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An Analysis of Economic Cost Minimization and Biological Invasion Damage Control Using the *AWQ* Criterion[1]

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Abstract

DeAngelo *et al*. (2006) have recently used the *AWS* criterion in a $M/G/1$ queuing model to show that there is *no* necessary tension between economic cost minimization and inspection stringency in non-native species management. In this paper, we use an alternate cost criterion (*AWQ* criterion) to investigate the generality of this central result in DeAngelo *et al*. (2006). Our theoretical analysis shows that there is no unambiguous answer to this question. Therefore, we use numerical methods and our numerical analysis leads to two findings. First, for many values of the model parameters that describe the strictness of inspections, there *is* a tension between cost minimization and inspection stringency. Second, for most values of the model parameter that depicts the volume of maritime trade handled by the seaport under consideration, there is *no* tension between cost minimization and inspection stringency.

Keywords: *AWQ* Criterion, Inspection, Invasive Species, Maritime Trade, Queuing Theory

JEL Codes: Q58, L51, D81

1. Introduction

In modern times, airplanes, ships, and trucks have all been used to carry goods from one region of the world to another. Representative textbooks in international trade such as Feenstra (2004) and Krugman and Obstfeld (2005) tell us that unrestricted trade between different regions of the world is welfare improving. This notwithstanding, researchers in both the life and the social sciences have increasingly pointed out that the extent of these welfare improvements is likely to be less than what most investigators have hitherto posited. Why? As Parker *et al.* (1999), Batabyal (2004), and Work *et al.* (2005) have noted, this is because in addition to carrying goods between regions, airplanes, ships, and trucks have also managed to carry a whole host of non-native plant and animal species (also known as alien or invasive species) from one geographical region of the world to another.

There are many ways in which airplanes, ships, and trucks have transported non-native plant and animal species from one region of the world to another. Non-native animal species have sometimes succeeded in lodging themselves in the landing gear of airplanes and in this way they have traveled as stowaways from one nation to another. Similarly, a number of marine non-native species have been introduced unintentionally into a region by ships dumping their ballast water. Cargo ships commonly carry ballast water in order to augment vessel stability when they are not carrying full loads. When these ships come into a seaport, this ballast water must be released before cargo can be loaded. This means of species introductions is important and very recently the problem of managing alien species that have been introduced into a particular region by means of the dumping of ballast

water has received some attention in the literature.[5]

Ships routinely use containers to carry cargo from one nation to another and these containers are often the source for the introduction of one or more non-native species. Such introductions take place because non-native species can remain hidden in containers for long periods of time. In addition, substances such as wood—often used to pack cargo in containers—may themselves contain non-native species. In fact, as noted by Batabyal and Nijkamp (2005), a joint report from the United States Department of Agriculture (USDA), the Animal and Plant Health Inspection Service (APHIS), and the United States Forest Service (USFS) has shown that nearly 51.8% of maritime shipments contain solid wood packing substances and that infection rates for solid wood packing substances are non-trivial (USDA, APHIS, and USFS (2000, p. 25)). To see this, consider the following case. Inspections of wooden spools from China revealed infection rates between 22% and 24% and inspections of braces for granite blocks imported into Canada were found to hold live insects 32% of the time (USDA, APHIS, and USFS (2000, pp. 27-28)).

When non-native species invade new habitats, they give rise to immense costs in the nations in which these novel habitats are located. Here are two illustrations of such costs from the United States. First, the Office of Technology Assessment (OTA (1993)) has established that the Russian wheat aphid caused $600 million worth of crop damage between 1987 and 1989. Second, Pimentel *et al.* (2000) have calculated the total costs of all non-native species at around $137 billion per year. Economic costs are not the end of the story. In fact, in addition to these economic costs, non-native species have caused a lot of ecological damage as well. For example, Vitousek *et al.* (1996) have

[5] See Yang and Perakis (2004), Batabyal *et al.* (2005), and Batabyal and Beladi (2006) for more on this literature.

noted that non-native species can change ecosystem processes, act as vectors of diseases, and diminish biological diversity. In addition, Cox (1993) has observed that out of 256 vertebrate extinctions with a known cause, 109 are the outcome of the actions of non-native species. Because of these reasons, both economists and ecologists are very interested in the management of non-native species.

Now, from the standpoint of a manager, there are a number of actions that this individual can take to address the problem of biological invasions. These actions are typically *pre-invasion* or *post-invasion* in nature. The objective of pre-invasion actions is to prevent non-native species from invading a new habitat. In contrast, post-invasion actions involve the optimal control of a non-native species, given that this species has already invaded a new habitat. The nascent economics literature on the management of non-native species has generally focused its attention on the properties of alternate post-invasion actions. For instance, Barbier (2001) has noted that the economic impact of a biological invasion can be discerned by analyzing the nature of the interaction between the native and the alien species. Using an intertemporal management model Eiswerth and Johnson (2002) point out that the optimal level of management effort is responsive to ecological factors that are not only species and site specific but also probabilistic in nature. Olson and Roy (2002) have used a stochastic framework to examine the situations in which it is optimal to wipe out a non-native species and the situations in which it is not optimal to do so. Finally, Eiswerth and van Kooten (2002) have shown that in some cases, it is possible to use information furnished by specialists to create a model in which it is optimal to not eradicate but instead regulate the spread of an alien species.

Inspections are a basic pre-invasion tool that is available to managers interested in precluding biological invasions. They are routinely used at airports, land border crossings, and in seaports to

screen humans, the cargo carried by humans, and the cargo carried in containers. As a result, several researchers have now begun to formally study inspections and their properties in the context of non-native species management. In this regard, McAusland and Costello (2004), Batabyal *et al.* (2005), Batabyal and Beladi (2006), and DeAngelo *et al.* (2006) have all studied the properties of alternate ways of structuring the inspection function given that inspections are a very useful practical pre-invasion management tool. McAusland and Costello (2004) show that when one takes a dynamic view and considers the future effects of current species introductions, one is naturally led to favor more stringent inspections. Batabyal and Beladi (2006) use queuing theory to show how maximization problems for choosing the optimal number of inspectors can be formulated after one undertakes a stationary state analysis of two multi-person inspection regimes. Batabyal *et al.* (2005) have analyzed $M/M/1$ and $M/M/2$ queuing models of inspections and have concluded that there *is* a tension between economic cost minimization and inspection stringency in non-native species management. What this means is that greater inspection stringency with a larger number of inspectors leads to higher economic costs and laxer inspection stringency with a smaller number of inspectors results in lower economic costs.

The paper that is most closely related to our paper is the one by DeAngelo *et al.* (2006). Focusing their attention on an arbitrary seaport, these researchers have studied the properties of inspections by utilizing the "average wait of a ship in the port system" or *AWS* criterion in a $M/G/1$ queuing model. Their basic result is that there is *no* necessary tension between economic cost minimization and inspection stringency in non-native species management. In the context of their paper, greater (lesser) inspection stringency reflects an enhanced (decreased) concern for the potential damage from a biological invasion. Therefore, a seaport manager who places a relatively big (small)

weight on invasion damage control will, all else being equal, want to inspect ships more (less) stringently.

As we have noted previously, inspections clearly constitute an important part of the general task of pre-invasion non-native species management. Therefore, we use an alternate cost criterion, namely the "average wait of a ship in queue" or *AWQ* criterion to investigate the generality of the central "no necessary tension" result in DeAngelo *et al.* (2006). Note that we're not saying that *AWS* is a useless measure of costs. On the contrary, it is a perfectly reasonable way to model the economic cost of inspections. Further, we stress that within the context of a queuing model of non-native species management, there are two standard ways of modeling the economic cost imposed on society by inspections.[6] DeAngelo *et al.* (2006) have used *AWS* and have hence concentrated on the first of these two ways. Therefore, a natural question to ask is whether the central DeAngelo *et al.* (2006) result holds when costs are modeled using the second of these two ways. That is what we're doing in this paper by focusing on *AWQ* and this is the sense in which our paper is an extension of the earlier DeAngelo *et al.* (2006) paper.

Our theoretical analysis demonstrates that there is an ambiguous answer to this tension question. Hence, we use numerical methods and our numerical analysis leads to two conclusions. First, for many values of the model parameters that describe the strictness of inspections, there *is* a tension between cost minimization and inspection stringency. Second, for most values of the model parameter that depicts the volume of maritime trade handled by the seaport under consideration, there is *no* tension between cost minimization and inspection stringency. Our results in this paper are

6 For more on this point see Ross (2003, p. 477).

different from the findings in Batabyal *et al.* (2005) with the $M/M/1$ and the $M/M/2$ queuing models. The general reason for this variance is that the queuing model that we employ in this paper is *different* from the queuing models used by Batabyal *et al.* (2005). More specifically, the random inspection times in the Batabyal *et al.* (2005) paper are *exponentially* distributed and the exponential distribution is the unique distribution that has the so called memoryless property.[7] In contrast, in the present paper, the inspection times are *generally* and not exponentially distributed.

The rest of this paper is arranged as follows. Section 2 provides a primer on queuing theory and then this section describes the queuing theoretic model that we use in this paper. Section 3 first delineates the "average wait of a ship in queue" or AWQ criterion that we use in this paper to explore the generality of the findings obtained by DeAngelo *et al.* (2006). Next, this third section conducts a detailed theoretical and numerical analysis of the aforementioned tension question. Section 4 concludes and offers suggestions for future research on the subject of this paper.

2. Economic Cost Minimization and Inspection Stringency

2.1. Queuing theory: a primer

Queuing theory—see Taylor and Karlin (1998) and Ross (2003) for textbook expositions—studies waiting lines or queues from a mathematical perspective. All queuing models have the following three features. First, there is a random arrival process. Second, there is a probabilistic service process. Finally, there is a deterministic number of servers. In the queuing model of this paper, the Poisson process constitutes the arrival process. In this case, the times between successive arrivals are exponentially distributed and the exponential distribution is memoryless.

[7] For additional details on this property see Ross (2003, pp. 272-273).

Therefore, the letter M is commonly used to describe the Poisson arrival process.[8]

Like the interarrival times of the previous paragraph, in general, the service or inspection times are also stochastic. The reader will recall that the main aim of our paper is to investigate the generality of the findings in DeAngelo *et al*. (2006). Therefore, like DeAngelo *et al*. (2006), we also use the letter G to denote the *general* cumulative distribution function of the random inspection times.[9] Finally, the deterministic number of inspectors is generally denoted by some positive integer and in our paper we suppose that this positive integer is one. In the language of queuing theory, the inspection regime that we're analyzing in this paper corresponds to the $M/G/1$ queuing model. In words, in our model, the arrival process of ships in the seaport is Poisson, the time it takes to inspect a ship is arbitrarily or generally distributed, and there is one representative inspector.

2.2. Inspections in alien species management

Consider a stylized seaport in a specific coastal region of some nation that is publically owned. Ships with ballast water and/or cargo in containers arrive at this seaport to either load or unload cargo. If they have arrived to load cargo then these ships carry this cargo to a seaport in some other region of the world. The arrival of these ships coincides with the arrival of a whole host of possibly damaging non-native animal and plant species. We suppose that the arrival rate of these animal and plant species

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[8] We use the Poisson process in part because this process has been used extensively in the literature on natural resources and the environment to model arrivals. For a more detailed corroboration of this claim, see Uhler and Bradley (1970), Arrow and Chang (1980), Mangel (1985), and Batabyal (2003).

[9] Note that when we say that the random inspection time is arbitrarily distributed, this does *not* mean that there are absolutely no restrictions imposed on this random variable. In fact, we are restricting the support of this random variable to be the non-negative real line. A second restriction is that we need the inspection time random variable's first two moments (mean and variance) to be finite. Beyond these two basic restrictions, we intend our analysis in this paper to be as general as possible. That is why, in what follows, we begin with the theoretical analysis and then proceed to the numerical analysis when it is clear that the theoretical analysis will not provide unambiguous results. Finally, it is quite possible that the idiosyncracies of inspections in specific practical situations will impose further restrictions on the level of inspection stringency that a seaport manager will want to have in place. We suppose that these restrictions are captured in *different* values of the first two moments of the inspection time random variable.

is proportional to the arrival rate of the ships and hence we shall not model these species directly. Instead, we shall concentrate on the ships that bring these species to our seaport by means of either their ballast water or the containers that are used to carry the cargo. The arrival process of the ships in our seaport denotes the arrival process for the queuing theoretic inspection regimes that we analyze in this paper.

Following the discussion in section 2.1, we assume that the ships in question arrive at our seaport in conformity with a Poisson process with rate $\lambda>0$. The reader should note that, *ceteris paribus*, a higher λ indicates two things. First, because the arrival rate of the various non-native animal and plant species is proportional to the arrival rate of the ships, a higher λ means a larger volume of possibly deleterious biological organisms and hence a higher chance of a biological invasion. Second, a higher λ also means that our seaport is now dealing with more cargo or a higher volume of maritime trade. This discussion tells us that λ serves as a proxy for both the likelihood of a biological invasion and the volume of maritime trade.

A key objective of our seaport manager is to prevent invasions by the potentially destructive animal and plant species entering the seaport under study. Hence, arriving ships must be inspected before they can either load or unload cargo. We suppose that ships are inspected on a first-come-first-served basis and one inspector is assigned to each dock in our seaport. In what follows, we shall analyze a *representative* dock inspector's decision problem. Also, we shall think of the inspection function broadly. What this means is that for some ships, only the ballast water will be inspected. For other ships, only the containers carrying cargo will require inspection. Finally, for a third group of ships, both the ballast water and the containers will be inspected. Therefore, inspections will generally require random amounts of time. To model this explicitly, we allow the inspection times to be

arbitrarily distributed. The seaport system under study consists of ships that are being inspected, ships that are waiting to be inspected, the representative dock inspector, and the seaport manager.

It is reasonable to expect that the amount of time it takes to complete inspections has a direct bearing on the stringency of inspections. Hence, to model this idea, we assume that there are two feasible inspection regimes in our seaport. In the first or *more* stringent inspection regime, the average inspection time is ν_M and the variance of this time is τ_M^2. In the second or *less* stringent inspection regime, the mean inspection time is ν_L and the variance of this time is τ_L^2. Further, we assume that $\nu_M > \nu_L$ and that $\tau_M^2 < \tau_L^2$. These two inequalities together tell us that inspection regime M is *more* stringent than inspection regime L. Why? Because relative to regime L, on average, regime M requires that more time be spent on the inspection function. Also, the variability of the time spent inspecting ships in regime M is less than the variability of the time spent inspecting ships in regime L. As a consequence, the more stringent M regime's inspection times have a smaller coefficient of variation and thus are consistently smaller compared to those of the less stringent L regime.

The reader should note that we are measuring the *reliability* of the two inspection regimes with the two *variance* parameters τ_M^2 and τ_L^2. In other words, the stringent regime is stringent not only because on average the inspector spends more time inspecting ships but also because, having spent more time, the inspector can be *more certain* that he has not made either type I or type II errors while discharging his duties. This feeling "more certain" corresponds to greater reliability and this greater reliability, in turn, corresponds to a lower variance. That is why we have $\tau_M^2 < \tau_L^2$.[10] Given this interpretation, note that the $\tau_M^2 > \tau_L^2$ case is intuitively and practically implausible because this case

[10] There is support in the extant literature for our "lower (higher) variance implies more (less) reliable" interpretation. For additional details on this point see Salvucci *et al.* (1997) and Yu (2005).

would mean that even though the inspector spends more time on average in the stringent regime inspecting ships, he is still less certain about the reliability of the inspection that he has undertaken.

The basic description of our two queuing theoretic inspection regimes is now complete. The more stringent inspection regime M corresponds to a $M/G/1$ queuing model with average inspection time ν_M and variance τ_M^2 and the less stringent or L inspection regime also corresponds to a $M/G/1$ queuing model but now with mean inspection time ν_L and variance τ_L^2. The reader should understand the manner in which we have mathematically depicted the basic question of this paper: When seeking to preclude a biological invasion by inspecting the ballast water and/or the containers of ships, which inspection regime, M or L, ought our seaport manager to have in place? We now proceed to theoretically and numerically analyze the inspection regime choice question for the *AWQ* cost criterion that we identified in section 1.

3. The *AWQ* criterion

Inspections that lead to the preclusion of a biological invasion by non-native animal or plant species undoubtedly result in benefits to the citizens of the coastal region that we are studying. However, during the time that arriving ships are being inspected, there is neither loading nor unloading of cargo, and hence, in general, economic activity resulting from maritime trade is at a standstill. This ephemeral stoppage of economic activities imposes *costs* on the economy of our coastal region. This cost can be measured by computing a specific criterion such as "the average wait of a ship in the port system" or *AWS*. In this way of looking at the problem, the longer (shorter) the average wait in the port system or *AWS*, the larger (smaller) the costs from the cessation of economic activities. Therefore, a seaport manager who is concerned primarily about the economic costs that are imposed on society by the activities of the representative inspector will want to keep *AWS* as low as possible.

In contrast, a seaport manager who frets more about the possible damage to society from a biological invasion will want to have the more stringent or M inspection regime in place. DeAngelo *et al.* (2006) have used this AWS criterion in a $M/G/1$ queuing model and have shown that contrary to the central finding in Batabyal *et al.* (2005), there is *no* universal tension between economic cost minimization and inspection stringency in non-native species management.

As noted in section 1, the AWS criterion is one of two possible criteria that we can use in thinking about the above mentioned economic costs in the context of a queuing model. As such, suppose we adopt a somewhat looser interpretation of these costs and say that the loading and/or the unloading of cargo may proceed on a ship that is presently being inspected for potentially invasive species but that such activities may not take place on ships that have yet to be inspected and are waiting in queue. In this way of looking at the problem, ships in *queue* are the ones that are most likely to impose economic costs on society. We shall refer to this second—and somewhat looser—economic cost criterion as the "average wait of a ship in queue" or AWQ criterion. Given this alternate cost criterion, a key issue that arises is this: Do the findings contained in DeAngelo *et al.* (2006) hold when the AWQ criterion and not the AWS criterion is used to measure the economic cost of inspections? We now address this question in detail.

Our first order of business is to compute AWQ for the two $M/G/1$ inspection regimes that we are presently studying. To do this, we shall use equations 1.2 and 3.17 in Taylor and Karlin (1998, p. 544 and p. 563). Using these two equations, our desired expressions for AWQ are

$$AWQ_M=\{\lambda(\tau_M^2+\nu_M^2)\}/\{2(1-\lambda\nu_M)\} \text{ and } AWQ_L=\{\lambda(\tau_L^2+\nu_L^2)\}/\{2(1-\lambda\nu_L)\} \quad (1)$$

respectively for the two regimes. We can use the inequalities $\nu_M>\nu_L$ and $\tau_M^2<\tau_L^2$ to show that $2(1-\lambda v_M)<2(1-\lambda\nu_L)$. However, because $(\tau_M^2+\nu_M^2)$ may be larger or smaller than $(\tau_L^2+\nu_L^2)$, simply

knowing that $\nu_M > \nu_L$ and that $\tau_M^2 < \tau_L^2$ does *not* permit us to say anything unambiguous about the relative magnitudes of AWQ_M and AWQ_L. In other words, when our seaport manager sanctions the use of the more stringent M inspection regime in the seaport under study, it is *not* always the case that economic costs measured by the AWQ criterion will be higher. So, in the general case, there may or may not be a tension between economic cost minimization and inspection stringency. This tells us that even when we use the AWQ criterion, the finding in DeAngelo *et al.* (2006) that there is no necessary tension between economic cost minimization and inspection stringency holds.

We have just seen that there is no unique resolution of this tension question. To provide additional insight into this issue, in the remainder of this paper, we use a numerical perspective to study this tension question in three different ways. However, before we move to the specifics of the numerical analysis, let us stress three points. First, it is clearly infeasible to work with the infinitely many combinations of the model parameters $(\lambda, \nu_M, \nu_L, \tau_M^2, \tau_L^2)$ that are possible. As such, the reader should understand that the primary point of the subsequent numerical analysis is *illustrative*. We wish to demonstrate not only the functional dependence of the AWQ criterion on the various model parameters but also the *different* results that obtain as we *vary* these parameters. Second, we have conducted numerical analyses of the sort delineated below with many different values of the distinct model parameters. Rather than bore the reader with umpteen graphs of the various possible results, what we are reporting below is a selection of model parameters that generates—to the best of our knowledge—*representative* results. Finally, the collective lesson from the above two points is that the answer to the central tension question that we are investigating in this paper is *seaport specific*. Different seaports are likely to have different values of the arrival rate λ. Therefore, in a particular practical situation, a seaport manager will typically want to choose the inspection regime stringency

parameters (ν,τ) to account for the specific value of λ confronting him as he optimizes a particular objective function such as AWQ.[11]

Let the arrival rate of ships be $\lambda=1$ per unit time. Further, suppose that the parameters of the two inspection regimes are $(\nu_M,\tau_M^2)=(0.5,0.2)$ and $(\nu_L,\tau_L^2)=(0.4,0.9)$. Now, employing equation (1), it is straightforward to confirm that $AWQ_M=0.45\lambda/(2-\lambda)$ and $AWQ_L=1.06\lambda/(2-0.8\lambda)$. When $\lambda=1$, these two expressions reduce to $AWQ_M=0.45$ and $AWQ_L=0.88$.

Examining these two expressions for AWQ_M (AWQ_L) we see that as the arrival rate of ships λ approaches 2 (2.5), economic costs measured by the AWQ_M (AWQ_L) criterion approach infinity. This means that there *is* an upper limit on the volume of maritime trade that our seaport can handle and when this limit is approached, the economic costs of inspections become immeasurably large. Second, when $\nu_M,\nu_L,\tau_M^2,$ and τ_L^2 are as stated in the previous paragraph, the economic costs of inspections are lower when the more stringent M inspection regime is in place. The reader will note that this is also a case in which there is *no* tension between economic cost reduction and inspection stringency.

3.1. The tension question in terms of the volume of maritime trade

For the parameter values specified above, we now analyze the dependence of AWQ on λ. Equating $AWQ_M=0.45\lambda/(2-\lambda)=0.45$ and $AWQ_L=1.06\lambda/(2-0.8\lambda)=0.88$ and then simplifying gives us

$$0.70\lambda^2-1.22\lambda=0. \qquad (2)$$

The two solutions to equation (2) are $\lambda_1^*=1.74$ and $\lambda_2^*=0$. Because λ must be positive, we conclude that $\lambda=1.74$ is the only economically meaningful solution in this case. Figure 1 plots AWQ on the

Figure 1 about here

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[11] Clearly, AWQ is not the only possible objective function for a seaport manager. Depending on the specifics of a particular situation, a seaport manager may want to minimize costs in addition to those that we are capturing in AWQ.

vertical axis against the arrival rate of ships λ on the horizontal axis. Looking at figure 1 we see that for all values of λ, $0<\lambda\leq 1.74$, our seaport manager will prefer to have the more stringent or M inspection regime in place because this regime leads to lower economic costs as measured by the AWQ criterion. Only when $\lambda>1.74$ does it make sense for the seaport manager to use the less stringent or L inspection regime to inspect arriving ships at the seaport under study. Put differently, when $\lambda\in(0,1.74]$ there is *no* tension between economic cost minimization and biological invasion damage control. In contrast, there *is* a tension between economic cost minimization and the stringency of inspections when $\lambda>1.74$.

3.2. The tension question in terms of the mean inspection times

We now numerically investigate the functional dependence of AWQ on the means (ν_M,ν_L) of the two inspection regimes and in section 3.3 we shall conduct a similar exercise from the standpoint of the two variances (τ_M^2,τ_L^2). As in our earlier numerical analysis, we have $\nu_M>\nu_L$ and $\tau_M^2<\tau_L^2$. Further, in order to conduct the subsequent numerical analysis in two dimensions, we suppose that $\nu_M=a\nu_L$, $a>1$ and that $\tau_M^2=b\tau_L^2$, $b\in(0,1)$. In other words, the two means and the two variances are assumed to be linearly related to each other and the parameters a and b are the two constants of proportionality. From an economic standpoint, we can think of the parameter a as a measure of the difference in the stringencies of the two inspection regimes M and L. Similarly, the parameter b can be thought of as a measure of the difference in the variability—and hence the reliability—of the same two inspection regimes.

Now, using the section 3 parameter values, we have $\lambda=1,\nu_M=a\nu_L,\nu_L=0.4,\tau_M^2=b\tau_L^2,\tau_L^2=0.9$ and we set b equal to its midpoint, i.e., $b=0.5$. Note that this $b=0.5$ stipulation means that the more stringent inspection regime M is twice as reliable as the less stringent regime L. Using these values

of the different parameters in equation (1), we get $AWQ_M = (0.45 + 0.16a^2)/(2 - 0.8a)$ and $AWQ_L = 0.8833$. Setting these two values equal gives us the following quadratic equation in a

$$0.16a^2 + 0.71a - 1.32 = 0. \tag{3}$$

The two solutions to equation (3) are $a_1^* = 1.41$ and $a_2^* = -5.83$. Because we must have $a > 1$ it follows that the only economically meaningful solution to equation (3) is $a_1^* = 1.41$.

Figure 2 plots the economic cost criterion AWQ on the vertical axis against alternate values

Figure 2 about here

of a on the horizontal axis. Looking at figure 2 we see that when $a = 1.41$ our seaport manager is indifferent between the two inspection regimes. Further, for all $a < 1.41$ the use of the more stringent M inspection regime results in lower economic costs as measured by the AWQ criterion. Finally, for all $a > 1.41$ the use of the less stringent L inspection regime leads to lower economic costs. This tells us that when $a > 1.41$ there *is* a tension between economic cost minimization and biological invasion damage control. In contrast, when a lies in the interval $(1, 1.41]$ there is *no* tension between economic cost minimization and biological invasion damage control. Note that this last "no tension" result may appear counterintuitive but it holds for some and *not* all values of a. In addition, this last result does depend on our assumption that $\tau_M^2 < \tau_L^2$ but as we have already pointed out in section 2.2, the alternate assumption that $\tau_M^2 > \tau_L^2$ is both intuitively and practically improbable.

3.3. The tension question in terms of the variances of the inspection times

Our final task is to numerically examine the functional dependence of AWQ on the variances (τ_M^2, τ_L^2) of the M and the L inspection regimes. As in section 3.2, in order to conduct the analysis in two dimensions, we have $\tau_M^2 < \tau_L^2$, $\nu_M > \nu_L$, $\tau_M^2 = b\tau_L^2$, $b \in (0,1)$, and $\nu_M = a\nu_L$, $a > 1$. Further, using the previous values of the pertinent parameters, we have $\lambda = 1, \nu_L = 0.4, \tau_L^2 = 0.9$, and we shall set $a = 2$. The reader

should note that setting $a=2$ means that relative to the less stringent inspection regime $L,$ on average, twice as much time is spent in the more stringent regime $M.$ Substituting these values of the various parameters in equation (1), we get $AWQ_M=1.6+2.25b$ and $AWQ_L=0.8833.$ Inspection of these two expressions for the economic cost criterion and some reflection tell us that there is *no* value of b for which our seaport manager is indifferent between the two inspection regimes being studied.

Figure 3 plots the economic cost criterion AWQ on the vertical axis against alternate values

Figure 3 about here

of b on the horizontal axis. Figure 3 tells us that AWQ is *always* lower when the less stringent L regime is used to inspect arriving ships in our seaport. In other words, for *all* values of b which measures the difference in the variability—and hence reliability—of the two inspection regimes, there *is* a tension between economic cost minimization and inspection stringency or biological invasion damage control.

Does the above result depend on the specific value of a that we have chosen to conduct the numerical analysis with? The answer is yes and to see this consider what would happen if instead of setting $a=2,$ we set $a=1.2.$ In this case, once again substituting the values of the various parameters in equation (1), we get $AWQ_M=0.2215+0.8654b$ and $AWQ_L=0.8833.$ Now setting $AWQ_M=0.2215+0.8654b=0.8833=AWQ_L$ we get $b=0.7647.$ This tells us that when we set $a=1.2,$ there is *no* tension between economic cost minimization and biological invasion damage control as long as $b\in(0,0.7647].$ In contrast, when $b\in(0.7647,1),$ there *is* a tension between these two objectives. In terms of figure 3, what is happening is that as we reduce the value of a from $a=2$ to $a=1.2,$ the slope of the graph of AWQ_M declines from 2.25 to 0.8654 and the graph itself gets pulled down vertically toward the horizontal graph of $AWQ_L.$ The reader should note that this finding—that the

result obtained in the previous two paragraphs depends on the specific value of a—is consistent with the general illustration and demonstration of seaport specificity objectives of our numerical analysis as stated in section 3.

Our analysis thus far leads to four conclusions. First, the theoretical analysis tells us that the question as to whether there is or isn't a tension between economic cost minimization and biological invasion damage control *cannot* be resolved unambiguously. Second, for many possible values of the a parameter and for all possible values of the b parameter when $a=2$, there *is* a tension between economic cost minimization and biological invasion damage control. Third and at variance with the second conclusion, for several values of λ or the volume of maritime trade parameter, there is *no* tension between economic cost minimization and inspection stringency. Finally, by varying both a and b, we have graphically shown the impact that *alternate choices* of these two parameters have on the AWQ objective function. In addition, this variation exercise also shows that for these two parameters, inspection stringency, defined in terms of the mean and the variance of the inspection time random variable, lies in the *interval* $a\in(1,\infty)$ and $b\in(0,1)$. These four conclusions are consistent with the main findings obtained by DeAngelo *et al.* (2006) with the AWS cost criterion and hence we note that the basic findings of DeAngelo *et al.* (2006) are general in the sense that they hold not only for the AWS cost criterion but also for the AWQ cost criterion.

For real world applications of the model of this paper, we would need to procure values for the arrival rate of ships and the averages and the variances of particular inspection regimes. In the United States, information about the arrival rate of ships can be procured from the administrative offices of individual seaports such as Long Beach and, on occasion, from governmental agencies such as the Office of Mobile Sources of the Environmental Protection Agency (EPA). Similarly, information

about actual inspections in the United States can be procured from documents that are periodically produced by the Congressional Research Service and from the Animal and Plant Health Inspection Service (APHIS).

4. Conclusions

Non-native animal and plant species often succeed in invading new habitats as a result of maritime trade in goods by means of ships. Hence, if an appropriate authority such as a seaport manager's goal is to prevent biological invasions, then he must inspect arriving ships for potentially deleterious biological organisms. Given this context, we used the *AWQ* cost criterion in the $M/G/1$ queuing model to investigate the generality of the findings obtained recently by DeAngelo *et al.* (2006). Our theoretical analysis showed that there is *no* unique answer to the question as to whether there is or isn't a tension between economic cost minimization and biological invasion damage control. In addition, our numerical analysis identified particular values of the essential model parameters for which there is a tension between economic cost minimization and biological invasion damage control. The general outcome of our combined theoretical and numerical analysis is twofold. First, the main findings of DeAngelo *et al.* (2006) are general in the sense that they hold for the *AWS* and for the *AWQ* cost criteria. Second, whether or not there is tension between economic cost minimization and biological invasion damage control depends greatly on the organizational details—the arrival rate of ships and the degree of stringency of inspections—in individual seaports.

The analysis in this paper can be extended in a number of directions. We now suggest one such direction. One issue of interest concerns the analysis of situations in which because of heavy traffic in a particular seaport, ships do not enter this seaport but go instead to some other seaport. From the perspective of the manager of a *single* seaport, this heavy traffic situation can be analyzed with a

queuing model in which “balking” is permitted. In other words, if an arriving ship finds n other ships already in our seaport then this ship enters our seaport only with some probability p_n and it goes to some other seaport with probability $1-p_n$. If we assume that long queues discourage ships from entering a seaport then we would expect p_n to be a decreasing function of n. A special case of this balking scenario is one in which a seaport has a finite capacity F so that $p_n=1$ for $n<F$ and $p_n=0$ for $n\geq F$. As in this paper, one can analyze the properties of alternate inspection regimes in a model with these heavy traffic related features.

From the perspective of a social welfare maximizing manager, who is responsible for *all* seaports in a nation, a queuing analysis of the issues studied in this paper would have to determine the desirable inspection stringency level at a particular seaport and *coordinate* inspection strategies in all the seaports in this nation. This way, differential inspection standards would not exist and if they did exist they would not, in and of themselves, provide incentives for arriving ships to favor certain seaports over others. If this coordination aspect of the problem is not addressed then, in any particular nation, the risk of one or more biological invasions may actually increase despite the presence of inspections in all national seaports. Research on maritime trade driven biological invasions that incorporate these aspects of the problem into the analysis will provide additional insights into a management problem that has considerable economic and ecological ramifications.

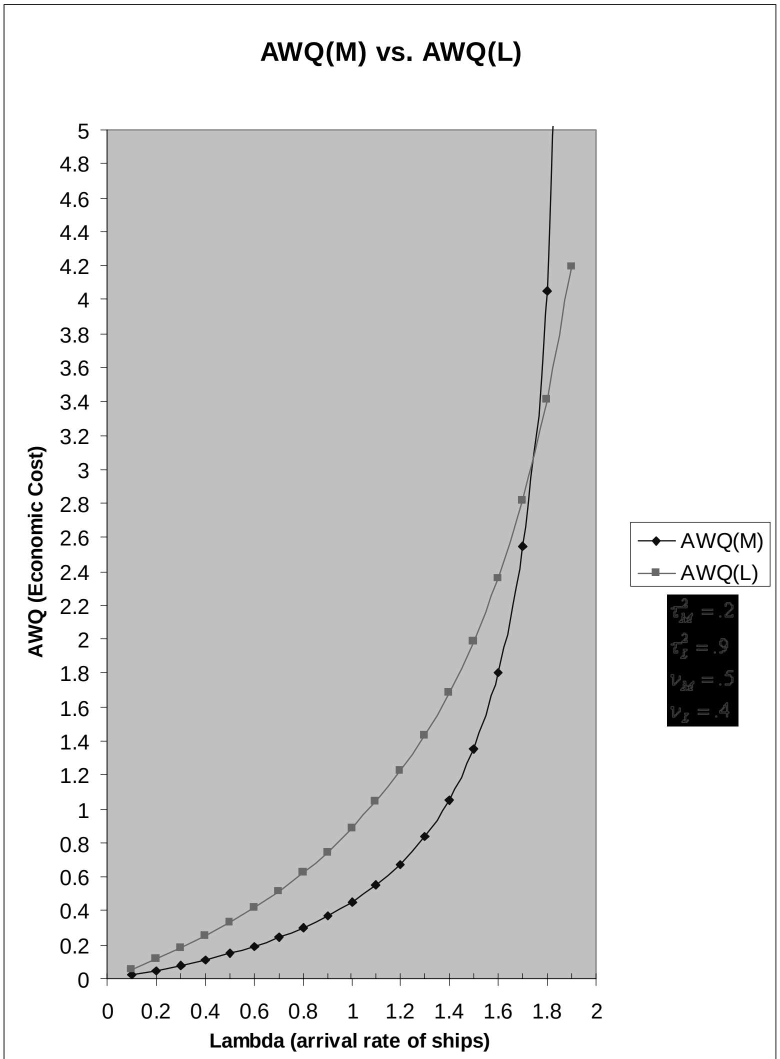
AWQ(M) vs. AWQ(L)
AWQ (Economic Cost)
5
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Lambda (arrival rate of ships)
AWQ(M)
AWQ(L)
$\tau_M^2 = .2$
$\tau_L^2 = .9$
$\nu_M = .5$
$\nu_L = .4$

Figure 1

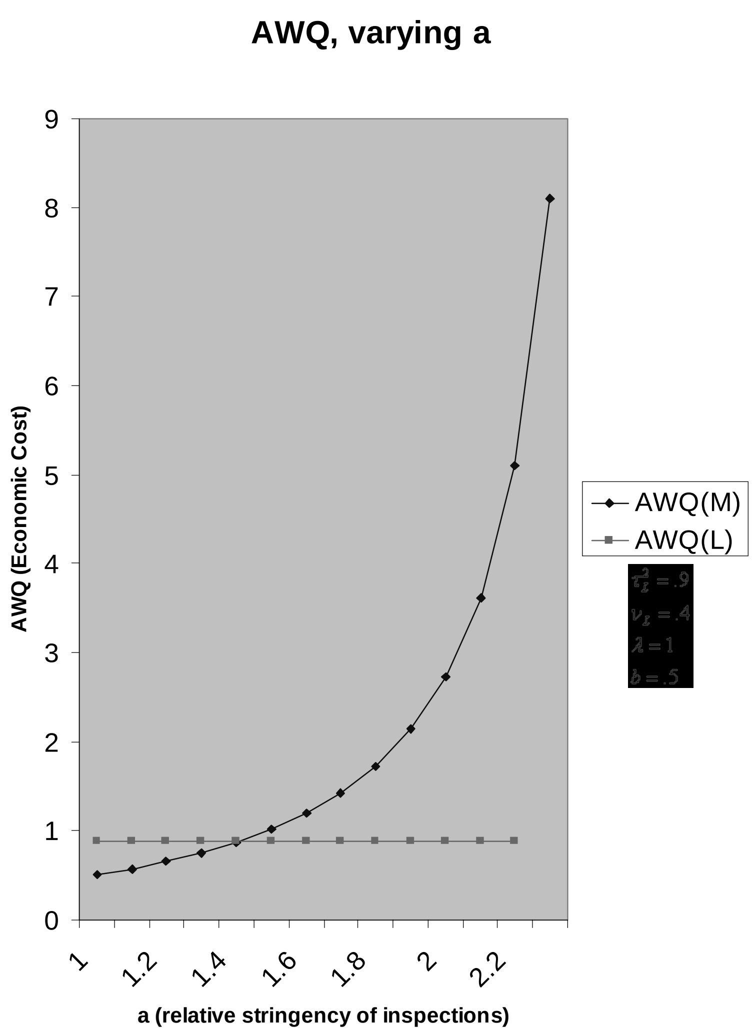
AWQ, varying a
AWQ (Economic Cost)
9
8
7
6
5
4
3
2
1
0
1
1.2
1.4
1.6
1.8
2
2.2
a (relative stringency of inspections)
AWQ(M)
AWQ(L)
$\tau_z^2 = .9$
$\nu_z = .4$
$\lambda = 1$
$b = .5$

Figure 2

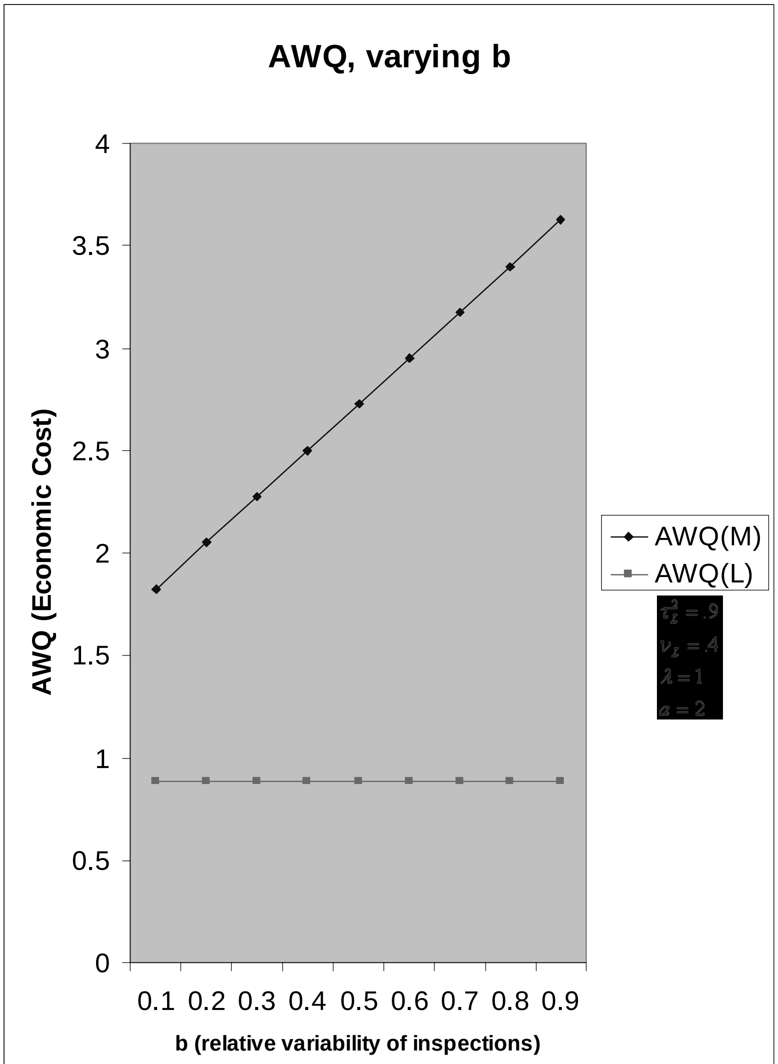
AWQ, varying b
AWQ (Economic Cost)
4
3.5
3
2.5
2
1.5
1
0.5
0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
b (relative variability of inspections)
AWQ(M)
AWQ(L)

Figure 3

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