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A Theoretical Analysis of Random Inspections and Fines in Invasive Species Management[1]

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Abstract

In this paper, we conduct a theoretical analysis of inspections in a stochastic environment and we shed light on two hitherto unstudied issues concerning inspections in the context of invasive species management. First, given a particular port of entry in a country, we study the properties of a *random* inspection scheme. Second, we compute the average total *fines* that will be collected in the long run by an inspection agency that uses the above inspection scheme to screen arriving ships for the presence of one or more invasive species.

Keywords: Invasive Species, Fine, Random Inspection, Uncertainty

JEL Codes: Q580, C440

1. Introduction

There is no gainsaying the fact that we now live in an era of globalization. The phenomena of globalization in general and shocking recent events involving terrorism in the United States (US), Spain, and the United Kingdom have generated great interest in issues concerning security across the world. In the US in particular, this interest has manifested itself in the substantially increased interest in inspecting goods that are brought into the country from other parts of the world by means of airplanes, trucks, and, perhaps most notably, ships. This concern with seaport security in particular is not misplaced. As *The Economist* (Anonymous, 2006) has recently noted, only about five percent of the containers that bring two billion tonnes of cargo to US seaports are actually inspected. Therefore, it is not difficult at all for all kinds of illegal goods and possibly detrimental animal and plant species to get into the US.

Batabyal (2004), Work *et al.* (2005) and DeAngelo *et al.* (2007) have clearly demonstrated that in addition to transporting goods between regions, airplanes, trucks, and ships have unwittingly also managed to carry all manner of invasive plant and animal species[4] from one part of the world to another. This inadvertent carriage has taken place in many different ways. Three examples follow. First, on occasion, invasive animal species have succeeded in lodging themselves in the landing gear of airplanes and, in this way, they have traveled as stowaways from one part of the world to another. Second, a number of marine invasive species have been introduced inadvertently into a particular part of the world by ships dumping their ballast water. Cargo ships often carry ballast water in order to boost vessel stability when they are not carrying full loads. When these ships come into a seaport, this ballast water must be discarded before cargo can be loaded. Finally, and perhaps most

4 Invasive species are also referred to as alien species, as exotic species, and as non-native species.

significantly, ships and trucks have introduced invasive species into a particular part of the world by means of the containers they routinely use to carry cargo from one part of the world to another. In this context, the reader should understand that invasive species can remain concealed in containers for extended periods of time. In addition, the material such as wood that is commonly used to pack the cargo in the containers may itself contain invasive species.

Biological invasions of new habitats by non-native species have frequently resulted in great losses to society. For the US alone, the extent of these losses is massive. In this regard, Keller and Lodge (2007) have noted that the state of Indiana spends more than $600,000 each year to control a particular invasive species, namely, the *Eurasian watermilfoil*. Similarly, Kolar and Lodge (2001) have pointed out that the total costs of all invasive species is around $137 billion per year. In addition to these economic costs, invasive species have also given rise to serious biological damage. For instance, Vitousek *et al.* (1996) have demonstrated that invasive species can change ecosystem processes, act as vectors of diseases, and diminish biological diversity. Cox (1993) has pointed out that out of 256 vertebrate extinctions with a known cause, 109 are the outcome of biological invasions. The implication of the discussion in this paragraph is clear. Invasive species have frequently been a great menace to society.

Broadly speaking, there are two kinds of managerial actions that one can take to control the spread of invasive species and their deleterious effects. These are *pre-invasion* and *post-invasion* actions. The purpose of pre-invasion actions is to preclude non-native species from invading a new habitat. In contrast, post-invasion actions are intended to control a non-native species, given that this species has already invaded a new habitat. In recent times, several researchers have analyzed a particular kind of pre-invasion action, namely, inspections. McAusland and Costello (2004) have shown that when one considers the future effects of current invasive species introductions, one is led to a course of action that may involve the use of higher or lower tariffs but certainly involves more stringent inspections. Batabyal and Nijkamp (2005) have shown that in an inspection cycle, the so called "container policy" is preferable to the so called "temporal policy" because the former policy leads to lower long run expected net costs from inspections. Using a model of seaport inspections, Batabyal (2006, 2008) has provided a rationale for and has developed aspects of the differential regulatory treatment of imports when invasive species are a potential problem. Batabyal and Yoo (2006) have analyzed the statistical properties of what they call a generic container inspection policy. Finally, DeAngelo *et al.* (2007) have used a queuing theoretic model of inspections to show that the question as to whether there is or is not a tension between the objectives of economic cost reduction and biological invasion damage control cannot be resolved unambiguously.

The papers discussed in the previous paragraph have surely advanced many aspects of our understanding of the role of inspections in invasive species management. Even so, there are two salient issues about inspections that have received *no* attention in the literature. Hence, in this paper, we conduct a theoretical analysis of these two hitherto unstudied issues in a stochastic environment. Specifically, in section 2.1, we describe a stylized model of inspections in which ships—possibly with injurious invasive species—arrive at a seaport in a country called Home. Next, in section 2.2, we study the properties of a *random* inspection scheme. Then, in section 2.3, we compute the average total *fines* that will be collected in the long run by an inspection agency that uses the above inspection scheme to screen arriving ships for the presence of invasive species. Finally, section 3 concludes and then makes suggestions for extending the research described in this paper.

2. The Theoretical Model

2.1. Preliminaries

Consider a port of entry such as a seaport in an arbitrary country called Home.[5] Our subsequent analysis is conducted from the perspective of an inspection agency that has been entrusted with the task of inspecting arriving ships in this seaport for the presence of one or more invasive species. The reader should note that as used in this paper, the term "inspection" refers to the examination of the containers that are used by ships to transport cargo or to the examination of the ballast water occasionally held by arriving ships or to the examination of both containers and ballast water.

Home engages in goods trade with a whole host of nations and hence ships from these various nations arrive in our seaport in Home to unload and/or to load cargo. Now, as noted in Batabyal (2006, 2008), the risk of inadvertent biological invasions in Home typically varies by trading partner. Therefore, consistent with the analysis in Batabyal (2006, 2008), we suppose that our seaport inspection agency has distinct protocols for inspecting the arriving ships from distinct nations. Put differently, ships arriving from country A are treated differently than ships arriving from country B, for any two arbitrary countries A and B. Let us now delineate the random inspection scheme that is the first of two key issues that we are studying in this paper.[6]

2.2. Random inspection scheme

We focus on the ships coming into the seaport under study from some arbitrary country—say

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We stress that our subsequent analysis does *not* depend on the port of entry being a seaport. Our analysis would go through for land ports of entry—such as a border crossing or an airport—as well.

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This random inspection scheme is based on the "continuous sampling" plan first formulated by Dodge (1943) and subsequently extended by White (1966) and by Bebbington *et al.* (2003).

country A—that is also a trading partner of Home. These ships come into the Home seaport over time and sequentially. We suppose that on the basis of previously collected historical data, our seaport inspection agency has determined that there is a fixed probability p that a given arriving ship from country A will have one or more invasive species on it. Hence, such an arriving ship will fail to pass our agency's inspection. We also suppose that whether a particular ship from country A does or does not have a problem with invasive species does not depend on the status of any other ship arriving in the Home seaport from this same country A.

Our seaport inspection agency in Home proceeds as follows. Initially, it inspects every ship from country A until i consecutive ships are found not to have any invasive species on them. Once this happens, our agency then inspects only one out of every r ships from country A at *random* until another ship with one or more invasive species on it is discovered. When this happens, our agency reverts to one hundred percent inspections until i consecutive ships with no invasive species on them are found. The agency's inspection continues in this way. The task before us now is to compute the average fraction of all country A ships that are and are not inspected. In what follows, we shall use the acronyms *AFSI* and *AFSNI* to refer to these two averages. Our computation proceeds in three steps.

In the first step, let state D_k $(k=0,1,2,...,i-1)$ denote the k consecutive country A ships with no invasive species that have been found during the one hundred percent inspection part of the scheme. Also, let state D_i denote the fact that the inspection scheme under study is in the second stage in which one out of every r country A ships is being inspected randomly. Time n follows the nth ship, whether or not it is inspected. Now, the reader should note that the above described sequence of states is a Markov chain[7] with transition probability P_{jk}=*Prob*{*state is* D_k *after* n+1 *ships / state is* D_j *after n ships*}. Mathematically, we have

$$P_{jk}=\begin{cases} p \quad for\ k=0,\ 0\leq j<i, \\ 1-p \quad for\ k=j+1\leq i, \\ p/r \quad for\ k=0,\ j=i, \\ 1-(p/r) \quad for\ k=j=i, \\ 0 \quad otherwise. \end{cases} \tag{1}$$

In the second step, we specify the limiting probabilities for the Markov chain whose transition probabilities are given in equation (1) and then we solve the equations that are satisfied by these limiting probabilities. To this end, let π_k be the limiting probability that the stochastic system we are studying is in state D_k for k=0,1,2,...,i. To solve for these limiting probabilities, we have to specify the equations that these limiting probabilities satisfy. These equations are

$$p\pi_0+p\pi_1+...+p\pi_{i-1}+(p/r)\pi_i=\pi_0, \tag{2}$$

$$(1-p)\pi_0=\pi_1, \tag{3}$$

$$(1-p)\pi_1=\pi_2, \tag{4}$$

and we keep going in this manner until we get to

$$(1-p)\pi_{i-1}+\{1-(p/r)\}\pi_i=\pi_i \tag{5}$$

and

$$\pi_0+\pi_1+\pi_2+...+\pi_i=1. \tag{6}$$

Manipulating equations (3) through (5) we can tell that $\pi_k=(1-p)^k\pi_0$ for k=0,1,...,$i-1$. Similarly, simplifying equation (5) we get $\pi_i=(r/p)(1-p)^i\pi_0$. Having ascertained π_k in terms of π_0 for k=0,1,...,i, we can now use equation (6) and then simplify the resulting expression to get

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[7] For textbook accounts of Markov chains, the reader should consult Taylor and Karlin (1998, chapter 4) or Ross (2003, chapter 4).

$$\pi_0 = \frac{p}{1+(r-1)(1-p)^i},\ \pi_i = \frac{r(1-p)^i}{1+(r-1)(1-p)^i},\ \pi_k = \frac{p(1-p)^k}{1+(r-1)(1-p)^i},\ k=0,1,...i-1. \quad (7)$$

In the third step, we provide explicit closed-form expressions for the two averages of interest, that is, *AFSI* and *AFSNI* respectively. Because each ship is inspected when in states D_0, D_1,...,D_{i-1} but only one out of r ships is inspected in state D_i, we can infer that $AFSI=(\pi_0+\pi_1+...+\pi_{i-1})+(1/r)\pi_i$. Simplifying this last expression and then using the fact that $AFSNI=1-AFSI$, we get

$$AFSI = \frac{1}{1+(r-1)(1-p)^i} \text{ and } AFSNI = \frac{(r-1)(1-p)^i}{1+(r-1)(1-p)^i}. \quad (8)$$

Equation (8) tells us that in the random inspection scheme of this paper, the average fraction of arriving ships from country A that are inspected depends fundamentally on the fixed probability p that a given arriving ship will have one or more invasive species on it and on the positive integer r describing the number of ships out of which one will be inspected at random in the second stage. It is straightforward to verify that when either $p=1$ or $r=1$, our random inspection scheme becomes a deterministic scheme in which all arriving ships from country A are inspected by the agency. Finally, when $p=0$, the average fraction of ships that are inspected depends only on the positive integer r and as r increases (decreases), the average fraction of ships inspected decreases (increases). This completes the discussion of the first of two key issues that we are studying in this paper. We now proceed to the second key issue. This involves computing the average total fines that will be collected in the long run by our inspection agency when it uses the random inspection scheme of this section to screen arriving ships for the presence of invasive species.

2.3. Average total fines

In the previous section, we described the way in which our random inspection scheme would work for ships arriving from a particular country A. However, it is clear that in addition to country A, ships from many other countries—with which Home trades—also arrive in the seaport under study. Further, there is an inspection protocol in place for the ships from every relevant country. Having said this, the next question that arises concerns the status of ships that fail our agency's inspection. In practice, agencies responsible for the management of invasive species in many countries such as Japan and the US levy fines on non-compliant entities.[8] Therefore, in the remainder of this section, we suppose that ships—from all the pertinent countries—that fail our agency's inspection are fined and that the magnitude of these fines depends on the extent to which a particular ship is not in compliance with existing laws and regulations in Home. Put differently, the magnitude (dollar value) of the individual ship fines are *random* variables.

To model this feature of the problem, we proceed as follows. At the beginning of each time period, ships from the various countries with which Home trades arrive in the seaport under study at the times of a renewal process with distribution law given by $F(x)$. We suppose that for every arriving ship, there is an inspector available to inspect this ship. Upon the completion of the inspection process, each ship pays a random fine to our agency and the amounts of this fine are described by the distribution law $G(y)$ where $y>0$.[9] Let $W(t)$ denote the total amount of all the fines

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For a more detailed corroboration of this claim, see Wanamaker (2008) and go to www.env.go.jp/en/nature/as/040427.pdf, www.state.hi.us/dlnr/Aliens3.html, and www.aphis.usda.gov/lpa/pubs/fsheet_faq_notice/fs_phcivilp.html.

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If we were to explicitly separate fine paying ships from non-fine paying ships then the underlying mathematics would get unduly complicated. Therefore, to keep the subsequent mathematics straightforward, we are supposing that every ship pays a fine. The reader should *not* interpret this modeling feature literally. Put differently, the reader should interpret the "fines" paid by ships that pass inspection as a processing fee and not as a punitive measure. Having said this, the salient point to note here is that the individual ship fines are *random* variables and we are explicitly modeling this point.

from the various ships that have been collected by our inspection agency by time t. The outstanding task before us now is to provide an explicit stochastic characterization of the total amount $W(t)$.

To this end, let $Y_1,\ Y_2,\ Y_3,...$ denote the successive individual ship fines and let $N(t)$ denote the total number of ships that arrive in the Home seaport in the time interval $(0,t]$. We can now express the fine total $W(t)$ as a particular sum and that sum is

$$W(t)=\Sigma_{k=1}^{N(t)+1}\ Y_k. \tag{9}$$

The reader will note that the sum $W(t)$ in equation (9) is a random variable. Therefore, it makes sense to focus not on $W(t)$ *per se* but on its expectation $E[W(t)]$. Consistent with the discussion in section 1, the most convenient way to compute the above expectation would be to take a long run view of inspections and fines and compute the limiting expectation given by $\lim_{t\to\infty} E[W(t)]/t$. Now, the theory of renewal processes[10] tells us that $\lim_{t\to\infty} E[W(t)]/t=E[Y]/E[X]$, where Y and X denote the fines and time respectively. The two expectations on the right-hand-side (RHS) of the previous expression can be simplified further. This simplification gives us the limiting expectation we seek in its simplest form. Specifically, we get

$$\lim_{t\to\infty}\frac{E[W(t)]}{t}=\frac{E[Y]}{E[X]}=\frac{\int_0^\infty\{1-G(y)\}dy}{\int_0^\infty\{1-F(x)\}dx}. \tag{10}$$

Equation (10) gives us a closed-form expression for the average total fines that will be collected in the long run by our inspection agency when it uses the random inspection scheme of section 2.2 to screen arriving ships for the presence of invasive species. The information contained

10 For textbook expositions of renewal theory, the reader should consult Taylor and Karlin (1998, chapter 7) or Ross (2003, chapter 7).

in equation (10) can be used to facilitate the general task of invasive species management in two ways. First, this equation can be used to determine whether it is feasible to make the conduct of inspections by our agency a revenue-neutral operation. Put differently, the objective here would be to ascertain whether it is possible to meet the agency's costs with the revenue from the collected fines. Second, equation (10) can play the role of a constraint in an expected net social benefit from inspections maximization problem. The idea here would be to conduct ship inspections efficiently so that the net social benefit from inspections is maximized and, at the same time, the fine based revenue generated by these inspections does not fall below an exogenously given threshold. This concludes our discussion of the second key issue of this paper.

3. Conclusions

In this paper, we conducted a theoretical analysis of inspections in a stochastic environment and we shed light on two hitherto unstudied issues concerning inspections in the context of invasive species management. First, given a particular port of entry, we analyzed the properties of a random inspection scheme. Second, we computed the average total fines that will be collected in the long run by an inspection agency that uses the above inspection scheme to screen arriving ships for the presence of one or more invasive species.

The analysis in this paper can be extended in a number of directions. Here are two suggestions for extending the research described in this paper. First, we treated the probability p that an individual ship from a particular country will have one or more invasive species on it as exogenous to the analysis. Therefore, it would be useful to formally study the estimation of this important probability. Second, following the discussion towards the end of section 2.3, it would be useful to set up and solve an optimization problem involving the efficient allocation of inspection resources and the attainment of a threshold level of revenue from fines. Studies of inspections in invasive species management that incorporate these features of the problem into the analysis will provide further insights into a management function that has significant economic and ecological implications.

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