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Economic effects and the efficacy of intervention: exploring unintended effects of management and policy on the spread of non-indigenous species

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Abstract Models have been well developed describing human movements as vectors of the spread of non-indigenous species (NIS). However, to be maximally useful, predictions need to be integrated with management models of how different policies change human behaviour and lead to concurrent changes in invasion risk. Using the dispersal of freshwater organisms by recreational boaters as our study system and mandatory boat washing as our management strategy, we conducted a survey of recreational boaters (n = 580 respondents, t = 2354 boating trips) in Ontario, Canada, and performed counterfactual analysis of

boater behavior across different management options. We developed a model to quantify three responses to mandatory boat washing policies: (1) the continued use of a policy lake; (2) switching to a non-policy lake ("trip redistribution"); or, (3) a reduction in boating trips ("trip loss"). We found that boater and locational traits did not have a significant effect, but even modest user fees at washing stations greatly influenced trip redistribution and loss, explaining 87% of the variation in boater choices. These results indicate that user fees can strongly reduce the effectiveness of boat washing programs to mitigate invasion risk and could have unintended local economic effects, supporting the need to minimize boater expense as a program goal. In contrast, only minor redistribution and loss occurred if users washed but did not pay, and when taken together with the lack of effect for boater and locational traits, suggest that simple human-mediated dispersal models would be sufficient to prioritize management actions under "zero fee" scenarios. Simulating management scenarios using an existing spread model for 10 aquatic NIS in Ontario further emphasized the benefit of zero fees. Although averted invasions increased monotonically with effort (number of lakes with washing stations), the relative effectiveness (number of invasions averted per unit effort) was high even with management of a single lake, given zero fees, but required washing stations at far more lakes to maximize relative effectiveness when user fees were imposed.

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Introduction

Preventing the introduction and establishment of non-indigenous species (NIS) into new ecosystems is a central challenge for resource managers. Once a species has been detected in a new area, efforts often switch toward controlling secondary spread (Vander Zanden and Olden 2008; Epanchin-Niell and Hastings 2010; Parry et al. 2013), which can lessen the impacts exerted on the surrounding recipient ecosystem or, if detected early, to contain spatial extent while eradication is attempted (Edwards and Leung 2009). For freshwater NIS, secondary spread often occurs across a landscape of discrete patches (lakes) connected by vectors of overland dispersal. In watersheds across North America, overland dispersal is driven by human vectors, mostly via the movement of anglers or trailered boats on which species 'hitchhike' from one body of water to another (Johnson and Carlton 1996; Johnson et al. 2001; Drake and Mandrak 2014; Papenfuss et al. 2015). By quantifying the movement of human vectors, previous studies have successfully predicted the spread of aquatic NIS (Bossenbroek et al. 2001; Leung et al. 2004; Gertzen and Leung 2011; Drake and Mandrak 2014), thereby providing an important tool for NIS risk assessment and management.

While the utility of human-mediated dispersal models for predicting the spread of NIS has been well demonstrated, integrating them with management models aimed at reducing the spread of NIS has been less developed (but see Macpherson et al. 2006; Timar and Phaneuf 2009; Morandi et al. 2015). Developing a better understanding of NIS-centric management models could answer numerous questions related to NIS policy: how effective will various intervention approaches be to reduce the spread of NIS? Who should pay—should the cost of treatment be borne by users or by government? How strongly does who pays (e.g., user fees) interact with management effectiveness? Are there other unintended ecological or economic consequences associated with implementing a spread reduction policy? These are central

questions in the management of NIS, which we believe can best be explored through human-mediated dispersal models when they incorporate the response of users to alternative policies.

In this study, we focus on recreational boating as our human-mediated vector of NIS movement, mandatory boat washing at designated lakes as our management strategy, different user fees imposed on recreationalists as alternative policy designs, gravity models as our model of human-mediated movement, and a counterfactual survey of boater behaviour to understand individual responses to policy options. Recreational boating is a prominent vector for the human-mediated dispersal of NIS across North America and Europe (Chivers and Leung 2012; Bacela-Spychalska et al. 2013) due in part to the magnitude of boating activity (an estimated 24 million yearly trips in Canada alone) and frequent among-lake movements by a subset of users (Drake 2017). Compared with natural dispersal, Gertzen and Leung (2011) found that the spread of Spiny waterflea *Bythotrephes longimanus* in Ontario, Canada was driven almost entirely by boater movement, while boating activity in the United States has led to NIS range expansions of greater than 1500 km (Bossenbroek et al. 2007). We focused on boat washing as our focal management strategy because government agencies throughout North America have begun implementing mandatory washing stations at key boat launches (Rothlisberger et al. 2010). Boat decontamination through high-pressure spraying can reduce propagule abundance on an individual boat by roughly ninety percent (Rothlisberger et al. 2010) and numerous studies have also confirmed hot water spraying as an effective decontamination strategy (e.g., Beyer et al. 2011; Anderson et al. 2015).; Therefore, boat washing has shown promise as a propagule reduction measure, but several questions remain about widespread implementation of washing stations on spread dynamics as a whole.

Here, we explore the behavioural responses of boaters to mandatory boat washing stations, focusing on how boater survey responses can be incorporated into a gravity model, which describes human-mediated dispersal (Leung et al. 2006). We use this combined model to estimate the effect of management options (fees imposed on users and the time required for cleaning) on changes in behavior across a landscape of lakes. Our approach provides a generalizable decision support tool for managers who are

aiming to mitigate the secondary spread of NIS. The decision support tool developed here has several desirable features. First, it captures both the potential reduction in overall trip-taking ("loss"), as well as redistributive trip-taking behaviours ("redistribution") imposed by mandatory cleaning stations. By separating the user's response to management into these two components, we account for site-specific avoidance behaviours that, while protective for a particular target lake, may lead to an increased delivery of propagules and associated risk of invasion to nearby lakes, as well as potential local economic losses due to reduced boating activity. Second, the approach is not data intensive. We show that the behavioural responses to management can be estimated using a simple survey design employing randomized counterfactual scenarios and stated preferences techniques (Dillman 2000; Heckman and Vytlacil 2007). Third, the approach can be extended beyond freshwater systems to any species whose dispersal is primarily human-mediated across a landscape of discrete patches (e.g., forest pests spreading via the movement of infested firewood, Prasad et al. 2010; Koch et al. 2012) and for which the implications of management intervention are of interest. We explore the implications of our approach by focusing on spread predictions for 10 NIS across Ontario and reporting on the number of invasions mitigated across a range of boat washing scenarios.

Methods

Boater survey

During January and February of 2011, survey invitations were mailed to 5000 Ontario recreational fishing licence holders. Invitation cards requested individuals to complete an online survey of boating activity that was taken during the 2010 season. The participants were selected using a stratified random sampling process where approximately 100 invitations to participate were mailed to each of 47 geographic regions defined by the first two characters of their postal code.

To facilitate rapid collection of destination lake information from respondents, we developed an online survey tool with an interactive map interface. Respondents were asked to identify which lakes they visited as well as how many times they launched their boat

into each lake during 2010. By collecting these responses using an interactive map, we were able to avoid the tedious and error-prone disambiguation process of reported lakes based on lake names and nearest towns alone.

Once boaters identified all lakes visited during 2010 and had answered additional questions about their boating behaviours (e.g., whether activities such as water skiing or fishing were undertaken while boating; see "Appendix" for survey content) they were presented with a counterfactual management scenario. Counterfactual analysis is used to understand how individuals respond to management intervention (Challen and Hagger 1983). The common approach is to compare what actually happened with what would have happened in the presence (or absence) of intervention (Phaneuf 2013). Our social survey quantified destination lake choices under status quo and management scenarios.

In the management intervention scenario, a mandatory boat cleaning station is implemented at the launch site of one of the respondent's two most frequently visited lakes. The scenario included a description of the cleaning process as well as the estimated time to complete cleaning of 15 min. In addition, a randomized estimate of the mandatory user-borne expense (0–16\$) that would be incurred out of pocket at this wash station was also presented to the respondent, reflecting a range of 'user-pay' boat washing scenarios. After reading this description, the respondent was reminded how many times they reported launching their boat at the policy lake and was then asked how many times they would have launched, given the washing station implemented at that location. Next, they were asked how many times they would have visited the non-policy lake under the boat washing scenario. Responses to these questions were then used to fit the modified gravity model, from which we could estimate the remainder of the trip-taking behaviors. The process of eliciting stated preferences for modelling the choices of individuals is commonly used in the econometrics literature (Haider 2002).

Using the survey design method of Dillman (2000) we field tested our survey tool using a pilot run on location at several boat launch locations in the District Municipality of Muskoka in central Ontario. By directly observing respondents interact with the questionnaire and identifying common problems and any misinterpretations of the instructions, we were able to

streamline the user experience and clarify the written guide before sending out invitations to our main sample.

Model formulation

Production-constrained gravity model

Gravity models (GMs) are particularly suited for human mediated dispersal since they account for "attractiveness" of destinations (e.g., water quality, lake area, sportfish presence) and distance to the destination, both of which are determinants of where boaters choose to visit. These are weighted by the distance and attractiveness of all the other potential destinations a boater may otherwise choose, which in combination allows trips to be distributed across destinations, and provides a natural structure to build in redistribution and loss of boater trips.

In particular, "production-constrained" GMs can be parameterized with fairly modest data, and have been well demonstrated for predicting the spread of aquatic NIS (Bossenbroek et al. 2001; Leung et al. 2004; Gertzen and Leung 2011). Further, while there may be instances where boaters travel directly from one lake to another (competitive anglers, for instance; Rothlisberger et al. 2010), the production-constrained formulation has been found to be the most predictive version of the GM family (Muirhead and MacIsaac 2011). Finally, Chivers and Leung (2012) demonstrated that GMs and another human-mediated spread model (Random Utility Model, RUM; MacPherson et al. 2006; Timar and Phaneuf 2009) could be reduced to alternative functional forms of boaters' trip-taking distributions, but that the basic form used in production-constrained GMs provided a better fit to observed trip-taking behaviour in Ontario, where the current study was conducted.

To estimate boater traffic among Ontario lakes, we followed Chivers and Leung (2012), and following their disaggregated notation, the site selection probability distribution for an individual boater n can be written as (Eq. 1):

$$P\left(T_{nj}\right) = A_n W_j^e D_{nj}^{-d}, \quad n = 1, \ldots, N, \quad j = 1, \ldots, J. \tag{1}$$

where W_j is the attractiveness of lake j (expressed as lake surface area in hectares), and D_{nj} is the distance

between lake j and the home location of individual boater n (where they keep their boat when not in use). The parameters e and d describe the shape of the relationship between the 'pull' of lake j with lake size and distance from source n. A_n is the total 'pull' of all lakes (Eq. 2):

$$A_n = 1 \left/ \sum_{K=1}^{J} W_k^e D_{nk}^{-d} \right. \tag{2}$$

This term imposes the constraint that $\sum_{K=1}^{J} P(T_{nj}) = 1$, making Eq. 1 a proper probability distribution representing the probability that boater n will choose lake j on a given outing. The formulation given by Eqs. 1 and 2 is similar to that used by Leung et al. (2004), with the addition of non-linearity on the W_j term. Further details of the base gravity model can be found in Chivers and Leung (2012).

Boater response to management model

As with most policy interventions, there are costs involved with implementing mandatory boat washing stations. Irrespective of whether or how the operational costs are borne directly by the users in the form of a mandatory per-use fee, there is a time cost involved in cleaning which may affect the destination lake choices of individual boaters. We consider the two most likely a priori aspects of this behavioural change. First, faced with the increased cost of compliance, boaters may choose to reduce the number of times they visit the policy lake, instead substituting some other non-boating activity. In this case, the policy has successfully limited the propagules entering and leaving the lake, although this also has the negative effect of discouraging overall participation in recreational boating. Secondly, boaters may choose to visit the policy lake less often but instead visit alternative, otherwise similar lakes. In this situation, propagule pressure will be reduced at the policy lake, but the redistribution of boater traffic has the effect of increasing the flow of propagules between alternative lakes in the vicinity, assuming that some infested lakes exist without washing stations across the landscape.

To demonstrate how we estimate the strength of these behavioural responses to management action, let us define the two quantities of interest. First we wish to quantify the proportional reduction in attractiveness θ_m that occurs as a result of implementing

management intervention at lake m. The effect of this quantity will be to make the policy lake less attractive or have less 'pull' relative to the alternative lakes, to use the gravity analogy. Second, we wish to quantify the proportional reduction in the overall number of trips taken φ_m by individual boaters as a result of management intervention at lake m. These two quantities enter into our original gravity equations as modifiers on the relative attractiveness of the policy lake m and non-redistributed reduction of the trip-taking probability to lake m, respectively (Eqs. 3, 4).

$$P^*(T_{nj}) = A_n \theta_j W_j^e D_{nk}^{-d} \varphi_j, \quad n = 1, \ldots, N, \\ j = 1, \ldots, J. \quad (3)$$

$$A_n = 1 \left/ \sum_{K=1}^{J} \theta_k W_k^e D_{nk}^{-d}. \right. \quad (4)$$

At all non-policy lakes $w = w_1, \ldots, w_W$ the vectors θ_w and φ_w are equal to 1. At all policy lakes $m = m_1, \ldots, m_M$ where the management intervention has been implemented, θ_m and φ_m are $\in [0, 1]$. Notice that θ appears in both the numerator and the denominator, while φ only appears in the numerator. We can see from this that $\sum_{j=1}^{J} P^*(T_{nj}) = 1$ in the strictly redistributive case where $\theta_m \le 1$, $\varphi_m = 1$. We refer to this effect as 'redistribution' because the net result is that there are no fewer trips taken by boaters under management than under the status quo condition, rather only that some trips have been redistributed from policy lakes to non-policy lakes. However, in the case of some reduction in overall trip-taking where $\varphi_m \le 1$, then $\sum_{j=1}^{J} P^*(T_{nj}) \le 1$. In this case there is some probability $1 - \sum_{j=1}^{J} P^*(T_{nj})$ that an individual boater will choose to abstain from taking a boating trip entirely. We call this reduction effect 'loss' as it represents a net loss of boating activity resulting from management intervention.

In order to estimate θ_m and φ_m from our survey data, we reformulate the trip outcomes under each of the status quo (reported actual trips taken) and the counterfactual policy condition (trips that would have been taken given management intervention) as random samples from binomial distributions. Within each, the binomial success probability parameter is described by the probabilities given by Eqs. 1 and 3. We can then construct the likelihood function by substituting the number of trips taken to each of the

policy and non-policy lakes before and after implementation (Eq. 5):

$$L(\theta_m, \varphi_m | D) = \prod_{n=1}^{N} \binom{S_{na}}{S'_{na}} \delta_{na}^{S'_{na}} (1 - \delta_{na})^{S_{na} - S'_{na}} \binom{S'_{nb}}{S_{nb}} \\ \times \delta_{nb}^{S_{nb}} (1 - \delta_{nb})^{S'_{nb} - S_{nb}} \quad (5)$$

where $\delta_{na} = \frac{P^*(T_{na})}{P(T_{na})}$ and $\delta_{nb} = \frac{P(T_{nb})}{P^*(T_{nb})}$, which are the proportional changes in the probability of visiting each lake under status quo (Eq. 1) and management (Eq. 3). S_{na} and S'_{na} are the number of trips taken by boater n to the policy lake under status quo and management, respectively. S_{nb} and S'_{nb} are the number of trips taken by boater n to the non-policy lake under the same two conditions. Importantly, survey responses on only two lakes (a policy and non-policy lake) are sufficient to fit the management component of the model. Further, by integrating these responses within the gravity model, we can extrapolate to all other destinations, and account for variation in responses due to the different attractiveness and locations (distances) of the alternative lakes.

To illustrate what has been modeled, imagine that a boater made 10 trips to lake a and 5 trips to lake b. After considering a mandatory washing station implemented at lake a, the boater decides that they would have visited lake a only 6 times, and redistributed the remaining 9 trips to lake b. The likelihood function can be broken down into two binomial likelihoods. The first half of Eq. 5 is the likelihood of having observed 6 (S'_{na}) out of 10 (S_{na}) trips at the policy lake if the probability has been modified by the fraction δ_{na}. The second half can be thought of as an inverse process at the non-policy lake, where we calculate the likelihood of observing 5 (S_{nb}) out of 9 (S'_{nb}) trips taken between the status quo and management conditions, under the modification in probability predicted by the gravity model (δ_{nb}).

Incorporating cost to boaters

In keeping with the predictions of econometric models of recreational demand, we expect the behavioural responses to be a function of the direct cost to the boater imposed by the mandatory cleaning policy. Recall that each respondent was presented with one

cost estimate, chosen at random between 0 and 16$. To factor this in, we model θ_m and φ_m in Eqs. 3 and 4 as a function of the cost (Eqs. 6 and 7, respectively):

$$
\begin{aligned}
\theta_m &= f(cost) \\
&= \frac{1}{1 + e^{-(\alpha_\theta + \gamma_\theta * cost)}}
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
\varphi_m &= g(cost) \\
&= \frac{1}{1 + e^{-(\alpha_\varphi + \gamma_\varphi * cost)}}
\end{aligned} \tag{7}
$$

where $\alpha_\theta, \gamma_\theta, \alpha_\varphi, \gamma_\varphi$ are shape parameters estimated using MCMC by substituting Eqs. 6 and 7 into Eq. 5 (Calder et al. 2003). The functional forms for $f(cost)$ and $g(cost)$ were chosen as they capture several properties that we would logically expect. First, they range between 0 and 1, matching our definitions of θ_m and φ_m. Second, they are flexible enough to capture an intercept greater than zero (non-zero θ_m, φ_m via translation through γ), as there may be a behavioural response even when the monetary cost to the boater is zero, since there is an unavoidable time cost involved. Finally, they are able to capture how the strength of the response changes (accelerating or decelerating) as monetary costs increase through the α parameters. In addition to these functional forms, we also fit a linear model to each, as well as a null model in which θ_m and φ_m are both independent of cost and performed model selection using Bayesian Information Criterion (Burnham and Anderson 2002). An overview of model parameters is provided in Table 1.

Management scenarios

We applied the management scenarios to an existing gravity model (Chivers and Leung 2012), and spread predictions for 4 aquatic or semi-aquatic plants (Eurasian Water-milfoil *Myriophyllum spicatum* L., Common Reed *Phragmites australis*, Flowering Rush *Butomus umbellatus* L., Purple Loosestrife *Lythrum salicaria* L.) and 6 aquatic invertebrate (Banded Mysterysnail *Viviparus georgianus*, Chinese Mysterysnail *Cipangopaludina chinensis*, Quagga Mussel *Dreissena bugensis*, Zebra Mussel *Dreissena polymorpha*, Rusty Crayfish *Orconectes rusticus*, Spiny Waterflea *Bythotrephes longimanus*) NIS, as described in Chivers (2014). For boats that visited washing stations, we modeled a 90% reduction in propagule pressure, which is a reasonable reduction in fouling following Rothlisberger et al. (2010).

We examined 17 management scenarios. The baseline scenario represents the projected spread of all 10 species with no management (Chivers 2014). We then investigated the reduction in the spread of each NIS if mandatory washing stations were implemented at the top 1, 2, 4, 8, 16, 32, 64, and 128 "donor" lakes. The ranking of "donor" lakes was determined by ordering all invaded lakes, using the total potential outbound propagule pressure (outbound traffic), multiplied by the probability that the site is invaded. We then summed this quantity across each of the 10 species and selected the top M locations at which to implement the cleaning policy. We repeated the analysis for two scenarios: one in which no cost is incurred by boaters and one at the full $16 per-use fee. To account for stochastic uncertainty associated with future spread, for each scenario we simulated 5000 stochastic realizations of spread over the ten year time horizon, and calculated the mean number of lakes invaded.

Results

Boater survey results

Of the 580 respondents (11.6% response rate), 146 respondents indicated visiting multiple lakes. The number of unique lakes visited by individual respondents was 3.78 ± 1.2 (mean $\pm$ SD), with a maximum number of unique lakes reported visited by a single respondent of 7.

We tested for correlations between respondents' behavioural changes under the management condition and several boater-specific and spatial factors. No significant relationships (Pearson's r, $p > 0.05$) were found, indicating that neither boater location, lake location, log(lake surface area), distance to lake, or type of boat outing (angling, water skiing/wake boarding/tubing, sightseeing) were correlated to the proportion of trips diverted (both redistribution and loss) across respondents.

Behavioural response to user fees

The estimated proportion of trips in which boaters would redistribute to other lakes, as well as trips that

Table 1 Overview of parameters used to model redistribution and loss of boating trips resulting from management intervention

Parameter	Description
n	Boaters
$P(T_{nj})$	Probability that boater n will choose lake j on a given outing
A_n	Total 'pull' of all lakes accessible to boaters
W_j	Attractiveness of lake j, measured as lake surface area (ha)
D_{nj}	Euclidean distance between a boater's residence (trip origin) and a given destination lake (km)
e	Non-linear term imposed on lake attractiveness
d	Non-linear term imposed on Euclidean travel distance (rate of distance decay)
m	Lake selected for management intervention (placement of a boat wash station)
θ_m	Proportional reduction in attractiveness imposed by placing boat wash station at lake m
φ_m	Proportional reduction in total number of trips taken as a result of placing boat wash station at lake m
$1 - \sum_{j=1}^{J} P^*(T_{nj})$	Probability that boater will choose to abstain from taking a trip, given the placement of a boat wash station at lake m
S_{na}	Number of trips taken by boater n to policy lake under status quo scenario
S'_{na}	Number of trips taken by boater n to policy lake under boat washing scenario
S_{nb}	Number of trips taken by boater n to non-policy lake under status quo scenario
S'_{nb}	Number of trips taken by boater n to non-policy lake under boat washing scenario
$\alpha_\theta, \gamma_\theta, \alpha_\varphi, \gamma_\varphi$	Shape parameters, estimated using likelihood function and MCMC

would be entirely foregone under management intervention, increased with the magnitude of cost incurred (Fig. 1). Of the three models tested, our full model (Eqs. 6 and 7) was strongly selected, with BIC improvement of 39.1 over the linear model and 411.2 over the null model (Table 2). Even at no direct monetary cost, representing a scenario in which user fees do not exist and the only increase in cost is the additional inbound or outbound 'travel' time imposed by mandatory washing, 2.8% (1.2–4.9%) (posterior mean [95% BCI]) of trips to policy lakes would be lost and 5.5% (2.0–6.6%) of remaining trips replaced by trips to alternative locations, given the projected washing time of $\sim$15 min (Fig. 1). Both curves show
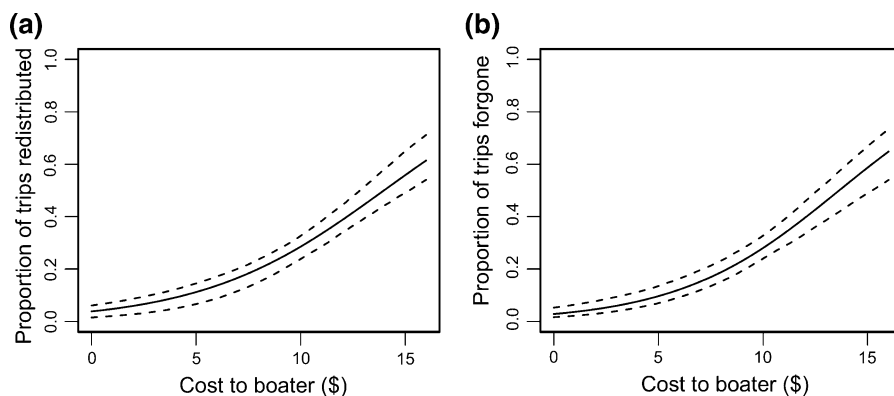

Fig. 1 Proportion of boater trips diverted as a function of the cost incurred by boaters at wash stations. **a** The proportion of the trips that would have been taken to a policy lake under the status quo which were diverted to alternative lakes $(1 - \theta_m)$. The point estimate parameter values underlying θ_m were $\alpha_\theta = 3.219, \gamma_\theta = -0.23$ (see Eq. 6). **b** The proportion of trips that would have been taken to a policy lake under the status quo which were forgone due to the policy $(1 - \varphi_m)$. The point estimate parameter values underlying φ_m were $\alpha_\varphi = 3.53, \gamma_\varphi = -0.26$ (see Eq. 7). *Solid lines* are posterior mean relationships and *dashed lines* are 95% credible intervals

Table 2 Model comparison of the relationship between cost and θ_m and φ_m

Model	k	ΔBIC
$\theta_m = \frac{1}{1+e^{-(z_\theta + \gamma_\theta * cost)}}$	4	0
$\varphi_m = \frac{1}{1+e^{-(z_\varphi + \gamma_\varphi * cost)}}$		
$\theta_m = m_\theta(cost) + b_\theta$	4	39.1
$\varphi_m = m_\varphi(cost) + b_\varphi$		
$\theta_m = c_\theta$	2	411.2
$\varphi_m = c_\varphi$		

Three alternative models of the relationship between the direct cost of a cleaning policy at lake m and the proportion of redistributed (θ_m) and lost (φ_m) trips to a lake m with a cleaning policy. The value of k is the number of estimated parameters for each model

an accelerating relationship between the proportion of trips redistributed/lost and the cost of washing. At the maximum projected cost of $16, 64% (56–73%) of the trips were lost and of the remaining trips 62% (53–70%) were redistributed (Fig. 1), signifying a strong behavioural response to the management option. Overall, the full model captured 87% of the variance in the total change between the number of trips taken under status quo and the reported number of trips that would be taken under the counterfactual management scenarios (Fig. 2).

Management scenarios

When washing stations were provided at no cost to boaters the result was a greater number of mitigated invasions compared to when fees were imposed, as expected from our theoretical framework (Fig. 3). However, as the number of policy lakes increased to the maximum of 128 locations, the additional benefit from providing the cleaning stations at no cost was generally diminished, and in some cases eliminated. In several cases, implementing washing stations mitigated all invasions over a 10 year period, though when this occurred, a large number of washing stations were required ($\sim$ 32 stations, Banded Mysterysnail *V. georgianus*; $\sim$ 16 stations, Eurasian water-milfoil *M. spicatum* L.; 32 stations; Quagga Mussel; *D. bugensis*). Summed across the 10 species, the effectiveness, measured as a ratio of mitigated invasions divided by the number of policy lakes, was high even for a single policy lake with the no pay scenario, but required 16
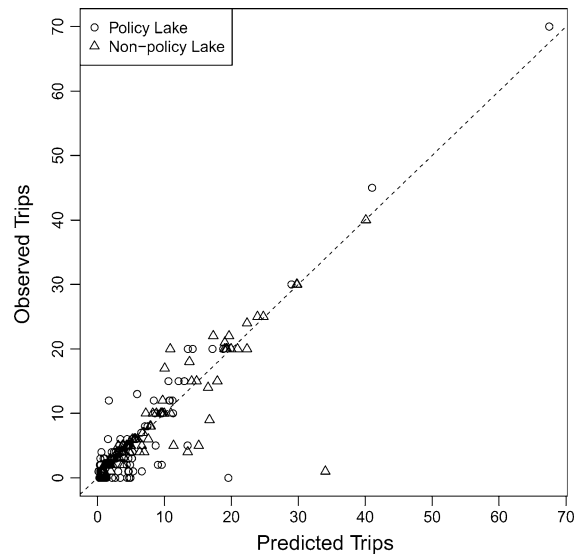

Fig. 2 Comparison of model predictions versus observed number of trips taken under policy scenarios. The number of trips that a boater reported they would take to both a lake with a mandatory cleaning and inspection station (*open circles*) and without (*open triangles*) under the counterfactual management scenario. The model predictions capture 87% of the variance in the reported behaviours. The *dashed line* represents the 1:1 equivalence line

policy lakes to reach maximum effectiveness given a $16 user-fee (Fig. 3b).

Discussion

Predicting how management strategies reduce the spread of NIS is a core component of formal NIS risk assessment and management programs and is central to the management decision-making process (Simberloff et al. 2005; Stohlgren and Schnase 2006; Epanchin-Niell and Hastings 2010; Mandrak and Cudmore 2015). In many cases, the efficacy of prevention programs will be dictated by the response of stakeholders to management intervention. Therefore, it is imperative to assess the response of resource users to alternative management options, which is often difficult due to complex connections between social, economic, and ecological factors (Perrings et al. 2002). To address these challenges, we have built upon the concept of gravity models (Bossenbroek et al. 2001; MacIsaac et al. 2004; Leung et al. 2006), joined with boater surveys and counterfactual analysis, to understand how user-pay scenarios change the
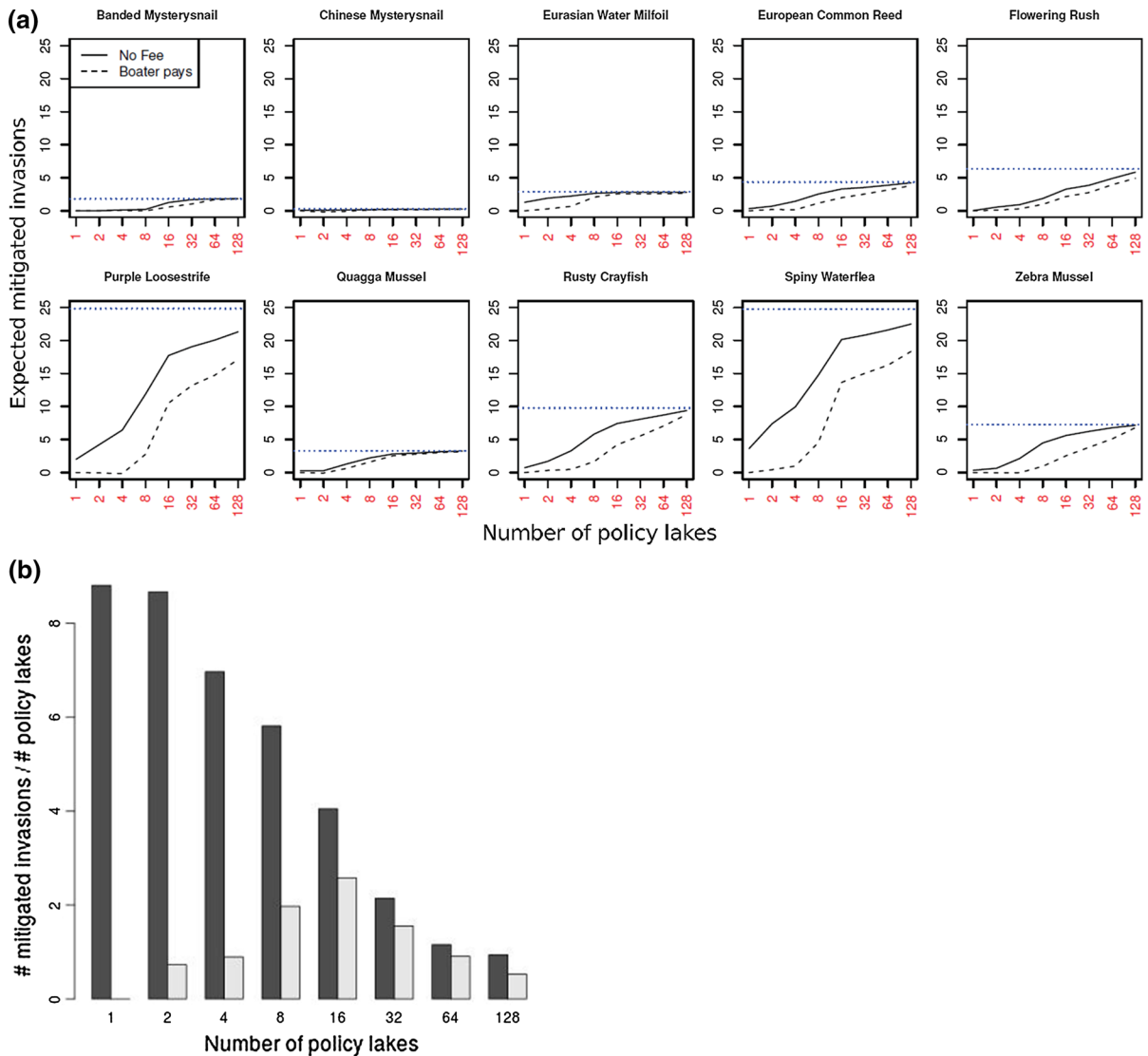
Fig. 3 Application of boat washing scenarios to the spread of 10 NIS, given modelled effect on trip loss and redistribution. Both no-fee and a $16 user-fee policy are presented for different numbers of policy lakes. Lakes with the highest cumulative risk were chosen as the policy lakes. In (**a**) the number of averted invasions is broken down into each individual NIS (*solid line* no fee, *dashed line* $16 fee, *horizontal line* expected # invasions over a 10 year time horizon, given no management). In (**b**) the cumulative number of mitigated invasions across NIS is shown as a proportion of effort (# policy lakes). *Dark bars* no fee, *light bars* $16 fee

efficacy of mandatory boat washing policies and thus the dynamics of human-mediated dispersal.

The results of this study are timely given that numerous management agencies have begun implementing mandatory boat washing programs to reduce the secondary spread of a variety of NIS (e.g., Zebra Mussel, Spiny Water Flea, and Eurasian Watermilfoil, among other boater-transported species). Currently, boat washing requirements vary widely among

agencies (Table 3) but most involve some degree of mandatory washing, usually among a high volume of users (e.g., Alberta, British Columbia; 27,300 boat inspections conducted during 2015; K. Wilson, Province of Alberta, L.-M. Herborg, Province of British Columbia, pers. comm.). Given the scale and scope of boater-mediated invasions throughout North America (Rothlisberger et al. 2010; Drake 2017), and our finding that a large majority of survey respondents

Table 3 Summary of boat inspection and washing programs in Canada by provincial and municipal governments during the 2015 boating season

Province	Summary of Boat Inspection and Washing Activity
British Columbia and Alberta	A total of 23,000 (Alberta) and 4300 (British Columbia) mandatory roadside inspections were conducted in 2015 as part of early detection and monitoring programs. Inspection station locations are not advertised, but locations are revealed to boater population as on-water season progresses. No fee for inspection. Mandatory washing/decontamination if infested vessel found (primary target is Zebra Mussel *Dreissena polymorpha*). Mobile wash station also operated by East Kootenay Invasive Plant Council
Newfoundland	Mobile wash station owned by provincial government. Used primarily for targeted decontamination following discovery of an infested boat
Ontario	Mobile wash stations owned and operated by provincial government (Ontario Parks/Ontario Ministry of Natural Resources and Forestry), used for educational purposes and targeted decontamination following discovery of infested boats
Quebec	Mobile units operated by municipalities/watershed associations

reported that they did not always take steps to clean their boats or check for fouling plants and animals [86 ± 1% (mean ± SE)] (see also Rothlisberger et al. 2010), results of this study and the underlying model will be of direct interest to managers tasked with making decisions about the design of boat washing programs.

In particular, our results suggest that user pay scenarios could compromise the effectiveness of any boat washing strategy, increasing redistribution to as much as 62% ($16 CAD cost imposed). Although the magnitude of local economic loss due to user pay scenarios is unquantified, it could be substantial as 64% of the trips would be lost due to individuals who choose to do other non-boating activities. Therefore, redistribution and loss are important unintended consequences of NIS policies that impose costs to resource users. In comparison to the user-fee scenario, there was minimal loss of trips (2.8%) or redistribution (5.5%) if boat washing was free. As a consequence, management was effective at reducing invasions relative to effort with even a single policy lake for the zero-fee scenarios (i.e., # invasions mitigated/# lakes with policy). Of course, in an absolute sense, many more washing stations were needed to mitigate invasions over the modeled 10-year period, implying that important thresholds exist for some species and scenarios. In comparison, the $16 user-fee scenario had reduced effectiveness overall, especially at lower management effort (i.e., fewer policy lakes), due to redistribution of boating trips. Therefore, given the logical goal of reducing propagule pressure by boaters and maintaining user participation in boating, government-borne fees and rapid cleaning times are

important program objectives. In contrast, high user cost can have the unwanted effect of increasing boating activity at some non-policy lakes, implying that poorly designed washing programs could, in theory, increase propagule pressure to some lakes relative to status quo, contingent on the spatial coverage of infested versus policy sites. On a positive note, most boat washing programs are currently free in Canada and parts of the United States, and our modeling results provide strong support that these programs maximize ecological protection compared to user-pay scenarios. In summary, these results illustrate that no-cost, mandatory washing stations can provide measurable ecological benefits by mitigating invasions at timeframes (<10 years) and with effort (1–128 stations) likely to be meaningful for management agencies.

Logically, boater traits and locations might also influence behavioural responses to management programs. However, in contrast to the strong effect of user fees, we found no effect of boater traits (e.g., the choice of recreational activity and vessel type) and locational traits (e.g., primary residence), suggesting that managers do not need to consider these interactions in program design, at least given the traits measured. This, however, does not mean that management at all locations is equally effective, because the underlying gravity model already predicts different effects of management due to site attractiveness and distance in the context of other potential destinations. As such, our findings indicate that the effect of location on changes in trip taking behaviour was no greater than those already predicted by the gravity model, and that the coefficients describing

redistribution and loss in the model were constant with respect to boater and location traits. Thus, if boat washing were rapid and free, given the low redistribution and loss under this "zero fee" scenario, a simple gravity model (or similar spread model) may be sufficient to determine the best distribution of boat washing effort across lakes.

Future directions

Our quantitative estimates of how user fees cause redistribution and loss provide support for government-borne costs of boat washing programs. We used a stated preference technique, given that the alternative user-fee policies have not been implemented (currently, existing programs (Table 3) are all free and operate sporadically). However, in the future, one could statistically measure the realized changes in behaviour, if data becomes available for the number of boater visits before and after policy implementation and variation exists in user-fees for boat cleaning.

In terms of the implementation of management programs, challenges will inevitably arise because management jurisdictions are often fragmented into multiple independent zones (e.g., neighboring states or provinces), which may be uncoordinated. It is unknown what the consequence would be for heterogeneous policies in terms or trip redistribution and loss, although generally, the "weakest link" may determine the overall behavior of the system as is common in many NIS policy scenarios (Perrings et al. 2002; Peters and Lodge 2009). Additional studies exploring how heterogeneous management policies (vs. coordinated policies) influence the pattern of redistribution and loss and their consequence for biological invasions would be worthwhile.

Additionally, while we have presented a model for incorporating behavioural responses to management aimed at controlling the human-mediated spread of aquatic NIS, such management actions represent one aspect of a broader, multi-faceted strategy for controlling secondary spread (Vander Zanden and Olden 2008). For instance, washing policies could be implemented in concert with other regulations or educational campaigns (Padilla and Williams 2004). It has been noted that some recreational boaters in Alberta, Canada have been known to change travel routes to intentionally enter government-run boat inspection stations, presumably to ensure that watercraft are free

of NIS and reduce the risk of future enforcement action (K. Wilson, Government of Alberta, pers. comm.). Moreover, in a study of boaters in five US states, individual boaters were willing to pay an average of $1.90 in additional fees for boater registrations to fund AIS prevention efforts (Jensen 2010). Thus, with appropriate education, a subset of boaters may be willing to accept additional trip costs imposed by washing programs if the desired result, a NIS-free waterway, has been achieved, potentially allowing the redistributive effect of cleaning to be overcome. Nonetheless, how these willingness to pay values change with education and what the consequence of such fees are for trip taking should be explicitly explored. Analyses such as ours would complement these willingness to pay studies in assessing the changes in human behavior for the fraction of individuals not willing to pay a given rate, which would be important for projecting future spread under management scenarios.

Finally, although we focused on gravity models and recreational boaters, the approach developed here can be applied to other human movement models and other study systems where landscape-level feedbacks are of interest. While our analysis was principally centered around understanding changes in invasion risk due to recreational boating, we expect that similar desired outcomes, such as reductions in propagule pressure, and undesired outcomes, such as trip loss, are likely to be important across a range of aquatic and terrestrial scenarios, including the release of aquarium species to the wild (Gertzen et al. 2008) and the human-mediated movement of forest pests via firewood (Koch et al. 2012). It is unknown the extent to which management interventions for NIS will lead to changes in site utility for these other systems, but similar models such as presented here could be derived. For example, an analysis could make use of camper decisions to stay at a given site, pending controls or fees on locally available firewood. Moreover, this is likely not the only way to incorporate management into spread models of NIS, and we suggest that an even greater diversity of management models should be explored, given the unexpected and potentially harmful responses that can result when behavioural feedbacks are ignored.

Appendix

Counterfactual survey administered to boaters in Ontario, Canada during January and February 2011: responses describe boating activity undertaken during 2010 season

1. Did you operate a boat in Ontario during the 2010 boating season?

● Yes

● No

2. If you answered yes, What type of boating do you do? (Please mark all that apply)

☒ Angling

☐ Water skiing/wake boarding/tubing

☐ Sight seeing

Other: _____

3. What type of boat do you own?

☐ Canoe

☐ Row Boat

☐ Motor Boat (<14')

☐ Motor Boat (>14')

☐ Seadoo or Jet Ski

☐ Pontoon

Other: _____

4. Please enter the name of the city/town of your primary residence:

_____

5. Where was your boat kept most often during the 2010 boating season?

☐ On a trailer at home

☐ On a trailer at a cottage/camp

☐ In a water body at home

☐ In a water body at a cottage/camp

☐ In a water body at a marina

☐ Out of the water at a marina

6. In 2010, did you launch your boat into more than one water body?

⬣Yes

⬣No

7. Please enter the lakes/rivers which you visited during the last boating season:

(if you visited more than 10 lakes, report the 10 lake you visited most often)

	Name of the lake or river visited	Nearest city/town	Number of trips (times launched)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

8. When removing your boat from a waterway, how often do you:

- *Inspect your boat for attached plants and animals?*

  ☐Always ☐More than half the time ☐Less than half the time ☐Never

- *Wash off the hull and propeller?*

  ☐Always ☐More than half the time ☐Less than half the time ☐Never

- *Allow your boat to dry for 5 days or more, before re-launching?*

  ☐Always ☐More than half the time ☐Less than half the time ☐Never

Part 2: In order to reduce the spread of harmful invasive species, consider the following policy

Upon removing your boat from the lake, you would be required to pass your boat and trailer through a hull, trailer and gear cleaning station.

At this station, you would be required to:

- Empty all bilges and live wells
- Ensure that all ropes, fishing lines, propellers, and trailer parts are clear of any plants or animals

Time required to complete the cleaning process will vary depending on the size of your vessel, but it is estimated to take approximately 15 min.

The cost of this mandatory procedure is 2$.

If this policy was implemented at the <u>FIRST</u> lake you indicated above in 2010:

9. How many times would you have visited that lake in the 2010 boating season?

☐

10. If you would have visited this lake fewer times, what would you have done on these occasions?

●Boated on a different lake(s)

●Participated in another (non-boating) activity

●Stayed home

Thank you for your time and cooperation.

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