Inspection, Surveillance, and Biological Invasion

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Abstract

International economic activities have helped species spread into non-native habitats, which cause significant ecological and economic burden of invaded countries. Therefore, an intuitive method to prevent exotic species from invasion is to use tariff or non-tariff trade barriers to limit trade. Nevertheless, restriction on trade has its own costs; and besides, trade barriers may not be available for control under World Trade Organization rules. Thus, to look for options other than trade barriers is crucial to mitigate impact of bioinvasion with trade. This study will build a model to analyze using two other control options, inspection of cargo containers and surveillance programs, in preventing biological invasion via international trade. These results indicate that if a country has fewer imported containers or has a limited budget for prevention, inspection of containers may be a better policy. Otherwise, surveillance is optimal.

1. Introduction

International economic activities, traditionally, are regarded as the major pathways of bioinvasion. Commodities, tourists, vehicles, vessels, or flights from other countries risk bringing invasive species across national borders. This argument is supported by numerous empirical studies at seaports and airports around the world. A survey in Australia found exotic insects in 40% of imported sea cargo containers (Stanaway et al., 2001). New Zealand Customs has recorded a total 4355 cases of introduced ants in incoming commodities, including 115 species from 52 genera (Ward et al., 2006). Caton et al. (2006) evaluate the risk from hitchhiking pests on cargo aircraft at Miami and find an overall contamination rate of 10.5%.

Many policies can be used to reduce risk of bioinvasion associated with international trade. Implementing fumigation and heat treatment before transporting commodities may eradicate nuisance hitchhikers and interrupt their spread. Inspection and quarantine of products can monitor invasive species after commodities are imported and prevent them from entering home countries. These policies are regarded as non-tariff trade barriers, which focus on eradication of invasive species in commodities. On the contrary, tariff barriers, such as Pigouvian taxes, lower risk of introduction of exotic species by reducing import volume.

The use of tariffs to control invasive species has attracted many researchers' interests.

Jenkins (1996) argued that tariffs should be used to decrease imports and to mitigate the threat of invasive species. Recently developed analytical models further clarify the interaction between tariffs and the risk of bioinvasion (Costello and McAusland, 2003; Margolis et al., 2005; McAusland and Costello, 2004). Although tariffs have their own costs, they still work to control invasive species in some circumstances.

The effectiveness of non-tariff barriers has also been quantified. Bartell and Nair (2004) evaluate the risk reduction associated with fumigation and heat treatment of commodities. Economic issues related to effectiveness and efficiency of the effects of quarantine on the spread of invasive species via international trade are discussed by Mumford (2002). Other options for lowering invasion risk from international trade, such as debarking and removing woody packing materials from imports, have also been studied (Maguire, 2004; Olson and Roy, 2005; Prestemon et al., 2006).

Among policies for invasive species control, the role of surveillance on preventing invasion due to trade is less often addressed. Surveillance has shown its effectiveness in control of invasive species. The "Slow-the-Spread" program in USA uses pheromone-baited traps to locate populations of gypsy moths beyond population frontiers and then eradicate those isolated populations. This program has dramatically reduced the spread rate by more than 70%, from 13 miles per year, the historical average, to 3 miles per year (Tobin et al., 2004). Another successful case is New Zealand's national invasive ant surveillance program. After confirming invasion of RIFA, New Zealand took action to eradicate RIFA immediately and started a fire ant surveillance program at the same time. In a sea port without prior information about invasion of RIFA, a surveillance team found RIFA in attractant bait traps and then found and eradicated the RIFA's small colony. These active surveillance actions made New Zealand a RIFA-free country (MAF, 2005). Although these successful cases of surveillance programs exist, theoretical analyses on the relationship between surveillance and invasion risk from international trade are still limited.

Discussion of inspection on imported cargo containers and invasion risks is also lacking. Rather than general fumigation and heat treatment to eradicate hitchhikers in commodities or in packing materials, inspection of imported containers tries to detect infection of invasive species during transportation of containers. Invasive species may fly or walk into containers which are not targets of some control options in open areas waiting for export or for transit. Therefore, containers have been identified an important pathway of bioinvaison; this argument also gets supports from empirical studies. Inspection programs carried out in Australia, New Zealand, the USA and other regions all record many live or dead exotic species on the floors of containers and in soil stuck to the bottoms of containers (Caton et al., 2006; Stanaway et al., 2001; Ward et al., 2006; Whinam et al., 2005; Work et al., 2005). Thus, analyses of trade-related plans to prevent the spread of invasive species should give more consideration to inspection of cargo containers.

Besides these technical reasons, inspection and surveillance activities are important for small island countries' bioinvasion policies because of their lack of economic power in the international trade system. To increase tariff or non tariff trade barriers may cause trade disputes among countries. Some empirical cases have shown that trade barriers based on a home country's environmental concerns are often rejected by the World Trade Organization (WTO). Even though a given country can apply some barriers on trade temporarily, those barriers may have to be abandoned after the WTO's judgment (Appleton, 1999; Copeland and Taylor, 2004; Melser and Robertson, 2005; Neumayer, 2004). Inspection and surveillance activities, however, are domestic policies, which cause fewer disputes than trade barriers under multilateral trade mechanisms.

This study will build a model to analyze the trade-off of inspection of cargo containers and surveillance programs in preventing biological invasion via international trade, not only because these two policies are less analyzed in the economic literature and fit to island countries' needs, but also because they are more appropriate options for control of RIFA, a new threat for the tropical Pacific islands. RIFA's spread behaviors make commodities during transportation at higher risk of infection of RIFA than during production or packing processes. RIFA can spread by flying or by walking. Flying queens are attracted to vehicles, cargo containers, and ships because of light reflection from such equipment. Thus, any of these vehicles in open areas close to RIFA colonies are at risk of hitchhiking RIFA. Once disturbed during transportation of infected containers, RIFA also may move to other nearby containers or vehicles. Therefore, treatments on commodities are less effective at controlling infection of RIFA and other invasive species with similar spread patterns. Inspection and surveillance, however, may fill this gap in prevention measures.

The following sections will present a general model to analyze inspection and surveillance and their effect upon bioinvasion from international trade. Specifically, RIFA populations in Taiwan are used as a case for empirical analysis. Because information about how RIFA spread via international trade or transportation of cargo containers is limited, I adopt results from research evaluating the invasion risk of RIFA with cargo containers imported to Australia for parameters and conduct a sensitivity analysis to justify results with uncertain parameters.

2. Theoretical Model of Prevention of RIFA in Taiwan

This section considers alternative strategies for reducing the probability of introduction of RIFA. The probability of introduction is a function of the number of containers imported, v, and each container’s infection probability, p. Thus, the probability of invasion of RIFA can be presented as f(v, p). If the discounted total cost of infestation of RIFA, which is calculated in chapter four, is C, then the expected cost of RIFA's invasion can be expressed as *C'*=*C**f(v,p).

Assume that inspection of incoming shipments[1] and surveillance around ports[2] are two major strategies for preventing RIFA entry. If Taiwan inspects *b* units of containers with unit cost P_b to decrease the probability of RIFA passing the border by g(b), the chance of RIFA's arrival in Taiwan is 1-g(b). If Taiwan pays *s* units to monitor RIFA resulting in a detection rate of h(s), the invasion probability is 1-h(s). If Taiwan pursues both strategies to prevent the introduction of RIFA, the projected success rate of RIFA's invasion is (1-g(b))*(1-h(s)).

If the preventative actions are successful, then the invasion of RIFA is deferred by one year. The expected discounted cost of RIFA invasion will become C'/(1+r). The difference, rC'/(1+r), is the benefit (reduced cost) of one year of successful prevention. Under any pair of *b* and *s*, there is a probability of 1-(1-g(b))*(1-h(s)) of detecting and preventing the introduction of RIFA successfully. The expected benefit is therefore rC'/(1+r)*[1-(1-g(b))*(1-h(s))], and the costs are P_b*b and P_s*s. The net benefit is rC'/(1+r)*[1-(1-g(b))*(1-h(s))]- P_b*b and P_s*s.

Each year, the social planner's decision-making problem is

[1] Inspection on border means to inspect the external and internal surfaces of imported containers during unloading and to decontaminate containers if RIFA is found (MAF, 2002).

[2] Surveillance includes visual survey and laying pit fall and baited ground traps to ensure that no RIFA colonies are established around airports (MAF, 2002).

$$\underset{\{b,s\}}{\text{Max}}\ \frac{\mathrm{r}}{1+\mathrm{r}} C'\{1-[1-g(b)]*[1-h(s)]\} - P_b * b - P_s * s \tag{1}$$

Let

$$\mathrm{C}_1 = \frac{\mathrm{r}}{1+\mathrm{r}} C'$$
$$g_1(b) = 1 - g(b)$$
$$h_1(s) = 1 - h(s)$$

and assume[3] $g'(b) > 0,\ g''(b) < 0,\ h'(s) > 0,\ h''(s) < 0$.

We can rewrite equation 1 as

$$\text{Max}\ C_1[1 - g_1(b) * h_1(s)] - P_b * b - P_s * s\ , \tag{2}$$

and get first order conditions (FOC's) of:

$$-C_1 g_1^{'}(b) h_1(s) - P_b = 0$$
$$-C_1 g_1(b) h_1^{'}(s) - P_s = 0.$$

Optimal values of *b* and *s* can be derived by rearranging the first order conditions:

$$g_1^{'}(b^*) = \frac{-P_b}{C_1 h_1(s)}$$
$$h_1^{'}(s^*) = \frac{-P_s}{C_1 g_1(b)}$$

or

$$g'(b^*) = \frac{P_b}{C_1(1-h(s^*))},$$
$$h^{'}(s^*) = \frac{P_s}{C_1(1-g(b^*))}. \tag{3}$$

If the expected cost of RIFA (C_1) increases, the optimal inspection on containers (b^*) or

[3] These assumptions imply that inspection and surveillance can detect invasive species, but the marginal detection rate is decreasing. If inspection and surveillance cannot detect invasive species, they are not of interest for policy-making. If the marginal detection rate is not decreasing, a country may have zero probability of introducing invasive species when the country put forth high enough effort to do inspection and surveillance.

surveillance s^* also must increase.

3. Empirical analysis of Taiwan

The probability of invasion of RIFA, f(v, p), depends on the number of containers imported, v, and the infection rate of each container, p. The probability that all containers do not have RIFAs is $(1-p)^v$, therefore f(v, p)=1- $(1-p)^v$. Stanaway et al. (2001) surveyed 3001 randomly selected containers in Australia and found dead RIFAs in one container. Because the share of importation into Australia from RIFA infected regions is 18% (Australian Bureau of Statistics, 2006), the probability of a container infected by RIFA is 1.83×10^{-3}. This is not the final probability of introduction of RIFA to Taiwan, because RIFA individuals may be dead during transportation, as in this case in Australia. Due to lack of information about the survival rate of RIFA in transportation, 0.1% is taken as the rate for the following analysis, and the introduction rate of RIFA becomes 1.83×10^{-6}. Other survival rates, 10%, 1%, and 0.01%, are selected for sensitivity analysis in the next section.

Taipei International Airport annually receives 38,932 containers from RIFA infected regions (USA, Brazil, Australia, and New Zealand),[4] and the probability of any given container from a

[4] I assume that only containers exported by these four countries are at risk of infection of RIFA, and Taiwan may only inspect these containers. However, this assumption may be incorrect. First, containers exported by other countries but transited via these four countries also can carry RIFA to Taiwan. Second, containers from these four countries transmitted to other countries via Taiwan may also bring RIFA to Taiwan. Third, containers shipped to Taiwan from other countries may become RIFA- infected from containers on the same flight which are exported by

region infected by RIFA introducing RIFA into Taiwan is 1.83×10^{-6}. Thus, annual probability of introduction of RIFA to Taiwan is 0.069. Because import rates may vary with Taiwan's and these four countries' economic status, the sensitivity analysis section will discuss how change in number of containers imported influences results as well.

The cumulative probability of the failure of surveillance measures can be estimated based on the New Zealand National Fire Ant surveillance programme (NIAS). In NIAS, surveillance activities are restricted to risk areas in international sea ports and airports (O'Connor, private communication, 2006). O'Connor[5] provides data on the cost and rate of detection of RIFA surveillance under NIAS. Assume the rate of detection is a logistic function of budget (Currie, 2005). Based on the data from NIAS, h(s) is

$\exp(-10.75+2.1\times10^{-6}\times s)/(1+\exp(-10.75+2.1\times10^{-6}\times s))$, where *s* is the surveillance expenditure.

If containers are selected randomly for inspection and *b* containers are checked, then the number of risky containers decrease by *b* or *b/v**100%. Thus, g(b) is b/v.

Because $g''(b)$ equals zero, the solution of equation 3 is a saddle point[6] rather than an optimum

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these four countries to countries other than Taiwan. Forth, even in the same country, the risks are various across airports. Because there is not enough information to deal with these four issues, I can only assume that containers from these four countries have the same risk of carrying RIFA.

[5] Director of New Zealand National Fire Ant surveillance programme.

[6] Assume b* is the solution of g'(b)=0. If g''(b*)>0, then b* is the minimum. If g''(b*)<0, then b* is the maximum. If g''(b*)=0, then b* is neither minimum or maximum and is a saddle point. Because g(b)=b/v and g''(b)=0, thus b* is a saddle point.

solution. Whether the solution is maximum or minimum depends on its location, the value of s*. The solution can be derived by iteration. A summary of iteration steps is listed in table 1 (refer to tables 4.1 to 4.10 for costs of RIFA (C)). Given the optimal budget for surveillance, the net benefit of inspection decreases as more containers are inspected (Table 2). The optimal prevention strategy is to spend US$258,000 for surveillance and none to check containers.

If the budget to prevent RIFA is limited and less than US$ 258,000, the optimal strategy for prevention depends on how much money is available. Surveillance is still the optimal choice when the budget is higher than US$115,000. If the budget is less than US$115,000, inspection generates a higher net benefit than surveillance[7].

A combination of these two strategies is worse than one alone (Table 2). If the prevention budget is less than US$ 115,000, the marginal benefit of any surveillance input is smaller than that of inspection and all budgets should be used in inspection of RIFA. Other wise, the marginal benefit of any spending on surveillance, which is over US$ 115,000, is higher than inspection; surveillance should be the only strategy used in this circumstance.

[7] Surveillance is aimed at the risk from total containers imported. One more container imported has an ignorable marginal cost to the surveillance system. Nevertheless, inspection is aimed at individual containers directly and a cost is ascribed each inspection. From the cost perspective, inspection has the same marginal cost with no fixed cost, but surveillance has decreasing marginal cost with fixed cost. Thus, inspection may be preferred when the number of containers imported is few.

4. Sensitivity Analysis

Empirical case studies have shown a significant introduction rate of invasive species in general. Nevertheless, these results are not enough for statistical tests of significance. Besides, because such research focuses on multiple species, its results may not be appropriate for analysis of an individual species. Thus, findings in the last section, which adopt parameters from those empirical studies, may not be valid if invasion rates are different across species.

Because the empirical surveys on the invasion rate of each species, including RIFA, are still limited, there is no more precise data available for this analysis. This dilemma makes the results of essential prevention analysis questionable. I use sensitivity analysis to deal with this issue. If change of parameters has little effect on the results in sensitivity analysis, conclusions in the prior sections should be reliable even though the parameters used are uncertain; other wise, more accurate surveys are necessary for making conclusions and devising prevention strategies.

The parameters considered for sensitivity analysis here are the introduced infection rate of RIFA per container and total containers imported to Taiwan. Introduced infection rate is determined by infection rate at export ports and the survival rate of each container. For two reasons, these two parameters will not be discussed individually. First, policies which used to control these two rates are not included in the analysis. Next, introduced infection rate determines the final expected impact after import. Thus, only introduced infection rate is used for validation.

Another parameter which effects invasion rate of RIFA is number of containers imported. Although this figure from the customs' record is reliable, it may change from year to year. It is therefore important to test how change in number of imported containers can show how a country, such as Taiwan, may adjust its prevention strategies according to its own (expected) trade status. Besides, other things being equal, this result also shows how countries having the same expected damage but with different trade volumes should respond to threat of RIFA.

Introduced infection rates of RIFA selected for the sensitivity analysis are 1.83×10^{-4}, 1.83×10^{-5}, and 1.83×10^{-7}. Number of containers imported are analyzed from -75% to +75% of reference cases at 25% increments. Results are listed in table1 and table 2. These results show that change of surveillance is not extremely sensitive to each of these parameters; level of optimal surveillance is positively associated with introduced infection rate and containers imported; inspection is preferable when the budget available for preventing invasive species is less than a threshold value.

One of the most important findings of the sensitivity analysis is that change of surveillance is little sensitive to either introduced infection rate or number of containers imported. Given a specific introduced infection rate, 1.83×10^{-7} for example, the maximum change rate for optimal surveillance is 8% when container numbers are reduced by 75%. On the other hand, given imported containers, the maximum change rate of optimal surveillance is 21% when infection rate is increased by 100 times. Therefore, conclusions in the last section should be valid even when the parameters are not certain.

The second finding is that optimal surveillance is positively associated with introduced infection rate and number of containers imported. This correlation is consistent with economic intuition. The optimal quantity of surveillance increases when marginal benefit of surveillance rises. Increase of either infection rate or number of imported containers raises the invasion risk of RIFA and the expected damage, thus the marginal benefit of surveillance also increases.

Surveillance is still the optimal strategy for highly trade-dependent countries. If a country has the same expected damage but the country has 75% more containers than Taiwan, cost of the optimal surveillance for that country will be 0% to 4% higher than that of Taiwan, depending on the infection rate. Because increased surveillance cost is so limited compared with the increase in number of containers imported, surveillance is preferable over inspection when the country has higher trade volume.

5. Conclusion

Small island countries are more trade dependent but have less international market power in setting trade requirements. Though they are at risk of bioinvasion, they have limited options in terms of invasive species control strategies. This analysis focuses on small island countries' prevention strategies for invasive species, and especially examines inspection and surveillance available to those countries. Results of analysis show that surveillance is the best option for such countries to control bioinvasion when it is affordable. If surveillance is not affordable, the optimal strategy depends on the scale of countries' prevention budgets.

For Taiwan, surveillance should be the preferred strategy for preventing the introduction of RIFA. The optimal budget for surveillance (USD $258,000) is about 5×10^{-8} of Taiwan's total governmental expenditures in 2004. Therefore, the optimal level of surveillance is an affordable option for Taiwan. If Taiwan allocates a prevention budget of more than USD $258,000 per year, Taiwan should only use surveillance activities to prevent RIFA from entering Taiwan and only use USD $258,000 for these activities. If the available budget for RIFA prevention is no more than USD $115,000 in Taiwan, inspection of containers becomes Taiwan's optimal option for RIFA control. Inspection of containers would also be preferred if fewer containers were imported. Thus, the optimal strategy for prevention depends on budget level and number of containers imported.

These results may be generalized for developing the prevention policies of other island countries. If a country has fewer imported containers or has a limited budget for prevention, inspection of containers may be better policy. Otherwise, surveillance is optimal.

Any combination of these two options will lower net benefits. Only one of these two strategies should be adopted at a time. This result comes from the assumption of function of surveillance. This assumption implies the economics of scale of surveillance input.

These results are validated by a sensitivity analysis, which shows that these suggestions have negligible sensitivity to the parameters included in analysis. However, some other factors not included in this analysis may influence conclusions. Success rate of inspection and escape of RIFA during transportation of infected commodities are two examples of such factors.

This study assumes that all inspection is successful, which means any inspection on a given container can find invasive species if the container is infected. However, many case studies show this assumption is faulty. The effectiveness of detecting exotic ant species at the New Zealand border ranges from 48–78% (Ward, et al., 2006). Work et al. (2005) suggest that the successful detection rate on the US–Mexico border is only 19–28%. Low success rate of inspection makes inspection less efficient.

Surveillance programs, however, also have their own problems. Surveillance activities can work well when invasive species escape and spread only from entrance ports. Nevertheless, invasive species can still escape from commodities during transportation after leaving ports. Therefore, the efficiency issues of surveillance may be overlooked in this model.

The assumption of no market power of small island countries is the other weakness of this model. An individual island country may have no power to negotiate trade barriers with other large countries. However, those countries may form a trade group to set requirements related to bioinvasion with other big countries. This coordinate action should improve management of invasive species in such countries.

Although sensitivity analysis has proven these results robust, various assumptions may influence conclusions. These strict assumptions are necessary for this study because of the lack of data at the time of research. However, these data may be collected by further research. Each assumption in this study indicates a kind of information associated with invasive species control policy. How invasive species reach airports, how the species spread and survive during transportation, and how the species relocate in transit are all relevant to control policy. Future research should address these issues to provide information to improve results of analyses.

Research efforts on control of international spread of invasive species have been focused directly or indirectly on commodities. However, other control options which are not targeted on commodities also work on invasive species prevention. This study highlights the role of surveillance activities on bioinvasion caused by international trade. Furthermore, this study also calls attention to the spread of invasive species through transportation or transit among regions and countries.

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Tables

Table 1. Budgets and net benefits of prevention (in USD).

Budget	h(s)	g(b)	Net benefit with surveillanve only	Net benefit with inspection only
30,000	0.0002	0.018	-270,000	305,000
45,000	0.0005	0.028	-36,000	457,000
60,000	0.001	0.037	-34,000	610,000
75,000	0.004	0.046	-1,000	762,000
90,000	0.012	0.055	120,000	915,000
106,000	0.032	0.064	486,000	1,067,000
121,000	0.087	0.073	1,476,000	1,220,000
136,000	0.215	0.083	3,791,000	1,372,000
151,000	0.439	0.092	7,870,000	1,525,000
166,000	0.691	0.101	12,462,000	1,678,000
181,000	0.865	0.11	15,623,000	1,830,000
196,000	0.948	0.119	17,133,000	1,983,000
212,000	0.981	0.128	17,724,000	2,135,000
227,000	0.993	0.138	17,931,000	2,288,000
242,000	0.998	0.147	17,995,000	2,440,000
258,000	0.9992	0.156	18,008,000*	2,598,000
272,000	0.9997	0.165	18,002,000	2,745,000
287,000	0.9999	0.174	17,991,000	2,898,000
303,000	0.9999	0.184	17,977,000	3,050,000

*Maximal net benefit

Table 2. Net benefit of inspection given optimal surveillance (in USD).

Budget of inspection	g(b)	Net benefit
0	0	18,008,000
1,000	0.0006	18,007,000
2,000	0.0013	18,006,000
3,000	0.0018	18,005,000
6,000	0.0036	18,002,000
9,000	0.0055	17,999,000
12,000	0.0073	17,996,000
21,000	0.013	17,987,000
30,000	0.018	17,978,000

Table 3. Sensitivity analysis of containers imported and infection rate (in USD)

	Change of containers imported						
Infection rate	-75%	-50%	-25%	0%	+25%	+50%	+75%
1/5470	295,000	298,000	298,000	298,000	298,000	298,000	298,000
1/54700	270,000	279,000	285,000	288,000	288,000	292,000	292,000
1/547000	242,000	248,000	255,000	258,000	261,000	264,000	267,000
1/5470000	206,000	215,000	221,000	224,000	227,000	230,000	233,000