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By

Rebecca Moore, Alex Macpherson & Bill Provencher

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Alexander Macpherson
University of Florida

Rebecca Moore
Agricultural and Applied Economics
University of Wisconsin
304 Taylor Hall, 427 Lorch St., Madison, WI 53706

Bill Provencher
Agricultural and Applied Economics
University of Wisconsin
416 Taylor Hall, 427 Lorch St., Madison, WI 53706

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This paper presents a dynamic principal-agent model of aquatic species invasions in which a manager, concerned about the spread of invasive species across lakes by boaters, sets *interseasonal* management controls on a lake-by-lake basis, and boaters make a series of *intra*seasonal trip decisions to maximize random utility during the course of the season, conditional on the controls imposed by the manager. The results of a simulated invasion of Eurasian watermilfoil (*myriophyllum spicatum*) highlight interesting aspects of the optimal management policies under two different management objectives: maximizing boater welfare and minimizing milfoil spread.

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I. Introduction

This paper presents a dynamic principal-agent model of aquatic species invasions in which a manager, concerned about the spread of invasive species across lakes by boaters, sets *interseasonal* management controls on a lake-by-lake basis, and boaters make a series of *intra*seasonal trip decisions to maximize random utility during the course of the season, conditional on the controls imposed by the manager. As such, this paper represents the first attempt we have seen in the literature to endogenize resource user behavior in the management decisions related to a species invasion, allowing a more complete understanding of the impact of different policy instruments.

There are two fundamental reasons to endogenize boater movements in a model of the spread of aquatic invasions by boaters. The first is to provide a better forecast of the rate and direction of spread of the invader. Recent work concerning the spread of zebra mussel (*Dreissena polymorpha*) is instructive. The zebra mussel invasion has been well documented, is economically important, proceeds at a rapid but tractable pace, and has provided an opportunity to examine a variety of dispersal models, including human-based models, within a context of an ongoing invasion (Johnson and Carlton 1996). Zebra mussels are limited to aquatic environments with discrete boundaries and well-defined connections. This permits ecologists to make clear distinctions between dispersal modes within a lake, within a watershed, and between watersheds to determine the dispersal mechanism that best describes zebra mussel spread (Johnson and Carlton 1996). The human-mediated potentials for zebra mussel dispersal are plentiful; any submerged object or activity that moves water (like recreational boating) can transport the mussels (Johnson and Carlton 1996).

Much of the work on zebra mussel dispersal focused on predictive and risk analysis models. Schneider et al. (1997) developed a production-attraction transportation model of zebra mussel spread in Illinois streams to analyze the risks posed by the invasive species to native mussels in Illinois streams. The model was parameterized using Illinois boat ramp activity data to predict the frequency of boat movements between lakes and the likelihood that zebra mussels are transported. Bossenbroek et al. (2001) used a gravity models that allows for prediction of long-distance dispersal by considering the source populations and the spatial configuration and ecology of the potential colonization sites. Like Schneider et al. (1997), the gravity model predicted inter-lake trips and multiplied trips against a probability of colonization to predict the dispersal of zebra mussels. The model included a measure of the vulnerability (i.e. the attractiveness of the lake to the invader) of potentially invaded lakes to better model when and where long-distance dispersal will happen (Bossenbroek 2001). Buchan and Padilla (1999) compared a standard diffusion model with patterns of recreational boater activities to find that boater behavior was a better predictor of the observed pattern of the zebra mussel invasions. The diffusion model approach underestimated the maximum rate and geographic extent of the invasions because it was less capable of incorporating the long-distance movements across unsuitable habitat that the mussels achieve via human-mediation. The authors concluded that management activities that slow the spread of the invasive species should focus on boater movements (Buchan and Padilla 1999).

None of the foregoing models accounts for the response of boaters to species invasions and management controls. Simple extrapolation of boater movements, while perhaps a better predictor of invasions than transportation and diffusion models, will prove unsatisfactory if such reactions are significant. Suppose, for instance, that Lake A is uninfected by the invasive species, and the lake manager chooses to close the lake to cross-lake boater traffic (while perhaps leaving the lake open to boats that remain on the lake full-season) to protect it from an invasion. The boater trip pattern across the landscape may change as a result of the policy. Not all of the trips previously taken to Lake A are lost; some are diverted to other lakes. This raises the possibility that the lake closure effectively *advances* the spread of the invasive species, by, for instance, causing boaters to "leapfrog" closed lakes in favor of more distant, "clean" lakes.

This example also illustrates our second justification for endogenizing boater behavior in studies of aquatic invasions: it is necessary to accurately estimate welfare effects. The welfare effect of closing Lake A has an obvious *direct* welfare effect because now access to the lake requires keeping a boat on the lake, but it also has an *indirect* welfare effect because it shifts the spread of the invasive in a way that may leave society worse off overall.

The next section of the paper presents the integrated economic and ecological model of aquatic invasions. The third section presents a simulated Eurasian watermilfoil (*myriophyllum spicatum* hereafter called "milfoil") invasion to highlight interesting aspects of the optimal management policies under two different management objectives: maximizing boater welfare and minimizing milfoil spread, both subject to a program budget. The fourth section discusses the specific challenges of applying this model to an actual lake system, and proposes techniques in survey research and dynamic programming that will address these challenges. The final section concludes.

II. The Model

A diagram of the model is presented in Figure 1. This schematic lays out the basic logic of the model: the sequence of decisions made by the manager and boaters, and the resulting transitions in the biological state of the lake system.   Suppose there is a system of J lakes, $j = 1,\ldots,J$, each with a unique vectors of characteristics that make it attractive to resource users and vulnerable to species invasions. At the beginning of each season s, the principal –the lake system manager –chooses seasonal controls affecting boaters and therefore the spread of the invasive species. The lake manager is forward-looking; in setting controls, he anticipates the future spread of the invasive species and accounts for boater reactions to the controls.

There are T days in each season, indexed by $t = 1,\ldots,T$. On each day, boaters, acting as the agents in the problem, decide whether to make a trip to a lake within the system. Because a boater might make multiple trips within a season, invasive propagules from a source lake can become attached to equipment and transported to uncolonized lakes in the district. For our purposes, boaters are assumed to be the unique "carriers" of the invasive species via the accidental transport of propagules. Boater behavior is dependent on the current state of the invasion, lake-specific variables, and the controls chosen by the manager at the start of the season. As the season progresses, the rate and direction of the invasive species spread is determined by the controls chosen by the lake manager at the start of the season, the stochastic trip decisions of boaters, and the stochastic ecological processes underlying the invasion.

State of the Lake System and Management Controls

To make it easier to describe the essential features of the model, we present it in terms of a specific invasive species –Eurasian Water Milfoil (*myriophyllum spicatum*; hereafter called "milfoil") –and two specific management controls relevant to the control of milfoil spread. These controls are the mandatory use of boat-cleaning equipment upon exit from a lake, to wash away milfoil propogules attached to the boat; and closing lakes to interlake boat traffic, so that access to a lake, although still possible –for instance, via an *in situ* boat livery –is nonetheless more expensive.

At the start of season *s*, the lake system is defined by three sets of dichotomous state variables relevant to the manager's decision problem: i_{js}, taking a value of 1 when lake *j* is infected by milfoil, and 0 otherwise; e_{js}, taking a value of 1 if boat-cleaning equipment is already installed (with boater use required) on lake *j*, and 0 otherwise; and a_{js}, taking a value of 1 if a lake is already closed to interlake boater traffic, so that lake access is possible only via a costly alternative, and 0 otherwise. In the discussion below, the full set of state variables is defined by $\{\mathbf{i}_s, \mathbf{e}_s, \mathbf{a}_s\}$, where each element is a *J*-dimensioned vector of state values.

At the start of the season, the manager executes two sets of decisions to control the spread of milfoil, conditional on the state of the system $\{\mathbf{i}_s, \mathbf{e}_s, \mathbf{a}_s\}$. The first pertains to the installation and required use of cleaning equipment, and the second pertains to the closure of lakes to interlake boat traffic. In the discussion below we treat management controls implicitly, by using e'_{js} and a'_{js} to denote state variable values *after* the manager's control decisions. So, for instance, $a_{js} = 0$, $a'_{js} = 1$ indicates that at the start of season *s* lake *j* was open to interlake boat traffic, and the manager closed the lake; and $a_{js} = 1,\ a_{js}{}' = 1$ indicates that at the start of season *s* lake *j* was closed, and the manager chose to keep it closed. The upshot is that whereas the manager chooses controls conditional on the state $\{\mathbf{i}_s, \mathbf{e}_s, \mathbf{a}_s\}$, boaters make trip decisions conditional on the state $\{\mathbf{i}_s, \mathbf{e}'_s, \mathbf{a}'_s\}$.

Boater Trip Decisions

In the model, a single representative boater decides on each day of the season whether to take a trip to a lake within the district.[1] Baseline utility (the utility associated with no trip) is zero and the boater choosing to visit lake *j* on day *t* during season *s* receives money-measured utility:

$$\begin{aligned} V_{jst} &= U_{js} + \varepsilon_{jst} \\ &= -C_j - comply \cdot E \cdot e'_{js} - A \cdot a'_{js} + \beta Z_{js}(i_{js}) + \varepsilon_{jst} \end{aligned} , \qquad (1)$$

where C_j is the travel cost of a trip to lake *j*; *comply* is the fraction of boaters who use the cleaning equipment; *E* denotes the cost of cleaning a boat, so $E \cdot e'_{js} = 0$ when boat cleaning equipment is not installed on lake *j* in season *s*, and $E \cdot e'_{js} = E$ when boat cleaning equipment is installed; *A* is the cost of a trip on a closed lake, so $A \cdot a'_{js} = 0$ when a lake is open to boater traffic, and $A \cdot a'_{js} = A$ when the lake is closed; Z_{js} is a vector of lake characteristics affecting trip decisions, such as lake size, and other lake attributes affected by whether the lake is infected by milfoil, such as the quality of fishing; and ε_{jst} is the component of the utility known to the user

[1] Nothing is gained by scaling up the model to *N* identical boaters.

but unobserved by the analyst. We assume that this unobserved component is identically and independently Gumbel-distributed.

User welfare on day *t* during season *s* is measured in terms of expected utility, here corresponding to the well-documented *inclusive value*, $\ln\left(\sum_{j=0}^{J}\exp(U_{js})\right)$. Seasonal expected utility is then given by,

$$IV_s\left(\mathbf{i}_s, \mathbf{e}'_s, \mathbf{a}'_s\right) = T\ln\left(\sum_{j=0}^{J}\exp(U_{js})\right) . \tag{2}$$

Invasive Species Dispersal

To fully develop the human-mediated dispersal model, we need to link the RUM to the ecological characteristics of the species and habitats in question. Under the assumption that boaters are the only means of interlake dispersal for milfoil, and invasive propagules remain viable for one day, the likelihood of an uninfected lake *k* being colonized at time *t+1* can be represented as the probability that the representative boater visits an infected lake on day *t*, picks up a propagule from this lake, and visits lake *k* on day *t+1*, with the propogule then establishing a colony.

Let D_{st} be the event that the boater visits an infected lake and becomes a propagule carrier on day *t* of season *s*. We denote by J_s^* the set of lakes actually infected in season *s*, and we denote by $f(e'_{ks}, a'_{ks}, X_k)$ the probability that the boater becomes a propagule carrier upon a visit to lake $k \in J_s^*$; this probability depends on whether boat cleaning is required, whether the lake is closed to interlake boat traffic, and ecological characteristics of the lake, X_k. Keeping in mind that the unobserved component of utility is Gumbel-distributed, the probability of event D_{st} is given by

$$\Pr\left[D_{st}\right] = \sum_{k \in J_s^*} \left(f(e'_{ks}, a'_{ks}, X_k) \frac{\exp(U_{ks})}{1 + \sum_{j=1}^{J} \exp(U_{js})} \right). \tag{3}$$

We define $I_{ks,t+1}$ as the event that lake k is first colonized on day $t+1$ of season s.[2] The probability of this event occurring, *conditional* on the probability that the representative boater became a carrier on day t, is given by

$$\Pr\left[I_{ks,t+1} \mid D_{st}\right] = g(X_k) \frac{\exp(U_{ks})}{1 + \sum_{j=1}^{J} \exp(U_{js})}, \tag{4}$$

where $g(X_k)$ relates the ecological characteristics of lake k to the probability of an introduced propagule establishing a colony. Combining equations (3) and (4) gives the *unconditional* probability of lake k being colonized on day $t+1$:

$$\begin{aligned} \Pr\left[I_{ks,t+1}\right] &= \Pr\left[I_{ks,t+1} \mid D_{st}\right] \cdot \Pr\left[D_{st}\right] \\ &= g(X_k) \frac{\exp(U_{ks})}{1 + \sum_{j=1}^{J} \exp(U_{js})} \sum_{j \in J_s^*} \left(f(e'_{js}, a'_{js}, X_j) \frac{\exp(U_{js})}{1 + \sum_{r=1}^{J} \exp(U_{rs})} \right). \end{aligned} \tag{5}$$

Left implicit in (5) is that $\Pr\left[I_{ks,t+1}\right]$ depends on the entire state of the system (through f and U).

Now we must extend the formulation of the colonization probability from a single day to the full season. Consider the probability that lake k is colonized by the end of season s,

[2] For the sake of simplicity, in this model a lake first colonized anytime during season s does not enter an infected state, thereby affecting boater and manager decisions, and becoming itself a source of propogules, until the start of season $s+1$. One might interpret this as representing the lag between the time at which an invasive species actually begins propagating at a new location, and the time at which its presence generates social costs.

transitioning the lake into an infected state at the start of season *s+1*. On the first day of the season, there is no chance of colonization because there is no possibility of a trip on a previous day. On the second day of the season, the probability of an infection of lake *k* is given by (5). On the third day of the season, the probability of colonization of lake *j* is given by the probability of colonization on day three (from (5) again), multiplied by the probability of *not* being colonized on days one and two *plus* the probability of being colonized on days one and two. Letting *t* and *q* index the days within the season, the probability of colonization of lake *k* during season *s* assumes the following recursive structure:

$$\begin{aligned}\Pr\left[I_{ks} \mid \mathbf{i}, \mathbf{e}'_s, \mathbf{a}'_s\right] &= \Pr\left[I_{ks2}\right] + \Pr\left[I_{ks3}\right]\left(1 - \Pr\left[I_{ks2}\right]\right) + \ldots + \Pr\left[I_{ksT}\right]\prod_{t=2}^{T-1}\left(1 - \Pr\left[I_{kst}\right]\right) \\ &= \sum_{t=2}^{T}\left[\Pr\left[I_{kst}\right]\prod_{q=1}^{t-1}\left(1 - \Pr\left[I_{ksq}\right]\right)\right]\end{aligned} \tag{6}$$

Management Objective: Maximizing Discounted Net Benefits of Invasion Control

We represent the cost of management controls in season *s* by $tc\left(\mathbf{e}_s, \mathbf{a}_s, \mathbf{e}'_s, \mathbf{a}'_s\right)$; this formulation recognizes that the cost of a control depends on the state of the management variables at the start of the season, and the manager's control choices. For instance, mandating that all boats exiting a lake must be cleaned is likely much less costly if cleaning equipment already exists at the lake. Seasonal net benefit, given that only boaters draw utility from changes in the state of the invasion (a modeling simplification, of course), is denoted by:

$$B\left(\mathbf{i}_s, \mathbf{e}_s, \mathbf{a}_s, \mathbf{e}'_s, \mathbf{a}'_s\right) = IV\left(\mathbf{i}_s, \mathbf{e}'_s, \mathbf{a}'_s\right) - tc\left(\mathbf{e}_s, \mathbf{a}_s, \mathbf{e}'_s, \mathbf{a}'_s\right) \ . \tag{7}$$

As already noted, in this simple model a lake's state of invasion is a binary variable, taking a value of 1 if milfoil is present in the lake and 0 otherwise. It follows that there exist 2^J possible states of invasion for the system as a whole. We denote this set of feasible invasion states by **I**. Let $p_{\mathbf{i}'}\left(\mathbf{i};\mathbf{e}',\mathbf{a}'\right)$ denote the probability that the system transitions to invasion state $\mathbf{i}' \in \mathbf{I}$ at the start of the next season, given the state of the invasion in the current season, and the manager's choice of controls for the current season (as indicated by the management state vectors $\mathbf{e}'$ and $\mathbf{a}'$). Then denoting the discount factor by δ, with $0 < \delta < 1$, and dropping the season subscript *s* to reduce notational clutter, the problem of a manager who wishes to maximize discounted utility, subject to a seasonal budget constraint *Y*, can be succinctly stated in Bellman's form as,

$$\begin{aligned} V\left(\mathbf{i},\mathbf{a},\mathbf{e}\right) &= \max_{\mathbf{a}',\mathbf{e}'}\left[B\left(\mathbf{i},\mathbf{a},\mathbf{e},\mathbf{a}',\mathbf{e}'\right)+\delta\sum_{\mathbf{i}'\in\mathbf{I}} p_{\mathbf{i}'}\left(\mathbf{i},\mathbf{a}',\mathbf{e}'\right)V\left(\mathbf{i}',\mathbf{a}',\mathbf{e}'\right)\right] \\ & s.t. \quad tc\left(\mathbf{e},\mathbf{a},\mathbf{e}',\mathbf{a}'\right) \le Y \end{aligned} \quad . \qquad (8)$$

Management Objective: Minimizing the Discounted Rate of Spread

An alternative objective is for the manager to choose seasonal values of $\mathbf{a}'$ and $\mathbf{e}'$ to minimize the rate of spread of the invasive species to new lakes, subject to a budget constraint. :

$$\begin{aligned} V\left(\mathbf{i},\mathbf{a},\mathbf{e}\right) &= \min_{\mathbf{a}',\mathbf{e}'}\left[\sum_{k\notin J^*}\Pr\left[I_k \mid \mathbf{i},\mathbf{e}',\mathbf{a}'\right]+\delta\sum_{\mathbf{i}'\in\mathbf{I}} p_{\mathbf{i}'}\left(\mathbf{i},\mathbf{a}',\mathbf{e}'\right)V\left(\mathbf{i}',\mathbf{a}',\mathbf{e}'\right)\right] \\ & s.t. \quad tc\left(\mathbf{e},\mathbf{a},\mathbf{e}',\mathbf{a}'\right) \le Y \end{aligned} \quad , \qquad (9)$$

where $\sum_{k\notin J^*}\Pr\left[I_k \mid \mathbf{i},\mathbf{e}',\mathbf{a}'\right]$ is effectively the expected number of newly infected lakes in the current season. It follows from a strictly positive discount rate (that is, the discount factor is strictly less than one) that even in the case where no control is foolproof –so that infection of the entire system is eventually assured –it is worthwhile to control an infestation. Put another way, the timing of the invasion matters; the manager prefers to postpone an invasion for as long as possible.

III. Eurasian Watermilfoil Case Study

Eurasian watermilfoil is a perennial herbaceous freshwater submersed plant. The plant forms a dense canopy of branches floating at the surface (Madson 1999) and grows best in fertile, fine-textured, inorganic sediments. An opportunistic species, milfoil establishes in highly disturbed lakes that receive significant nitrogen and phosphorus-containing runoff (Wisconsin Department of Natural Resources 2004). Milfoil largely spreads asexually through vegetative fragments and not sexually by seed dispersal (Madson et al. 1988). Because of this vegetative reproduction, milfoil spreads quickly via accidental carriage by boats, motors, trailers, bilges, live wells, or bait buckets (Madson et al. 1988). Given damp conditions, milfoil fragments can remain viable for several days (Wisconsin Department of Natural Resources 2004). Between unconnected lakes, milfoil is spread primarily through accidental introductions by boats and boat trailers (Madson et al. 1988).

Milfoil has several ecological effects once it establishes in a lake. First, the presence of significant submerged macrophyte biomass can contribute to nutrient enrichment in lakes (Carpenter 1980). This phenomenon occurs because the decaying shoots of the macrophyte release dissolved phosphorus and organic matter, which can make an important contribution to the pelagial production in a lake. This nutrient contribution can accelerate eutrophication processes (Carpenter 1980). Second, abundant milfoil can severely impact the diversity and density of native aquatic plant communities. Species richness and abundance decline with increased milfoil growth. These results are expected to extend to other components of the food web as well (Boylen et al. 1999). Third, high densities of submerged macrophytes can harm the quality of a fishery (Wiley et al. 1984; Bettoli et. al 1992). Feeding rates are reduced in lakes with dense beds of macrophytes by reducing predator efficiency by providing increased prey refuge (Olson et al. 1998). The lower mortality rates of the smaller fishes cause greater population densities and stronger competitive interactions among forage fish (Mittelbach 1988). Experiments have shown that cutting channels though macrophyte beds may cause fish populations to increase, showing that harvesting may be a valuable management tool in infested lakes (Olson et al. 1998; Unmuth et al. 1999).

Results from a four lake simulation

Simulating the model requires a variety of data concerning boater preferences, probabilities of colonization, boater travel costs, management costs, and boater compliance rates. Given little of this information is currently available, we simulated a minimal version of the model with realistic but mostly hypothetical data.

The lake system used in the simulations is comprised of four lakes, differentiated by the cost of travel to the lake and lake size. In the simulated model, the differential appeal of the lakes is straightforward, and supported by empirical evidence and/or economic theory: boaters prefer larger lakes to smaller ones, and closer lakes to more distant ones. The spatial distribution of lakes across the landscape is expected to have a large impact on boater trip behavior. For this reason, we explore two possible spatial arrangements of the four lakes. One arrangement places the largest lake farthest from the population center, and the smallest lake nearest. This arrangement presents the boater with a clear tradeoff between lake size and trip cost. The second arrangement is one in which the largest lake is nearest the population center, and the smallest lake is farthest –a likely scenario in a region that develops around the use of its lakes. In the discussion below we call this the "endogenous development" scenario, and in the context of this scenario we refer to the large lake close to the population center as the "dominant" lake.

A variety of parameters and initial conditions were used in the simulations in an attempt to obtain a general sense of the role of boater traffic, and boater responses to management controls, on milfoil infestations. Though clearly minimal, the model is expected to reflect the key dynamics of managing an invasive aquatic plant species on a portfolio of lakes.

Several observations can be made based on the patterns that emerge across the scenarios examined in the simulations. First, the difference in expected welfare value between a system entirely free of milfoil, and one where all lakes contain milfoil, appears to be greatest in the endogenous development scenario. In other words, the tendency for lake regions to develop around the largest lakes serves to increase the value of keeping the lake system free of an invasive. The explanation is that invasions tend to hit the most attractive lakes first, and endogenous development reinforces the stratification of lakes based on their "natural" appeal; the best lakes also become the closest lakes.

A corollary to this result is that under welfare maximization in the endogenous development scenario, if the dominant lake is milfoil-free, the expected time to colonization of the entire system is relatively long, as significant resources are put into protecting the dominant lake, and trips to infected "satellite" lakes are relatively few; on the other hand, once the dominant lake is infected, the entire system quickly becomes infected.

Second, under welfare maximization, management resources will often remain unspent, and the optimal policy is often to impose no controls, in order to avoid imposing excessive costs on boaters. This result obviously could change –perhaps drastically –in a more realistic model in which milfoil negatively affects non-boating shoreline property owners (Halsted et al. 2003).

A corollary to the above is that managers use controls more readily under spread minimization than under welfare maximization. Moreover, under spread minimization an increase in the budget can result in a *decrease* in welfare. This effect varies significantly with the spatial arrangement of the lakes.

Third, controls may cause a dramatic decrease in trips to regulated lakes, without a full redistribution of the trips to other lakes in the system. The expected size of this decline varies significantly with the spatial arrangement of the lakes. Overall, a policy that accounts for boater responses to controls is much more effective –no matter the objective –than one that does not.

IV. Obstacles to a Large Scale Application

The simulations described in the previous section illustrate the types of policy recommendations that can be derived from the model, but their usefulness from an applied perspective is limited by the small number of lakes considered. Though a larger, more complex system could be expected to behave similarly in many respects, it is not likely that an application to an actual lake system would generate exactly the same policy recommendations. Yet applying the model on a large scale is a daunting challenge, for two reasons.

The first and most obvious is that the dynamic programming problems (8) and (9) suffer from the well-known “curse of dimensionality”: as additional lakes are added to the system, the size of both the state space and the control space increase exponentially. The second reason is that estimation of a RUM model of boaters for a large-scale lake system is problematic. In particular, such estimation requires that the analyst define the choice sets of boaters at the lake level. Several authors have noted the bias in the estimation of RUMs when the choice set is misspecified (Haab and Hicks 1997, 1999). Most RUM studies use researcher-defined choice sets, such as including all lakes within a certain distance of the individual's residence, based on the maximum distance an individual would travel for a day trip (*see* Parsons 2003). Another possible option is to approximate larger choice sets by drawing a random subset of lakes. A series of studies (Parsons and Kealy 1992; Parsons and Needelman 1992; Feather 1994; Feather et al. 1995; Lupi and Feather 1998) examines the bias and efficiency of aggregation and random selection.

It appears possible to surmount the challenges posed in applying our model to a large-scale aquatic system. With respect to the matter of solving a large dynamic programming problems, Woodward, Wui, and Griffen (2005) present an innovative method of carrying out dynamic optimization in the context of a large simulation model of a red snapper fishery. With this method, an approximate optimization of an "aggregate" problem is solved using information from the full simulation model. While the application presented in their paper differs from our problem in a few key details –for instance, the fishery model control variables are continuous, while our model uses discrete control variables –we believe their "direct approach" to solving the dynamic programming simulation problem could be adapted to examine species invasions of large-scale aquatic systems.

Concerning the matter of identifying the lakes within a boater's choice set, several authors argue persuasively that the best approach is to directly query decision makers about their choice sets (Peters, Adamowicz, and Boxall 1995; Hicks and Strand 2000). Yet this approach ultimately confronts the practical question of survey design: How does the analyst induce a respondent to identify all the lakes considered in the trip decision?

One possibility is to list all relevant lakes and request that survey respondents specify those they consider when making the trip decision. Another possibility is to pose the choice set as an open-ended question in which the respondent lists those lakes they contemplate visiting. With both approaches, respondent fatigue is likely to bias responses.

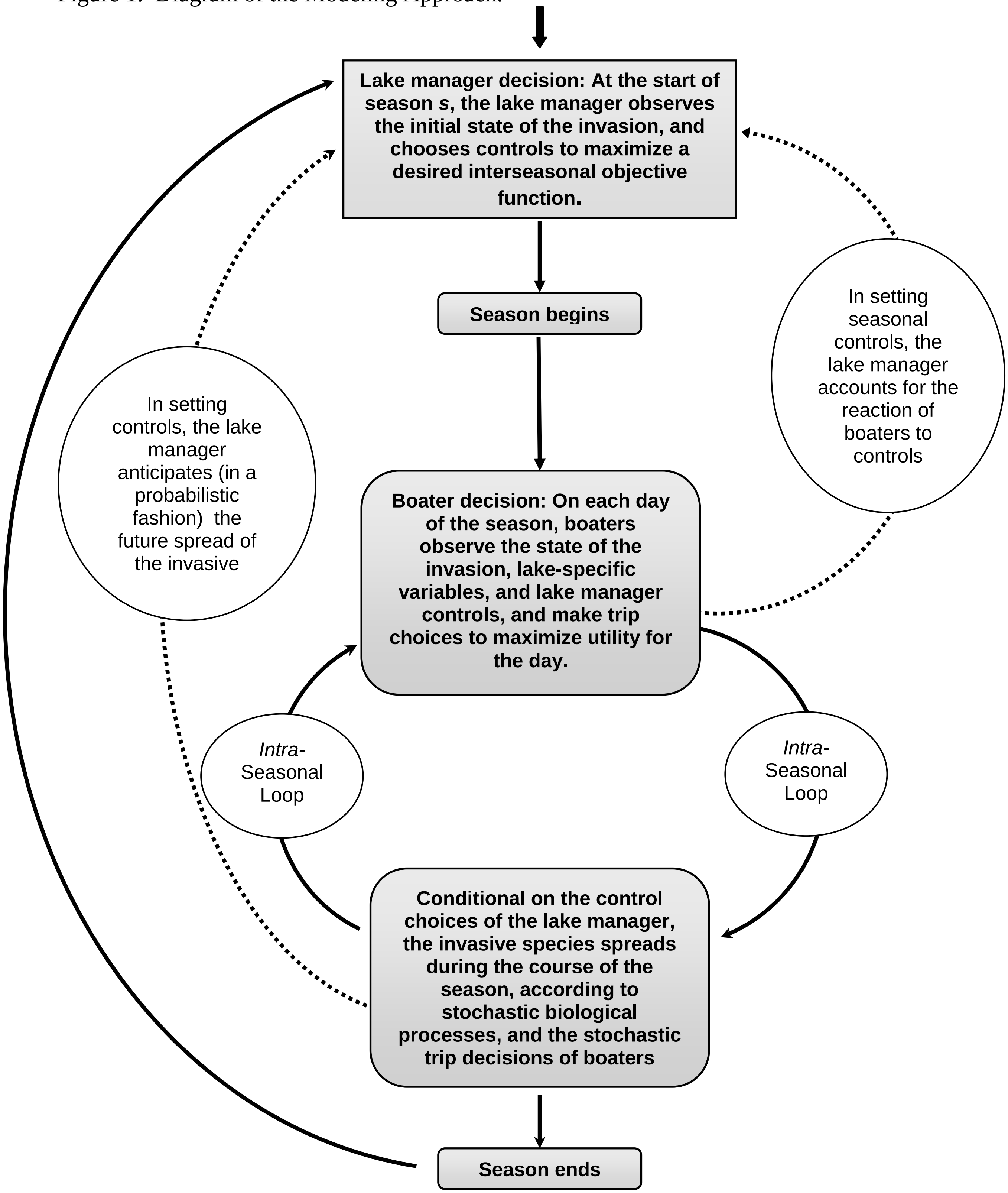
Recent advances in the use of internet-based surveys offer a possible solution to this problem. Internet surveys allow for more flexibility and control over which questions the respondent actually sees. One could imagine, for instance, a clickable map of the study region. The respondent could click on the part of the region they most often visit. Zooming to this smaller region, the user could then simply click on all the lakes that should belong in the choice set –a much simpler task than writing down all of the lake names. The rest of the survey questions could then be tailored to those lakes identified by the respondent. In short, the Internet platform allows for relatively individualized survey design while still appearing concise and linear to the respondent.

Conclusions

This paper represents the first attempt in the literature to endogenize resource user behavior in the management of a species invasion by developing a general model of aquatic plant species invasions in which lake users are the primary vector of invasion. In the model, recreational boaters respond to both the presence of the invader *and* the actions taken by the lake manager. The lake manager acknowledges boater responses and makes management decisions accordingly. By incorporating a model of human behavior into a dynamic ecological system, we can better understand the complex interactions between human activity and the environment.

The simulated milfoil case study presented here illustrates the potential benefits of using this model to generate policy recommendations for lake managers. Though a large-scale application is desirable, there are several hurdles to its implementation. The discussion above argues that recent advances in the literature could allow us to overcome these obstacles. Doing so will allow simulations at a regional-scale. With these results, managers will then be able to consider the full impacts of their policies, and so make more informed decisions.

Figure 1. Diagram of the Modeling Approach.



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