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On Container Versus Time Based Inspection Policies in Invasive Species Management[1]

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Abstract

We study the problem of precluding biological invasions caused by ships transporting internationally traded goods in containers between different regions of the world. Using the long run expected net cost (*LRENC*) of inspections as the apposite managerial objective, we address the following important question: Given that inspection is a *cyclical* activity, is the *LRENC* lower when a port manager's inspector inspects cargo upon the arrival of a specified number of containers (container policy) or is this *LRENC* lower when this inspector inspects cargo at fixed points in time (temporal policy)? We construct a queuing theoretic model and show that in an inspection cycle, irrespective of whether the inspection policy choice is made on the basis of an explicit optimization exercise or on the basis of rules of thumb, the container policy is superior to the temporal policy because the container policy results in lower *LRENC* from inspection activities.

Keywords: Biological Invasion, Inspection Policy, Queuing Theory, Uncertainty

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1. Introduction

It is now well known that maritime trade in goods comprises a significant fraction of the world's total international trade in goods. Ships are the primary vehicle in maritime trade and, in contemporary times, ships are routinely used to transport a whole host of goods in containers from one region of the world to another. Although there are clear gains to the involved parties from such voluntary trade between the different regions of the world, researchers have increasingly noted that the magnitude of these gains is likely to be less than what most observers have hitherto believed. Why is this the case? As Heywood (1995), Parker *et al.* (1999), and Batabyal (2004) have pointed out, this is because in addition to transporting goods in containers between regions, ships have also succeeded in transporting a variety of alien plant and animal species[4] from one geographical region to another.

Broadly speaking, ships have transported non-native species in two main ways. First, a variety of marine alien species have been introduced into a region, often unwittingly, by ships dumping their ballast water. Cargo ships routinely 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 released before cargo can be loaded. This method of species introductions is important and very recently the problem of managing invasive 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]

The second way in which alien species have been introduced into a specific region is by means

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[4] In the rest of this paper, we shall use the terms "alien species," "invasive species," and "non-native species" interchangeably.

[5] For additional details on this subject, the reader should consult Batabyal and Beladi (2004), Batabyal *et al.* (2004), and the many references in these two papers.

of the containers that ships commonly use to transport cargo from one region to another. Indeed, non-native species can remain undetected in containers for long periods of time. In addition, the material (such as wood) that is used to pack the cargo in the containers may itself contain alien species. In this connection, 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 noted that approximately 51.8% of maritime shipments contain solid wood packing materials and that infection rates for solid wood packing materials are non-trivial (USDA, APHIS, and USFS (2000, p. 25)). For example, 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 contain live insects 32% of the time (USDA, APHIS, and USFS (2000, pp. 27-28)).

The non-native species that we have been discussing generally thus far have frequently succeeded in invading their new habitats and the resulting biological invasions have turned out to be very costly for the regions in which these novel habitats are located. For the United States alone, the dollar value of these costs is mind boggling. To see this, consider the following two examples. First, the Office of Technology Assessment (OTA (1993)) has calculated that the Russian wheat aphid caused $600 million worth of crop damage between 1987 and 1989. Second, Pimentel *et al.* (2000) have estimated the total costs of all non-native species at around $137 billion per year.

In addition to the economic costs that we have just noted, invasive species have given rise to significant biological damage as well. In this regard, Vitousek *et al.* (1996) have demonstrated that non-native species can change ecosystem processes, act as vectors of diseases, and decrease biological diversity. Further, Cox (1993) has noted that out of 256 vertebrate extinctions with a known cause, 109 are the result of biological invasions. The implication of the discussion in this and the preceding paragraph is clear: Biological invasions have frequently been a great menace to society.

Very recently, economists and regional scientists have acknowledged the salience of the problem of biological invasions. Even so, it is still true that “the economics of the problem has...attracted little attention” (Perrings *et al.* (2000, p. 11)). Therefore, our knowledge of the economic and the management aspects of invasive species is very incomplete. Now, from the standpoint of a manager, there are various actions that he can take to deal 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 purpose of pre-invasion actions is to preclude alien species from invading a new region. Therefore, the reader should think of pre-invasion actions as fundamentally prophylactic in nature. In contrast, post-invasion actions involve the optimal control of an alien species, given that this species has already invaded a novel region.

The focus of the small extant literature on biological invasions has, for the most part, been on the desirability of actions in the *post-invasion* scenario. Here mention here four examples of such analyses. First, Barbier (2001) has shown that the economic impact of a biological invasion can be determined by examining the nature of the interaction between the alien and the native species. He notes that the economic impact depends on whether this interaction involves interspecific competition or dispersion. Second, Eiswerth and Johnson (2002) have studied a dynamic model of alien species stock management. They show 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 stochastic framework to explore the conditions under which it is optimal to wipe out an alien species and conditions under which it is not optimal to do so. Finally, Eiswerth and van Kooten (2002) have shown that in some circumstances, it is possible to use information provided by experts to develop a model in which it is optimal to not eradicate but instead control the spread of an invasive species.

Our search of the pertinent literature located only three papers that have theoretically analyzed the prevention problem; that is, the regulation of a possibly injurious alien species before it has invaded a particular region. These three papers are Horan *et al.* (2002), Batabyal and Beladi (2004), and Batabyal *et al.* (2004). Horan *et al.* (2002) compare the properties of management strategies under full information and under uncertainty. Batabyal and Beladi (2004) study optimization problems stemming from the steady state analysis of two multi-person inspection regimes. Finally, Batabyal *et al.* (2004) show that if decreasing the economic cost associated with inspections is significant then it makes more sense for a port manager to choose the inspection regime with fewer inspectors and less stringent inspections. In contrast, if reducing the damage from biological invasions is more salient then this manager ought to pick the inspection regime with more inspectors and more stringent inspections.

Like Batabyal *et al.* (2004), we also focus on the inspection aspect of the management problem. However, unlike their paper, we study here a very different question. Specifically, using the long run expected net cost (*LRENC*) of inspections as the apposite managerial objective, we address the following important question: Given the cyclical nature of the inspection function, is the *LRENC* of inspections lower when a port manager follows a policy of inspecting cargo upon the arrival of a specified number of containers (the container policy) or is this *LRENC* lower when this manager inspects cargo at fixed points in time (the temporal policy)? We construct a queuing model—that is different from the model used in Batabyal *et al.* (2004)—and show that in an inspection cycle, irrespective of whether the inspection policy choice is made on the basis of an explicit optimization exercise or on the basis of rules of thumb, the container policy is superior to the temporal policy because the container policy results in lower *LRENC* from inspection activities.

The theoretical framework of this paper is adapted from Batabyal *et al.* (2001) and Ross (2003, pp. 515-519) and the rest of this paper is organized as follows. Section 2 first provides a primer on queuing theory and then this section provides a stylized account of biological invasions in the context of a queuing theoretic model of the inspection policy choice problem faced by a port manager. Section 3 analyzes this choice problem for the case in which the port manager wishes to minimize the *LRENC* from cargo inspections by optimally choosing the number of containers to inspect in an inspection cycle. Section 4 studies a similar model. However, in this section, the port manager minimizes the *LRENC* from cargo inspections by optimally choosing the temporal inspection point in an inspection cycle. Section 5 compares the optimized value of the port manager's *LRENC* from sections 3 and 4 and thereby determines which inspection policy results in lower *LRENC*. Section 6 concludes and offers a suggestion for future research on the subject of invasive species management.

2. Queuing Theory and the Choice of Inspection Policy

2.1. Preliminaries

The purpose of queuing theory—see Wolff (1989), Kulkarni (1995), Taylor and Karlin (1998), and Ross (2003) for textbook accounts—is to mathematically analyze waiting lines or queues. Three features are common to all queuing models. Specifically, they can be described by a stochastic arrival process, a probabilistic service time distribution function, and a fixed number of servers. In the queuing model that we employ in this paper, the arrival process is the Poisson process. Therefore, the times between successive arrivals are exponentially distributed and the exponential distribution is *memoryless* or Markovian. Hence, the Poisson arrival process is commonly described by the letter M.

In general, the service times are random variables. Therefore, these times can, in principle, be arbitrarily distributed and this is assumed in our paper. Therefore, we use the letter G to denote the *general* service time distribution function. Finally, the deterministic number of servers is typically denoted by some positive integer. In this paper, servers are inspectors. Moreover, our analysis will be conducted from the perspective of a port manager who employs a so called representative inspector (hereafter inspector). As such, we shall work with a single inspector. In the language of queuing theory, our model corresponds to the well known $M/G/1$ queuing model.

2.2. A stylized account of biological invasions

Consider a stylized, publically owned port in a particular coastal region of some country. Upon arrival at this port, ships unload their containers carrying cargo. The arrival of these containers coincides with the arrival of a whole host of conceivably deleterious biological organisms. Now, before this incoming cargo can be moved to various points in the interior of the country under consideration, the containers must first be *inspected* at the inspection facility in our port. The purpose of this protective activity is to ensure that one or more biological invasions—with potentially adverse consequences for the economy and the ecology of the country under study—do not in fact take place. We suppose that the arrival rate of the various biological organisms is proportional to the arrival rate of the containers at the inspection facility. Therefore, we shall not model the biological organisms directly. Instead, we shall focus on the containers that bring these organisms to our port. Further, the arrival process of the containers at the inspection facility in our port represents the arrival process for the queuing model that we analyze in this paper. Finally, we assume that the containers in question arrive at the inspection facility in accordance with a Poisson process with rate α.

The manager of our port is interested in precluding invasions by the possibly injurious biological organisms. As such, in this paper, his basic choice problem is to determine which of two possible inspection policies he ought to have in place. Now, from the standpoint of invasive species management, note the following key features of inspections. First, inspections are physically costly to undertake. Second, quite apart from the cost of conducting physical inspections, inspections also impose an economic cost on society. This cost arises from the fact that while containers are being inspected, there is no unloading or loading of cargo and hence economic activity in our port is very slow if not at a standstill. Third, properly conducted inspections reduce (and perhaps even eliminate) the likelihood of a biological invasion. In the following sections 3 and 4, we shall explicitly model these three features of inspections.

The reader will note that inspections generally require varying amounts of time. For example, if the inspector knows that a batch of containers awaiting inspection are all from a particular country from which either zero or few invaders have emerged in the past then he may be able to clear this batch of containers relatively quickly. On the other hand, if the containers awaiting inspection are either from several nations or from a nation with a known history of invasive species problems then more time will generally be needed to clear the containers in question. The upshot of this discussion is that the inspection times are *random* variables. Given this state of affairs, let I denote the inspection time random variable and let $E[I]$ denote its expectation. The reader will recall that I has a *general* cumulative distribution function. Let us denote this function by $G(\cdot)$. The key pieces of our queuing theoretic model are now in place. Therefore, we now systematically analyze the container policy first in section 3 and then the temporal policy in section 4.

3. The Container Policy

Containers arrive at the inspection facility in accordance with a Poisson process with rate α.

The port manager's inspector examines the containers that have arrived at the inspection facility and he continues to do so until all the containers that are present have been inspected. When this busy period ends, the inspector leaves the inspection facility and he returns only when N new containers have arrived and are awaiting inspection. As a result of these inspections, the inspector—and ultimately the port manager—incurs costs and obtains benefits from two sources. The first source of net cost (total cost less total benefit) arises from things like the expense of paying the inspector and operating the inspection equipment (a cost) and from the reduction in the likelihood of a biological invasion (a benefit). We model this first source of net cost by supposing that our inspector incurs net cost at the rate of c dollars per container per unit time. The second source of net cost stems from things like the deleterious impact on society from the slowdown in economic activity while the containers are being inspected (a cost) and from the determination of whether the containers actually contain what they are supposed to contain (a benefit). We account for this second source of net cost by supposing that the inspector incurs a net cost of C dollars each time he returns to the inspection facility.

The reader should note that the inspection function is *cyclical* in nature. In other words, when containers have arrived at the facility in our port, the inspector is busy inspecting these containers until there are no more containers waiting to be inspected. This is the *busy* period. Then comes an *idle* period in which the inspector has no specific duties to perform. Then, when N additional containers arrive at the facility to be inspected, a new busy period commences. This busy period is followed by an idle period and so on and so forth. Given this state of affairs, if we say that a cycle is completed whenever the inspector *returns* to the inspection facility, then the delineation of events in the previous paragraph constitutes a renewal-reward process.[6] Therefore, we can use the renewal-reward theorem to compute our port manager's *LRENC* from inspection activities.[7] Let $E[net\ cost\ per\ cycle]$ denote the expected net cost of inspections per cycle. Similarly, let $E[length\ of\ cycle]$ denote the expected length of an inspection cycle. Then, the renewal-reward theorem tells us that the inspector's *LRENC* is given by a specific ratio and that ratio is

$$LRENC = \frac{E[net\ cost\ per\ cycle]}{E[length\ of\ cycle]}. \tag{1}$$

Given this setup, our port manager's problem is to choose N optimally to minimize the *LRENC* of inspections.

Let us now calculate the two expectations on the right hand side (RHS) of equation (1). Consider a time interval of length L_j which begins at the first time during an inspection cycle in which there are j containers in the facility and ends at the first time thereafter that there are only $j-1$ containers. Then $\Sigma_{j=1}^{j=N} L_j$ is the total amount of time that the inspector is *busy* checking containers during an inspection cycle. To this time we now add the average time for which our inspector is *idle* until N new containers arrive at the inspection facility. Doing this gives us

$$E[length\ of\ cycle] = \sum_{j=1}^{j=N} E[L_j] + \frac{N}{\alpha}. \tag{2}$$

6

See Ross (1996, pp. 132-140) and Ross (2003, pp. 416-425) for more on renewal-reward processes in general and the renewal-reward theorem in particular.

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We shall soon describe the port manager's optimization problem as a long run expected *net cost minimization* problem. This notwithstanding, the reader should note that without any substantive changes, we could also have delineated this manager's optimization problem as a long run expected *net benefit maximization* problem.

Now consider the moment in time when an inspection is about to begin and there are $j-1$ containers waiting to be inspected. We assume that the inspection times do *not* depend on the order in which the containers are inspected. As such, suppose that the order of inspection is last in, first out or LIFO. Then, as noted in Ross (2003, pp. 322-324), this means that the amount of time it takes to go from j containers waiting in the facility to be inspected to $j-1$ containers waiting to be inspected has the same distribution as the length of the busy period B of the $M/G/1$ queuing model. Now, from equation 8.31 in Ross (2002, p. 253), it follows that

$$E[L_j]=E[B]=\frac{E[I]}{1-\alpha E[I]}, \tag{3}$$

where I, the reader will recall, is the inspection time random variable. For equation (3)—and indeed many of the subsequent equations in this paper—to make sense, we must have $\alpha E[I]<1$. Therefore, in the rest of this paper we assume that this inequality holds. Now, using equation (3) to simplify equation (2), we get

$$E[length\ \ of\ \ cycle]=\sum_{j=1}^{j=N}\frac{E[I]}{1-\alpha E[I]}+\frac{N}{\alpha}=\frac{N}{\alpha(1-\alpha E[I])}. \tag{4}$$

This completes the task of calculating the expected length of an inspection cycle. We now compute the numerator on the RHS of equation 1 or the expected net cost per inspection cycle incurred by our port manager's inspector.

To compute $E[net\ \ cost\ \ per\ \ cycle]$, let $\hat{C}_j$ be the net cost incurred by the inspector during a time period of length L_j, where L_j is as described in the paragraph immediately preceding equation

(2). Then it follows that the total net cost incurred during the busy period of an inspection cycle is $\Sigma_{j=1}^{j=N}\hat{C}_j+C$. To this, we now have to add the net cost incurred during the idle period of the inspection cycle. Note that because the containers arrive at the inspection facility in accordance with a Poisson process with rate α, there will be j containers in the facility for an exponential amount of time with rate α and the index j runs from 1 to $N-1$.[8] Therefore, the total expected net cost during the idle period is $c(1+2+3+...+N-1)/\alpha=cN(N-1)/2\alpha$. With this computation in place, the total expected net cost in an inspection cycle or $E[net\ \ cost\ \ per\ \ cycle]$ is

$$E[net\ \ cost\ \ per\ \ cycle]=\sum_{j=1}^{j=N}E[\hat{C}_j]+C+\frac{cN(N-1)}{2\alpha}. \tag{5}$$

Our next task is to find an expression for $E[\hat{C}_j]$. To do this, recall the time interval of length L_j. During this time interval, let S_j be the *sum* of the initial inspection time and the sum of all the times spent in the inspection facility by the containers that have arrived and have been inspected until the L_j time interval ends and there are only $j-1$ containers in the inspection facility. Mathematically, we can write this as $\hat{C}_j=(j-1)cL_j+cS_j$. To proceed further, it is important to recognize that S_j is distributed as the *sum* of the times spent in the inspection facility by all the arriving containers during the busy period of the $M/G/1$ queuing model. Let us denote this sum random variable and its expectation by B_s and by $E[B_s]$ respectively. Then, using equation (3) and the expression for $\hat{C}_j$ above, we get

$$E[\hat{C}_j]=(j-1)cE[L_j]+cE[S_j]=(j-1)c\frac{E[I]}{1-\alpha E[I]}+cE[B_s]. \tag{6}$$

8 This result follows from proposition 2.2.1 in Ross (1996, p. 64) and proposition 7.2.1 in Ross (2002, p. 203).

From Ross (2003, p. 518), we conclude that $E[B_s]=\alpha E[I^2]/\{2(1-\alpha E[I])^2\}+E[I]/(1-\alpha E[I])$. Using this last expression for $E[B_s]$ and equation (6), we can simplify equation (5). This simplification gives

$$E[net\ cost\ per\ cycle]=cN[\frac{\alpha E[I^2]}{2(1-\alpha E[I])^2}+\frac{E[I]}{1-\alpha E[I]}]+C+\frac{cN(N-1)}{2\alpha(1-\alpha E[I])}. \qquad (7)$$

Now dividing the RHS of equation (7) by the RHS of equation (4), we get our required expression for the $LRENC$ of inspections. That expression is

$$LRENC=\alpha cE[I]+\frac{\alpha^2 cE[I^2]}{2(1-\alpha E[I])}+\frac{c(N-1)}{2}+\frac{\alpha C(1-\alpha E[I])}{N}. \qquad (8)$$

Having computed the expression for the $LRENC$ of inspections, we are now in a position to state our port manager's optimization problem. Specifically, this manager chooses the number of containers N to minimize the $LRENC$ from inspection activities. Formally, our port manager solves

$$\min_{\{N\}}[\alpha cE[I]+\frac{\alpha^2 cE[I^2]}{2(1-\alpha E[I])}+\frac{c(N-1)}{2}+\frac{\alpha C(1-\alpha E[I])}{N}]. \qquad (9)$$

Treating N as a continuous control variable and using calculus, we see that the optimal number of containers N^* that minimizes the port manager's $LRENC$ is given by[9]

[9] The reader can check to see that the relevant second order condition is satisfied.

$$N^* = \sqrt{\frac{2\alpha C(1-\alpha E[I])}{c}}. \tag{10}$$

In words, equation (10) tells us that the optimal number of containers N^* equals the square root of the ratio of the product of twice the Poisson arrival rate of containers (α), the second source of net cost (C), and the term $(1-\alpha E[I])$ to the first source of net cost (c). Inspecting equation (10) it is easy to verify two properties of the optimal number of containers N^*. First, as the second source of net cost (C) increases, it is in the interest of the port manager to *raise* the optimal number of containers in the inspection cycle. Second, if the first source of net cost (c) goes up, then the port manager finds it desirable to *lower* the optimal number of containers in the inspection cycle.

Let us now substitute the expression for the optimal number of containers from equation (10) into the minimand in equation (9). This gives us an expression for the minimal $LRENC$ that our port manager will incur by selecting the number of containers in the inspection cycle optimally. Let this minimal $LRENC$ be $(LRENC)^*_{CP}$, where the subscript CP denotes the container policy. Some algebra tells us that

$$(LRENC)^*_{CP} = \alpha c E[I] + \frac{\alpha^2 c E[I^2]}{2(1-\alpha E[I])} + \sqrt{2\alpha c C(1-\alpha E[I])} - \frac{c}{2}. \tag{11}$$

Inspecting equations (8) and (11), we see that the first two terms on the RHSs of these two equations are independent of the optimal number of containers N^* and hence these two terms are identical. However, N^* affects the last two terms on the RHS of equation (8). Hence, when we substitute the optimized value of N, N^*, into equation (8), we get the last two terms on the RHS of equation (11). These last two terms on the RHS of equation (11) depend on the Poisson arrival rate of the containers (α), the first source of net cost (c), the second source of net cost (C), and the expectation of the inspection time random variable I.

We now analyze the case in which the focus of our port manager is not on the optimal number of containers in an inspection cycle but on the temporal frequency of inspections. After computing the optimal temporal frequency of inspections, we shall compare equation (11) with the corresponding equation for this latter case in which the port manager's focus is on the temporal dimension of the inspection function.

4. The Temporal Policy

Instead of selecting the number of containers optimally, our port manager now pursues an alternate strategy. In particular, whenever there are no containers in the inspection facility, the inspector leaves this facility and he returns only after a fixed time period T has gone by. The specific task at hand now is to choose T optimally to minimize the $LRENC$ from inspection activities.

Let us now calculate the port manager's $LRENC$ when his focus is on the control variable T and not on the optimal number of containers. As in the previous section, we suppose that containers arrive at the inspection facility in the port under study in accordance with a Poisson process with rate α. Further, also as in section 3, we shall use the theory of renewal-reward processes in general and the renewal-reward theorem in particular to compute the $LRENC$ from inspections.

To this end, let us say that a new cycle begins every time the inspector *leaves* the inspection facility.[10] Also, from the discussion in the previous section, recall that every cycle has a period during which the inspector is busy and a period during which the inspector is idle. Given these two points,

[10] The reader should note the difference in the meanings of the word "cycle" in this section and the previous section 3. In section 3, a new cycle *began* every time the inspector *returned* to the inspection facility. In contrast, in this section, a new cycle *begins* every time the inspector *leaves* the inspection facility.

we now follow Batabyal *et al.* (2001) and condition on $N(T)$, the number of container arrivals in the time period in which the inspector is away from the inspection facility, to compute the two expectations of interest, i.e., $E[net\ cost\ per\ cycle]$ and $E[length\ of\ cycle]$. Conditioning on $N(T)$, we get

$$E[net\ cost\ per\ cycle/N(T)] = \sum_{j=1}^{j=N(T)} E[\hat{C}_j] + C + \frac{cN(T)T}{2}. \tag{12}$$

We shall now use the following four pieces of information to simplify equation (12) further. First, from equation (6) we get an expression for $E[\hat{C}_j]$. Second, from theorem 2.3.1 in Ross (1996, p. 67) we can tell that the times at which the containers arrive at the inspection facility are independently and uniformly distributed random variables on the interval $(0,T)$. Third, from Ross (1996, pp. 59-60) we conclude that $N(T)$ is distributed as a Poisson random variable with mean αT. Finally, from Ross (2003, p. 519) we reason that $E[N(T)\{N(T)-1\}] = E[N^2(T)] - E[N(T)] = (\alpha T)^2$. Using these four pieces of information to simplify equation (12), we get

$$E[net\ cost\ per\ cycle] = \frac{(\alpha T)^2 cE[I]}{2(1-\alpha E[I])} + \alpha cTE[B_s] + C + \frac{\alpha cT^2}{2}. \tag{13}$$

Our next task is to determine $E[length\ of\ cycle]$. Once again, conditioning on $N(T)$ and then using the properties of the expectation operator (see Ross (1996, p. 21)) we get

$$E[length\ of\ cycle] = E[E[length\ of\ cycle/N(T)]] = E[T + N(T)E[B]]. \tag{14}$$

We now focus on the expectation on the extreme RHS of equation (14). Specifically, let us simplify this expectation using equation (3) and the fact that $E[N(T)] = \alpha T$. This gives us

$$E[length\ of\ cycle] = T + \frac{\alpha E[I]T}{1-\alpha E[I]} = \frac{T}{1-\alpha E[I]}. \tag{15}$$

We now divide the RHS of equation (13) by the RHS of equation (15) and then use the result $E[B_s] = \alpha E[I^2]/\{2(1-\alpha E[I])^2\} + E[I]/(1-\alpha E[I])$ to eliminate $E[B_s]$. After some algebra, we get

$$LRENC = \alpha c E[I] + \frac{\alpha^2 c E[I^2]}{2(1-\alpha E[I])} + \frac{\alpha c T}{2} + \frac{C(1-\alpha E[I])}{T}. \tag{16}$$

Having computed the expression for the *LRENC* of inspections, we are now in a position to state our port manager's optimization problem. Specifically, this manager chooses the time during which the inspector is absent from the inspection facility T to minimize the *LRENC* from inspection activities. Formally, our port manager solves

$$\min_{\{T\}}[\alpha c E[I] + \frac{\alpha^2 c E[I^2]}{2(1-\alpha E[I])} + \frac{\alpha c T}{2} + \frac{C(1-\alpha E[I])}{T}]. \tag{17}$$

Using calculus, the optimal time T^* during which the inspector ought to be absent from the inspection facility is given by[11]

$$T^* = \sqrt{\frac{2C(1-\alpha E[I])}{\alpha c}}. \tag{18}$$

In words, T^* equals the square root of the ratio of the product of twice the second source of net cost (C)

[11] The reader can check to see that the pertinent second order condition is satisfied.

and the term $(1-\alpha E[I])$ to the product of the Poisson arrival rate of the containers (α) and the first source of net cost (c). Inspecting equation (18) it is straightforward to verify two properties of the optimal leave period T^*. First, as the second source of net cost (C) goes up, the port manager's optimal response calls for *lengthening* the time period during which the inspector is away from the inspection facility. In contrast, when the first source of net cost (c) increases, it is optimal to *shorten* the time during which the inspector is absent from the inspection facility.

Let us now substitute the expression for T^* from equation (18) into the minimand in equation (17). This gives us an expression for the optimized $LRENC$ from inspections given that the inspector's leave period has been selected optimally. Denote this optimized $LRENC$ by $(LRENC)^*_{TP}$, where TP denotes the temporal policy. After several steps, we get

$$(LRENC)^*_{TP} = \alpha c E[I] + \frac{\alpha^2 c E[I^2]}{2(1-\alpha E[I])} + \sqrt{2\alpha c C(1-\alpha E[I])}. \tag{19}$$

Inspecting equations (16) and (19), we see that the first two terms on the RHSs of these two equations are independent of the optimal leave period T^* and hence these two terms are identical. Even so, T^* impacts the last two terms on the RHS of equation (16). Hence, when we substitute the optimized value of T, T^*, into equation (16), we get the last term on the RHS of equation (19). This last term on the RHS of equation (19) is a function of the Poisson arrival rate of the containers (α), the first source of net cost (c), the second source of net cost (C), and the expectation of the inspection time random variable I.

Recall that the objective of our paper is to provide an answer to the following question: Is the $LRENC$ of inspections lower with the container policy or the temporal policy? We now provide a precise answer to this question.

5. The Optimal Inspection Policy in Invasive Species Management

Equations (11) and (19) provide us with expressions for the optimized *LRENC* when the number of containers and the leave period have been chosen optimally. Comparing these two expressions, we see that

$$(LRENC)^*_{CP} = \alpha c E[I] + \frac{\alpha^2 c E[I^2]}{2(1-\alpha E[I])} + \sqrt{2\alpha c C(1-\alpha E[I])} - \frac{c}{2} <$$

$$\alpha c E[I] + \frac{\alpha^2 c E[I^2]}{2(1-\alpha E[I])} + \sqrt{2\alpha c C(1-\alpha E[I])} = (LRENC)^*_{TP}. \quad (20)$$

Equation (20) clearly tells us that the port manager's *LRENC* with an optimally chosen number of containers in the inspection cycle is *lower* than his *LRENC* with an optimally chosen leave period in the inspection cycle. It is in this sense that the container policy is superior to the temporal policy. Put differently, if the port manager had to choose a single control variable from a control set consisting of the number of containers and the leave period, then this manager would choose the number of containers over the leave period.

The reader will note that the result described in the previous paragraph is based on explicit optimization by the port manager. Therefore, it is of some interest to determine whether the superiority of the container policy result holds when, instead of optimizing, our port manager chooses the leave period for the inspector on the basis of a rule of thumb. In this inspection context, what might a rule of thumb temporal policy look like? To answer this question, let us reconsider the expressions for the two *LRENCs* in equations (8) and (16).

Inspecting the RHSs of these two equations, we see that the first two terms in both equations are identical. So no rule of thumb emerges by "eyeballing" these two terms. However, if our port manager were to equate the two third terms in these two equations, i.e., set $c(N-1)/2=\alpha cT/2$, then he would select $T_1=(N-1)/\alpha$ and this is our first rule of thumb. Obviously, this is not the only possibility. If the manager equated the two fourth terms on the RHSs of equations (8) and (16), i.e., set $\alpha C(1-\alpha E[I])/N=C(1-\alpha E[I])/T$, then he would choose $T_2=N/\alpha$ and this is our second rule of thumb. By substituting these values of T_1 and T_2 into equation (16) and then comparing the emerging two equations with equation (8), the reader can verify that our previous result $(LRENC)^*_{CP}<(LRENC)^*_{TP}$ holds for both the above mentioned rules of thumb. From this we conclude that our basic result about the superiority of the container policy is *robust*. It holds not only when the port manager chooses the inspection policy on the basis of an explicit optimization exercise but also when this manager chooses the inspector's leave period with rules of thumb.

6. Conclusions

Maritime trade today routinely involves the transport of goods by means of containers on ships from one region of the world to another. This transport of goods by means of containers on ships often results in detrimental invasions of new regions by alien plant and animal species. Therefore, if an apposite authority such as a port manager's aim is to prevent biological invasions, then this manager must inspect arriving containers for potentially deleterious biological organisms. Given this state of affairs, what kind of inspection policy ought a manager to optimally have in place? In particular, is the *LRENC* of inspections lower when a port manager follows a policy of inspecting cargo upon the arrival of a specified number of containers (the container policy) or is this *LRENC* lower when this manager inspects cargo at fixed points in time (the temporal policy)? Our analysis shows that *irrespective* of whether the inspection policy choice is made on the basis of an explicit optimization exercise or on the basis of rules of thumb, the container policy is superior to the temporal policy because the container policy results in lower *LRENC* from inspection activities.

The analysis in this paper can be extended in a number of directions. We now make one substantive suggestion for extending the research described in this paper. Given the work of Roberts and Spence (1976), environmental economists and regional scientists now know that a pure price control instrument (fee or tax) and a pure quantity control (emissions permit scheme) instrument can be combined to create a hybrid control instrument that is part-price and part-quantity in nature. Roberts and Spence (1976) showed that this hybrid control instrument can always be converted into a pure price or a pure quantity control instrument. Therefore, in comparison with either a pure price or a pure quantity control instrument, a regulator will typically do at least as well and possibly much better with this hybrid control instrument.

Building on this basic Roberts and Spence (1976) insight, it would be useful to ascertain whether it is possibly to design a hybrid inspection policy that is part-container and part-temporal in nature. If this can be done, then the next step would be to determine whether this part-container and part-temporal hybrid inspection policy dominates the pure container and the pure temporal inspection policies in terms of, for instance, the *LRENC* criterion. Studies of invasive species management that incorporate this aspect of the inspection policy choice question into the analysis will provide additional insights into a management problem that has considerable economic and biological consequences.

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