectors (Table 1.1; Figures 1.4 and 1.5). We noted that time spent removing AIS was positively correlated with the percent of AIS removed (Figure 1.5), although inspectors were comparable with decontaminators despite spending much less time with their AIS removal process (Table 1.1; Figures 1.4 and 1.5). All participant types touched the propeller most frequently and looked at the trailer axle without touching it. The majority of boaters and inspectors missed the transducer and lights/wiring and both inspectors and decontaminators often missed the interior compartments (Table 1.2).

The percent of AIS removed and participant type were significantly associated, with both inspectors and decontaminators removing significantly more AIS than boaters (1.27 ± 0.42, $p = 0.002$ and 1.97 ± 0.75, $p = 0.009$, respectively; Table 1.4). A post hoc analysis indicated inspectors and decontaminators did not significantly differ in the percent of AIS removed (difference of 0.70 ± 0.79, $p = 0.64$).

The percent of AIS removed and AIS type were significantly associated, with both residual water and zebra mussels being removed less often than plants (-1.71 ± 0.37, $p <$

0.001 and -2.73 ± 0.32, $p < 0.001$, respectively; Table 1.4). Additionally, when comparing removal of spiny water fleas and plants, the coefficient estimate was -20.48, which indicated a strong negative effect. However, the uncertainty around that estimate was very high (SE = 33.05), so it was not statistically significant ($p = 0.536$). While this lack of significance could indicate that spiny water flea removal is highly inconsistent or that its low observed removal rate was due to chance alone, another explanation is limited sample size. Because spiny water fleas were only placed in one location on the boat versus several locations for plants and zebra mussels, fewer data were available to use in hypothesis testing. In addition, our model results indicate that inspectors and decontaminators are predicted to remove spiny water fleas at approximately a 20% higher rate than boaters on average (Table 1.6).

A Tukey's post hoc analysis of the interaction between participant type and AIS type showed that boaters removed significantly fewer plants than both inspectors and decontaminators (-2.0 ± 0.35, $p < 0.0001$ and -2.5 ± 0.62, $p = 0.0002$, respectively). This same trend was observed for zebra mussels (-2.1 ± 0.36, $p < 0.0001$ and -2.6 ± 0.47, $p < 0.0001$, respectively), but not for spiny water fleas or residual water (all p values > 0.05; Table 1.4).

Our model showed that outstate participants removed AIS at significantly lower rates than metro participants (-1.0 ± 0.28, $p < 0.0001$; Table 1.4). Our post hoc analysis showed that boaters removed significantly more AIS in the metro than outstate (0.74 ± 0.33, $p = 0.026$) while inspectors removed significantly fewer in the metro than outstate (-0.72 ± 0.34, $p = 0.036$); however, there was no difference for decontaminators between regions ($p = 0.55$; Table 1.4).

A Tukey's post hoc analysis of the interaction between AIS type and region showed that zebra mussels were removed significantly more in the outstate region than in the metro region (1.3 ± 0.34, $p = 0.0002$). All other interactions between AIS types and regions were not significant (all p values > 0.05; Table 1.4).

1.4.2 Decontamination

Most decontaminators conducted a two-part decontamination process consisting of a watercraft inspection followed by decontamination using both hot and ambient water temperatures to kill and remove AIS. Two decontaminators opted to not complete a decontamination step due to equipment failure (the unit water recall system was not working; n = 1) and personal discretion (they perceived the boat was free of AIS; n = 1). Data from the individual that experienced equipment failure was excluded from the hot water decontamination analysis and data from the individual that chose not to complete a decontamination was still included in the analysis because the boat would have posed a risk of spreading AIS in a real-life scenario. During the initial watercraft inspection process, decontaminators (n = 22) removed an average of 78.1% (sd = 21.3%) of the AIS, and this step took on average 5:31 minutes (min. 1:10 minutes; max. 13:19 minutes). Based on our observations during the decontamination step of the process, an average of 6.3% additional AIS were removed from the boat by hand or as a result of the water spray, bringing the total effectiveness of decontaminators to 84.4% (sd = 10.2) on average. The additional hot water decontamination step took on average 26:02 minutes (min. 9:14 minutes; max. 1:02:31 minutes; Table 1.1).

According to the UMPS IV standards for decontamination, we observed that, on average, a decontaminator sufficiently decontaminated 10 (sd = 8.93) out of 40 boat sections, giving a 25% (sd = 22.3%) success rate per decontamination. To examine the sufficiency of water sprayed on larger boat portions (i.e., the underside of the hull, stern, port, starboard, and equipment) rather than section by section, multiple boat sections were combined. Of the 22 decontaminations observed for this study, the percentage that reached a sufficient temperature and duration for the boat underside was 35.2%, 35.2% for the stern, 19.5% for the port side, 16.8% for the starboard side, and 19.7% for equipment. Due to equipment failure during the motor flush process (the boat motor would not start), the sample size for this area of the boat was reduced to 13 participants, of which 23.1% sufficiently decontaminated inside of the motor (Figure 1.6). We also observed variability in the decontamination process used (i.e., low flow spray with hot water, motor flush, etc.) completed by decontaminators (Table 1.3).

Three types of decontamination units were used in this study, with the majority of decontaminators using a Landa ECOS-7000 (76.2%) and others using a stationary hot water boiler (14.3%) or a HydroTek SS Series Mobile Wash Skid (9.5%). The temperatures reached by each unit type varied throughout the decontamination process, with the Landa ECOS-7000 effectively staying up to the UMPS IV-recommended temperature (60°C or 48.89°C) and time (10 or 130 seconds) for 16.0% of the boats' sections, the stationary hot water boiler for 17.3%, and the HydroTek SS Series Mobile Wash Skid for 27.5%. A sinuating temperature pattern was observed with the Landa ECOS-7000 and Hydrotek SS Series Mobile Wash Skid wherein water temperatures would peak to sufficient temperatures and then fall below lethal thresholds in a cyclical pattern. This sinuating pattern was not observed with the stationary hot water boiler system, which stayed at a relatively constant temperature throughout a decontamination.

1.4.3 Post-experimental AIS removal trial survey

Of the 69 boaters that completed an experimental AIS removal trial, 56 fully answered the post-trial survey and 13 boaters completed it partially. All partial and fully completed survey results were used in the analysis. Our population of boaters was on average 50 years old (min = 21, max = 79, sd = 16), skewed heavily male (94.2%), and generally had completed some college (32%) or had a 4-year degree (30%). The average experience operating a watercraft was high, with an average of 26 years (min = 1; max = 66). Most boaters reported that they go boating once a week (43%) or 2-5 times a week (32%) and most visit 2-5 lakes each boating season (52%). In addition, 69% of boaters use a fishing boat when they go boating and 58% of boaters were on the water to go fishing. There was no significant association between percent of AIS removed by boaters and their age, gender, education level, number of years operating a watercraft, boating frequency, boat type used, number of lakes visited per season, or water recreation activity (all p values > 0.3).

Of the 52 inspectors that completed an experimental trial, all fully completed the post-trial survey. The average age of inspectors was 39 years old (min = 19 years old, max = 72 years old, sd = 21.3 years) and 24 identified as being male, 27 as female, and 1 as non-binary. Most inspectors had completed some college (59.6%) or had a 4-year degree (19.2%). For most inspectors, this was their first year inspecting watercraft (55.8%). Ten inspectors worked for the Minnesota Department of Natural Resources (MN DNR) and 42 worked for counties or local government units. The majority of inspectors worked at 2-5 lakes (46.2%) or 6-10 lakes (30.8%) each boating season and worked 16-30 hours (40.4%) or over 31 hours a week (44.2%). There were no significant associations among the percentages of AIS removed by inspectors and their age, gender, education level, number of years inspecting watercraft, organization, number of lakes inspected per season, or hours worked per week (all p values > 0.2).

Of the 23 decontaminators that completed an experimental trial, all fully completed the post-trial survey. The average age of decontaminators was 46 years old (min = 20 years old, max = 70 years old) and 18 identified as being male and 5 as female. Most decontaminators had completed a 4-year degree (47.8%) or some college/technical school (39.1%). Decontaminators that had “some high school” education removed significantly fewer AIS from the boat than decontaminators that completed “high school/GED” ($p = 0.0089$, CI = [15.13, 124.87]), “some college/technical school” ($p < 0.0001$, CI = [42.43, 124.23]), “a 4 year degree” ($p < 0.0001$, CI = [41.29, 122.34]), or “a graduate or professional degree” ($p = 0.0089$, CI = [15.13, 124.87]). For six decontaminators (26%), this was their first year inspecting or decontaminating watercraft, and the rest had 1-10 years of experience. Eight decontaminators worked for the MN DNR and 15 for counties or local governments. The majority of decontaminators inspected and/or decontaminated boats at 6-10 different lakes (43.5%) or 2-5 lakes (34.8%) each boating season and worked over 31 hours a week (82.6%). There were no significant association between the percent of AIS removed by decontaminators and their age, gender, number of years inspecting watercraft, organization, number of lakes inspected per season, or hours worked per week (all p values < 0.1).

1.5 DISCUSSION

This study evaluated three common prevention methods aimed at reducing AIS spread through the recreational boating pathway. These prevention methods were performed at public water access sites by volunteer boaters and trained professionals. Boaters were less effective at removing AIS than were trained, paid personnel, but they were not ineffective (average removal = 56.4%). We identified opportunities for improvement by targeting education efforts toward high-risk areas of a boat that were often overlooked.

Although we did not evaluate boater education directly in this study, previous research suggests that the vast majority of boaters in Minnesota have been exposed to AIS outreach and are aware of at least some AIS impacts (Jensen 2010). Boater education is a common and scalable prevention method that can be implemented by managers across a wide range of funding amounts and efforts. However, its effectiveness is most often studied through surveys (Cole *et al.* 2016; Sharp *et al.* 2017; Cimino and Strecker 2018) that examine intended actions boaters say they would do in a given situation. But reported intentions do not always match actual behaviors (Ajzen 1985), resulting in a mismatch between expectations and reality that is rarely explored. This intention-action gap will be explored in a future manuscript (Campbell *et al.* in prep.). Despite our findings that boaters removed fewer AIS from a contaminated boat than do trained professionals, we emphasize that boaters still likely play a critical role in preventing the spread of AIS. This is particularly important at the majority of public water access sites where trained watercraft inspectors or decontaminators are not present and whose availability is limited by staffing and funding.

Ample opportunities exist to improve boater education and outreach efforts. Consistent use of outreach messaging and branding can help reinforce the prevention actions boaters need to perform (Aquatic Nuisance Species Task Force 2011). Message testing approaches have revealed message framing that increases desirable behaviors among boaters (Shaw *et al.* 2021) or relates to high intentions to perform prevention actions (Wallen and Kyle 2018; Golebie et al 2023). There are also opportunities to segment boating audiences and provide them with more targeted messaging (Witzling et al 2016). Research also supports that training targeted to water users and people interested in AIS can increase knowledge and intention to engage in AIS management (Shannon *et al.* 2020; Weber *et al.* 2022). Using any of these approaches could improve the ability of boaters to remove AIS from their watercraft.

Most boaters focused their AIS removal efforts on the trailer frame and motor propeller and often overlooked other smaller high-risk areas such as the transducer and bow/tow ropes. These results may reflect the success of current outreach messaging focused on removing AIS from large and obvious locations on the boat, but also shows that there is room for improvement in messaging about other smaller boat locations. For example, boaters are also directed to remove AIS and drain water from their boat, trailer, and water related equipment, but often aren't provided with extensive directions on which equipment this includes depending on the recreational activity they are completing. This shows opportunities for targeted outreach to ensure boaters understand the locations where AIS contamination is both likely and easily missed (Johnson *et al.* 2001; Rothlisberger *et al.* 2010; Sharp *et al.* 2017).

Eiswerth *et al.* (2011) and Cole *et al.* (2016) found that there are regional differences in boaters' awareness of AIS. We found that boaters in metro locations were significantly better at removing AIS when compared to outstate boaters, which could be a result of exposure to AIS education, improved signage at public water access sites, or differences in demographics, attitudes, or behaviors. Moreover, a gender bias emerged from boater participants in this study with only ~3% identifying as female, which aligns with data noting that Minnesota boaters are disproportionately male (MN DNR 2021). Future research is needed to understand heterogeneity between and within populations (e.g., region, gender, etc.) to better inform boater education and prevention strategies.

We found that trained AIS professionals were significantly more effective than boaters at removing AIS, with comparable results for both watercraft inspectors and decontaminators. Possibly due to the high variability between decontaminators' approaches, water temperatures, and contact durations, only a marginal increase in effectiveness over hand-removal alone was observed following hot water decontamination. On average, the effectiveness of hot water decontaminations alone was relatively low and effectively kill-treated fewer than a quarter of the boat sections. This low percentage is likely due to a combination of equipment failure and the inherent subjectivity of the standardized protocol that decontaminators are trained to follow. For example, decontaminators must make quick decisions about where and how to decontaminate a boat based upon the level of risk they perceive the boat poses which leads to inconsistent practices and decrease efficiency (Minnesota Department of Natural Resources 2023f, Elwell and Phillips 2021). Additionally, while hot water decontamination is intended to kill microscopic AIS, we did not fully test viability or mortality of AIS, but rather we determined decontamination sufficiency based on the standard baseline lethal temperature defined by UMPS IV which is designed to kill 100% of adult zebra mussels (Elwell and Phillips 2021).We acknowledge that the value of hot water decontamination exists over a range of temperature and duration thresholds, where by the standards used here, 'insufficient' decontamination may still be lethal to some percentage (<100%) of microscopic AIS. In addition, we recognize that other temperatures and durations could still be effective for more sensitive organisms (Branstrator *et al.* 2013; Doll 2018) and that manual removal with ambient water (e.g. high pressure car wash) also has removal benefits. Further research is needed to quantify the many combinations of water temperature, contact duration, species, and life stage to more accurately assess the benefits of hot water decontamination that fail to reach the UMPS IV recommendation.

There are difficulties in establishing and applying a standardized protocol for killing the wide variety of AIS of concern within and among jurisdictions. The current UMPS IV decontamination protocol is based on well-studied thresholds for lethal temperatures and durations needed to kill 100% of adult zebra mussels (Morse 2009). However, similar scientific evidence on sufficient temperatures and durations for many other AIS is understudied, not standardized, and often tested with actions or thresholds not practical under real-world conditions (Blumer *et al.* 2009; Beyer *et al.* 2011; Branstrator *et al.* 2013; Anderson *et al.* 2015; Mohit *et al.* 2021). For example, spiny water fleas and juvenile zebra mussels and veligers have lethal thresholds lower than that of adult zebra mussels and would therefore require less rigorous decontamination protocols (Mcmahon 1996; Elderkin *et al.* 2004; Morse 2009; Mohit *et al.* 2023). Moreover, Eurasian watermilfoil is killed at either lower temperatures and longer durations (Blumer *et al.* 2009) or higher temperatures and shorter durations (Mohit *et al.* 2023) than adult zebra mussels (Morse 2009).

As a result, a precautionary approach is recommended by the UMPS IV protocol. However, individual decontaminators were observed instead making a professional judgment about the potential risk of the experimental boat, modifying their approach accordingly, despite being informed by a standardized scenario intended to elicit full decontamination. We observed decontaminators focusing most time on boat sections they considered risky (i.e., underside/below the water line) and spending less time on "non-risky" sections (i.e., winch, above the water line). A risk assessment to distinguish exactly which areas are low and high risk should be a priority in the future to better guide and standardize decontaminator training. Additional, subjectivity in decontaminator procedures was observed because fewer than half of decontaminators in this study followed the same set of decontamination steps, and only 5 of the 21 decontaminators (23.8%) completed all necessary steps (low flow hot water spray, a high-pressure rinse, and a motor flush) as recommended by the UMPS IV. In addition, the amount of time a decontamination took varied from approximately 9 minutes to over an hour, with both ends of the spectrum being undesirable (non-lethal conditions achieved or long boater wait times and not intervening on as many boats). We also observed that the variability in decontamination sufficiency was spread across all levels of decontaminator experience. This suggests that ambiguous protocols may be responsible for continued variation and not necessarily an individual's risk-based decisions informed by experience. These observations highlight that decontamination protocols may need to be updated and/or reinforced to increase feasibility and match realistic expectations. In addition, guidance should be provided in the protocols to better define the ‘gray areas’ where ambiguity exists or risk-based changes to the protocol may be warranted.

Decontaminators took over six times longer than inspectors to complete their process of AIS removal, required additional training, and used more expensive equipment (i.e., a hot water decontamination unit). The marginal increase in decontamination effectiveness (+5.2%) may not be a result of the additional training or equipment but instead that the decontaminators took a second, more thorough look at the boat during their decontamination. Throughout the decontamination process, 38% of decontaminators were observed removing AIS by hand that were missed during their initial inspection process. This suggests that additional search efforts by watercraft inspectors could increase their effectiveness without specialized equipment and this idea is backed by our comparison of time spent inspecting versus AIS removed in Figure 1.5.

A sinuating temperature pattern was observed with the most commonly used decontamination unit, the Landa ECOS-7000, resulting in less-than-lethal water temperatures, as defined by UMPS IV, being sprayed 60% of the time. The Landa ECOS-7000 mobile units are manufactured for industrial cleaning (Kärcher 2023), not necessarily for the unique and temperature-sensitive application of decontaminating a watercraft. While a similar sinuating temperature pattern was observed with mobile Hydrotek units, the stationary hot water boiler system stayed at a relatively constant temperature throughout the decontamination. This suggests that further research and development of mobile decontamination units is needed to support their unique requirements.

Another factor contributing to the low observed ability to maintain a killing temperature during hot water decontamination may be non-specificity in decontamination protocols for certain boating equipment. We noticed that 48% of decontaminators failed to treat spiny water fleas planted on a fishing rod, which could be attributable to the UMPS IV protocol not stating a threshold for decontaminating fishing equipment. This gap in protocols leaves a high risk for spiny water flea spread, an invader currently found in a relatively few inland lakes throughout the state of Minnesota (MN DNR 2023). Treating at 50°C for 5 seconds would be sufficient to kill these organisms, according to Mohit *et al.* (2023). Decontaminating angling equipment may need to be considered in future protocols to ensure containment of spiny water fleas.

Our study showed that macrophytes were the easiest for all participants to see and remove. Rothlisberger *et al.* (2010) found that macrophyte removal by visual inspection and hand removal was ~88 ± 5%, which is similar to our findings (~90%). In contrast, for small-bodied organisms, Rothlisberger *et al.* (2010) found that removal was 65 ± 4%, which is higher than the results from our study for both zebra mussels (45%) and spiny water fleas (26%). Differences in small-bodied organism removal could be due to the differences in personnel/participants inspecting the boat in each study, although in both studies the removal rate was relatively low. We noted that the ability for participants to easily see and remove macrophytes could be attributable to the draping morphology of the plant, making it hang off the boat and easily stand out, whereas zebra mussels and spiny water fleas are much smaller, blend in with their surroundings, and were in harder-to-see locations (i.e., inside the motor mount). Additionally, we noted high uncertainty around our estimates for spiny water flea removal by all participants. To further explore this uncertainty, we calculated the predicted probabilities of removal success for spiny water fleas by each participant type in each region. We found that spiny water fleas had the lowest removal rates among boaters and metro participants perhaps due to differences in awareness and education (Table 1.6).

Depending on resource availability and local risks, managers could consider all three interventions viable options for reducing the spread of AIS. For example, for transient boats that spend little time in the water and have low risk for microscopic AIS attachment, inspections are likely a good option and hot-water decontaminations are not necessary. However, for high-risk boats that have the ability to retain microscopic AIS, hot-water decontaminations should be considered. In both cases, boater education is important for reducing risk when trained professionals are not present.

Although we attempted to replicate real-world conditions by recruiting volunteer boaters, watercraft inspectors, and decontaminators at public water access sites, and we used a scripted narrative to simulate a realistic situation, there is nevertheless the potential for experimental bias. For example, participants knew they were participating in a scientific study and, during the experiment, two researchers observed participants' behaviors, likely resulting in a much more thorough inspection of the boat than would occur under normal circumstances (Mahtani 2018). In addition, we standardized the type, location, and amount of AIS placed on the boats to support robust comparisons. This may have unintentionally introduced bias because some species or locations may be easier or more difficult for participants to remove or locate. Methods to address these biases (e.g., hidden cameras, experimental variability, etc.) should be considered as a complement to more standardized approaches for evaluating the real-world effectiveness of AIS spread prevention methods.

Although results from this study provide strong evidence for the real-life effectiveness of three common AIS prevention methods, the wide variety of AIS and the feasibility of spread prevention strategies must be considered as managers work to reduce the risk of AIS movement across the landscape. Furthermore, managers will need to consider these results in the context of limited resources, making decisions to optimize the cost-benefit of spread prevention (Haight *et al.* 2021; Kinsley *et al.* 2022). More research is needed to develop and evaluate lethal thresholds for hot water decontamination that can be incorporated into implementable standardized protocols. In addition, there is a need to implement cost-effective boater education to reduce risk when trained AIS staff cannot be present. Finally, we must emphasize that, given the heterogeneity we observed among individuals conducting AIS prevention and the complex landscape in which this work is done, there is no "best" AIS spread prevention design or allocation of resources. Indeed, AIS spread prevention requires a collaborative, multi-pronged approach aimed at risk reduction (not elimination) and informed by the best available science.

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CHAPTER 2

AIS Explorer: Intervention Impact – An application for planning cost-effective AIS prevention programs

2.1 ABSTRACT

The movement of aquatic invasive species (AIS) between waterbodies is often facilitated by overland transport on recreational boats. Once established, AIS have detrimental ecological effects that are expensive and arduous or impossible to manage. Because prevention is the most cost-effective intervention, many management efforts focus on implementing spread prevention techniques such as boater education, watercraft inspection, and hot water decontamination. However, deciding which of these three strategies to place across a region and where to place them is difficult and often based on the best judgement of managers. In this study, I collected data for, developed, and tested a new tool entitled *"Intervention Impact*" for the AIS Explorer, an online AIS program-planning dashboard. This tool assists AIS managers in developing prevention plans based on user-defined lake-level budgets, effort, and effectiveness of interventions. The outputs provide estimates for risk reduction and infestations averted for both zebra mussel and starry stonewort. I demonstrate the utility of this application using Cass County, Minnesota, USA as a case study. Simulation outputs highlighted the benefits and liabilities of each prevention applied. Our results demonstrate that this new application could help managers to implement cost-effective prevention plans.

2.2 INTRODUCTION

Aquatic invasive species (AIS) introductions present a worldwide threat to freshwater environments, causing ecosystem impacts, declines in biodiversity, and degraded human health (Reid *et al.* 2019, Thomaz *et al.* 2015, Mazza *et al.* 2014). Additionally, the immense economic burden of AIS management affects not only water recreationalists but also taxpayers through various funding pathways. For example, in the U.S., federal excise taxes directly and indirectly support AIS research and management by providing funds to the Sportfish Restoration and Boating Trust Fund (Norris-Tull 2020, USFWS 2006). In addition, many states within the U.S. have implemented systems to support AIS research and management, and significant resources and capacity are provided by local governments, non-profits, and the public (Mich. Leg. 1994, Minn. Stat. 2022b, Wisc. Stat. 2020, UMN Extension 2023)). Overall, non-native aquatic species management likely accounts for over 23 billion dollars in annual expenditures worldwide, and that cost is rising as AIS introductions occur more frequently (Cuthbert *et al.* 2022).

Recreational boats are a major pathway of AIS spread into and between waterbodies by facilitating overland movement (Johnson et. al. 2001, Rothlisberger *et al.* 2010). In Minnesota, there is a highly connected network of 800,000+ registered boats and ~10,000 lakes, hundreds of which are already infested with AIS, providing ample opportunity for spread within the state and to neighboring states (Minnesota Department of Natural Resources 2023e, Minnesota Geospatial Commons 2023, Kao et. al. 2021). This puts many Minnesota lakes at risk of new invasions and justifies a management emphasis on preventing further spread. While there are many AIS prevention strategies, three commonly implemented methods used in Minnesota are boater education, watercraft inspection, and hot water decontamination (Minnesota Department of Natural Resources 2023b, Minnesota Department of Natural Resources 2023g). Determining which prevention method (or combination) to implement in a given context is difficult, and managers have limited tools and funding with which to make these decisions. Recent approaches include linear integer programming techniques established by Fischer et al (2021) and Haight *et al.* (2021) to predict optimal watercraft inspection locations to mitigate the spread of a variety of high-risk AIS. While these approaches are a significant advancement in optimizing AIS prevention plans, the underlying variables (i.e., available budgets, effort, and effectiveness) are considered equal across space and time. Adding complexity and an ability for users to define model parameters within decision support tools has been identified as an important next step. Additionally, tools of this nature have been shown to be effective in other fields (Seitzinger *et al.* 2022, Stark *et al.* 1998, Schoenbaum and Disney 2003, Ausvet 2023).

Within Minnesota, AIS are managed statewide, regionally, and locally by various agencies, tribes, local governments, watershed districts, and other entities. In addition to state-level management, the state allocates $10 million dollars annually to counties to support their prevention efforts (Minn. Stat. 2022a). To receive that funding, counties must submit a document outlining their proposed use of the funds to prevent the introduction or limit the spread of AIS at all watercraft access sites within their jurisdictions. Many counties plan their AIS programs by placing interventions at waterbodies with the highest perceived risk, such as those that have high amounts of incoming and outgoing boat traffic or are located near infested waters. Chapter one of this thesis evaluated statewide preventions implemented in Minnesota, finding that AIS prevention effectiveness is situational and dependent upon a number of factors, including the region of the state, species of AIS present, and level of AIS training or education of the individual completing the intervention. With this variability in effectiveness, determining the best prevention in every situation is extremely challenging.

Examining both the costs and the effectiveness of alternative AIS prevention strategies has, to our knowledge, not been evaluated in the present literature despite each factor being important in decision-making. Here I estimate the costs of common AIS prevention methods used in Minnesota by interviewing county AIS managers and obtaining real-life prevention program expenditure amounts. I also describe an AIS program-planning application, “*Intervention Impact*”, developed to help inform the AIS prevention program-planning process The application is available through the online interactive platform *AIS Explorer (www.aisexplorer.umn.edu).* It allows users to set values for the effectiveness, costs, and effort of three common AIS preventions (boater education, watercraft inspection, hot water decontamination) and hypothetically apply these preventions at specific lakes within Minnesota. The tool reports the impact on risk that results from the hypothetical scenario input by the user over a five year period.

I assessed the utility of our tool's simulation-based approach using one county in Minnesota, Cass County, as a case study. I applied various effort and effectiveness values for AIS interventions applied at lakes throughout the county to compare and contrast prevention planning approaches. By applying these varying inputs I showcase the wide range of outputs that could occur with real life variability in prevention plan decision making. Ultimately, our intention is for this application to allow users to try out hypothetical prevention scenarios virtually and see the projected impacts of those scenarios before applying them in real life. This will allow users to search for a scenario that fits both their budget and their prevention goals, saving time and money while maximizing impact.

2.3 METHODS

2.3.1 Interviews with County AIS Managers

To better understand how Minnesota's AIS prevention aid funding is being used at the county level, interviews were held with county AIS program managers to determine general expense trends and variability in prevention plans. Cost estimates of watercraft inspection, hot water decontamination, and boater education were obtained via interviews with 24 county AIS program managers in Minnesota of which 19 yielded usable data with few undefined expenses. I chose which counties to interview based on the level of detail and completeness of data that each county relayed to the Minnesota Department of Natural Resources voluntary AIS Prevention Aid reporting program (Minnesota Department of Natural Resources 2023d). Counties that reported their spending habits with few data gaps were emailed using a standardized email template asking for voluntary participation in this study and informing them of what monetary information I would be collecting (Data Repository of Minnesota, *in progress*).

Interviews were conducted for one hour, with email conversations following the interview, if needed. During these interviews, itemized spending information was obtained for each prevention method of interest. The itemization of boater education included the money the county spent on prompts (items given out to boater/the public), signage (signs at public water access), print material (fliers, pamphlets, watchcards, etc.), marketing (billboards, advertising, etc.), events (tabling, school events, etc.), time (time personnel spent handing out/delivering items or time spent at an event), and other (any other expense pertaining to boater education). The itemization of watercraft inspection and decontamination separately included the amount of money spent on salary and fringe (worker wages/salary and any benefits they receive), supplies (consumable supplies less than $500), equipment (multi-year supplies over $500), administration (partitioned salary of management and program oversight), travel (fleet vehicles and any other mileage accounted for), and other (any other expense pertaining to the prevention in question). Funds spent on multi-year equipment were divided by the expected lifespan of the equipment to obtain an annual equipment expense.

Once all data were obtained, the cost per AIS intervention was calculated for each county by adding together the itemized amounts spent for each intervention annually and dividing that total amount by the number of interventions completed annually. The 19 cost-per-intervention values were then averaged to obtain one representative cost-per-intervention value for each of the three prevention types. These representative estimates were used as the default cost for each prevention type in the *Intervention Impact* application.

2.3.2 Simulation Model

I developed a multilayer network model based on the methods outlined in Kinsley *et al.* (under review) that simulates the spread of zebra mussels and starry stonewort between lakes in Minnesota. Within the model, both species can spread from infested to uninfested lakes via boater movements, based on lake-to-lake connections in a boater-movement network, and physical connections such as, through a river connection network. The model also incorporated the lakes' suitability for each species.

The boater movement network consisted of estimated annual boat movement totals between every pair of lakes throughout Minnesota (Kao *et al.* 2021) and was obtained from the University of Minnesota's Data Repository (Kao *et al.* 2020) and published by Kao *et al.* (2021). This network included all lakes and shallow wetlands greater than 10 acres and was created using a series of predictive models informed by Watercraft Inspection Program surveys collected by the MN DNR during open water seasons from 2014-2017 (Minnesota Department of Natural Resources 2023g). This network also served as one layer of our multilayer network model to forecast reduction in changes in risk when different interventions are applied at lakes throughout an area of interest.

The river connection network was constructed using the MN DNR Hydrography data to estimate the length of a river connecting lakes (described in detail in Kinsley et al, under review). The strength, or weight, of the connection, was calculated as the inverse length of the connecting river.

The probability that zebra mussels or starry stonewort spreads from an infested to uninfested lake through boater movements was estimated based on 1) the probability that a boat is contaminated when leaving an infested lakes and 2) the probability that the boat remains contaminated upon arrival at an uninfested lake (Kinsley *et al.*, under review). Within the river connection network, zebra mussels or starry stonewort could drift from an infested to an uninfested lakes if the river that connected the two lakes flowed from the infested towards the uninfested lake. I used a calibrated species-specific migration risk and assumed the risk decreased as the length of the river connecting the two lakes increased (Kinsley *et al.*, under review).

2.3.3 Interventions

When intervention impacts are being assessed, the probabilities in the boater movement network are multiplied by two factors: the risk-reduction factors of the two lakes involved in each edge. A lake's risk-reduction factor is determined by summing the products of the efforts and effectiveness values (both proportions between 0 and 1) for each of the three interventions together. Our model assumes interventions do not impact spread probabilities in the river network.

Effort for a given intervention is the proportion of boats intervened upon at a lake in a year divided by the total number of boats coming into plus exiting that lake in a year. Effectiveness for a given intervention is the proportion of risky boats intervened upon at a lake in a year rendered harmless by that intervention divided by the total number of boats intervened upon at that lake in that year in that way.

For each run of the simulation, a single value for each naive spread probability described above is drawn randomly from a distribution determined by Kao *et al.* (2021) and then held constant thereafter.

Each year in a simulated replicate, the yearly spread probabilities from all edges in both networks are compared to an equal-length set of random values between 0 and 1. If a random value is lower than its corresponding yearly probability, the model simulates an infestation spread along that edge for that species. Each subsequent year, infestation statuses are updated so that new probabilities of spread can be calculated for every potential edge in both networks.

By default, two runs are performed for each simulation requested by a user: 100 replicates of a "status quo" scenario wherein all risk-reduction factors are set to 1 (no risk reduction), and 100 replicates of a user-defined scenario wherein all risk-reduction values are as described above, based on user inputs.

2.3.4 Intervention Impact Application – Design, Development, and Parameterization

The AIS Explorer Intervention Impact application was created as a new feature for the existing AIS Explorer dashboard (aisexplorer.umn.edu) and is referred to within the dashboard as the 'Intervention Impact' tab. This application consists of two main parts – a new page within the AIS Explorer dashboard, and a supporting Amazon Webs Services EC2 instance running an API to run the Intervention model itself without disrupting usage of the AIS Explorer dashboard.

The 'Intervention Impact' tab is a five-stage process whereby a user can specify lakes, species, effort per effectiveness values per lake and cost breakdowns per intervention and per lake (Figure 2.2). Each stage is represented separately within the application in a linear order, so that settings specified in earlier stages will be built upon for later stages. This also allows a user to freely move backward and forward between stages to customize their settings before submitting them to be run. A summary of each stage is outlined below:

<u>Stage 1 – Choose Lakes</u> (Figure 2.3)

The user specifies which species they would like to produce a report for by selecting from a drop-down menu. At the time of publication, these choices include zebra mussels (*Dreissena polymorpha*), starry stonewort (*Nitellopsis obtusa*), or 'all' species (both zebra mussels and starry stonewort). The user will then select a list of lakes to inspect by picking individual lakes and/or groups of lakes from a data table of uninspected lakes. The table of uninspected lakes can be filtered down to one county at a time using a drop-down menu. Each entry in the table contains relevant details about the lake, including the DOW number (Minnesota basin identification number), the county or counties that the lake is in, and any invasive species present in that lake. The selected lakes for inspection will be carried over into Stage 2.

<u>Stage 2 – Define Effort</u> (Figure 2.4)

The user sets an effort percentage for each of the three intervention categories – watercraft inspections, hot water decontamination and education and outreach. These are populated by default with percentages that yield the following approximate numbers of local boats intervened on across all chosen lakes: inspections: 20,000 across all chosen lakes or 15% effort, whichever is lower; hot water decontamination: 140 across all chosen lakes or 0.1% effort, whichever is lower; education and outreach: 40,000 across all chosen lakes, or 50% effort, whichever is lower. The users can apply these default values to the entire selection, set their own default values, or edit the effort for each lake and/or intervention type individually within the data table view. The selected intervention effort percentages are then carried through into Stage 3.

Stage 3 – Define Effectiveness (Figure 2.5)

The user sets an effectiveness percentage for each of the three intervention categories. Default values are provided for each category with a further subdivision into ‘low’, ‘medium’ and ‘high’ effectiveness, however these default values can also be modified. Default values were obtained from a study completed by Angell *et al.* (*in prep*) where researchers observed boaters and trained AIS professionals remove AIS from a boat that had been purposely staged with AIS. The study estimated that on average boaters were 56% effective in AIS removal efforts, inspectors were 79% effective, and hot water decontaminators were 84% effective, and these values were set as the “medium” effectiveness default value in the tool. The “low” and “high” effectiveness levels are set to the lower and upper 95% Confidence Interval bounds of the average estimates from Angell *et al.* (*in prep*). The users can apply these default values to the entire selection, set their own custom values, or edit the effectiveness for each lake and/or intervention type individually within the data table view. The selected intervention effectiveness percentages are then carried through into Stage 4.

Stage 4 – Define Cost (Figure 2.6)

The user sets a cost estimation for each of the three intervention categories. Default values are provided; however, these can also be modified. The default cost per

AIS intervention values were obtained via spending data obtained through interviews with county AIS managers as previously described. These values include $20 per inspection, $362 per hot water decontamination, $0.40 per education and outreach (Angell *et al.*, *in prep*). The user can apply these default values to the entire selection, set their own custom values, or edit the total yearly cost for each lake and/or intervention type manually. The default 'total yearly cost' for each lake is determined by multiplying the cost per boat movement (defined in the default cost values) against the number of boater movements at each lake. The user can also see an overview of the total costs and total costs for each intervention category. The total yearly costs per lake are then carried through into Stage 5.

<u>Stage 5 – Summary</u> (Figure 2.7)

Here the user can view a summary data table of the settings that they have specified in the preceding four stages. A summary provides information about the selected species and included lakes, including the total number of lakes and unique counties for this model run. The table includes the lakes that they have selected for inspection, lake details, effort per effectiveness percentages and total yearly cost for each intervention category.

Once the user is satisfied with their settings, clicking on 'submit' will allow them to enter a name for the model run, along with their email address, before clicking 'run' to submit the model run to the AIS Explorer OpenCPU API for later processing. At this point the user is free to continue using the AIS Explorer dashboard – the Intervention model will run in the background and the user will receive an email with a link to their results once the model is complete.

2.3.5 Running the Intervention Model

The intervention model takes some time to run after submitting the settings (approximately 10 minutes from start to finish), so it would be impractical to run the model through the existing AIS Explorer Dashboard. This would require the user to keep the dashboard open and waiting on the intervention page until their results were ready. Not only would this prevent the user from interacting with other parts of the AIS Explorer application, it could also lead to delays for other users accessing the application due to the ‘single threaded’ functionality of the R programming language. As an alternative, an Application Programming Interface (API) was developed using OpenCPU and R on an Amazon Web Services EC2 instance, which is used to receive requests to the Intervention model and run the model outside of the AIS Explorer Dashboard environment (referred to as the ‘processing server’). Using this processing server, requests can be processed independently from the AIS Explorer dashboard – the user can ‘set and forget’ the model settings and automatically receive their email results upon completion.

When the user clicks ‘Run’ on the final stage of the Intervention Impacts tab, their settings are converted to a JavaScript Object Notation (JSON) file, which is then sent to the API. The API then runs a function that queues those settings in an .RData file on the server. Multiple requests are stored in a queue following the “First In First Out” (FIFO) method, so that the older requests will have a lower ID assigned. The server runs a scheduled CRON job every 12 minutes to pick up the oldest queued request (i.e. the queued request with the lowest ID number), load the settings, run the intervention model and send the results to the provided email.

Once the model is finished running on the processing server, the results are compiled into an interactive HTML report. The report structure is built using R Markdown and the contents of the report are prepared using a combination of the DT, Plotly and Leaflet R packages(Cheng Karambelkar and Xie 2023, Sievert 2020, Xie 2023, Xie 2015, Xie 2014, Xie Cheng and Tan 2023). The results of the model run, model settings and a variety of result visualizations are shown in the report; this includes a summary of costs, change in risks for selected lakes for each selected aquatic invasive species of interest, number of infestations averted (number of infestations estimated to happen under the status quo (no interventions) minus the number of infestations estimated to happen under the input intervention scenario), and a summary table of results for selected lakes. The number of infestations averted is the number of infestations that would occur in a status quo scenario where none of the three interventions are being applied minus number of infestations that would occur under the intervention scenario input by the user. This report is then moved to an accessible location on the processing server, and an access link is automatically emailed to the user who requested the model run. The report can either be viewed directly in a web browser or saved as a PDF for printing or offline access.

2.3.6 Hosting

The AIS Explorer is hosted on Amazon Web Services (AWS) in the US East (Ohio, us-east-2) region, on an auto-scaling group which is managed by a load balancer (1 minimum instance, 2 maximum, 1 desired) to spin up extra capacity when CPU usage or concurrent user access is high. Each Elastic Compute Cloud (EC2) instance managed by the scaling group is created at a t2.large specification (2 vCPUs, 8Gb Memory). The ocpu.epi-interactive.com API which is used to manage requests to the Intervention Model code is also hosted on an EC2 instance in the US East region, using a similar t2.large specification.

2.3.7 Simulating Spending Scenarios – A Case Study of Cass County, MN

Cass County in north-central Minnesota receives a relatively large allocation of prevention aid from the state due to the large number of public boat launches (116) and watercraft trailer parking spaces (1062) within the county (Minnesota Department of Revenue 2023). In addition, Cass County receives high boater traffic (321,571 boater trips estimated annually) and has a relatively low proportion of infested lakes (5%), making it high-risk for new infestations and thus an interesting county to use to assess impacts of various interventions. Cass currently has 20 lakes infested with zebra mussels and 3 with starry stonewort according to the Minnesota Department of Natural Resources' Infested Waters List at the time of publication (Minnesota Department of Natural Resources 2023c).

I ran 9 different intervention plans (3 scenarios each with 3 sub scenarios) on the *Intervention Impact* application involving lakes in Cass County that varied in effort and effectiveness inputs, but that all had the same amount available to be spent ($505,595), the yearly budget value provided to us by Cass County in our interview (D. Dutzmann, personal communication, April 4, 2022). The three spending scenarios split Cass County's budget into inspections:decontaminations:boater education with scenario 1 set to a 75:20:5 split, scenario 2 a 50:0:50 split, and scenario 3 a 40:20:40 split. Within each of these three spending scenarios three sub scenarios were run as follows: sub scenario A = intervention effectiveness values were set to the default (inspections=79%, decontaminations=84%, and boater education=56%; Angell *et al. in prep*); sub scenario B = default values except boater education effectiveness was set to the lower bound of a 95% Confidence Interval around the effectiveness estimate obtained by Angell et al *in prop*; sub scenario C = default values except decontamination effectiveness was set to the upper bound of a 95% Confidence Interval around the effectiveness estimate obtained by Angell *et al. in prep.* These values are available on the University of Minnesota Data Repository (Angell *et al.* 2023).

2.3.8 Applying Interventions within the Application

<u>Inspections</u>

To determine where to most effectively locate inspections within Cass County for our case study, lakes were ranked using the *Prioritization for Watercraft Inspections* application on the *AIS Explorer* dashboard (Kinsley *et al.* 2022). The top 30 lakes were selected to correspond to the number of lakes Cass County actually placed watercraft inspectors at in 2021 (Minnesota Department of Natural Resources 2023d). These 30 lakes accounted for ~49% of all estimated boater traffic that Cass County receives annually (158,609 boats out of 321,571).

Within the *Intervention Impact* application on the “Stage 1-Choose Lakes” page, Cass County's total budget for inspections under each spending scenario was distributed amongst the 30 lakes. The available budget was then divided by the cost per inspection to determine the total number of boats that could be inspected. Given the known number of risky boats visiting each lake (Kao *et al.* 2021), the model proportionally allocates the number of available inspections across the 30 lakes. The effort was held constant for each lake within a specific scenario and intervention. For example, in Scenario 1A, 75% of the total budget was available ($379,188) for watercraft inspections. At $20 per inspection, there are 18,595 inspections to allocate across the 30 lakes. I then used the Intervention Impact application, "Stage 2-Define Effort" page, to determine the effort needed to inspect the target number of boats. In this scenario, this process resulted in an inspection effort of 11.96% of risky boats at each lake (e.g., 2,988 inspected boats out of a total 24,974 risky boats at Leech Lake).

<u>Decontaminations</u>

In the same way that lakes were chosen for inspections, decontaminations were placed at the 3 highest ranked lakes selected to correspond to the number of lakes Cass County actually placed manned decontamination units at in 2021 (S. Henry, personal communication, June 21, 2023). These 3 lakes accounted for ~18% of the estimated boater traffic that Cass County receives annually (57,817 boats out of 321,571).

Similar to the application of inspections within the *Intervention Impact* tool, decontaminations were applied on the "Stage 1-Choose Lakes" page, Cass County's total budget for decontaminations under each spending scenario was distributed amongst the 3 lakes. The available budget was then divided by the cost per decontamination to determine the total number of boats that could be decontaminated. Given the known number of risky boats visiting each lake (Kao *et al.* 2021), the model proportionally allocates the number of available decontaminations across the 3 lakes. The effort was held constant for each lake within a specific scenario and intervention. For example, in Scenario 1A, ~20% of the total budget was available ($100,989) for decontaminations. At $362 per inspection, there are 279 inspections to allocate across the 3 lakes. I then used the Intervention Impact application, "Stage 2-Define Effort" page, to determine the effort needed to decontaminate the target number of boats. In this scenario, this process resulted in a decontamination effort of 0.48% of risky boats at each lake (e.g., 121 inspected boats out of a total 24,974 risky boats at Leech Lake).

Boater Education

Boater education was applied to all lakes within the county assuming once a boater receives AIS education, they take that knowledge with them and apply it at lakes throughout the county. Under this assumption, boater education was applied to account for all estimated boat traffic that Cass county receives in a year (321,571 boats).

Similar to the application of inspections and decontaminations within the *Intervention Impact* application, boater education was applied on the “Stage 1-Choose Lakes” page. Cass County's total budget for boater education under each spending scenario was distributed amongst all lakes within the county. The available budget was then divided by the cost per boat trip to determine the total number of boater trips that could be educated. Given the known number of risky boats visiting each lake (Kao *et al.* 2021), the model proportionally allocates the number of available boater education efforts across all lakes in the county. The effort was held constant for each lake within a specific scenario and intervention. For example, in Scenario 1A, ~5% of the total budget was available (~$25,280) for boater education. At $0.40 per boat trip, there are 63,200 boater trips available to educate across all the lakes. I then used the Intervention Impact application, “Stage 2-Define Effort” page, to determine the effort needed to educate the target number of boater trips. In this scenario, this process resulted in a boater education effort of 19.65% of risky boats at each lake (e.g., 4,908 educated boat trips out of a total 24,974 risky boats at Leech Lake). In scenarios 2 and 3, there were more funds available to be spent on boater education than there were boater trips to be educated, therefore there was excess funds leftover with boater education being applied at 100% effort to all boater trips at all lakes. These excess funds were purposely not re-applied toward any intervention to avoid altering the standardized effort that I had established prior and to mimic a realistic situation. Realistically, many AIS managers save money not spent within a contingency fund which is useful for future expenses and saving up for expensive equipment such as a decontamination unit (Minnesota Department of Natural Resources 2023d).

2.4 RESULTS

2.4.1 Prevention Costs – Interviews with County AIS Managers

I observed high variability in the ways that each county used their available AIS prevention budgets with 6 different general spending schemes arising. The first and most popular spending scheme was spending less than 5% of an available budget on boater education, 70-90% on inspection and the rest on decontamination (n = 6 counties). The second most popular spending scheme was spending over 60% of the available budget on inspections with a relatively even split between boater education and decontamination with the remaining balance (n = 4 counties). The third spending scheme observed was an even amount spent between boater education and inspection (~40% split) and the remaining balance spent on decontamination (n = 3 counties). The 3 final spending schemes all commonly shared no money being spent on decontamination, but ratios spent on inspections and boater education differed. These "no decontamination" spending schemes included: the majority of the budget spent on inspections (over 66%; n = 3 counties), a relatively even split between inspections and boater education (n = 2 counties), and the majority spent on boater education (over 62%; n = 1 county). I also observed high variability in the amount spent by each county on each itemized expense category (Table 2.2).

From the 19 counties I interviewed, 42% of counties hired a third-party contractor to implement inspections and decontaminations at lakes throughout their county. On average a county completed 13,503 (sd =12,863) inspections and 187 (sd = 111) decontaminations and received 129,501 (sd = 101,349) boater trips. It cost a county an average of $20.00 (min = $4.52, max = $145.70) per inspection, $362.01 (min = $74.37, max = 1,498.39) per decontamination and $0.40 (min = $0.04, max = $1.16) per educated boater trip. Our case study subject, Cass County, completes ~30,158 annual inspections per year and ~316 hot water decontaminations and experiences 321,571 boater trips annually.

2.4.2 Simulated Spending Scenarios – A Case Study of Cass County, MN

Scenario 1 (A-C)

In spending Scenario 1, of the money available to be spent ($505,595), all was used except for $35.93. The amount spent on watercraft inspections was $379,188.41, on decontaminations $101,090.71, and on boater education $25,279.95. The effort applied was 11.96%, 0.48%, and 19.65% for watercraft inspection, hot water decontamination, and boater education respectively. With this effort it was estimated that 18,595 boats were inspected, 279 decontaminated, and 63,195 boater trips educated. For scenarios 1:A-C, the 3 interventions were applied with different effectiveness percentages. Scenario 1A resulted in 12 (95% CI = 6-19) zebra mussel and 0.44 (95% CI = 0-3) starry stonewort infestations over the 5-year period of the simulation. When compared to the status quo scenario, scenario 1A resulted in 5 (95% CI = 3-5) zebra mussel and 0.56 (95% CI = 0-2) starry stonewort infestations averted. Scenario 1B resulted in 14 (95% CI = 8-22) zebra mussel and 0.75 (95% CI = 0-3) starry stonewort infestations. When compared to the status quo scenario, scenario 1B resulted in 3 (95% CI = 1-3) zebra mussel and 0 (95% CI = 0-0) starry stonewort infestations averted. Scenario 1C resulted in 12 (95% CI = 6-19) zebra mussel and 0.43 (95% CI = 0-2) starry stonewort infestations (Table 2.1). When compared to the status quo scenario, scenario 1C resulted in 4 (95% CI = 3-5) zebra mussel and 0.4 (95% CI = 0-1) starry stonewort infestations averted when compared to the status quo scenario.

Scenario 2 (A-C)

In spending Scenario 2, watercraft inspections took place at 30 lakes, hot water decontaminations at 0 lakes, and all lakes received boater education within Cass County, MN. Of the money available to be spent ($505,595), $124,192.30 was not used due to having money left over after applying 100% boater effort to all lakes in the county. The amount spent on watercraft inspections was $252,774.30, on decontaminations $0.00, and on boater education $128,628.40. The effort applied was 7.97%, 0%, and 100% for watercraft inspection, hot water decontamination, and boater education respectively. With this effort it was estimated that 12,632 boats were inspected, 0 decontaminated, and 321,571 boater trips educated annually. For Scenario 2:A-C the same effectiveness percentages were applied as in Scenario 1:A-C. Scenario 2A resulted in 2.1 (95% CI = 0-5) zebra mussel and 0.09 (95% CI = 0-1) starry stonewort infestations. Scenario 2A resulted in 13.9 (95% CI = 9-19) zebra mussel and 0.79 (95% CI = 0-2) starry stonewort infestations averted when compared to the status quo scenario. Scenario 2B resulted in 9.8 (95% = 4-16) zebra mussel and 0.31 (95% CI = 0-2) starry stonewort infestations. Scenario 2B resulted in 5.2 (95% CI = 4-7) zebra mussel and 0.43 (95% CI = 0-1) starry stonewort infestations averted when compared to the status quo scenario. Scenario 2C resulted in 2 (95% CI = 0-5) zebra mussel and 0.02 (95% CI = 0-1) starry stonewort infestations (Table 2.1). Scenario 2C resulted in 13 (95% CI = 9-18) zebra mussel and 0.87 (95% CI = 0-2) starry stonewort infestations averted when compared to the status quo scenario.

Scenario 3 (A-C)

In spending Scenario 3, watercraft inspections took place at 30 lakes, hot water decontaminations at 3 lakes, and all lakes received boater education within Cass County, MN. Of the money available to be spent ($505,595) all was used except for $73,649.99 due to having money left over after applying 100% boater effort to all lakes in the county. The amount spent on watercraft inspections was $202,225.79 on decontaminations was $101,090.71, and boater education was $128,628.40. The effort applied was 6.38%, 0.48%, and 100% for watercraft inspection, hot water decontamination, and boater education respectively. With this effort it was estimated that 10.111 boats were inspected, 279 decontaminated, and 321,571 boater trips educated annually. For Scenario 3:A-C the same effectiveness percentages were applied as in Scenario 1:A-C and 2:A-C. Scenario 3A resulted in 1.9 (95% CI = 0-5) zebra mussel and 0.05 (95% CI = 0-1) starry stonewort infestations. Scenario 3A resulted in 14.1 (95% CI = 9-18) zebra mussel and 0.78 (95%

CI =0-2) starry stonewort infestations averted when compared to the status quo scenario. Scenario 3B resulted in 10 (95% CI = 5-16) zebra mussel and 0.39 (95% CI = 0-2) starry stonewort infestations. Scenario 3B resulted in 6 (95% CI = 4-8) zebra mussel and 0.38 (95% CI = 0-1) starry stonewort infestations averted when compared to the status quo scenario. Scenario 3C resulted in 1.8 (95% CI = 0-5) zebra mussel and 0.05 (95% CI = 0-1) starry stonewort infestations (Table 2.1). Scenario 3C resulted in 15.2 (95% CI = 9-20) zebra mussel and 0.63 (95% CI = 0-1) starry stonewort infestations averted when compared to the status quo scenario.

Status Quo (No Interventions)

For the status quo scenario, $0.00 was spent on interventions, 0% effort was applied, and the default effectiveness percentage for each intervention was executed. This resulted in 16 (95% CI = 9-24) zebra mussel and 0.80 (95% CI = 0-3) starry stonewort infestations (Table 2.1).

2.5 DISCUSSION

This study quantified the costs of watercraft inspection, hot water decontamination, and boater education by gathering itemized expense data from AIS program managers in Minnesota. These data along with prevention effectiveness estimates from Angell *et al.* (*in prep*) were incorporated into a new AIS program planning application called *Intervention Impact*. This application is a user-friendly, interactive web-based tool that supports decision-making related to deploying common AIS prevention methods. It is freely available (www.aisexplorer.umn.edu) and allows users to virtually create and understand the cost-benefit of placing watercraft inspectors, hot water decontamination stations, and boater education at lakes throughout any region in the state of Minnesota.

From data collected during interviews with county AIS program managers, I observed that AIS prevention funds are spent in many different ways, and I highlight the diversity of plans being implemented across the state. To examine key differences in the effectiveness of various plans, I completed a case study that showcased outputs of 9 different scenarios that exhibit changes in AIS prevention cost and effectiveness. In our case study, I used the *Intervention Impact* application to hypothetically apply AIS preventions throughout Cass County, MN. By applying differing efforts for each intervention and manipulating intervention effectiveness under various spending regimes I could compare and contrast outputs from each plan.

When examining different spending scenarios (1-3) I noted that all spending regimes were predicted to produce fewer zebra mussel and starry stonewort infestations than the status quo (no interventions) showing that implementing AIS preventions is worthwhile (Figure 2.1). This idea is supported by several studies that have examined prevention effectiveness (Angell *et al. in prep*, Mohit *et al. in review*, Rothlisberger 2010, Sharp *et al.* 2017).

Scenarios 2 and 3 expended less money than scenario 1 while also being estimated to experience fewer infestations for both zebra mussel and starry stonewort. In scenarios 2 and 3 more money was spent on boater education (50% and 40% of available budget respectively) whereas scenario 1 spent much less (5% of available budget). This showcases the capability of boater education being highly cost-effective in more than one situation. This idea is supported when I examined the effects of changing prevention effectiveness (A-C) specifically looking to where boater education effectiveness is lower (B), noting that the number of infestations spikes for AIS types in all spending scenarios (Figure 2.1). This suggests boater education as a critical low cost ($0.40 per boat trip) prevention that can be implemented extensively by managers in a wide range of funding amounts and efforts.

Trivial differences in the number of predicted infestations occurred between scenarios 2 and 3 when the same proportional amounts of money were spent on watercraft inspection and boater education, but decontamination expenses differed. Despite scenario 3 spending 20% of its budget on decontamination and scenario 2 spending nothing, the addition of hot water decontamination did not have a significant impact on the number of infestations averted. This idea is supported when examining the effects of changing prevention effectiveness (A-C) specifically looking to where hot water decontamination is 100% effective (C) and I observe no major differences in the number of infestations from what would be normally expected for intervention effectiveness (A) (Figure 2.1). I do acknowledge that hot water decontaminators are used to target microscopic AIS that are not easily seen and removed with a hand inspection (i.e. zebra mussel veligers, spiny water flea (*Bythotrephes longimanus*), or viral hemorrhagic septicemia (VHS)) and that a larger risk reduction may be experienced when decontamination is implemented where these types of AIS are more prevalent. Cass county has few lakes infested with zebra mussels and no detections of spiny water fleas or VHS at the time of publication.

Additionally, I acknowledge that for the sake of standardization I applied effort for each intervention equally amongst the included lakes. However, these efforts would likely vary from lake to lake due to environmental variation and differences in infestation status. These results do not reflect the prevention decisions that Cass County would make because they would likely apply effort in varying amounts, which is why the development of the *Intervention Impact* application includes user-defined capabilities with effort, effectiveness, and costs being customizable at the lake level.

A key feature of the *Intervention Impact* application is its customizability. Angell *et al.* (*in prep*) showed that intervention effectiveness was highly situational based upon region the intervention took place, AIS type present, and level of training/education of the intervener. In addition, interviews with AIS county managers in this study revealed that costs are highly variable based upon location, available budget, and prevention goals. The *Intervention Impact* application provides default values for cost and effectiveness based upon real-life standards, but these variables along with effort and which lakes to intervene at are all customizable giving users the ability to create and implement prevention scenarios that match their situation even if atypical (e.g., they made their own or got a discount on a decontamination unit making its hot water decontaminations program cheaper per boat than the default).

Another key feature of the application is its stepwise functionality that leads users through the thought process of applying interventions at chosen lakes by implementing specific efforts, effectiveness's, and costs for said interventions. By incorporating ground-truthing abilities based on empirical cost-benefit data, this tool promotes a unique managerial approach to prevention planning. Users will have the opportunity to generate multiple intervention plans and receive output reports that they can then use to conduct side-by-side comparisons.

A final key feature of this application is its automatic updating abilities. The simulation behind the model retrieves information from the MN DNR's infested waters list twice daily making it useful over time as infestation status changes across the state (Minnesota Department of Natural Resources 2023c).

Risk based models and decision support tools that take into account monetary constraints are relatively well established in other fields such as epidemiology (Seitzinger et a. 2022, Stark *et al.* 1998, Schoenbaum and Disney 2003, Ausvet 2023) but less so in aquatic invasive species management. While there are many resources online that keep track of new AIS infestations via virtual maps and databases (Minnesota Department of Natural Resources 2023c, Reaser *et al.* 2019, NOAA (n.d.)), there are few that go beyond that to inform prevention allocation across the landscape (USGS (n.d.), USFWS (n.d.)) and none, to our knowledge, that incorporate both the cost and effectiveness of AIS preventions. The *Intervention Impact* tool models the framework for conservation-based tools summarized by Schwartz *et al.* by helping to answer: *what* future possibilities and uncertainties are, *where* action needs to take place, *what* actions will achieve desired outcomes, *how* to best use limited resources, and *how* effective the actions are.

Ground-truthing predictive tools is crucial to augmenting user trust and confidence in outputs (Cabitza *et al.* 2023). By incorporating 'real-life' data obtained from county managers into the *Intervention Impact* tool, key stakeholder relationships were built which is an essential step in the process of building an effective decision-support tool (Kanankege 2020).

Aside from increasing user trust there is immense value in stakeholder engagement including benefiting from diverse perspectives (Liu *et al.* 2011) and prioritizing key functions based on need (Shackleton *et al.* 2019). By interviewing and collaborating with county, state, tribal, and third-party partners to collect, refine, and implement data into the *Intervention Impact* tool I gained valuable insider knowledge that further improves the applicability and transferability of the tool between different parties of interest.

Not only has our approach to creating the *Intervention Impact* tool improved user confidence, but it also has strengthened predictive power and reduced uncertainty by allowing for user-driven adjustments to be made that match variational risk across the landscape. Stokes *et al.* 2006 points out that adjusting for different levels of risk can counter uncertainty in invasive species management and mathematical models serve as a foundational enabling tool.

In addition, the tool successfully incorporates cost-effectiveness of interventions and makes comparisons to status quo situations which, as Kanankege *et al.* and Stokes *et al.* points out, is a key component of effective decision making in natural resource management (Kanankege *et al.* 2020, Stokes *et al.* 2006)).

The *AIS Explorer-Intervention Impact* application is a unique prevention planning tool that is, to our knowledge, the first of its kind to consider the cost-benefits of implementing AIS prevention techniques for minimizing boater mediated spread. This tool supports decision making by allowing users to evaluate the trade-offs among intervention strategies based on their estimated performance and ability to meet prevention objectives serving as a bridge between research and management to achieve synergistic goals. While this application is currently focused on AIS prevention in Minnesota, spatial expansion is anticipated in the future. I hope this tool will not only aid in developing and implementing efficient AIS prevention program plans, but also help managers to approach their prevention implementation process with a newfound perspective and thought process.

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CONCLUSION

In this thesis I filled key knowledge gaps for aquatic invasive species prevention and collaboratively created an online decision-support tool to help managers in Minnesota allocate their limited prevention resources. More specifically, the application incorporates newly collected empirical data that takes into account real-world stochasticity such as infestation changes, boater movement, and the cost-effectiveness of AIS interventions being applied across the landscape. These data are used to predict future AIS infestations and have created a framework for tackling complex and multidisciplinary AIS issues in a standardized and understandable manner that considers the perspectives of key stakeholder groups.

This research quantified, for the first time, the real-world effectiveness and costs of boater education, watercraft inspections, and hot water decontamination as AIS preventions in the state of Minnesota. Results suggest that boater education is a cost-effective prevention method that is inexpensive and widespread across the landscape. Caveats of boater education include the potential for investing valuable resources where it's not necessary, such as on a boater that never visits an infested waterbody. However, boater education can also induce a "domino effect" where one boater educates another and that boater educates another setting off a chain reaction of boaters educating one another. This may indicate that spending resources on a "non-risky" boater could have a positive impact on "risky boater's" that learn best management practices from their boating peers (Clarke 1993). Watercraft inspection is a moderately priced and effective prevention tool that serves as both a form of education and AIS removal opportunity. This research suggests there is room for improving the effectiveness of watercraft inspection that involve minimal changes to training methods by adding emphasis to key locations that are most often missed by inspectors and encouraging inspectors to slow down their inspection process or double check the watercraft to find items that may have been missed the first time. Hot water decontamination, while highly effective, was also orders of magnitude more expensive than boater education and watercraft inspection. While decontamination is important in high-risk situations involving microscopic AIS, this research indicates that hot water decontamination could benefit from more standardized and practical protocols as well as reliable equipment manufactured with intentions to be used for decontaminating watercraft.

A key takeaway from this work is that there is high variability in the costs and effectiveness of AIS preventions due to several factors, including invasive species' physical appearances and life histories, environmental variation, and regional differences in human perceptions and knowledge. For example, AIS spread through the recreational boater pathway is impacted by the communities of flora and fauna within each exposed waterbody as well as water quality and anthropogenic influences that impact invasion susceptibility. Additionally, the quantity of an AIS being introduced by a recreational boat impacts AIS spread with higher propagule pressure increasing likelihood of establishment and proliferation (Drake and Lodge 2006). Every invasive species introduction is different and needs to be uniquely managed. This variation leads to data insufficiencies that were a limiting factor in conducting cost-effectiveness analyses. This study stops short of explicitly stating cost-effective values for each intervention due to situational volatility; however, the *Intervention Impact* application on the *AIS Explorer* dashboard gives users the framework to determine cost-effective values for each unique situation they are challenged with managing and is therefore a critical advancement in AIS prevention and management.

The *AIS Explorer-Intervention Impact* application is a free (www.aisexplorer.umn.edu) web-based decision support tool that exemplifies the power of mathematical models coupled with empirical data to achieve informative and actionable outputs. The use of empirical data to inform natural resource management is not a new idea, but there is a need for better and more widely adopted data collection and management plans that could inform research and adaptive management (Poteete and Ostrom 2008). Future versions of the AIS explorer could incorporate more types of invasive species and spatial expansion to further mitigate risk. Additionally, there is value in bringing more stakeholders to the table such as the boating public. This could be done through the addition of a new interactive virtual map to the dashboard that shows placement of inspection and decontamination stations across the state. This will allow boaters to be informed on where they can access these resources as well as familiarize them to the vast amount of effort and time put into AIS issues. Implementing this type of framework would bring together researchers who make the tools, managers who plan and implement the preventions, and boaters who utilize the resource. By connecting these diverse groups, knowledge sharing could inform future research and management while also influencing boater behavior.

While the three preventions focused on in this research are popular, they are not the only prevention options. Comparable methodologies could be used to understand the cost-effectiveness of canine AIS detection (Sawchuk 2018), self-cleaning stations (Campbell *et al.* 2020), ambient water rinses (PSMFC 2023), and targeted boater education campaigns (Sharp *et al.* 2017). In knowing more about these preventions, AIS managers could better adapt to challenges by having more prevention options to choose from in each situation. Additionally, the simulation model behind the *Intervention Impact* application is set up for quick and easy integration of new preventions as cost-effectiveness data becomes available for them.

Additionally, the scope of AIS issues is large, spanning much further than the state of Minnesota. This research provides a foundation for inquiring about the cost-effectiveness of AIS preventions in other states and areas of the world that experience AIS issues. In the future employing these methodologies in the Western United States where Minnesota's inspection and decontamination protocols were initially developed would be valuable and allow important comparisons to be made considering regional differences (Elwell and Phillips 2021). Furthermore, the experimental and survey designs used in this research to evaluate boaters' AIS knowledge can be applied to assess jurisdictional differences that impact the quantity and quality of boater education.

Stakeholder engagement was a large part of this project as I strove to capture realistic data from those that are most familiar with AIS management. In doing this, valuable insight was gained on the perspectives of both those planning where to implement AIS preventions and those actually completing them. This was extremely helpful in understanding the challenges that AIS managers are currently facing, which were prioritized as collaborators and I created the *Intervention Impact* application. While this stakeholder engagement was time consuming and sometimes involved difficult conversations, it provided invaluable insight to the project and its eventual outputs by helping to prioritize certain aspects of research based on user needs and by promoting concordance leading to higher acceptance and use of the final product. Future efforts to understand and combat AIS impacts should strive to incorporate diverse stakeholder groups to produce inclusive outcomes that are more robust and applicable to end users. To do this, an emphasis should be put on creating long-lasting relations with stakeholders and prioritizing an output that will benefit all parties involved.

While this research focused primarily on understanding AIS prevention in the state of Minnesota, this work provides contextual and in-depth information about the implications of AIS prevention applied in a real-world example. This study has broader implications about the stochastic nature of invasive species issues and solutions to them involving mathematical predictions that take into account empirical data. There is immense strength in predictive models and decision-making tools in that they consider a suite of variable tradeoffs, promote participatory decision making, and help in understanding and incorporating inherent uncertainty in composite socio ecological systems (Runge 2020) and this work shows that in action.

Minnesota's water resources are unique in scope and scale providing vast recreational, cultural, and economical opportunities (Schuldt and Schneider 2011). With such a highly dynamic and interconnected system of waterbodies (Kao *et al.* 2021) there are management tradeoffs that must be considered involving the risk of introducing AIS or limiting use to reduce that risk. This research has and will continue to help inform these management decisions by giving managers the opportunity to explore tradeoffs of prevention plans before applying them across the landscape. This will allow managers to find and implement prevention plans that will reduce AIS risk.

Implementing aquatic invasive species prevention plans are extremely arduous especially within highly stochastic ecosystems that synergistically undergo changes from anthropogenic influences. While currently implemented preventions have their own opportunities and obstacles, they each retain a role in prevention planning in adjustable quantities that depend on environmental and ecological conditions. Despite the tradeoffs and difficult decisions that lie ahead, there is room for deeper engagement and unity amongst water allies to protect water resources from aquatic invasions.

TABLES

Table 1.1. To understand the effectiveness of common AIS spread prevention practices, experimental AIS removal trials were completed at public water accesses and centrally located decontamination points within Minnesota and Wisconsin from June-August 2022. Participants in these trials (boaters, trained watercraft inspectors, and watercraft decontaminators) removed AIS from a realistically staged boat and removal rates are shown: mean (standard deviation).

	Boaters	**Inspectors**	**Decontaminators**
Total Participants (n)	69	52	23
Metro	36	23	7
Outstate	33	29	16
Minnesota	60	51	23
Wisconsin	9	1	0
Participation Rate	~33.3%	98%	100%
Total Public Water Access Sites (n)	9	47	16
Metro	5	21	6
Outstate	4	26	10
Minnesota	8	46	0
Wisconsin	1	1	0
Time (minutes:seconds)	2:49	4:22	26:02
Min	0:37	1:30	9:14
Max	18:00	16:56	62:31
Average Effectiveness of hand inspection (% AIS removed)	56.4 (17.0)	79.2 (9.8)	77.8 (20.9)
Metro	63.3 (16.1)	79.2 (9.8)	80.0 (11.5)
Outstate	48.8 (14.7)	79.2 (9.8)	76.9 (24.1)
Average effectiveness of entire AIS removal process (hand inspection + decontamination; % AIS removed)	NA	NA	84.4 (10.2)
Metro	NA	NA	82.9 (11.1)
Outstate	NA	NA	85.1 (10.1)
Removal per unit time (%/min)	25.6 (11.9)	21.0 (6.98)	19.4 (12.8)
Metro	24.3 (13.0)	23.6 (6.42)	20.1 (11.0)
Outstate	27.0 (10.6)	18.9 (6.79)	19.1 (13.9)

Table 1.2. Experimental AIS removal trials occurred at public water accesses in Minnesota and Wisconsin from June-August 2022. During these trials participants (boaters, trained watercraft inspectors, and decontaminators) were observed while completing prevention steps on a boat that had been realistically staged with AIS. Participants' actions were recorded during their AIS removal process and percent of participants completing a specific action are shown.

Participant Observations (% of total n)	Boater	Inspector	Decontaminator
Touched most frequently	propeller (97%) anchor (71%) trailer frame (65%)	propeller (100%) hull (94%) water intake valve (94%)	propeller (100%) anchor (96%) water intake valve (96%)
Looked most frequently (without touching)	trailer axle (67%) trailer rollers (61%) wheels (49%) transom well (49%)	trailer axle (82%) drain plug (67%) interior floor (60%)	trailer axle (85%) drain plug (65%) interior floor (44%)
Overlooked most frequently	winch (68%) bow line (64%) transducer (59%) tow rope (59%)	compartments (62%) transducer (52%) lights/wiring (44%)	tow rope (48%) compartments (43%) spare tire (43%) winch (43%)

Table 1.3. The steps that decontaminators took during experimental hot water decontamination trials occurring in Minnesota from June-August 2022. (LF = low flow spray with hot water; MF = motor flush with hot water; HP = high pressure spray with ambient water; HPH = high pressure spray with hot water)

process completed	decontaminators (n)
LF+MF	11 (47.8%)
LF+HP+MF	5 (21.7%)
HPH+MF	2 (8.7%)
LF+HPH	1 (4.4%)
HPH+HP+MF	1 (4.4%)
HPH	1 (4.4%)
None	2 (8.7%)

Table 1.4. Metadata from a binomial mixed-effects regression model with random intercepts for each participant that completed an AIS removal trial in June-August 2022 in Minnesota or Wisconsin. The random intercepts were included to account for potential pseudoreplication. Bolded values represent significant interaction terms ($p < 0.05$).

Predictors	estimate	SE	*z*	*p*
fixed effects				
main effects				
intercept (boater, plant, metro)	1.93	0.22	8.78	**<0.001**
inspector	1.27	0.42	3.06	**0.002**
decontaminator	1.97	0.75	2.61	**0.009**
spiny water flea	-20.5	33.1	-0.62	0.536
residual water	-1.71	0.37	-4.63	**<0.001**
zebra mussel	-2.73	0.32	-8.56	**<0.001**
outstate	-1.02	0.28	-3.70	**<0.001**
interaction effects				
inspector * spiny water flea	15.2	33.1	0.46	0.646
decontaminator * spiny water flea	15.8	33.1	0.48	0.633
inspector * residual water	-0.78	0.55	-1.40	0.162
decontaminator * residual water	-1.22	0.87	-1.41	0.160
inspector * zebra mussel	0.10	0.48	0.22	0.828
decontaminator * zebra mussel	0.06	0.75	0.08	0.937
inspector * outstate	1.46	0.46	3.15	**0.002**
decontaminator * outstate	1.07	0.65	1.64	0.100
spiny water flea * outstate	1.20	0.73	1.63	0.103
residual water * outstate	1.02	0.46	2.20	**0.028**
zebra mussel * outstate	-1.11	0.45	-2.48	**0.013**
random effect	**SD**			
participant ID	0.52			

Table 1.5. The percentage of AIS removed from a realistically staged boat during experimental AIS removal trials occurring from June-August 2022 in Minnesota and Wisconsin. Voluntary participants (boaters, inspectors, and decontaminators) were observed during the AIS removal process. Removal was recorded by species and location to understand the heterogeneity in AIS removal and impacts of those confounding variables.

AIS type	boat location	percent removed by boaters	percent removed by inspectors	percent removed by decontaminators
plant	anchor	73	90	96
plant	trailer frame	93	98	100
plant	boat hull	59	94	96
plant	motor intake	57	96	100
plant	propeller	99	100	100
plant	trailer roller	91	100	96
zebra mussel	motor mount	3	25	30
zebra mussel	strake/hull	36	85	91
spiny water flea	fishing rod	0	27	52
residual water	bait bucket	55	79	83

Table 1.6. Predicted probabilities of successful AIS removal and their associated 95% Confidence Intervals (CIs) for 24 hypothetical scenarios combining individual interveners, types of AIS removed, and region of the state in which removal occurs. Predicted removal percentages were generated via a randomization process using the coefficient estimates and standard errors from a binomial mixed-effects regression model assessing associations between these three variables and their two-way interactions and removal success, with a random intercept for individual participants.

region	AIS type	Individual intervening	Predicted percent removed (95% CI)
outstate	plant	inspector	99.5 (97.9-99.9)
outstate	plant	decontaminator	99.5 (97.5-100.0)
metro	plant	decontaminator	97.1 (89.8-99.6)
metro	plant	inspector	95.3 (86.7-99.1)
outstate	plant	boater	94.1 (85.4-98.5)
metro	plant	boater	85.7 (68.8-96.0)
outstate	zebra mussel	decontaminator	83.6 (35.2-99.4)
outstate	zebra mussel	inspector	83.3 (47.4-98.7)
metro	zebra mussel	decontaminator	72.3 (22.0-97.6)
metro	zebra mussel	inspector	61.2 (22.6-90.4)
metro	zebra mussel	boater	32.1 (10.7-61.0)
outstate	zebra mussel	boater	31.4 (6.8-67.5)
outstate	water	inspector	97.1 (85.0-99.9)
outstate	water	decontaminator	95.4 (71.3-99.9)
outstate	water	boater	87.9 (61.1-98.0)
metro	water	decontaminator	67.0 (14.4-96.9)
metro	water	inspector	62.7 (19.8-92.1)
metro	water	boater	55.5 (24.1-82.7)
outstate	spiny water flea	decontaminator	52.8 (0.0-100.0)
outstate	spiny water flea	inspector	51.5 (0.00-100.0)
metro	spiny water flea	decontaminator	49.6 (0.00-100.0)
metro	spiny water flea	inspector	47.8 (0.00-100.0)
outstate	spiny water flea	boater	31.2 (0.00-100.0)
metro	spiny water flea	boater	29.8 (0.00-100.0)

Table 2.1. A case study investigating the outcomes of 9 different aquatic invasive species (AIS) prevention program planning options applied to Cass County in Minnesota was completed using the *AIS Explorer-Intervention Impact* application. A summary of variables input into the tool and of outputs obtained are included and compared with a status quo situation where no interventions were applied. Each sub scenario corresponds to: A = default effectiveness (79% inspections, 84% decontaminations, 56% boater education); B = default effectiveness except boater education set to 20%; C = default effectiveness except for hot water decontamination set to 100%. The letters in front of each ratio value for the target and actual allocation amounts stand for inspections (I), decontaminations (D), and boater education (B).

Sub Scenario	**A**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Number of lakes										
Inspections	0		30			30			30	
Decontaminations	0		3			0			3	
Boater Education	0		961			961			961	
Intervention Effort										
Inspectors	0 %		11.96 %			7.97 %			6.38 %	
Decontaminators	0 %		0.48 %			0 %			0.48 %	
Boaters	0 %		19.65 %			100 %			100 %	
Estimated Number of Boats Intervened										
Inspections	0		18,595			12,632			10,111	
Decontaminations	0		279			0			279	

Boater Education	0	63,195			321,571			321,571		
Intervention Effectiveness										
Inspectors	79 %	79 %	79 %	79 %	79 %	79 %	79 %	79 %	79 %	79 %
Decontaminators	84 %	84 %	84 %	100 %	84 %	84 %	100 %	84 %	84 %	100 %
Boaters	56 %	56. %	20 %	56 %	56 %	20 %	56 %	56 %	20 %	56 %
Available Budget	$505,595	$505,595			$505,595			$505,595		
Target Allocation	0 I : 0 D : 0 B	75 I : 20 D : 5 B			50 I : 0 D : 50 B			40 I : 20 D : 40 B		
Actual Allocation	0 I : 0 D : 0 B	75 I : 20 D : 5 B			50 I : 0 D : 25 B			40 I : 20 D : 25 B		
Total Spent	$0.00	$505,559			$381,402			$431,945		
Inspections	$0.00	$379,188			$252,774			$202,226		
Decontaminations	$0.00	$101,091			$0			$101,091		
Boater Education	$0.00	$25,280			$128,628			$128,628		
Balance	$505,595	$36			$124,193			$73,650		
Predicted Infestation Amount (95% CI)										
Zebra Mussel	16 (9-24)	12 (6-19)	14 (8-22)	12 (6-19)	2.1 (0-5)	9.8 (4-16)	2 (0-5)	1.9 (0-5)	10 (5-16)	1.8 (0-5)
Starry Stonewort	0.80 (0-3)	0.44 (0-2)	0.75 (0-3)	0.43 (0-2)	0.09 (0-1)	0.31 (0-2)	0.02 (0-1)	0.05 (0-1)	0.39 (0-2)	0.05 (0-1)

Table 2.2. Itemized AIS prevention spending amounts obtained via Interviews with 19 MN County AIS managers. Itemized expense categories inquired about for inspection and decontamination include: Salary and fringe (worker wages/salary and any benefits they receive), supplies (consumable supplies less than $500), equipment (multi-year supplied over $500), administration (partitioned salary of management and program oversight), travel (fleet vehicles and any other mileage accounted for), and other (any other expense pertaining to the prevention in question). Itemized expense categories inquired about for boater education include: prompts (items given out to boater/thepublic), signage (signs at public water access), print material (fliers, pamphlets, watchcards, etc.), marketing (billboards, advertising, etc.), events (tabling, school events, etc.), time (time personnel spent handing out/delivering items or time spent at an event), and other (any other expense pertaining to boater education).

Itemized Expense Category	**Inspection**		**Decontamination**		**Itemized Expense Category**	**Boater Education**	
Salary/Fringe	$113,711	(sd = $98,163)	$21,142	(sd = $21,831)	Prompts	$2,730	(sd = 4,943)
Supplies	$837	(sd = $1,424)	$1,427	(sd = $2,995)	Signage	$884	(sd = 2,181)
Equipment	$1,049	(sd = $1,404)	$2,153	(sd = $3,106)	Print Materials	$935	(sd = $1,827)
Admin	$22,838	(sd = $23,332)	$4,135	(sd = 5,474)	Marketing	$884	(sd = $2,181)
Travel	$1,939	(sd = 3,450)	$308	(sd = $610)	Events	$4,535	(sd = 10,564)
Other	$1,357	(sd = 2883)	$477	(sd = 1,101)	Time	$4,863	(sd = 7546)
					Other	$7,369	(sd = $14,163)

FIGURES

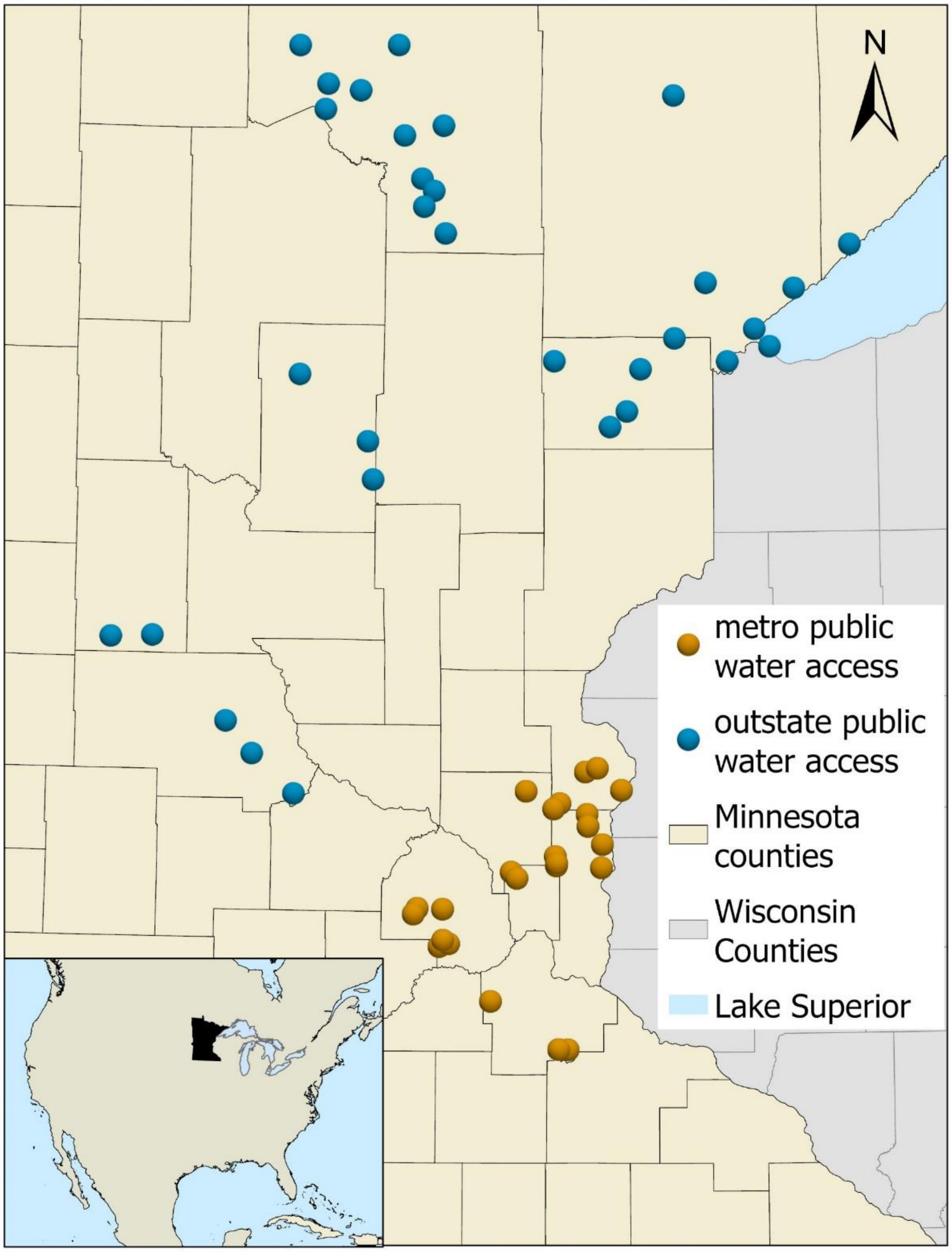

Figure 1.1. Public water access sites and centrally located decontamination stations across two regions (metro and outstate) of Minnesota and Wisconsin where experimental AIS removal trials took place from June-August 2022.

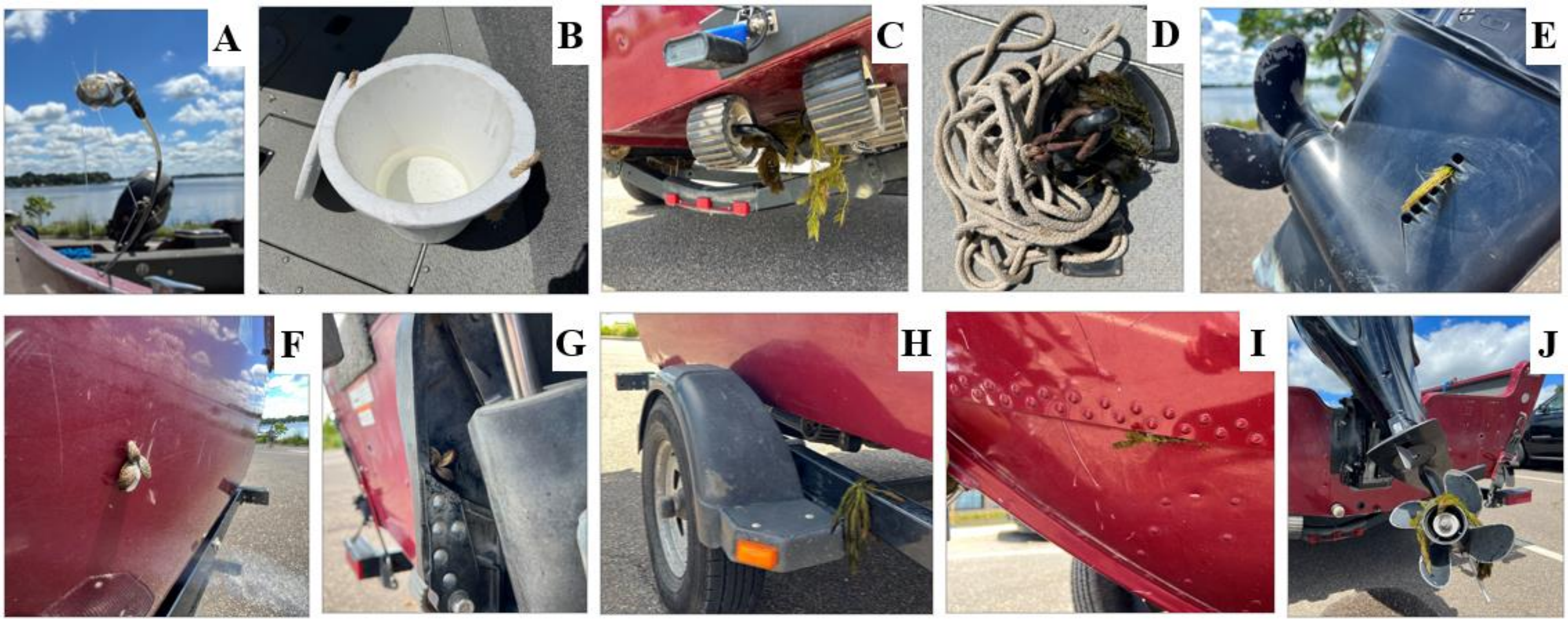

Figure 1.2. Ten standardized locations of aquatic invasive species staged on the boat during experimental AIS removal trials occurring from June-August 2022. (A) a clump of 10 spiny water fleas on the last eyelet of a fishing rod; (B) 500 ml of residual water in a bait bucket; (C) ~40 g of coontail on the boat trailer rollers; (D) ~40 g of coontail on the anchor; (E) ~0.2 g of coontail in the motor's water intake valve; (F) 3 adult zebra mussel shells placed on the boat hull; (G) 3 adult zebra mussel shells placed on the motor mount; (H) ~40 g of coontail placed on the boat trailer frame; (I) ~2 g of coontail placed on the boat strake; (J) ~40 g of coontail placed on the motor propeller. See Figure 1.3 for more information on placement of AIS.

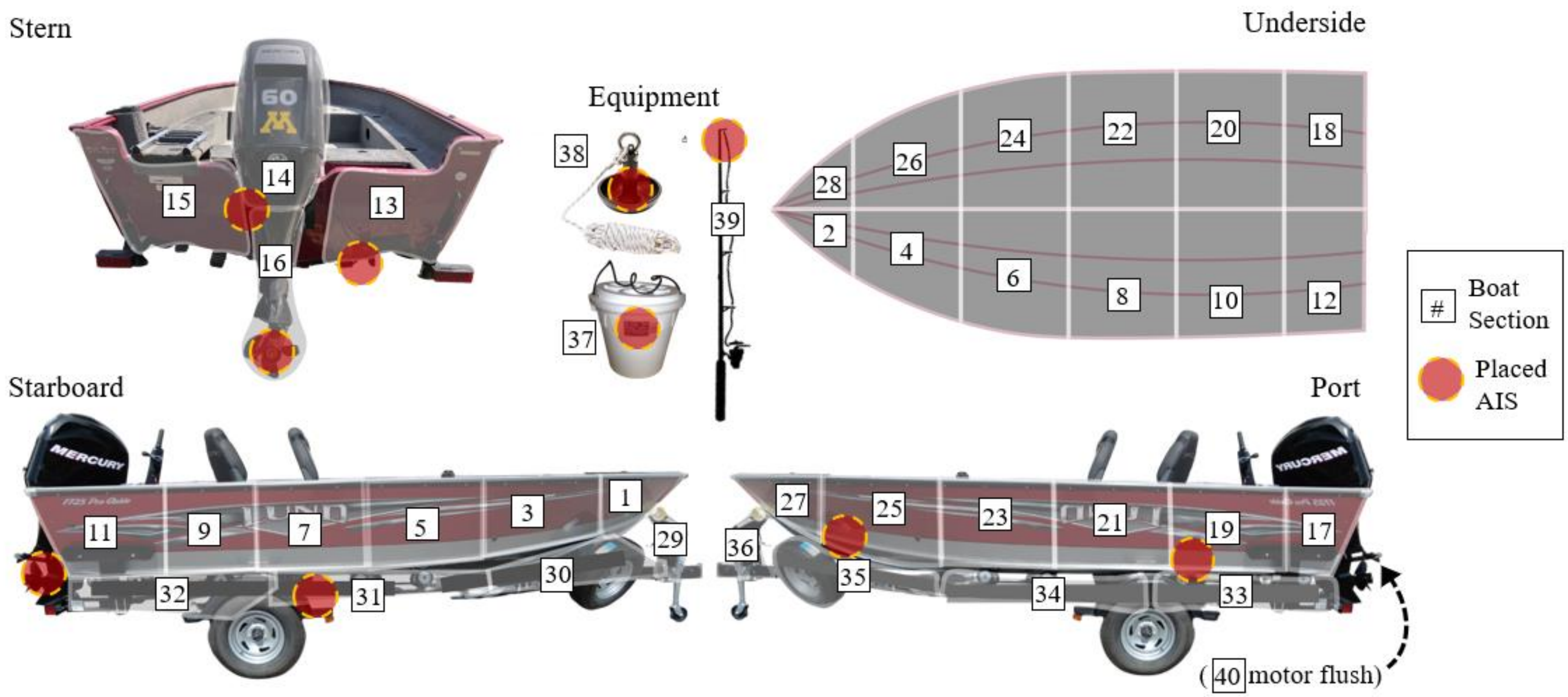

Figure 1.3. Aquatic invasive species placement and partitioning of the boat for determining hot water decontamination sufficiency during experimental AIS removal trials decontaminations occurring from June-August 2022.

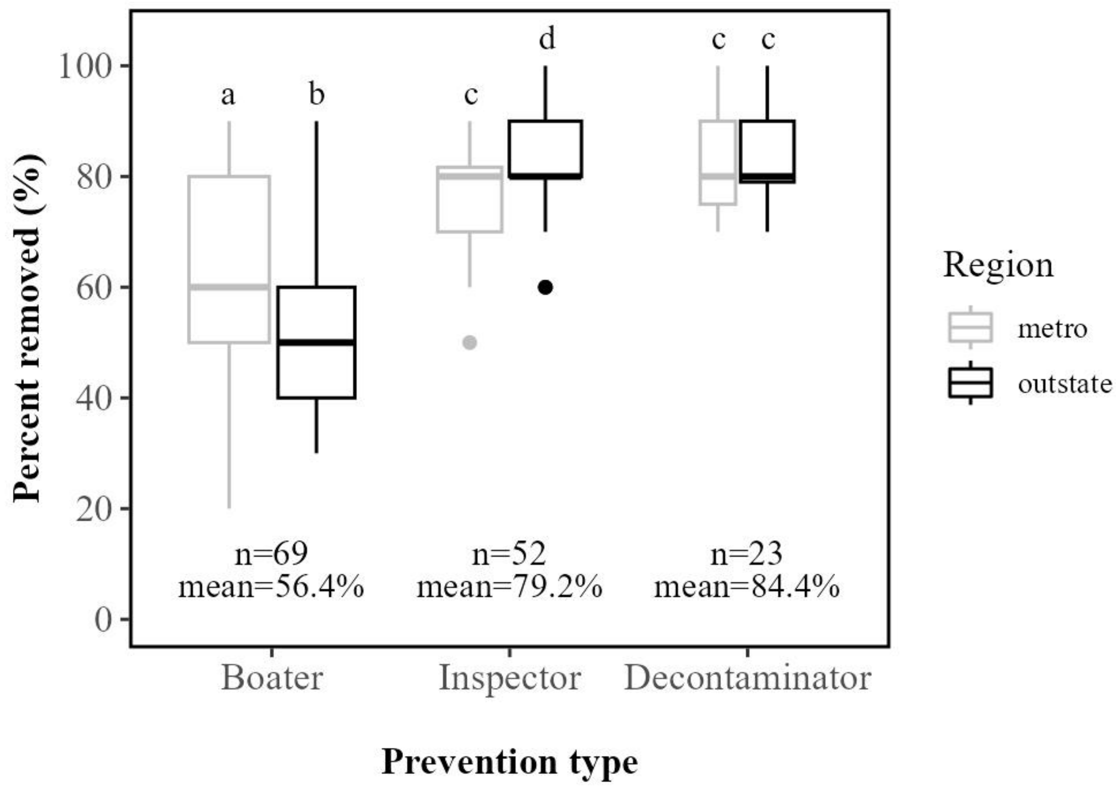

Figure 1.4. The percentage of AIS removed by boaters, watercraft inspectors, and watercraft decontaminators during experimental AIS removal trials at public water access sites across two regions (metro and outstate) in Minnesota and Wisconsin from June-August 2022. Different lower-case letters indicate significant differences among prevention types after running a binomial mixed effects model followed by a *post hoc* Tukey's test (all *p-values* ≤ 0.03).

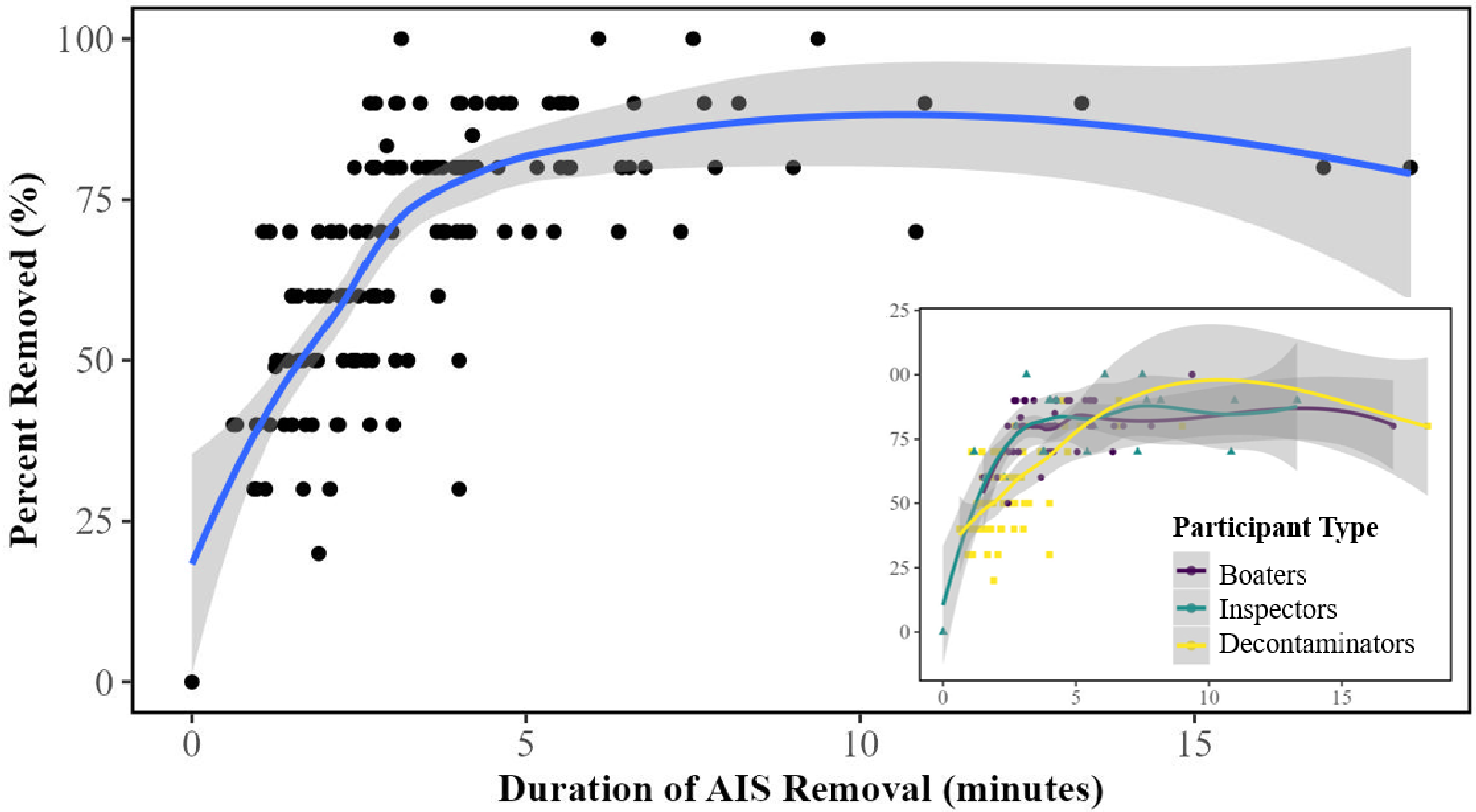

Figure 1.5. Hand removal of AIS per unit time from a boat that had been purposely staged with AIS during experimental AIS removal trials at public water access sites in Minnesota and Wisconsin from June-August 2022. The inset plot splits removal out by the three participant types that completed removal trials: boaters, inspectors, and decontaminators.

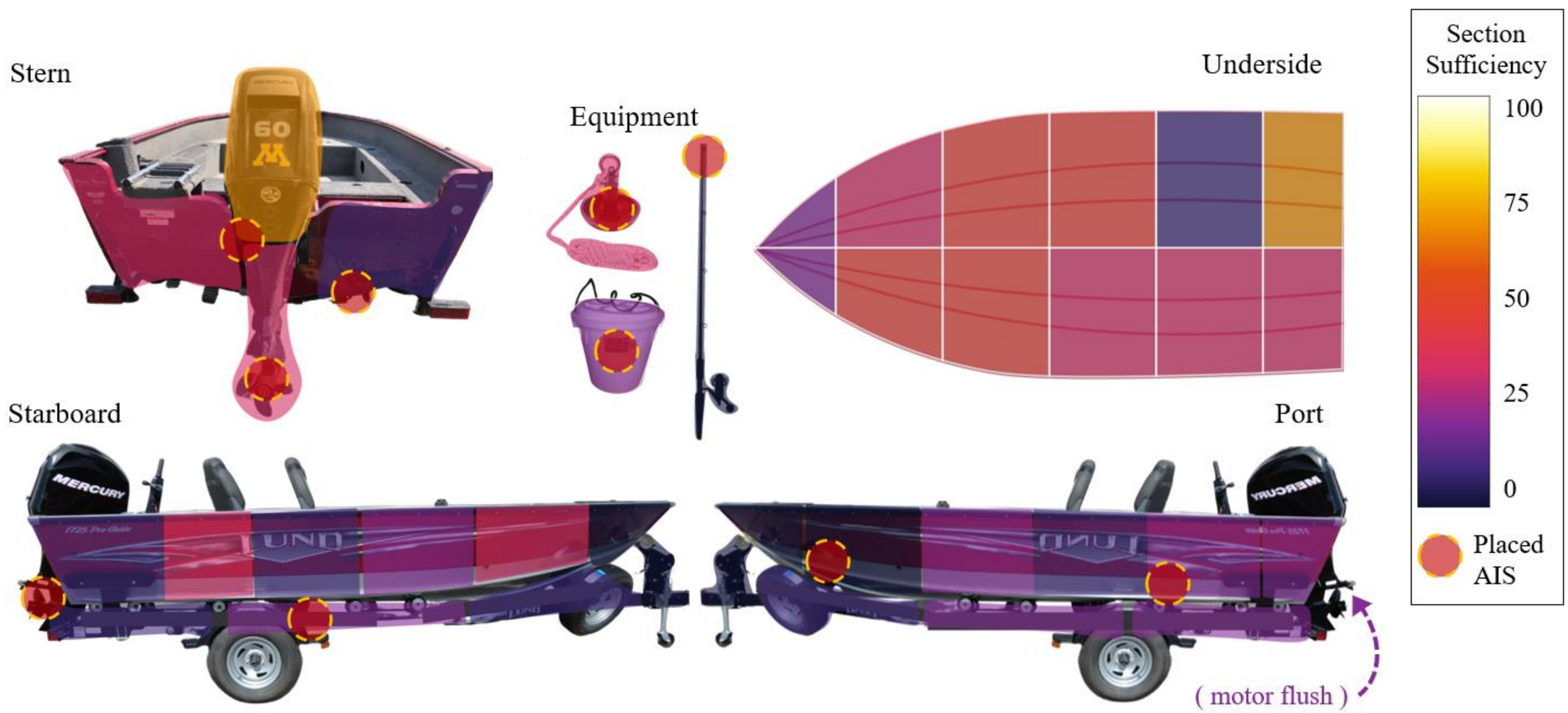

Figure 1.6. Boat section sufficiency from experimental hot water decontaminations completed from June-August 2022 at public water access sites and centrally located decontamination stations across Minnesota and Wisconsin. Shading gradients correlate to the average percent of decontaminators that sufficiently decontaminated each boat section (based on UMPS IV protocols) during their experimental watercraft decontamination process.

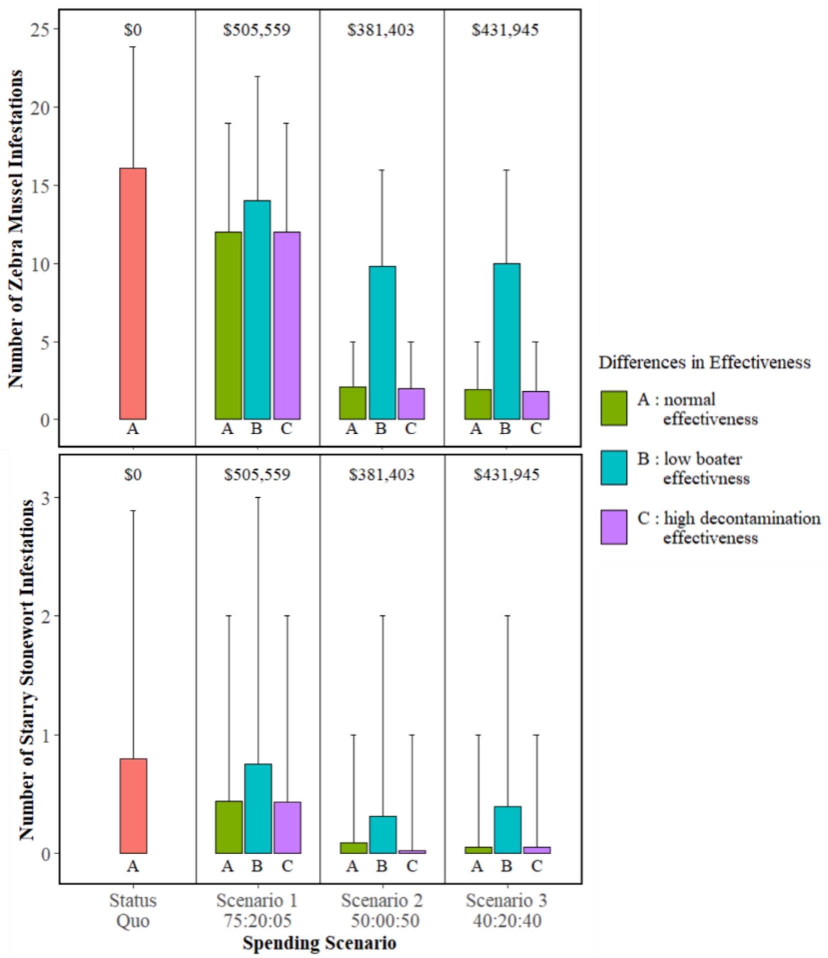

Figure 2.1. Results from using the *AIS Explorer-Intervention Impact* application to simulate 9 different aquatic invasive species prevention scenarios that apply watercraft inspection, hot water decontamination, and boater education differently in Cass County, MN to prevent zebra mussel and starry stonewort infestations. All scenarios had $505,595 available to be spent with each spending scenario using the funds on the three interventions in different ratios as seen on the x-axis. Results show the number of zebra mussel infestations and starry stonewort infestations by using the funds in various proportions and hypothetically applying different effectiveness percentages represented by letters A (default effectiveness as in Angell *et al.* (in prep)), B (default effectiveness for all interventions except boater education effectiveness which was decreased to 20%), and C (default effectiveness except for hot water decontamination which was increased to 100%). A default scenario with no interventions applied is shown as the “Status Quo”.

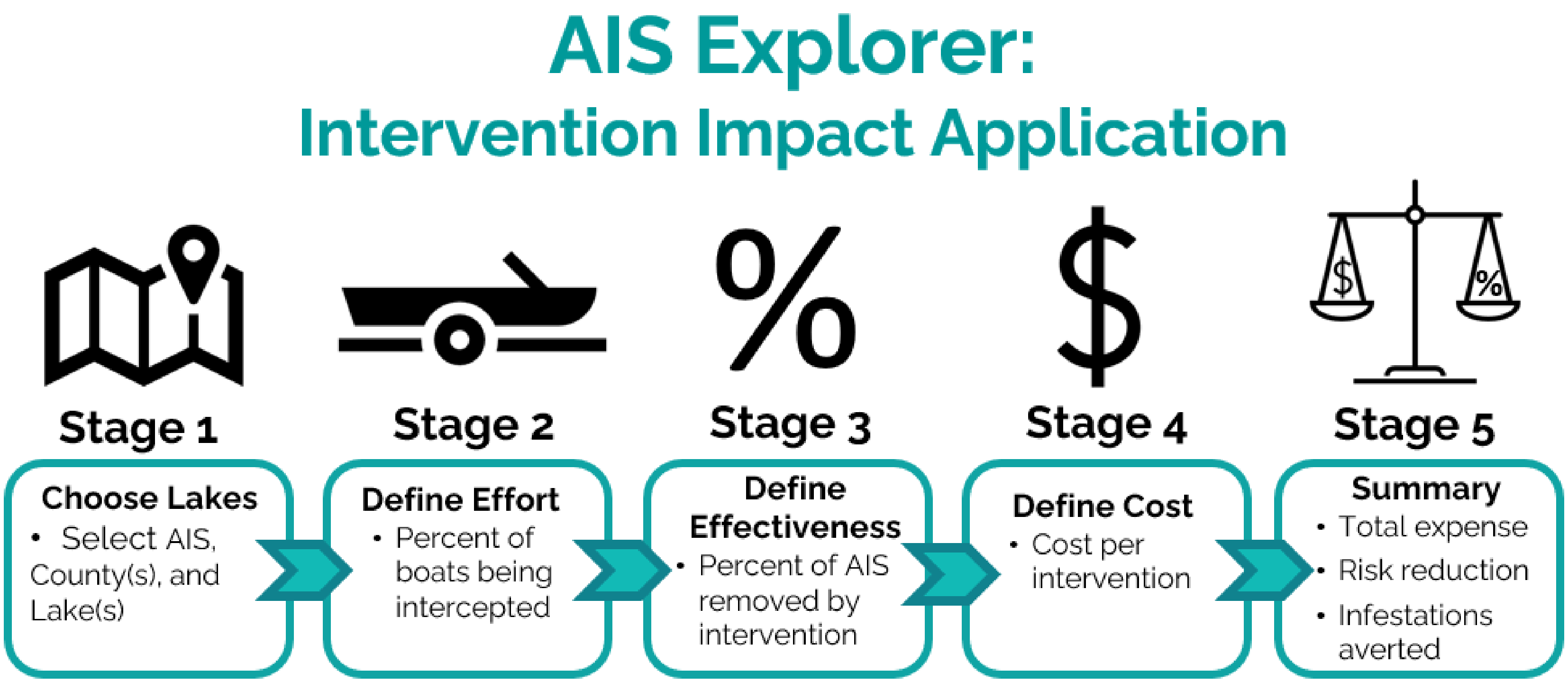

Figure 2.2. Summary workflow of the *AIS Explorer-Intervention Impact* application which is a decision support tool that allows users to create hypothetical AIS prevention plans via a web-interface and receive cost-benefit output information. The application has 5 tabs that allow users to customize AIS prevention location, effort, effectiveness, and costs before summarizing and giving output.

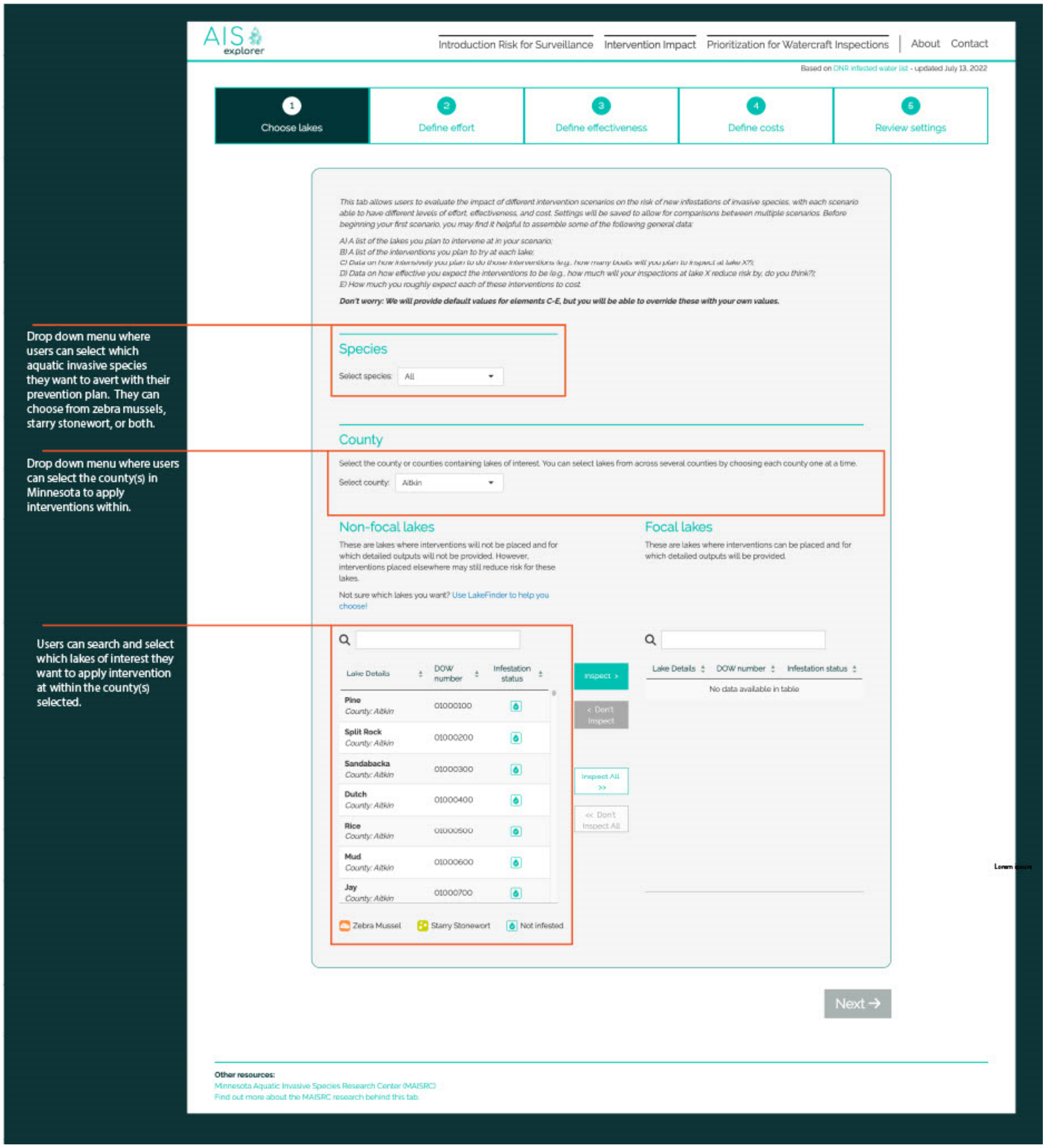

Figure 2.3. Depiction of Stage 1 of the *AIS Explorer - Intervention Impact* application. The user can select which aquatic invasive species (AIS), county(s), and lake(s) of interest to place AIS preventions. Lakes within county(s) chosen that are not included to inspect (non-focal lakes) will not contain interventions, but may still be impacted by interventions at other lakes.

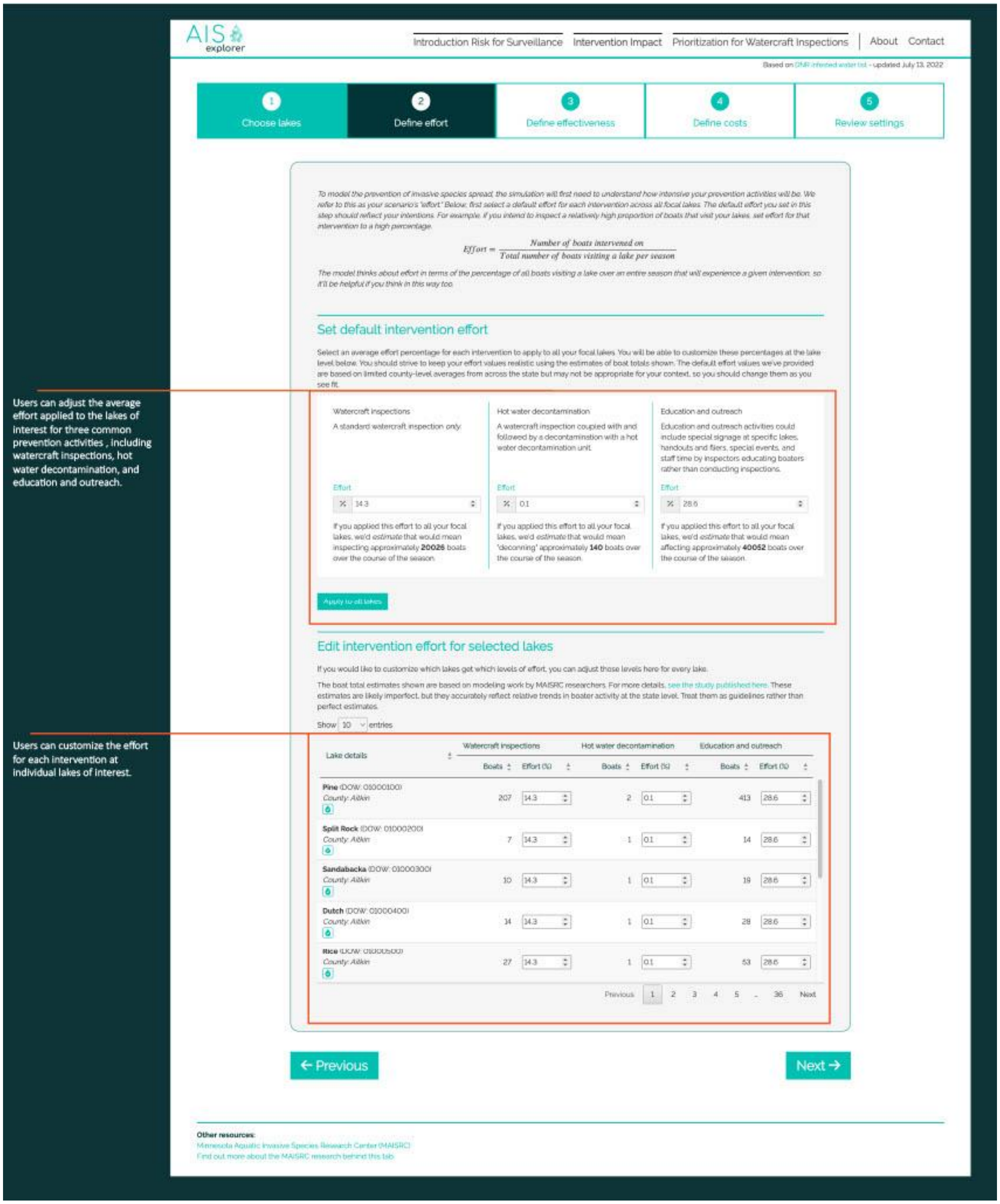

Figure 2.4. Depiction of Stage 2 of the *AIS Explorer - Intervention Impact* application. The user can input a standard effort percentage they want to apply across all lakes or they can customize effort amounts at each lake individually. Effort is the number of boats intervened on divided by the number boats visiting a lake annually.

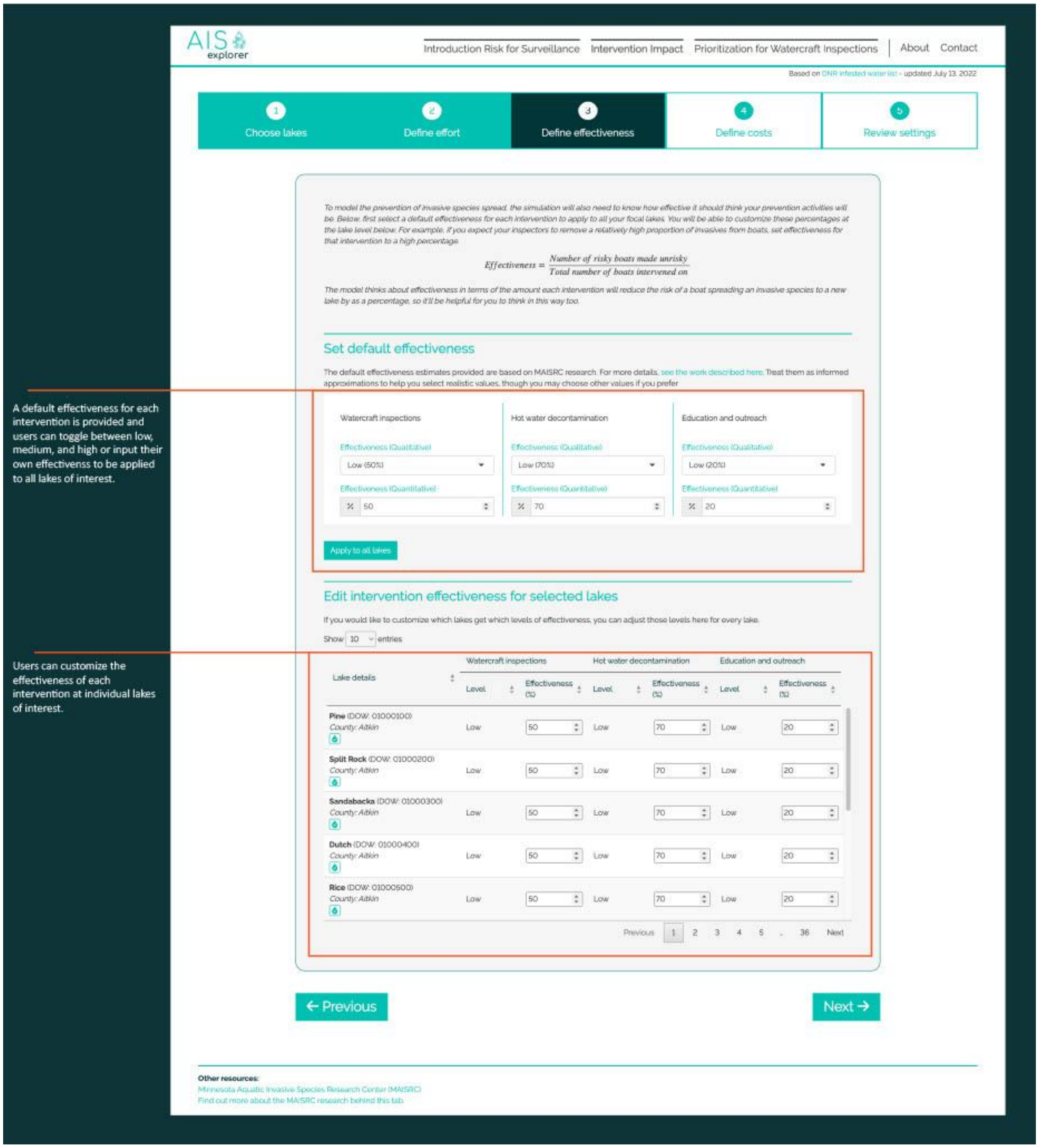

Figure 2.5. Depiction of Stage 3 of the *AIS Explorer - Intervention Impact* application. The user will be provided with default effectiveness estimates for each intervention but can also input a custom effectiveness across all lakes or at the individual lake level. Effectiveness is the proportion of risky boats intervened upon at a lake in a year rendered harmless by the intervention divided by the total number of boats intervened upon at that lake in that year in that way.

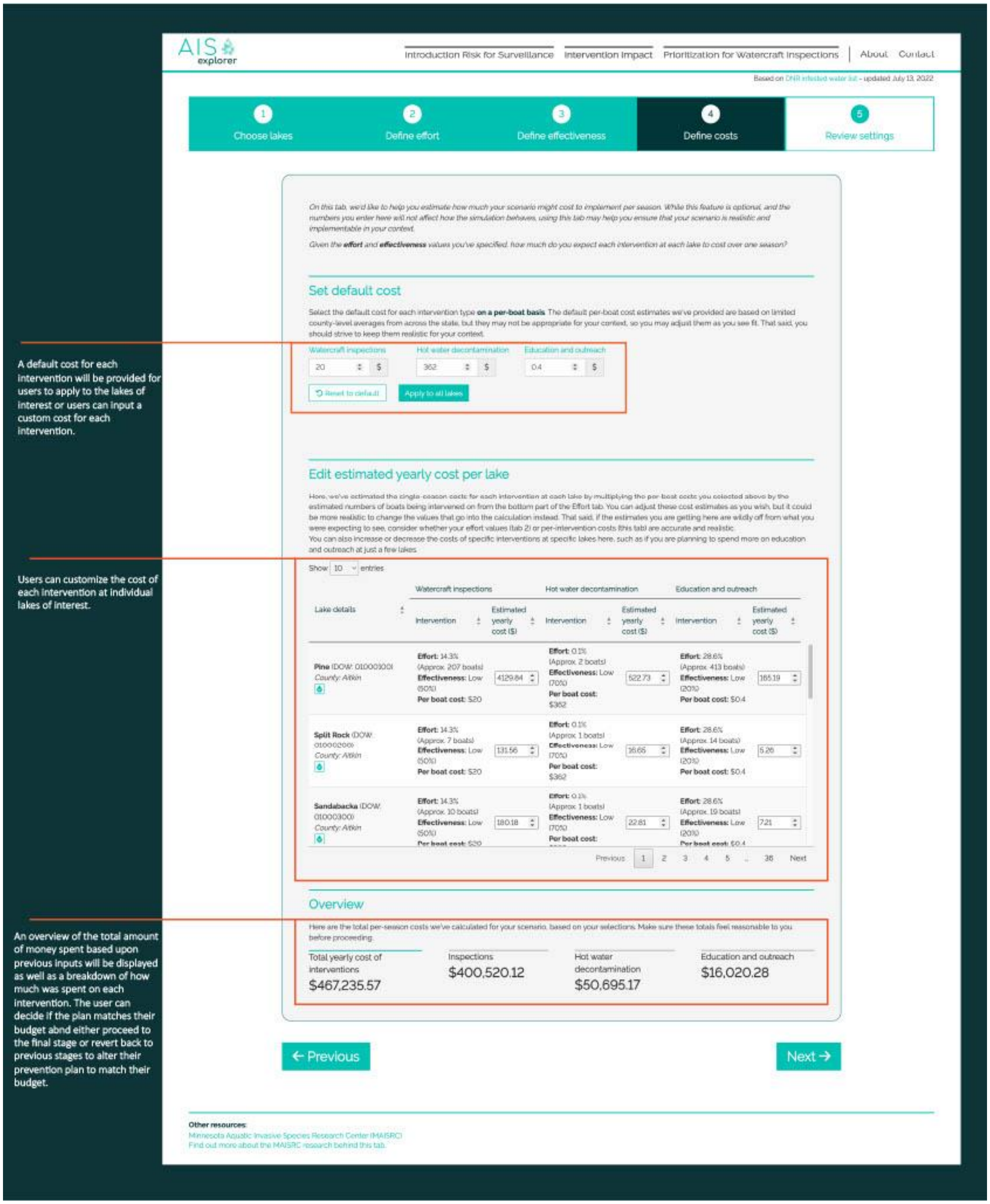

Figure 2.6. Depiction of Stage 4 of the *AIS Explorer - Intervention Impact* application. The user will be provided with default cost estimates for each intervention but can also input a custom effectiveness across all lakes or at the individual lake level.

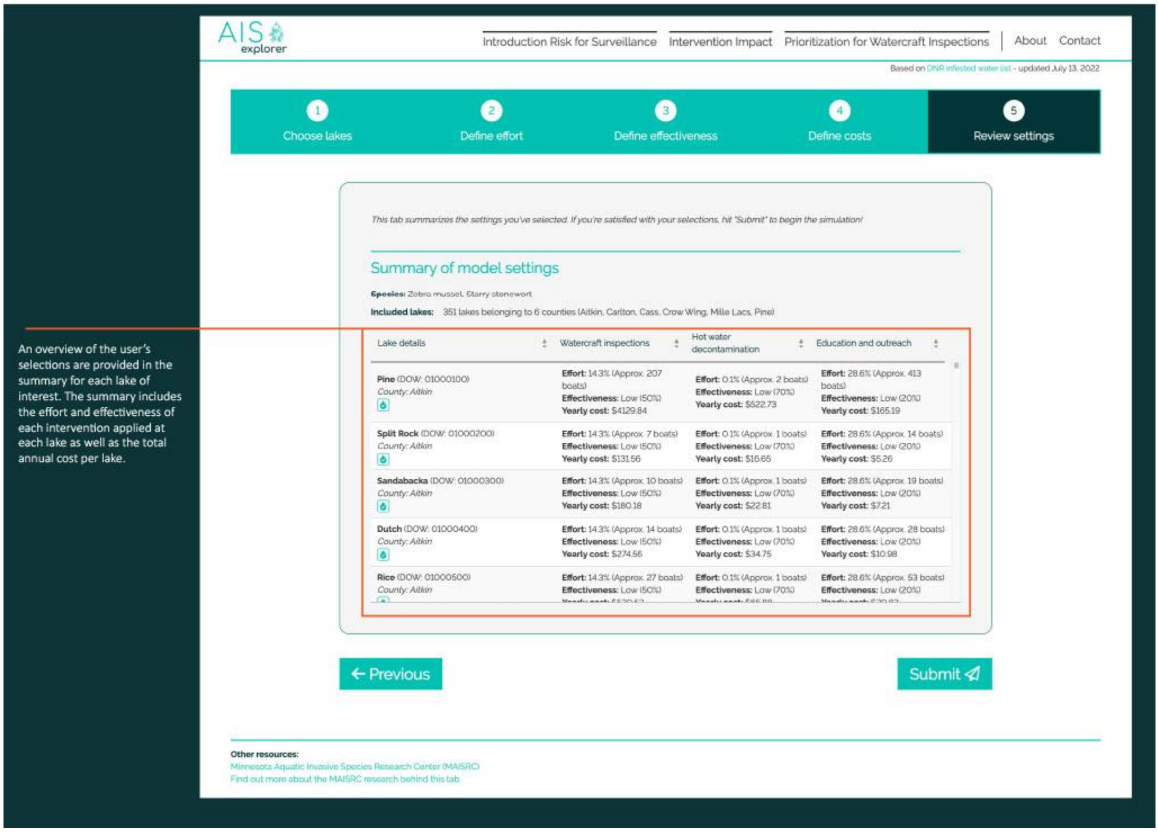

Figure 2.7. Depiction of Stage 5 of the *AIS Explorer - Intervention Impact* application. On this final tab the user will be provided with a summary of the settings specified in the preceding four stages. This summary includes selected species, lakes, and counties included in the plan as well individual lake details including effort per effectiveness percentages and total yearly cost for each intervention category. Once the user is satisfied with their settings, clicking on 'submit' will allow them to enter a name for the model run, along with their email address, before clicking 'run' to submit the model run to the AIS Explorer OpenCPU API for later processing.

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APPENDICES

A1. Supplementary information for Chapter 1

Data in support of Quantifying the effectiveness of three aquatic invasive species prevention methods. Available at: https://doi.org/10.13020/7n3e-yp45

A2. Supplementary information for Chapter 2

Data in support of *AIS Explorer: Intervention Impact* – A decision support tool for planning cost-effective AIS prevention programs. Available at: University of Minnesota Data Repository (*in progress*)