Maritime Trade, Biological Invasions, and the Properties of Alternate Inspection Regimes[1]

by

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Abstract

We analyze the problem of preventing biological invasions caused by ships transporting internationally traded goods between countries and continents. Specifically, we ask the following question: Should a port manager have a small number of inspectors inspect arriving ships less stringently or should this manager have a large number of inspectors inspect the same ships more stringently? We use a simple queuing-theoretic framework and show that if decreasing the economic cost of regulation is very important then it makes more sense for the port manager to choose the less stringent inspection regime. In contrast, if reducing the damage from biological invasions is more salient then the port manager ought to pick the more stringent inspection regime.

Keywords: Biological Invasion, Inspection, Maritime Trade, Queuing Theory, Uncertainty

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1. Introduction

Maritime trade accounts for a significant proportion of total international trade in the world. Ships are the key vehicle in maritime trade and, today, ships are commonly used to transport a whole host of goods between different countries. It is certainly true that international trade in goods is beneficial to the nations involved in such trade. This notwithstanding, as Heywood (1995) and Parker *et al.* (1999) have pointed out, in addition to transporting goods between countries, ships have also managed to transport—in their ballast water—a variety of alien plant and animal species from one geographical region to another.[5] These alien species have frequently succeeded in invading their new habitats and the ensuing biological invasions have turned out to be extremely costly to the nations in which these novel habitats are located. For the United States alone, the dollar value of these costs is staggering. Here are two examples. First, the Office of Technology Assessment (OTA (1993)) has estimated that the Russian wheat aphid caused $600 million worth of crop damage between 1987 and 1989. Second and more generally, Pimentel *et al.* (2000) have approximated the total costs of all non-native species at around $137 billion per year.

5

As Batabyal and Beladi (2004) have noted, the primary method of marine alien species introduction is through the dumping of ballast water. Cargo ships generally carry ballast water in order to increase vessel 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. Consider the case of Canada. 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 analysis by the Smithsonian Environmental Research Center (SERC) in Edgewater, Maryland computed that a liter of ballast water generally contains several billion organisms similar to viruses and up to 800 million bacteria. Two web sites that provide useful information on these issues are http://www.fundyforum.com/profile_archives and www.serc.si.edu

As noted by Perrault and Muffett (2002) and Settle and Shogren (2004), invasive species give rise to economic costs and to biological damage. For instance, Vitousek *et al.* (1996) have shown that alien species can change ecosystem processes, act as vectors of diseases, and decrease biological diversity. Further, Cox (1993) has pointed out that out of 256 vertebrate extinctions with a known cause, 109 are the result of biological invasions. In other words, biological invasions have often been a great threat to society.

Although social scientists have, very recently, recognized the salience of the problem of biological invasions, it is still true that "the economics of the problem has...attracted little attention" (Perrings *et al.* (2000, p. 11)). Consequently, our knowledge of the economics of biological invasions in general and the regulation of biological invasions in particular is very incomplete. Now, from a regulatory standpoint, there are several actions that a regulator can take to grapple with the problem of biological invasions. Following Batabyal and Beladi (2004), it is helpful to separate these actions into pre-invasion and post-invasion actions. The point of taking pre-invasion actions is to prevent alien species from invading a novel habitat. Therefore, the reader should think of *pre-invasion* actions as essentially *preventive* in nature. In contrast, post-invasion actions involve the optimal control of an alien species, given that this species has already invaded a novel habitat.

The small extant literature on the economics of biological invasions has, for the most part, addressed the desirability of actions in the *post-invasion* scenario. Here are four examples of such studies. First, Barbier (2001) has shown that the economic effect of a biological invasion can be ascertained by analyzing the nature of the interaction between the alien and the native species. He points out that the economic effect depends on whether this interaction involves interspecific competition or dispersion. Second, Eiswerth and Johnson (2002) have analyzed an intertemporal model of alien species stock management. They demonstrate that the optimal level of management effort is responsive to ecological factors that are not only species and site specific but also random. Third, Olson and Roy (2002) have used a probabilistic framework to investigate the conditions under which it is optimal to wipe out the alien species and conditions under which it is not optimal to do so. Finally, Eiswerth and van Kooten (2002) have shown that in some situations, it is possible to use information furnished by experts to develop a model in which it is optimal to not decimate but instead control the spread of an invasive species.

To the best of our knowledge, only two papers have theoretically studied the prevention problem, that is, the regulation of a potentially damaging alien species before invasion. These two papers are Horan *et al.* (2002) and Batabyal and Beladi (2004). There are two key differences between our paper and Horan *et al.* (2002). First, we do not compare the attributes of management strategies under full information and under uncertainty. Second, we use a simple queuing-theoretic framework to shed light on the properties of two inspection regimes that embody different ideas about the economic cost from regulatory activities.

Batabyal and Beladi (2004) is the paper that is most closely related to ours. This paper studies optimization problems arising from the steady state analysis of two multi-person inspection regimes. Although this paper does say something about alternate inspection regimes, it does not address the following cental question that we analyze in the present paper: When attempting to prevent a biological invasion by inspecting the ballast water of ships, is it a better idea for a port manager to have a *small* number of inspectors inspect arriving ships *less* stringently or should this manager have a *large* number of inspectors inspect the same arriving ships *more* stringently? We use a simple queuing-theoretic framework to show that the answer to the above question depends on the port manager's criterion function. In particular, we focus on two different criteria and show that in one case it makes more sense to have a small number of inspectors inspect arriving ships less stringently and in the other case it is more advantageous to have a large number of inspectors inspect arriving ships more stringently. The reader should note that the basic question that we are addressing in this paper is entirely consistent with the agenda for research on the regulation of invasive species recently proposed by Batabyal (2004).

The rest of this paper is organized as follows. Section 2 first provides a primer on queuing theory and then it describes the two queuing-theoretic models that we use to analyze the choice of inspection regime question facing our port manager. Section 3 first focuses on the "average wait of a ship in the port system" or *AWS* criterion for our port manager and then this section analyzes the relative desirability of the two queuing-theoretic inspection regimes described in section 2. Section 4 first focuses on the "average wait of a ship in queue" or *AWQ* criterion for our port manager and then this section undertakes the same analysis as in section 3. Section 5 concludes and offers suggestions for future research on the subject of this paper.

2. Queuing Theory and the Choice of Inspection Regime

2.1. A primer on queuing theory

The purpose of queuing theory is to mathematically analyze waiting lines or queues.[6] At an elementary level, all queuing models have three attributes. Specifically, they can be delineated by (i) a random arrival process, (ii) a probabilistic service time distribution function, and (iii) the deterministic number of available servers. In the queuing models of this paper, the arrival process is

6

Wolff (1989), Taylor and Karlin (1998), and Ross (2003) contain fine textbook accounts of queuing theory.

the Poisson process. In this case, the times between successive arrivals are exponentially distributed and the exponential distribution is memoryless. Therefore, the Poisson arrival process is routinely described by the letter M.

The service times are obviously random and hence these times can, in principle, be arbitrarily distributed. However, in the queuing models of this paper, these services times are exponentially distributed and hence they are also memoryless. Hence, once again, the letter M is used to symbolize the service time distribution functions. Finally, the non-stochastic number of servers is typically denoted by some positive integer.

Now, consistent with the approach taken in Batabyal (2004) and Batabyal and Beladi (2004), the first inspection regime that we analyze corresponds to the $M/M/1$ queuing model and the second inspection regime that we study corresponds to the $M/M/2$ queuing model. The reader should note that in both these tripartite representations, we are referring to inspection regimes in which the arrival process of ships is Poisson, the time it takes to inspect a ship is exponentially distributed, and the number of inspectors equals either one or two.[7]

2.2. A stylized depiction of biological invasions

Consider a stylized, publically owned port in a particular coastal region of some country. Ships with ballast water arrive at this port to load cargo and to then carry this cargo to some other port. On occasion, 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 possibly injurious biological organisms. We assume that the arrival

[7] It should be noted that different modeling techniques involve different cross space and time variation features for the underlying physical processes and the associated uncertainties.

rate of these biological organisms is proportional to the arrival rate of the ships. As such, we shall not model these biological organisms directly. Instead, we shall focus on the ships that bring these organisms to our port by means of their ballast water. The arrival process of the ships in our port represents the arrival process for the queuing-theoretic inspection regimes that we analyze in this paper. Now, consistent with the discussion in the last paragraph of section 2.1, we assume that the ships in question arrive at our port in accordance with a Poisson process with rate β.

The manager of our port is interested in precluding invasions by the possibly injurious biological organisms. Therefore, arriving ships must be inspected before they can either load or unload cargo. In the first model that we analyze, our port has a single inspector and in the second model that we focus on, our port has two inspectors. This means that at any particular point in time, our port will be able to simultaneously inspect either one or two ships. Ships are inspected on a first-come-first-served basis. If more than one or two ships arrive at our port during a particular time interval then the ships that are not already being inspected must wait in queue. The reader should think of this description as follows: Our port has either one or two docks and one inspector is assigned to a dock. Hence, at any particular point in time, a maximum of either one or two ships can be docked and inspected. The port system consists of ships that are being inspected, ships that are waiting in queue, the one or two inspectors, and the port manager.

Given that we are studying the prevention of biological invasions, ideally, our port manager would like the inspectors to have a zero tolerance policy. However, such a policy may be very costly to implement. As such, we suppose that our port manager is confronted with a choice between two scenarios. In the first scenario, the manager has one inspector inspect the ballast water of arriving ships not very stringently. In the second scenario, this manager has two inspectors inspect the ballast water of arriving ships more stringently. Examples of activities that an inspector might undertake 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.

Inspections generally require varying amounts of time. For example, if an inspector knows that a particular ship has taken on ballast water in an area where there are no known biological invaders then he may be able to clear a ship relatively speedily. In contrast, if a specific ship has taken on ballast water during a phytoplankton bloom, then the probability that this ship's ballast water will contain injurious organisms is much higher, and hence more time will be required to clear this ship. The upshot of this discussion is that the inspection times—and hence the stringency of inspections—are *random* variables. Given this state of affairs, we now make the following two assumptions regarding the stringency of inspections. In the first scenario of the previous paragraph, our single inspector inspects arriving ships at rate 2γ, where γ is a positive constant. In the second scenario of the previous paragraph, the two inspectors inspect arriving ships at rate γ. A faster rate of inspection implies lower stringency and a slower rate of inspection implies higher stringency. Therefore, the inspection regime of the first scenario is *less* stringent than the inspection regime of the second scenario because $2\gamma > \gamma$.

We now have all the necessary parts of our two queuing-theoretic inspection regimes. Using the language of queuing theory, the first or less stringent inspection regime is a $M/M/1$ model with inspection rate 2γ and the second or more stringent inspection regime is a $M/M/2$ model with inspection rate γ. The reader should note the way in which we have mathematically characterized the cental question of this paper: When attempting to prevent a biological invasion by inspecting the ballast water of ships, is it a better idea for a port manager to have a single inspector inspecting arriving ships at rate 2γ or should this manager have two inspectors inspecting the same ships at rate γ?

We now proceed to the theoretical discussion of the two queuing-theoretic inspection regimes for the case in which our port manager focuses on the "average wait of a ship in the port system" or *AWS* criterion.

3. The *AWS* Criterion

Inspection activities that result in the prevention of a biological invasion by alien plant or animal species clearly result in benefits to the citizens of the coastal region under consideration. However, during the time that arriving ships are being inspected, there is in particular no loading or unloading of cargo, and hence in general, economic activity resulting from maritime trade is at a standstill. This temporary stoppage of economic activities imposes costs on the economy of our coastal region and one way to proxy this cost is to suppose that this cost is directly proportional to the average wait of a ship in the port system. In this way of looking at the problem, the longer (shorter) this average wait in the port system or *AWS*, the larger (smaller) the costs from the suspension of economic activities. Therefore, in having inspectors inspect arriving ships for potentially injurious biological organisms, our port manager will want to keep *AWS* as low as possible. Now, in the rest of this section, we suppose that our port manager has this *AWS* (proxy for economic cost) criterion in mind when he is choosing between the less stringent and the more stringent inspection regimes.

3.1. M/M/2 inspection regime

Let us now calculate *AWS* for the $M/M/2$ inspection regime with inspection rate γ. We proceed by means of three steps. First, we explain the notion of a stationary probability. To this end, let $Z(t)$ denote the total number of ships in our port at time t. Then, we define P_n, $n \geq 0$ to be

$$P_n \equiv \lim_{t \to \infty} Prob\{Z(t)=n\}. \qquad (1)$$

In words, P_n is the long run or stationary probability that there are exactly n ships in our port system.

The second step requires us to set up and solve the so called balance equations. Now, following the procedure described in Ross (2003, pp. 480-483), the specific balance equations we seek are

$$\beta P_0 = \gamma P_1, \tag{2}$$

$$(\beta+\gamma)P_1 = \beta P_0 + 2\gamma P_2, \tag{3}$$

and

$$(\beta+2\gamma)P_n = \beta P_{n-1} + 2\gamma P_{n+1}, \ n \geq 2. \tag{4}$$

Let $\psi = \beta/\gamma$. Then, following the above cited procedure, it can be shown that the solutions to the balance equations (2)-(4) are $P_n = \psi^n / 2^{n-1} P_0$. In words, the stationary or long run or limiting probability that there are n ships in our port system is a multiplicative function of the stationary probability that there are zero ships in this port system. Now, it should be clear to the reader that $\sum_{n=0}^{n=\infty} P_n = 1$. This last condition tells us that

$$P_0 = \frac{1-\psi/2}{1+\psi/2} = \frac{2-\psi}{2+\psi}. \tag{5}$$

Note that equation (5) above only makes sense when $2 \geq \psi$. Because $\psi = \beta/\gamma$, this means that we must have $2\gamma \geq \beta$.

Third, now that we know the P_n, we can calculate the average number of ships in our port system S. From Ross (2003, p. 483), we infer that $S = \sum_{n=0}^{n=\infty} n P_n$. Using this expression and then simplifying, we get

$$S = \frac{4\beta\gamma}{(2\gamma+\beta)(2\gamma-\beta)}. \tag{6}$$

Now, having determined the expected number of ships in our port system, we can ascertain the average wait of a ship in our port system or AWS by using a well known result in queuing theory. This result—see Taylor and Karlin (1998, p. 542)—tells us that $AWS=S/\beta$.[8] Using this last finding, we get

$$AWS_{M/M/2}=\frac{4\gamma}{(2\gamma+\beta)(2\gamma-\beta)}. \tag{7}$$

This completes our three step derivation of the AWS criterion for the $M/M/2$ inspection regime. We now derive the same criterion for the $M/M/1$ inspection regime.

3.2. M/M/1 inspection regime

The derivation of the AWS criterion for the $M/M/1$ inspection regime is considerably simpler. In particular, to obtain the criterion we seek, we shall modify a result stated in Taylor and Karlin (1998, p. 551). This gives us

$$AWS_{M/M/1}=\frac{1}{2\gamma-\beta}. \tag{8}$$

Given equations (7) and (8), we now proceed to discuss the central question of this paper for the AWS criterion.

3.3. Discussion

When seeking to prevent a biological invasion by inspecting the ballast water of ships, is it a better idea for a port manager to have a *small* number of inspectors inspect arriving ships *less*

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8 This result is important because it relates two important metrics in queuing models, i.e., the average queue size and the average customer waiting time in the stationary state. In the context of our paper, the average queue size is the average number of ships in our port system and the average customer waiting time is our *AWS* criterion.

stringently or should this manager have a *large* number of inspectors inspect the same arriving ships *more* stringently? Our model of a small number of inspectors inspecting arriving ships less stringently is the $M/M/1$ regime with inspection rate 2γ. Similarly, our model of a large number of inspectors inspecting arriving ships more stringently is the $M/M/2$ regime with inspection rate γ. Consequently, we are now in a position to answer the above question for the AWS criterion.

Let us suppose that for the $M/M/1$ inspection regime, the condition $\beta<2\gamma$ holds. That is, the denominator of the right-hand-side (RHS) of equation (8) is positive. In words, this simply means that our queuing-theoretic inspection regime is stable. Now, $\beta<2\gamma$ implies that $\beta+2\gamma<4\gamma$ and this inequality tells us that $1<\{4\gamma/(\beta+2\gamma)\}$. This last inequality and equations (7) and (8) together tell us that $AWS_{M/M/1}<AWS_{M/M/2}$. Hence, we can now state

PROPOSITION 1: AWS is lower when our port manager chooses a small number of inspectors to inspect arriving ships less stringently.

Note that if one finds the queue empty in the $M/M/2$ inspection regime then it would not be beneficial to have two inspectors. Instead, one would always be better off with one faster (less stringent) inspector. This is the intuitive explanation for the Proposition 1 result that AWS is lower when our port manager selects a small number of inspectors to inspect arriving ships less stringently. In addition, the reader should note that the result contained in Proposition 1 is not based on general distribution functions for either the interarrival times or the inspection times. Instead, this result is based on Markovian distribution functions for the interarrival and the inspection times. A justification for the use of these distribution functions has been given in section 2.1.

Given the significance of the problem of biological invasions, it is perhaps intuitively plausible that our port manager ought to choose the inspection regime involving more stringent inspections and a larger number of inspectors, i.e., the $M/M/2$ inspection regime with inspection rate γ. However, using a larger number of more stringent inspectors imposes costs in the sense that the $M/M/2$ regime stops all economic activity in our port for a relatively long period of time. We modeled these costs by supposing that our port manager wishes to make the *AWS* criterion as small as possible. Our analysis thus far shows that there is a tension between *AWS* minimization and inspection stringency and that tension is this: If greater inspection stringency with a large number of inspectors is desired, then economic costs measured by the *AWS* criterion will be relatively high. Conversely, if our port manager is willing to live with less stringent inspections with a smaller number of inspectors, then *AWS* will be relatively low. We now consider the choice of inspection regime question for an alternate criterion function for our port manager.

4. The *AWQ* Criterion

We have already noted that the temporary stoppage of economic activities in our port imposes costs on the economy of our coastal region. However, the *AWS* criterion is not the only criterion that we can use in thinking about these costs. Suppose we adopt a somewhat looser interpretation of these costs and say that the loading and unloading of cargo may proceed on a ship that is currently being inspected but that such activities may not take place on ships that have yet to be inspected, i.e., those that are still in queue. In this way of looking at the problem, only ships that are in *queue* impose economic costs. We shall refer to this looser criterion as the "average wait of a ship in queue" or *AWQ* criterion. The reader will note that in this looser interpretation of costs, once inspection on a particular ship has commenced, there is a presumption of innocence rather than guilt. The basic question before us now is this: Does the section 3 answer to our port manager's inspection regime choice question change when we adopt the *AWQ* criterion? We now answer this question.

4.1. M/M/2 inspection regime

To compute AWQ for the $M/M/2$ inspection regime with rate γ, we begin by noting that $AWQ_{M/M/2}=AWS_{M/M/2}-1/\gamma$. Using this expression along with equation (7), it is easy to see that

$$AWQ_{M/M/2}=\frac{\beta^2}{\gamma(2\gamma+\beta)(2\gamma-\beta)}. \tag{9}$$

We now derive AWQ for the $M/M/1$ inspection regime with inspection rate 2γ.

4.2. M/M/1 inspection regime

In this case, the corresponding relationship between $AWQ_{M/M/1}$ and $AWS_{M/M/1}$ is that $AWQ_{M/M/1}=AWS_{M/M/1}-1/2\gamma$. Using this expression and equation (8) together, we conclude that

$$AWQ_{M/M/1}=\frac{\beta}{2\gamma(2\gamma-\beta)}. \tag{10}$$

Given equations (9) and (10), we are now in a position to discuss the central question of this paper for the AWQ criterion.

4.3. Discussion

To determine whether the section 3 answer to the choice of inspection regime question changes, we have to compare the RHSs of equations (9) and (10). Doing this, it is clear that

$$AWQ_{M/M/1}>AWQ_{M/M/2}\Leftrightarrow\frac{1}{2}>\frac{\beta}{2\gamma+\beta}\Leftrightarrow 2\gamma>\beta. \tag{11}$$

We now invoke the section 3.3 assumption about the stability of the $M/M/1$ inspection regime. Recall that this stability assumption is that the condition $2\gamma > \beta$ holds. Using this stability assumption along with equation (11), it is clear that $AWQ_{M/M/1} > AWQ_{M/M/2}$. Therefore, we can now state

PROPOSITION 2: AWQ is lower when our port manager selects a large number of inspectors to inspect arriving ships more stringently.

Given the salience of the problem of biological invasions, it makes intuitive sense that our port manager ought to select the inspection regime with more stringent inspections and a larger number of inspectors, i.e., the $M/M/2$ regime with inspection rate γ. Proposition 2 tells us that this intuitive line of reasoning is correct when the port manager focuses on the AWQ criterion. Proposition 2 also tells us that the section 3 answer to the choice of inspection regime question *does change* when our port manager focuses on the AWQ criterion. This means that whether it is better to have a small number of inspectors inspect arriving ships less stringently or have a large number of inspectors inspect the same arriving ships more stringently depends on which economic cost criterion our port manager adopts.

More generally, there is a tension between economic cost reduction on the one hand and biological damage control on the other. If total economic cost reduction is very important then the port manager will focus on the stronger AWS criterion and this focus means that the chosen inspection regime will be relatively less stringent. In contrast, if biological damage control is very important, then our port manager will select the more stringent $M/M/2$ regime and, as we have just seen, this selection is optimal only when the manager concentrates on the weaker AWQ criterion.

5. Conclusions

Maritime trade in goods by means of ships often results in injurious invasions of new habitats by alien plant and animal species. Consequently, if an appropriate authority such as a port manager's objective is to prevent biological invasions, then this manager must inspect arriving ships for potentially deleterious biological organisms. Given this state of affairs, what kind of inspection regime should this manager have in place? In particular, is it a better idea for this manager to have a *small* number of inspectors inspect arriving ships *less* stringently or should this manager have a *large* number of inspectors inspect the same ships *more* stringently? Our analysis shows that if decreasing economic cost is significant then it makes more sense for the port manager to choose the inspection regime with fewer inspectors and less stringent inspections. On the other hand, if reducing the damage from biological invasions is more salient then the manager ought to pick the inspection regime with more inspectors and more stringent inspections.

The analysis in this paper can be extended in a number of directions. In what follows, we propose two potential extensions of this paper's research. First, we analyzed the inspection regime choice question in a very simple manner. Therefore, it would be instructive to study the properties of $M/M/m$ and $M/M/n$ inspection models where m and n are positive integers, $m<n$, and the inspection rates in the two models are different. Second, it would also be useful to eschew the assumption that the inspection times are exponentially distributed and examine more general $M/G/m$ and $M/G/n$ inspection models where G denotes a general distribution function. Studies of maritime trade driven biological invasions that incorporate these aspects of the inspection regime choice question into the analysis will provide additional insights into a problem that has considerable economic and biological ramifications.

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