International Trade and Biological Invasions: A Queuing Theoretic Analysis of the Prevention Problem

by

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Abstract

We propose and develop a new framework for studying the problem of preventing biological invasions caused by ships transporting internationally traded goods between countries and continents. In particular, we apply the methods of queuing theory to analyze the problem of preventing a biological invasion from a long run perspective. First, we characterize two simple regulatory regimes as two different kinds of queues. Second, we show how to pose a publically owned port manager's decision problem as an optimization problem using queuing theoretic techniques. Third, we compare and contrast the optimality conditions emanating from our analysis of the $M/M/I/U$ and the $M/M/I/I$ inspection regimes. We conclude by discussing possible extensions to our basic models.

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JEL Classification: F18, L51, Q20

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1. Introduction

In this age of globalization, there is increasing mobility of both humans and goods between countries and continents. Ships are routinely used to transport a variety of internationally traded goods between different countries. There is no gainsaying the fact that this international trade in *goods* is generally beneficial to the countries involved. Indeed, there are several results in modern trade theory which show that voluntary goods trade between nations is welfare improving for all the nations involved.

This notwithstanding, as Heywood (1995), Parker *et al.* (1999), and others have pointed out, in addition to transporting goods between countries, by means of their ballast water, ships have also unwittingly transported all kinds of non-native plant and animal species from one geographical region to another.[1] These non-native or alien species have often been very successful in invading their new habitats and the resulting biological invasions have proved to be very costly to the countries in which these new habitats are located. For the United States alone, the magnitude of these costs is astounding. For instance, according to the Office of Technology Assessment (OTA (1993)), the Russian wheat aphid caused an estimated $600 million worth of crop damage between 1987 and 1989. More generally, Pimentel *et al.* (2000) have estimated the total costs of all non-native species

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The principal method of marine non-native species introduction is by means of the dumping of ballast water. Cargo ships typically carry ballast water in order to enhance maneuverability and stability when they are not carrying full loads. When these ships come into port, this ballast water must be discharged before cargo can be loaded. It is estimated that over 4000 species of invertebrates, algae, and fishes are being moved around the world in ship ballast tanks every day. Focusing on just one country, it has been estimated that as much as 13 billion gallons or 50 million metric tonnes of overseas ballast water enters Canadian coastal ports every year. A recent study by the Smithsonian Environmental Research Center (SERC) in Edgewater, Maryland calculated that a liter of ballast water typically contains several billion organisms similar to viruses and up to 800 million bacteria. For more details on these issues, go to http://www.fundyforum.com/profile_archives and to the SERC web site www.serc.si.edu to be around $137 billion per year.

It is important to understand that in addition to economic costs, invasive species also cause significant ecological damage. As Vitousek *et al.* (1996) have noted, non-native species can alter ecosystem processes, act as vectors of diseases, and diminish biological diversity. In this regard, the work of Cox (1993) tells us that out of 256 vertebrate extinctions with a known cause, 109 are the result of biological invasions. Even a single invasive species can cause tremendous damage. Savidge (1987) tells us that following an invasion of Guam by the brown tree snake, all twelve of this island's bird species became extinct.

The point of this discussion is clear. Biological invasions can be and frequently have been a huge menace to society. Given this state of affairs, one can ask what economists have contributed to increasing our understanding of the regulation of biological invasions. Unfortunately, the answer is not much. Although very recently economists have begun to address this question, it is still the case that "the economics of the problem has...attracted little attention" (Perrings *et al.* (2000, p. 11)).

From a regulatory perspective, there are a number of actions that one can take to deal with the problem of biological invasions. It is helpful to separate these actions into pre-invasion and post-invasion actions. Pre-invasion actions relate to the so called prevention problem. The idea here is to take actions that will effectively *prevent* a potentially damaging non-native species from invading a new habitat. In contrast, post-invasion actions involve the optimal control of one or more non-native species, given that the species has already invaded a new habitat.

Most economic analyses of the regulation of biological invasions have focused on the desirability of alternate actions in the *post-invasion* scenario. We now briefly discuss four representative studies. Barbier (2001) shows that the economic impact of a biological invasion can be determined by studying the nature of the interaction between the non-native and the native species. He notes that the economic impact depends on whether this interaction involves interspecific competition or dispersion. Eiswerth and Johnson (2002) analyze an optimal control model of the management of a non-native species stock. They show that given presently available scientific information, the optimal level of management effort is sensitive to ecological factors that are species and site specific and stochastic. Olson and Roy (2002) have used a model of a stochastic biological invasion to examine conditions under which it is optimal to eradicate the non-native species and conditions under which it is not optimal to do so. Finally, Eiswerth and van Kooten (2002) have shown that even when hard data about the spread of an invasive species are unavailable, it is possible to use information provided by experts to formulate a model in which it is optimal to not eradicate but instead control the spread of an invasive species.

The above studies have certainly increased our understanding of regulatory issues in the *post-invasion* scenario. This notwithstanding, to the best of our knowledge, the only paper that has formally analyzed the prevention problem, i.e., the regulation of a potentially damaging non-native species before invasion is Horan *et al.* (2002). These researchers model non-native invasive species as a form of "biological pollution." They then compare the properties of preventive management strategies under full information and under uncertainty. Our paper is different from this paper in three important ways. First, we are not interested in comparing the properties of management strategies under full information and under uncertainty. In this regard, we suppose from the start that uncertainty is an integral component of the prevention problem confronting a regulator. Second, we use queuing theory—to the best of our knowledge for the first time—to provide a long run perspective on the stochastic setting in which our regulator operates. Finally, we use aspects of this stochastic setting to set up objective functions that our regulator optimizes.

The rest of this paper is organized as follows. Section 2 first provides a brief primer on queuing theory and then it focuses on the two queuing models that we use to study the prevention problem confronting our regulator. Section 3 uses the first of these two queuing models to provide a detailed analysis of the regulator's prevention problem. Section 4 does the same using the second of our two queuing models. Section 5 compares and contrasts the optimality conditions emanating from our analysis of two specific queuing inspection regimes. Section 6 concludes and offers suggestions for future research.

2. Queuing Theory and the Prevention Problem

2.1. A primer on queuing theory

Queuing theory is concerned with the mathematical analysis of waiting lines or queues.[2] At a very basic level, all queuing models have three characteristics. In particular, they can be described by (i) a stochastic arrival process, (ii) a random service time or times distribution function, and (iii) the deterministic number of available servers. The arrival process is often but not always described by the Poisson process. When this is the case, the times between successive arrivals are exponentially distributed and, as is well known, the exponential distribution is memoryless or Markovian in nature. Consequently, the Poisson arrival process is commonly denoted by the letter M.

The service times are clearly stochastic and hence these times can, in principle, be arbitrarily distributed. However, these services times are frequently modeled with the exponential distribution function which is memoryless or Markovian in nature. Hence, in this case, the letter M is also used

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[2] Excellent textbook accounts of queuing theory can be found in Gross and Harris (1974), Wolff (1989), and Ross (2003).

to represent the service time distribution function. Finally, the deterministic number of servers is typically denoted by some positive integer.

So, for instance, the notation $M/M/1$ refers to a queuing model in which the arrival process is Poisson, the service time is exponentially distributed, and there is a single server. Similarly, the notation $M/G/5$ refers to a queuing model in which the arrival process is Poisson, the service times are generally distributed, and there are five servers. It is possible to complicate this basic three part construct in several ways and in this paper we shall do so by adapting this basic three part construct to our biological invasion prevention problem.

2.2. The biological invasion prevention problem

Consider a stylized, publically owned port in a specific coastal region of some country. Ships with ballast water arrive at this port typically to load cargo and to then transport this cargo to some other port. Occasionally, it may also be the case that some ships that come into our port with ballast water will first unload cargo and then load new cargo for shipment to some other port in the world. In either case, the arrival of these ships coincides with the arrival of a whole host of (potentially deleterious) biological organisms. It is reasonable to suppose that the arrival rate of these biological organisms is proportional to the arrival rate of the aforementioned ships. Consequently, we shall not model these biological organisms directly. Instead we shall focus on the ships that bring—by means of their ballast water—these organisms to our port. Given this interpretation, the arrival process of the ships in our port constitutes the arrival process for the queuing models that we employ in this paper. Now, consistent with a wide variety of queuing models, we suppose that the ships in question arrive at our port in accordance with a Poisson process with rate α.

Because we are interested in preventing invasions by the potentially deleterious biological organisms, arriving ships must be inspected before they can either load or unload cargo. We assume that our port has I inspectors, where I is any positive integer. Put differently, at any point in time, our port will be able to simultaneously inspect a maximum of I arriving ships. Further, ships are inspected on a first come first served basis. If more than I ships arrive at our port during a particular time interval then the ships that are not already being inspected must wait in queue. An alternate interpretation of this state of affairs is that our port has I docks and that one inspector is assigned to each of these I docks. Therefore, at any specific moment in time, a maximum of I ships can be docked and inspected. Finally, since no port is physically able to accommodate an arbitrarily large number of ships, we suppose that there is an upper limit U on the maximum number of ships that can be allowed to queue in our port. The port system consists of ships that are being inspected, ships that are waiting in queue, the I inspectors, and the port manager.

Note that because we are studying the prevention of biological invasions in this paper, all I inspectors will have a zero tolerance policy. As a result, inspection is necessarily a laborious and time consuming activity. Before a ship can be cleared for loading or unloading cargo, an inspector must guarantee that this ship's ballast water contains no potentially harmful organisms. To provide this assurance, a specific inspector can take a number of actions. These include (i) the shipboard filtration of ballast water, (ii) the treatment of ballast water with heat, chemicals, and ultraviolet radiation, and (iii) the shore based treatment of ballast water.

As indicated in the previous paragraph, inspections will typically require varying amounts of time. For instance, if an inspector knows that a particular ship has taken on ballast water in an area where there are no known biological invaders then (s)he may be able to clear a ship relatively quickly. In contrast, if it is the case that a particular ship has taken on ballast water during a phytoplankton bloom, then the chance of this ship's ballast water containing potentially detrimental organisms is much higher, and hence a lot more time will be required to clear this ship. This discussion should convince the reader that the time taken to complete an inspection is necessarily a *random* variable. As such, we suppose that this random variable is exponentially distributed with mean $1/\beta$.

We now have all the essential components of our queuing models. We shall analyze two specific inspection regimes. In both regimes the arrival process of ships is Poisson with rate α and the inspection times are exponentially distributed with mean $1/\beta$. In the first inspection regime, there are I inspectors and the upper limit on the maximum number of ships in our port is U. In the second inspection regime, the number of inspectors and the upper limit on the maximum number of ships in our port coincide and they are both denoted by the positive integer I. Using the language of queuing theory, our first inspection regime is a $M/M/I/U$ model and our second inspection regime is a $M/M/I/I$ model. In this notation, the meaning of the first two $M's$ has already been explained in the last paragraph of section 2.1. In addition, from the above explanation, it should be clear that the I refers to the number of inspectors and the U refers to the finite capacity of our port. We now proceed to a formal discussion of our queuing theoretic approach to the biological invasion prevention problem.

3. The *M/M/I/U* Inspection Regime

3.1. The probabilistic essentials

Recall that our analysis of the prevention problem is being conducted from a long run perspective. As such, our first task is to determine the long run or stationary probabilities for our $M/M/I/U$ inspection regime. To this end, let $X(t)$ denote the number of ships in our port at an arbitrary time t. Further, let

$$P_k \equiv \lim_{t\to\infty} Prob\{X(t)=k\} \tag{1}$$

denote the stationary probability that there are exactly k ships in our port. We are interested in determining the $\{P_k\}$. However, before we do this, it is important to note two things. First, in the queuing models of this paper, P_k can also be interpreted as the proportion of *time* that the port system contains exactly k ships. Second, because the finite capacity of our port is U, the state space of this inspection regime can be indexed by k where $k=0,...,U$. In words, this means that when there are U ships in the port no additional ships will be permitted to enter this port.

To compute the $\{P_k\}$, note that because of the upper limit U on the maximum number of ships that may enter our port, the relevant arrival rate of ships is not α but

$$\alpha_k = \begin{cases} \alpha & if \ 0 \le k < U \\ 0 & if \ k \ge U. \end{cases} \tag{2}$$

Similarly, because of the presence of this finite capacity, the pertinent inspection rate is also not β but

$$\beta_k = \begin{cases} k\beta & if \ 0 \le k < I \\ I\beta & if \ I \le k \le U. \end{cases} \tag{3}$$

Now, the correct expression for P_k will depend on whether the actual number of ships in our port (indexed by k) satisfies the condition $(0 \le k < I)$ or the condition $(I \le k \le U)$. The first condition says that the actual number of ships is less than the total number of inspectors I and hence at any given point in time some inspectors are idle. The second condition says that the actual number of ships lies somewhere in between the total number of inspectors and the finite capacity of the port U. Now, the threat of a biological invasion is greatest in ports where there is a lot of ballast water that needs to be inspected. In turn, there will be a lot of ballast water when a number of ships with ballast water arrive at our port. In this case, the actual number of ships will, most likely, exceed the total number of inspectors and hence inspectors are unlikely to be idle. The upshot of this discussion is that given the subject matter of this paper, the more interesting and the more realistic of the two conditions is the condition $(I \leq k \leq U)$. Therefore, in the rest of this section, we suppose that the condition $(I \leq k \leq U)$ holds. Using this condition, equations (2)-(3), and equations 3.24 and 3.25 in Gross and Harris (1974, p. 105), we can tell that the required stationary probability P_k satisfies

$$P_k = \left(\frac{1}{I^{k-I} I!}\right)\left(\frac{\alpha}{\beta}\right)^k \left[\sum_{k=0}^{k=I-1} \frac{1}{k!}\left(\frac{\alpha}{\beta}\right)^k + \frac{(\alpha/\beta)^I}{I!}\left(\frac{1-\rho^{U-I+1}}{1-\rho}\right)\right]^{-1}, \; k = I, \ldots, U, \tag{4}$$

where $\rho = \alpha / I\beta$.[3] This completes our first main task.

The reader should note that the arrival of ships into our port does not result only in the arrival of potentially damaging biological invasions. Specifically, the loading and the unloading of cargo in our port constitutes economic activity driven by international trade between our port and ports in other nations. This trade driven economic activity clearly results in benefits to society and hence any reasonable analysis of the biological invasion prevention problem must account for this positive impact of economic activity on society. If we suppose that the volume of trade driven economic activity is proportional to the number of ships S in our port then the *expected* number of ships $E[S]$ can serve as a useful proxy for the magnitude of this trade driven economic activity. Consequently,

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We are assuming here that $\rho \neq 1$. If this condition does not hold then the expression for P_k in equation (4) would be a little different. For additional details, see Gross and Harris (1974, p. 105).

our next task is to determine $E[S]$ for our $M/M/I/U$ inspection regime.

The reader should note that the expectation $E[S]$ is actually the sum of two parts. The first part is the expected number of ships that are in queue, waiting to be inspected, and the second part is the expected inspection time. Using this fact and equations 3.26 and 3.27 in Gross and Harris (1974, pp. 106-107), we can infer that in our model $E[S]$ is given by

$$E[S]=\frac{P_0(I\rho)^I\rho}{I!(1-\rho)^2}[1-\rho^{U-I+1}-(1-\rho)(U-I+1)\rho^{U-I}]+I-P_0\sum_{k=0}^{k=I-1}\frac{(I-k)(\rho I)^k}{k!}, \qquad (5)$$

where $P_0=[\sum_{k=0}^{k=I-1}(1/k!)(\alpha/\beta)^k+\{(\alpha/\beta)^I/I!\}\{(1-\rho^{U-I+1})/(1-\rho)\}]^{-1}$.

This completes our discourse on the probabilistic essentials. We now follow Batabyal (1996) and first formulate and then discuss an optimization problem that describes the prevention problem confronting the manager of our publically owned port.

3.2. The optimization problem

Our port manager understands that the international trade driven economic activity in this port coupled with the need for inspections to keep out potentially deleterious biological organisms generates benefits and costs to society. Therefore, our port manager is interested in optimizing the net benefit to society and this net benefit is given by the benefit resulting from international trade driven economic activity less the cost of biological invasions.

Let us consider the benefits from economic activity first. Ships arrive in our port at the rate α. However, a certain proportion of these ships, i.e., those that arrive when there are U ships already in the port do not enter this port. Now, P_U is the proportion of time that our port is full. From this it follows that in a particular time period, say a month, entering ships in effect arrive at our port at the rate of $\alpha(1-P_U)$.[4] Let the per month benefit to society from the trade driven economic activity resulting from the arrival of the kth ship be $B_k = B_k(E[S], 1/\beta, t_k)$ where $E[S]$ is the expected number of ships in the port, $1/\beta$ is the average time taken by an inspector to inspect a ship, and t_k is the total tonnage of the goods being loaded and/or unloaded from the kth ship. Given this specification of the individual ship benefit function, we can see that the total benefit facing our port manager per month equals $\alpha(1-P_U) \sum_{k=1}^{k=\alpha(1-P_U)} B_k(E[S], 1/\beta, t_k)$.

Moving to the costs, we suppose that the per month cost of biological invasions depends on the expected number of ships in our port system $E[S]$ and on the number of inspectors I who are working in this port. As such, this per month total cost can be expressed as $C(E[S], I)$. The reader should note two features of our benefit and cost modeling thus far. In particular, although the benefit function depends on a system aggregate, i.e., on $E[S]$, it also depends on the individual ship arguments $1/\beta$ and t_k. In contrast, the cost of biological invasions depends entirely on the system aggregates $E[S]$ and I. This modeling strategy reflects our belief that whereas the benefits from economic activity depend on individual ship features *and* on system wide characteristics, the cost of biological invasions depends less on what is happening at the level of each arriving ship and more on what is happening in our port in the aggregate.

Now using the delineation of benefits and costs from the previous two paragraphs, we can state our publically owned port manager's optimization problem. This manager chooses the number of inspectors I to solve[5]

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Because the arrival rate of ships must be a positive integer, strictly speaking, we should say that ships arrive at the rate of the integer part of $\alpha(1-P_U)$. We suppose the reader understands this. As such, in the rest of this paper, we shall not focus on this detail.

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The reader will note that we are implicitly supposing that I can be treated as a continuous choice variable. Put differently, we are assuming that the optimal integer I can be approximated by the optimal continuous I. If this is not the case then integer

$$\max_{\{I\}}\alpha(1-P_U)\sum_{k=1}^{k=\alpha(1-P_U)} B_k(E[S],1/\beta,t_k)-C(E[S],I). \qquad (6)$$

subject to $I \geq 0$. Now, suppose that the solution to problem (6) yields an interior maximum. Then, omitting the complementary slackness condition, the Kuhn-Tucker condition for a maximum is

$$\alpha[(1-P_U)\Sigma_{\forall k}\frac{\partial B_k(\cdot)}{\partial E[S]}\frac{\partial E[S]}{\partial I}-\Sigma_{\forall k}B_k(\cdot)\frac{\partial P_U}{\partial I}]=\frac{\partial C(\cdot)}{\partial E[S]}\frac{\partial E[S]}{\partial I}+\frac{\partial C(\cdot)}{\partial I}. \qquad (7)$$

The optimal number of inspectors I^* solves equation (7) and this equation reveals the basic tradeoff confronting our port manager in a straightforward manner. Specifically, equation (7) tells us that in selecting the number of inspectors optimally, the port manager will balance the benefit from economic activity with the cost from biological invasions. In particular, equation (7) informs us that in choosing the number of inspectors optimally, our port manager will equate the marginal benefit from economic activities (the LHS) with the marginal cost of biological invasions (the RHS).

Examining the LHS of equation (7) in greater detail, we see that the marginal benefit from economic activities is actually the weighted difference of two terms. The weight on the first term $\alpha(1-P_U)\Sigma_{\forall k}\{\partial B_k(\cdot)/\partial E[S]\}\{\partial E[S]/\partial I\}$ is $\alpha(1-P_U)$, the *effective* arrival rate of ships in our port. Further, this first term captures the *indirect* impact that the optimal number of inspectors has on the marginal benefit through the $E[S]$ variable, i.e., the expected number of ships in our port. The weight on the second term $\alpha\Sigma_{\forall k}B_k(\cdot)\{\partial P_U/\partial I\}$ is α, the arrival rate of ships not accounting for the fact that there is an upper limit on the number of ships that our port can accommodate at a specific point in

programming techniques will have to be used to determine the optimal number of inspectors. For more on integer programming, see Wolsey (1998).

time. This second term captures the *direct* effect that the optimal number of inspectors has on the marginal benefit through the stationary probability P_U that there are a maximum of U ships with ballast water in the port under study.

Unlike the expression for the marginal benefit, the marginal cost of biological invasions is the *sum* of two terms. The first term $\{\partial C(\cdot)/\partial E[S]\}\{\partial E[S]/\partial I\}$ captures the *indirect* effect that the optimal number of inspectors has on the marginal cost through the $E[S]$ variable, i.e., the expected number of ships in our port. The second term $\{\partial C(\cdot)/\partial I\}$ accounts for the *direct* impact that the optimal number of inspectors has on the marginal cost of biological invasions. Since equation (7) cannot, in general, be solved analytically, one will have to resort to numerical methods to obtain the optimal number of inspectors I^*. We now proceed to discuss the second of our two inspection regimes.

4. The *M/M/I/I* Inspection Regime

4.1. The probabilistic essentials

Unlike the $M/M/I/U$ inspection regime, in the regime of this section, the number of inspectors in the port is equal to the maximum number of ships that this port can accommodate. In symbols $I=U.$ Now given that our analysis is being conducted from a long run perspective, our immediate task is to compute the stationary probabilities $\{P_k\}$—given by equation (1)—for this $M/M/I/I$ inspection regime. Before we calculate the $\{P_k\}$, observe that in this section the condition $(0 \le k \le I)$ applies. This condition tells us that the actual number of ships in our port is less than or equal to the total number of inspectors I and hence at any given point in time it is possible that some inspectors are idle. The reader will note that because $I=U,$ it makes sense now to work with this condition $(0 \le k \le I)$ and not the condition $(I \le k \le U)$ of the previous section. Now, using equation 3.31 in Gross and Harris (1974,

p. 109), we infer that the long run probability P_k we seek is given by

$$P_k = \frac{(\alpha/\beta)^k/k!}{\sum_{j=0}^{j=I} (\alpha/\beta)^j/j!}, \quad k=0,\ldots,I. \tag{8}$$

This completes our first primary task.

As in section 3, the loading and the unloading of cargo in our port represents economic activity driven by international trade between our port and ports in other countries. This trade driven economic activity obviously results in benefits to society and hence we shall account for these benefits in our analysis. To this end, we assume that the *expected* number of ships $E[S]$ is a useful proxy for the magnitude of this trade driven economic activity. As such, our next task is to ascertain $E[S]$ for the $M/M/I/I$ inspection regime. To obtain the relevant $E[S]$, let us substitute $I=U$ in equation (5) and then simplify the resulting expression. This gives us

$$E[S] = I - P_0 \sum_{k=0}^{k=I-1} \frac{(I-k)(\rho I)^k}{k!}, \tag{9}$$

where $P_0 = [\sum_{k=0}^{k=I-1} (1/k!)(\alpha/\beta)^k + \{(\alpha/\beta)^I/I!\}]^{-1}$.

This completes our discussion of the probabilistic essentials. We now formulate and then discuss an optimization problem that characterizes the prevention problem facing the manager of our publically owned port.

4.2. The optimization problem

Our port manager is aware of the fact that the international trade driven economic activity in this port combined with the need for inspections to keep out possibly injurious biological organisms results in benefits and costs to society. As such, this port manager is interested in maximizing the net benefit to society and this net benefit is given by the benefit resulting from international trade driven economic activity less the cost of biological invasions.

Let us consider the benefits from economic activity first. Following the discussion in section 3.2, the gross benefit facing our port manager per month is $\alpha(1-P_I)\sum_{k=1}^{k=\alpha(1-P_I)} B_k(E[S],1/\beta,t_k)$, where the arguments of this benefit function are as in section 3.2. The reader will note that this benefit function is different from the benefit function of the $M/M/I/U$ inspection regime of section 3 in three ways. First, the effective arrival rate is $\alpha(1-P_I)$ and not $\alpha(1-P_U)$. Second, the upper limit of the summation now is $\alpha(1-P_I)$ and not $\alpha(1-P_U)$. Finally, as equations (5) and (9) tell us, the expression for the $E[S]$ argument in the above benefit function is not the same as the corresponding expression for the section 3.2 benefit function.

As far as the costs are concerned, we follow the logic of section 3.2 and suppose that the per month cost of biological invasions is a function of the expected number of ships in our port $E[S]$ and the number of inspectors I who are working in this port. Therefore, this per month cost is $C(E[S],I)$. Comparing this cost function with the cost function of the $M/M/I/U$ inspection regime we see that there is one key difference and this difference arises because the expressions for the $E[S]$ argument in these two functions are dissimilar (see equations (5) and (9)). As in section 3.2, we see that the benefit function depends not only on a system aggregate $E[S]$, but also on the individual ship arguments $1/\beta$ and t_k. In contrast, the cost of biological invasions is a function of the system aggregates $E[S]$ and I. This modeling strategy reflects our contention that whereas the benefits from economic activity depend on individual ship attributes *and* on system wide characteristics, the cost of biological invasions depends less on what is occurring at the level of each arriving ship and more on what is occurring in our port in the aggregate.

Keeping this discussion in mind, we can now state our publically owned port manager's maximization problem. This manager chooses the number of inspectors I to solve (also see footnote 8)

$$\max_{\{I\}} \alpha(1-P_I) \sum_{k=1}^{k=\alpha(1-P_I)} B_k(E[S],1/\beta,t_k) - C(E[S],I). \tag{10}$$

subject to $I \geq 0$. Note that $E[S]$ in this maximand is now given not by equation (5) but instead by equation (9). Suppose that the solution to problem (10) yields an interior maximum. Then, excluding the complementary slackness condition, the Kuhn-Tucker condition for a maximum is

$$\alpha[(1-P_I)\Sigma_{\forall k}\frac{\partial B_k(\cdot)}{\partial E[S]}\frac{\partial E[S]}{\partial I} - \Sigma_{\forall k}B_k(\cdot)\frac{\partial P_I}{\partial I}] = \frac{\partial C(\cdot)}{\partial E[S]}\frac{\partial E[S]}{\partial I} + \frac{\partial C(\cdot)}{\partial I}. \tag{11}$$

The maximal number of inspectors I^* solves equation (11) and this equation demonstrates the essential tradeoff confronting our port manager in a simple way. Specifically, equation (11) tells us that in choosing the number of inspectors optimally, the port manager will compare the benefit from economic activity with the cost from biological invasions. In particular, equation (11) informs us that in selecting the number of inspectors optimally, our port manager will equate the marginal benefit from economic activities (the LHS) with the marginal cost of biological invasions (the RHS).

As in section 3.2, the marginal benefit from economic activities is given by the weighted difference of two terms. The weight on the first term is $\alpha(1-P_I)$ and this weight is the *effective* arrival rate of ships in our port. This first term $\alpha(1-P_I)\Sigma_{\forall k}\{\partial B_k(\cdot)/\partial E[S]\}\{\partial E[S]/\partial I\}$ captures the *indirect* impact that the optimal number of inspectors I^* has on the marginal benefit through the expected number of ships in our port. The weight on the second term is α, the arrival rate of ships not accounting for the fact that there is an upper limit I on the number of ships that our port can accommodate at a specific point in time. This second term $\alpha\Sigma_{\forall k}B_k(\cdot)\{\partial P_I/\partial I\}$ captures the *direct* effect that the optimal number of inspectors has on the marginal benefit through the long run probability P_I that there are a maximum of I ships with ballast water in the port under study. We now compare and contrast the optimality conditions emanating from our analysis of the $M/M/I/U$ and the $M/M/I/I$ inspection regimes.

5. Inspection Regimes: *M/M/I/U* versus *M/M/I/I*

Comparing the optimality conditions (equations (7) and (11)) for the two inspection regimes that we are studying in this paper, we see that there are three essential differences. First, because $U \neq I$ in section 3.2 and $U = I$ in this section, equation (7) reflects the fact that ships in excess of the number of inspectors will be allowed into our port as long as the number of ships does not exceed the upper limit U. In contrast, equation (11) reflects the fact that once the number of ships equals the number of inspectors, no further ships will be allowed into the port under study. Put differently, there will be a queue of ships with ballast water in the $M/M/I/U$ inspection regime but there will be no such queue in the $M/M/I/I$ inspection regime.

Second, the existence and the non-existence of a queue in the two inspection regimes that we are studying has an implication for the effective rate at which ships with ballast water arrive at our port. The effective arrival rate in equation (7) is $\alpha(1-P_U)$ and the effective arrival rate in equation (11) is $\alpha(1-P_I)$. A comparison of equations (4) and (8) does not reveal any necessary general result about the relative magnitudes of the two long run probabilities P_U and P_I. Therefore, we cannot say for sure whether the equation (7) effective arrival rate is bigger or smaller than the equation (11) effective arrival rate. This notwithstanding, what we can say with some assurance is that because these two effective arrival rates are dissimilar, the marginal benefit (the LHSs) in the two optimality conditions (equations (7) and (11)) will generally be different. This in turn means that the marginal cost (the RHSs) in these two optimality equations will also be different, and hence, the optimal number of inspectors in the two inspection regimes being studied will be distinct.

Finally, inspection of equations (5) and (9) tells us that the expected number of ships in our port in the $M/M/I/U$ inspection regime will generally be greater than the expected number of ships in our port in the $M/M/I/I$ inspection regime. The general dissimilarity of these two expectations leads to three conclusions. First, the indirect impact that the optimal number of inspectors has on both the marginal benefit and the marginal cost in the two optimality conditions (equations (7) and (11)) will be distinct. Second, this means that the solutions to the two optimality conditions will also be distinct. In other words, consistent with the discussion in the previous paragraph, the optimal number of inspectors in the two regimes that we are studying will not be the same. Third, the volume of economic activity and hence the likelihood of a biological invasion will be greater in the $M/M/I/U$ inspection regime and lesser in the $M/M/I/I$ inspection regime.

6. Conclusions

In this paper we developed what we believe is a new framework for studying the problem of preventing biological invasions caused by ships transporting internationally traded goods between countries and continents. This new framework allowed us to study the problem of preventing a biological invasion from a long run perspective. Specifically, we first characterized two simple regulatory regimes as two different kinds of queues. We then showed how a publically owned port manager's decision problem can be posed and analyzed as an optimization problem using queuing theoretic techniques. Finally, we compared and contrasted the optimality conditions arising from our examination of the $M/M/I/U$ and the $M/M/I/I$ inspection regimes.

The analysis contained in this paper can be extended in a number of directions. In what follows, we suggest two possible extensions of this paper's research. First, the reader will note that we analyzed Markovian inspection regimes in this paper. As such, it would be useful to investigate the properties of more general inspection regimes in which either the arrival of ships or the service times of inspectors are characterized by general distribution functions. Second, on the numerical front, it would be useful to compare the approach of this paper—in which the optimal number of inspectors choice problem is viewed as a continuous choice problem—with an alternate approach in which this choice problem is cast as an integer programming problem. Studies of international trade driven biological invasions that incorporate these aspects of the prevention problem into the analysis will provide additional insights into a phenomenon that has frequently proved to be very costly for the involved parties.

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