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A model of optimal import phytosanitary inspection under capacity constraint

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Abstract

Growth and liberalization of world trade have increased the risks of introduction of quarantine plant pests into importing countries. Import inspection of incoming commodities is a major tool for prevention of pest introductions related to world trade, but inspection capacities are limited. This article develops a theoretical and an empirical model for the optimal allocation of inspection effort for phytosanitary inspection of imported commodities when the inspecting agency has a limited capacity. It is shown that the optimal allocation of inspection effort equalizes marginal costs of pest introduction across risky commodity pathways. The numerical illustration finds the optimal allocation of inspection effort of chrysanthemum cuttings imported in the Netherlands. The numerical results suggest that *ceteris paribus*, greater inspection effort should be allocated to pathways whose inspection yields a greater reduction in the expected costs of pest introduction. The numerical results also suggest that import inspection has a high marginal benefit. In particular, we found that each additional euro of the inspection capacity decreases the expected costs of pest introduction from 18 to 49 euros, depending on the initial inspection capacity.

JEL classification: Q17, Q51

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1. Introduction

International trade is the major vector for spread of quarantine plant pests and diseases in the world (Campbell, 2001). Quarantine pests are those pests that have potential economic importance to the area endangered thereby and not yet present there, or present but not widely distributed and being officially controlled (IPPC, 2006a). The yearly economic costs from the introduction of quarantine pests may reach tens of billions of dollars (Pimentel et al., 2005). Border phytosanitary inspection is a key element of the quarantine policy and is often a last barrier where quarantine pests associated with imported commodities can be intercepted. Inspections usually focus on agricultural, horticultural, and forestry products because these products pose the largest risks of carrying pests. Commodities belonging to these product groups have been responsible for introducing many plant pests in different parts of the world (Kiritani and Yamamura, 2003; National Research Council of the United States, 2002).

Inspecting agencies face ever-increasing volumes of imported commodities that require inspection. The range of commodities to be inspected is broad and expanding, especially in large importing countries. For example, the recent amendments to the European Union (EU) Directive 2000/29/EC (European Council, 2000)—the main document specifying the list of commodities requiring inspection upon import in the EU—implied a significant increase in the range of commodities to be inspected (European Commission, 2002a). At the same time, resources available for import inspection are limited (U.S. Office of Technology Assessment, 1993). In the United States, resources to conduct spot checks of less than 2% of all incoming shipments at borders, air, and seaports are available (National Research Council of the United States, 2002). In New Zealand, only about 18% of more than 300,000 containers imported annually can be inspected (Hayden cited in Everett, 2000). It should be noted that although in most cases importers pay fees that should cover (at least, partially) the inspection costs, it may still be impossible to fully inspect imported commodities because of, for example, the shortage of qualified inspectors (Simberloff, 2006).

To deal with the problem of limited resources, some countries introduced reduced inspections of certain commodities. Recently, in the EU the system of "reduced checks" has been

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introduced (European Commission, 2002b). Under this system, commodities (mainly cut flowers and fruits) from some countries may be inspected with a reduced frequency. However, the scientific underpinning for the "reduced checks" system is unclear. In the United States, import inspection is generally based on random sampling from the population of arriving commodity shipments (U.S. Department of Agriculture, 1998). It was, however, noted that the U.S. Animal and Plant Health Inspection Service had little assurance that the limited inspection resources were allocated efficiently because of the weaknesses in the staffing model used to make such decisions (U.S. General Accounting Office, 1997, p. 7).

The allocation of resources for import inspection has received little attention in the agricultural and resource economics literature. Existing studies theoretically analyzed a related but a more general issue of the economics of biological invasions[1] (see Olson, 2006, for a review). The main finding from this literature is essentially a first-best allocation of resources, that is, marginal costs of preventive measures should be equal to the expected marginal benefits (avoided pest costs) (e.g., Horan et al., 2002; Perrings, 2005). None of the studies in this literature recognized that in reality there are binding capacity constraints that may not allow reaching first-best outcomes (Barrett and Segerson, 1997). Another limitation of this literature is that it is entirely theoretical; no empirical applications of how the resources should be allocated are presented. Batabyal and Yoo focused on properties of import inspections in invasive species management (see Batabyal and Yoo, 2006, and references therein). Yet, neither the likelihood nor costs of pest introduction[2] factored in their analysis of resource allocation for import inspection, which is counterintuitive and strongly contradicts the regulatory[3] literature. Also, these authors have not accounted for the presence of a capacity constraint in import inspection.

More attention has been paid to the use of import tariffs as a regulatory measure (see Paarlberg et al., 2005, and references therein). Authors in this literature calculated import tariffs tailored to the risk of introduction of animal diseases, such as foot-and-mouth disease. McAusland and Costello (2004) analyzed the optimal policy mix of import tariffs and border inspections and concluded that when the proportion of infected commodities from a certain country is high, border inspection should be zero, replaced by a prohibitively high tariff. However, their analyses may have a limited value since it is unlikely that such tariff discrimination is allowed under the WTO rules. It is also unlikely that imported commodities have at present high rates of infestation by quarantine pests because this is against exporting countries' interests.

A general problem with the use of tariffs is that they are not a designated regulatory measure under the International Plant Protection Convention, which underpins the WTO Agreement on Application of Sanitary and Phytosanitary Measures (SPS Agreement). Thus, using the wording of Roberts (1998), tariffs may not be "rebuttably presumed" to be in compliance with the SPS Agreement. Accordingly, there is no evidence that any importing country has actually implemented tariffs tailored to the risk of introduction of a harmful pest or disease. Conversely, import inspection is a recognized regulatory measure applied worldwide but has been scarcely studied in relevant literature.

This article makes two distinctive contributions. First, motivated by the above-mentioned gaps in the agricultural economics literature, the article develops a model of constrained resource allocation for quarantine inspection of imported commodities. In this model, the agency needs to allocate its limited inspection capacity to minimize the expected costs of pest introductions associated with imported commodities. The only quarantine measure available is the import inspection of imported commodities. Thus, our model assumes that the agency accepts all the imported commodities and only needs to determine how these commodities should be inspected given the available capacity. The second contribution of the article is an empirical application that shows *how* the theoretical model can parameterized. Thus, we intend to fill in the gap in the literature on optimal management of invasive species, which is predominantly theoretical. The empirical application in the article focuses on finding an optimal inspection regime of chrysanthemum cuttings imported in the Netherlands.

The remainder of the article is structured as follows. First, a conceptual model is presented, followed by the application. The final section presents discussion and conclusions.

2. Conceptual model of optimal capacity allocation

Consider a country H that imports j commodities from i exporting countries in period t. Henceforth, each exporting country–commodity combination is referred to as a pathway. Let q be the pathway index and assume that there are Q ($q = 1, \ldots, Q$) pathways. Assume that each of the Q pathways may serve as a vector for k ($k = 0, \ldots, \kappa, \ldots, K$) quarantine pests. Assume further that $k \in [0, \kappa]$ pests are already established in H. As a result, the economic costs associated with the introduction[4] of the kth pest, d_k, may vary depending on whether this pest is already established in H or not. If the pest has already been established, then the economic costs due to new introductions have limited spillover effects for the economy or

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[1] Biological (biotic) invaders are species that establish a new range in which they proliferate, spread, and persist to the detriment of the environment (Mack et al., 2000).

[2] In Batabyal and Yoo (2006, p. 2), the costs of pest introduction were postulated as "stoppage in economic activity . . . " due to containers being inspected. It is questionable that such a definition correctly represents the actual costs that introduction of an invasive species imposes on society.

[3] According to the International Standard for Phytosanitary Measures (ISPM) no. 11 "Pest Risk Analysis for Quarantine Pests" (IPPC, 2006b), the likelihood and the associated economic impacts of pest introduction are to be taken into account when the appropriate risk management options are considered.

[4] Essential terminology and notation used in this article are presented in appendix.

trade.[5] Introduction of a new pest in H implies both direct (e.g., losses due to damaged or destroyed crops) and indirect costs (among others, higher future production costs due to higher application of pesticides, profits' decrease due to possible trade restrictions or environmental impacts). We assume that domestic prices for crops, which may be affected by pest outbreaks, are world market prices and hence changes in supply due to pest outbreaks would have only marginal impacts on prices in country H. Further, we assume that d_k is given by the present value of all the costs associated with the introduction of the kth pest, given the distinction between pests introduced above.

The probability of introduction of a pest, p_{qk}, via the qth pathway is the product of its probabilities of establishment $s_k(h_k)$ and entry $u_{qk}(V_q,\gamma_{qk},\alpha_{qk})$, that is:

$$p_{qk} = s_k(h_k)u_{qk}(V_q, \gamma_{qk}, \alpha_{qk}). \tag{1}$$

where $s_k(\cdot)$ depends on the conditions for survival existing for the kth pest in the importing country, denoted as h_k. $u_{qk}(\cdot)$ is a nondecreasing continuous function of the volume of import through the qth pathway, V_q, and the proportion of import infested with the kth pest, γ_{qk}. Also, the probability of entry u_{qk} depends on the probability α_{qk} that an import inspection applied with respect to imported commodities fails to detect a pest. We discuss α_{qk} in more detail below.

Following Horan et al. (2002), we assume that the probability of introduction p_{qk} via the qth pathway is independent of introductions via other pathways. This assumption requires that p_{qk}'s are small[6] for $\forall\, q,k$. This requirement implies that the agency accepts imported commodities along all the pathways: otherwise, if p_{qk}'s are too high for some pathways, H may simply impose an import ban on commodities imported through these pathways.

In the absence of any preventive quarantine measures, the present value of economic costs of k pests associated with the qth pathway is given by the sum of their economic costs d_k weighted by the respective probabilities of introduction p_{qk}, that is, $D_q = \sum_k p_{qk} d_k$. Thus, pathways with a larger number of pests (higher k), more dangerous pests (higher d_k), or higher probabilities of introduction p_{qk}, *ceteris paribus*, imply higher expected pest costs. The economic impact of a given pest depends largely on the biological characteristics of a pest itself (e.g., how fast it can spread). In turn, the range of pests associated with a given pathway is a result of the interplay of the commodity (how suitable is the commodity as a host for the pest) and the country (whether the conditions in an exporting country are suitable for certain pests) factors. Hence, identical commodities coming from different countries may have different pest ranges; as a result, the expected pest costs associated with these pathways may differ. Crop protection measures applied in the exporting countries influence p_{qk}; thus, pathways associated with countries with more effective crop protection measures and stricter export inspection procedures, which lower the probability of exporting an infested commodity, will have, *ceteris paribus*, lower p_{qk}'s and, thus, imply lower expected pest costs.

We assume that the agency's objective to minimize the expected pest costs from all pathways and import inspection of incoming commodities is the only available preventive measure. Inspection entails a visual examination of a sample taken from each arriving lot. If at least one specimen of a quarantine pest is detected in the sample, the entire lot is rejected for import; otherwise, it is freely imported. We assume that the inspection is not pest-specific; hence, sampling methods are not restricted to specific pests. The probability of an inspection error—the failure to detect a pest when it is present in a lot—is denoted as $\alpha_{qk}(b_q, \Omega_{qk}) \in [0,1]$, where α_{qk} is assumed to be a function of two variables: the capacity b_q available for inspection of lots coming through the qth pathway and a stochastic and unobservable variable Ω_{qk} that captures the variation in the probability of detection of different pests. Furthermore, Ω_{qk} accounts for characteristics of individual pathways that may influence the detection probability of a given pest (e.g., the way commodity units are arranged in a lot, the type, and way of packaging, etc.).

The problem of the agency is to choose α_{qk} as a function of the capacity b_q allocated for a given pathway. We assume that $\frac{\partial \alpha_{qk}}{\partial b_q} < 0$ and $\frac{\partial^2 \alpha_{qk}}{\partial b_q^2} \geq 0$, $\forall\, q,k$. Thus, the marginal productivity of import inspection is decreasing.

Furthermore, we assume that the probability of pest entry u_{qk} is also a convex function of the inspection capacity b_q. Specifically, we need to have $\frac{\partial u_{qk}}{\partial b_q} = \frac{\partial u_{qk}}{\partial \alpha_{qk}} \frac{\partial \alpha_{qk}}{\partial b_q} < 0$ and $\frac{\partial^2 u_{qk}}{\partial b_q^2} = \frac{\partial^2 u_{qk}}{\partial \alpha_{qk}^2} (\frac{\partial \alpha_{qk}}{\partial b_q})^2 + \frac{\partial u_{qk}}{\partial \alpha_{qk}} \frac{\partial^2 \alpha_{qk}}{\partial b_q^2} \geq 0$. These expressions have required signs, given the earlier assumptions on $\alpha_{qk}(b_q)$, as long as $\frac{\partial u_{qk}}{\partial \alpha_{qk}} > 0$ and $\frac{\partial^2 u_{qk}}{\partial \alpha_{qk}^2} \geq 0\ \forall q, k$. We assume that these conditions, implying that the probability of pest entry is an increasing function of the inspection error, are satisfied. Given the assumed convexity of u_{qk} in b_q and treating the probability of pest establishment s_k as constant, the probability of the kth pest introduction, p_{qk} (Eq. (1)), is a convex function of the inspection capacity b_q, allocated for a given pathway, that is, $\frac{\partial p_{qk}}{\partial b_q} < 0$ and $\frac{\partial^2 p_{qk}}{\partial b_q^2} \geq 0$. Therefore, the prevention efforts of the agency have a diminishing effect on the probability of pest introduction. This is in line with a common assumption that prevention costs have diminishing effects on the probability of an environmental risk (Barrett and Segerson, 1997). In the following, we will write the probability of pest introduction as a function of the allocated inspection capacity, that is, $p_{qk} = p_{qk}(b_q)$.

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[5] New introductions of a pest already present in a country H add new pest populations to the existing ones. The economic impacts in this case will only concern growers that have not been involved in outbreaks from existing pest populations. Similarly, no influence on trade is expected since trade partners should have already been aware of the presence of a pest on the territory of country H.

[6] This assumption also implicitly motivates positive imports along all pathways because pest risks are small compared to benefits resulting from importing commodities by importers in country H.

The expected pest costs associated with the qth pathway, as the function of the inspection measures, are given by $D_q(b_q) = \sum_k p_{qk}(b_q)d_k$. Thus, the agency's efforts influence the probabilities of pest introduction but not their costs.[7] The agency wants to minimize the expected costs of pest introduction from all pathways subject to the total inspection capacity, B:

$$\text{Minimize} \sum_q D_q(b_q), \tag{2}$$

subject to: $\sum_q b_q \leq B, b_q \geq 0\ \forall\, q$.

The relevant Lagrangean is given by:

$$L = \sum_q D_q(b_q) + \lambda\left(-B + \sum_q b_q\right), \tag{3}$$

where λ is the Lagrange multiplier, representing the shadow value of the inspection capacity constraint. The Kuhn–Tucker optimality conditions for (3) are given by:

$$\begin{aligned} \frac{\partial L}{\partial b_q} &= \frac{\partial D_q(b_q)}{\partial b_q} + \lambda \geq 0,\ b_q \geq 0 \text{ and} \\ & b_q\left(\frac{\partial D_q(b_q)}{\partial b_q} + \lambda\right) = 0 \quad \forall q \end{aligned} \tag{4}$$

and

$$\begin{aligned} \frac{\partial L}{\partial \lambda} &= -B + \sum_q b_q \leq 0,\ \lambda \geq 0 \text{ and} \\ & \lambda\left(-B + \sum_q b_q\right) = 0 \quad \forall q. \end{aligned} \tag{5}$$

The interpretation of the optimal conditions is intuitive. Condition (4) implies that the optimal pathway capacities b_q should be allocated such that the marginal pest costs are equalized across all pathways that receive a positive capacity allocation, that is, $\frac{\partial D_q(b_q)}{\partial b_q} = -\lambda\ \forall q$ with $b_q > 0$. Condition (5) means that the capacity constraint should be satisfied with equality in order to have $\lambda > 0$. If the constraint is not satisfied with equality, then λ should be zero. This means that a (small) change in the value of the constraint B will not change the optimal solution. Note that λ shows the marginal benefit of import inspection, which is higher than its marginal cost when $B \to 0$ and lower when $B \to \infty$.

3. A numerical application

We apply the conceptual model to inspections of chrysanthemum cuttings (*CCs; Dendranthema grandiflora*) imported in the Netherlands. Cuttings are a propagation material that goes directly to the production chain; because of that, their risk of introduction and spreading of pests is greater than of, for example, cut flowers, which are destined for consumer market (Roozen and Cevat, 1999). In view of the high phytosanitary risk, the EU Directive 2000/29 prescribes that every lot of propagating materials should be inspected at import. Note that from a regulatory perspective, any optimization of the CCs inspection regime is not needed simply because the current policy requires that every lot of CCs be inspected. Nonetheless, the choice of inspection of CCs for a numerical application is pertinent because, (i) the situation of a limited inspection capacity can easily be created, (ii) the obtained results for any alternative inspection regimes can be compared with a benchmark case of the current policy, in which all lots should be inspected, and (iii) because inspection of CCs has been compulsory, sufficient data for parameterization of the numerical model are available.

The inspection of CCs occupies a large share of the overall inspection workload of the Dutch Plant Protection Service (Plantenziektenkundige Dienst, PD). For example, during 1998–2001, out of more than 135,000 imported lots with ornamental products (including cut flowers, potted plants, and propagation materials) inspected at the Dutch border, approximately 5.3% (7,151) were lots of CCs. In total, lots originated from 28 countries. For numerical analysis, we selected the six largest countries with a combined share of import of approximately 95% in terms of the number of inspected lots (see Table 1). Thus, in the numerical model there are six pathways ($q = 6$) A to F.[8] Next, we defined pest species that have been associated with these pathways. We analyzed data on pest interceptions during import inspections of CCs presented in the two databases: the annual reports of the diagnostic department of the PD for 1998–2000 (PD Diagnostic Department, 1998–2000) and the electronic database of import inspections for 1998–2001.

From these databases, we selected the cases of interceptions of pests that have a quarantine status for the Netherlands.[9] The rationale for restricting our application to quarantine pests was that quarantine pests imply greater economic losses than pests not having this status.[10] According to the data set (Table 1), three quarantine pest species were intercepted in lots coming through the selected pathways in the period 1998–2001: *Bemisia tabaci* (tobacco whitefly), *Thrips palmi* (palm thrips), and *Liriomyza huidobrensis* (serpentine leaf miner). Of these pests, only *T. palmi* has the "absent" status in the Netherlands

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[7] A reviewer suggested that actions of the agency may influence the supply and price of an imported commodity. However, this assumption is justified only if imports have high proportions of infestations. In reality, most commodities currently have low proportions of infestation. If this were otherwise, large shares of imported commodities would be detained at the border, which is not the case now. Thus, in our framework we assume that detention of some shipments due to pest infestation has no noticeable impacts on the import volumes and prices.

[8] We coded the real names of exporting countries for confidentiality.

[9] The quarantine pests for the Netherlands are listed in the EU Directive 2000/29/EC.

[10] In fact, a mere definition of the pest as "quarantine" implies that it has an economic importance compared to a pest not having this status.

Table 1
Inspected and rejected lots of chrysanthemum cuttings, 1998–2001

Parameter	Pathway						All pathways
	A	B	C	D	E	F	
Number of imported lots	2,303	855	594	1,071	1,229	703	6,755
Average lot size (1,000 cuttings)	725	943	1,033	879	552	608	748
Lots rejected due to							
B. tabaci	3	0	0	0	0	0	3
T. palmi	0	1	0	0	0	0	1
L. huidobrensis	0	0	0	1	1	0	2
Nonquarantine pests	3	3	3	6	1	1	17
Total rejected lots	6	4	3	7	2	1	23

Source: Authors' calculation based on the PD electronic database of import phytosanitary inspections and PD Diagnostic Department (1998–2000).

while the other two pest species are currently present (and are officially controlled) in the country (EPPO, 2006). In estimating their costs of introduction, we took the difference in pest statuses into account (see Section 3.2.2).

3.1. Empirical model

The empirical model is specified so as to represent the actual inspection activities of the PD. Currently, the PD charges importers for each minute of inspection of every imported lot of CCs. Specifying the empirical model, we adopt and extend this setting by relating the length and cost of a minute of inspection to the efficacy of inspection (the probability to detect a pest if it is present in a lot). The available inspection capacity is represented by a monetary "budget" constraint.[11] Note that, technically, the PD has no budget constraint. As mentioned in the Introduction, it is usually other constraints, for example, the lack of the qualified personnel, that render the complete inspection of all imported lots impossible. Nonetheless, imposition of a monetary constraint in the empirical model most naturally represents the problem of constrained resources.[12] Therefore, in the empirical model, in year t, the agency needs to choose the length of inspection l ($l = 0, \dots, L$) of every imported lot to:

$$\text{Minimize} \sum_q \sum_k p_{qk} d_k, \tag{6}$$

$$\text{subject to} \sum_q \sum_l b_{ql} \le B$$

$$b_{ql} = n_q \varepsilon_{ql} c_l$$

$$\sum_l \varepsilon_{ql} = 1 \quad \forall q, \quad \varepsilon_{ql} \in [0, 1]$$

$$b_q \ge 0 \qquad \forall q,$$

with $q = $ A, B, C, D, E, F, and $k = $ *B. tabaci*, *T. palmi*, *L. huidobrensis*, where n_q is the expected number of lots through the qth pathway, c_l is the cost of inspection of one lot with l minutes, ε_{ql} is the proportion of lots of the qth pathway inspected with l minutes, and b_{ql} is the cost of inspection of $n_q \varepsilon_{ql}$ lots with l minutes. Probability of introduction p_{qk} as a function of inspection efforts is given by the following expression[13]:

$$p_{qk} = 0.1 \left[1 - \prod_l (1 - \gamma_{qk} \alpha_l)^{n_q \varepsilon_{ql}} \right], \tag{7}$$

where α_l is the error probability not to detect a pest associated with inspection of length l and γ_{qk} is the proportion of lots of the qth pathway infested with the kth pest. For every pathway, the probability of the kth pest introduction p_{qk} is the increasing function of the proportion of lots infested with the kth pest, γ_{qk}, the volume of import along the qth pathway, n_q, and the inspection error α_l. The probability of pest establishment after inspection is assumed equal to 0.1 for all pests in the model.[14] The assumption is based on the "tens rule" of the literature on biological invasions (Williamson and Fitter, 1996), which says that approximately 10% of invading species establish themselves after initial entry.

The model has to find optimal combinations of the proportion of lots ε_{ql} inspected with a given length l and the associated inspection error α_l that minimize the probability of pest introduction (7) and thus the total expected pest costs (Eq. (6)). For simplicity, we assume that α_l is not pest specific; thus, the inspection error is the same for all pests. If none of the lots of a given pathway is inspected (i.e., $\alpha_l = 1 \; \forall \; n_q$), then inspection has no impact on the probability of pest introduction p_{qk}. Equation (7) also implies that the probability of introduction is zero, when $n_q = 0$ or $\gamma_{qk} = 0$.

3.2. Data

3.2.1. Proportion of infested lots

Proportion of infested lots γ_{qk} is one of the key parameters in the model. Historical data (Table 1) show that at most

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[11] Henceforth, we use the word "budget" to express inspection capacity in monetary terms. Thus the phrases "budget constraint" and "capacity constraint" are used interchangeably.

[12] Essentially any constraint can be represented in a monetary form. For example, the limited number of employees to conduct inspections could be expressed as the total funds to pay the direct costs (salary of inspectors). Alternatively, one could impose the same constraint in a nonmonetary form by, for example, specifying the total amount of employee hours available for inspection in a particular year.

[13] Alternatively, p_{qk} could be modeled using a linear approximation, viz., $p_{qk} = 0.1[1 - \prod_l (1 - \gamma_{qk} \, a_l \, \varepsilon_{ql} \, n_q)]$. In this case, however, the part in square brackets may be greater than one for some values of parameters, which is unrealistic. The formula in text avoids this problem. Note that because Eq. (7) is a power function, it is less sensitive to changes in the parameters, for example, inspection error α_l or the number of lots n_q, than its linear approximation.

[14] For example, Horan and Lupi (2005) used the same assumption when modeling the probability of establishment of a number of marine invasive species in the Great Lakes.

Table 2
Parameter values of n_q^{a} and γ_{qk}^{b} for the numerical model

Parameter	Pathway					
	A	B	C	D	E	F
Expected number of lots n_q	600	200	155	250	300	160
Proportion of infestation $\hat{\gamma}_{qk}$						
B. tabaci	0.00336	0.00350	0.00503	0.00279	0.00243	0.00425
T. palmi	0.00130	0.00554	0.00503	0.00279	0.00243	0.00425
L. huidobrensis	0.00130	0.00350	0.00503	0.00442	0.00385	0.00425

[a] Based on the average yearly number of lots imported during 1998–2001.

[b] Estimated using the upper 95% confidence interval (Eq. (8)) applied to historical numbers of inspected and rejected lots (Table 1).

one quarantine pest species was intercepted along pathways A, B, D, and E, and no quarantine pests were intercepted along pathways C and F. Thus, for most pathways, the proportion of lots infested with a particular pest cannot be calculated directly. We assume that the proportion of infested lots is approximated by its upper confidence interval, γ_{qk}^{U}, which can be calculated from the available data. Assuming that the proportion of infested lots γ_{qk} follows the binomial distribution with x successes (number of lots found infested with a pest) and n trials (the total number of inspected lots), the upper confidence interval for γ_{qk} is given by (Couey and Chew, 1986):

$$\sum_{x=0}^{x=s} \frac{n!}{x!(n-x)!} \left(\gamma_{qk}^{U}\right)^{x} \left(1-\gamma_{qk}^{U}\right)^{n-x} = 1 - C, \tag{8}$$

where C is the required confidence level.

Applying Eq. (8) to historical data (Table 1) and taking $C = 0.95$, we calculated $\hat{\gamma}_{qk} = \gamma_{qk}^{U}$ for all the pathways, including those with zero historical numbers of infested lots (Table 2). Estimated $\hat{\gamma}_{qk}$'s are, *ceteris paribus*, higher for pathways with lower historical number of inspected lots (e.g., pathways C and F) and pathways with a greater number of lots infested with a particular pest (pathway A, *B. tabaci*). Values in Table 2 are conservative estimates of the true proportion of infested lots γ_{qk} and may best represent an agency that is risk averse with respect to low numbers of inspected lots and zero historical pest interceptions associated with some pathways. In the former case, the agency has not accumulated sufficient data to consider a particular pathway as safe. In the latter case, the agency assumes that lots from all the pathways have nonzero proportions of infestations with *B. tabaci*, *T. palmi*, and *L. huidobrensis*.

Table 2 also shows the number of lots in year t expected through every pathway, which was taken at the average yearly level of import based on 1998–2001 data.

3.2.2. Costs of pest introduction

We estimated the costs of pest introduction following the approaches of Temple et al. (2000) and MacLeod et al. (2004). The costs included only the direct costs for the growers of susceptible crops; for simplicity, we ignored other possible costs of pest introduction (e.g., costs due to export bans; however, these costs would be pertinent for *T. palmi* only since this pest species is not present in the Netherlands). To estimate the costs of pest introduction, we defined the range of crops that are at risk of *B. tabaci*, *L. huidobrensis*, and *T. palmi* in the Netherlands. The selection of susceptible crops was based on literature (European Plant Protection Organization [EPPO], 2006; see also references to Tables 3 and 4) and interviews with Dutch experts.

The assumptions on the impact of an outbreak of *B. tabaci* and *T. palmi* on the affected grower of vegetable crops are summarized in Table 3 (we assume that outbreaks of *L. huidobrensis* do not affect vegetable growers). Table 4 presents similar assumptions for ornamental crops. Assumed impacts differ for vegetable and ornamental crops because stricter requirements are applied for visual quality of the latter. (The loss in the yield of ornamental crops if an outbreak occurs during harvest can be very large.) The assumed ornamental crops affected by different pests: *B. tabaci*—begonia, gerbera, and poinsettia; *L. huidobrensis*—cut and pot chrysanthemum. Because *T. palmi* is a highly polyphagous pest, following MacLeod et al. (2004), we assumed that 10% of all ornamentals in the Netherlands are susceptible; for these ornamental crops we calculated the costs of *T. palmi* introduction based on the gross margin for an average Dutch grower of ornamental crops.

Given the assumed pest impacts, we estimated the reduction in the average gross margin for a single grower of a given crop

Table 3
Assumed impacts of an outbreak of *B. tabaci* and *T. palmi* on vegetable crops, percent

Type of impact	Crop			
	Tomato	Cucumber	Sweet pepper	Eggplant
B. tabaci				
Yield reduction	−10[a]	−5[b]	−5[c]	—
Crop protection costs	+150[a]	+75[b]	+75[c]	—
T. palmi				
Yield reduction	—	−10[d]	−8[d]	−15[d]
Crop protection costs	—	+100[d]	+100[c]	+100[c]

[a] Assumption based on "low numbers of whiteflies" in Morgan and Macleod (1996).

[b] Based on Temple et al. (2000).

[c] Own assumption.

[d] Based on MacLeod and Baker (1998).

Table 4
Assumed impacts of an outbreak of *B. tabaci*, *T. palmi*, and *L. huidobrensis* on susceptible ornamental crops

Time of an outbreak	Crop protection costs (%)	Yield reduction (%)	Probability of an outbreak
Growing	+100[a]	−5[a]	0.95[b]
Harvest	+100[a]	−50[a]	0.05[b]

[a]Based on conversations with Dutch growers and extension specialists.
[b]Temple et al. (2000).

affected by the outbreak. The gross margin was calculated as the revenue minus variable costs based on data from Applied Plant Research (2004). Further, we determined scenarios representing the sizes of outbreaks, that is, the percentage of growers affected by yearly outbreaks. We assume that impacts of pest outbreaks on the overall supply of affected crops in the Netherlands are relatively small and do not affect the price (also see footnote 15). Assumed sizes of outbreaks included low (1%), medium (5%), and high (15%) percentage of growers of susceptible crops affected. The percentages of affected growers were multiplied with estimated costs of an outbreak per grower of a given crop, giving the total yearly costs of pest outbreaks for all growers of a given crop. These costs were summed over growers of different crops to give the total yearly costs of pest outbreaks per scenario. The estimated yearly costs of introduction for low, medium, and high scenarios of outbreaks were: *B. tabaci*—1.31, 7.03, and 21.45 million euros; *T. palmi*—1.09, 8.73, and 18.35 million euros; and *L. huidobrensis*—0.21, 1.14, and 3.42 million euros. The yearly costs of outbreaks of different sizes for every scenario were multiplied with the probability of each scenario occurring; the assumed probabilities of scenarios were: low, 0.96; medium, 0.03; and high, 0.01.[15] Finally, the expected pest costs per scenario were summed over all the scenarios to yield the total annual expected costs of pest introduction.

The estimated annual costs of introduction of *B. tabaci* and *L. huidobrensis* amounted to 1.68 and 0.277 million euros, respectively. Because *T. palmi* is currently not present in the Netherlands, its costs of introduction were assumed to extend up to 10 years. Thus, the estimated annual costs of *T. palmi* outbreaks, estimated at 1.46 million euros, were discounted ($r = 5\%$) and summed over the 10-year horizon, yielding the total costs of introduction equal to 11.33 million euros. For comparison, MacLeod et al.'s (2004) estimate of costs of *T. palmi* establishment in England over the same time horizon ranged from 16.9 to 19.6 million pounds. However, this estimate included export losses that were ignored in our calculations. Therefore, the estimated costs of pest introduction for *T. palmi* in the Netherlands are likely to be conservative.

3.2.3. Relating error probabilities of import inspection α_l, inspection lengths l, and inspection costs c_l

Statistically, the probability of detecting an infested cutting in a given lot is a function of the proportion of infestation in the lot and the sample size s (when s is small relative to the lot size), assuming binomial distribution of infested cuttings. Because the proportion of infestation in a given lot *a priori* is always unknown, in quarantine practice sample size s is chosen so as to maintain the probability $1 - \alpha$ of detecting an infested unit given that the proportion of infested units in the lot is not lower than a certain detection threshold p_t (Venette et al., 2002). The relevant formula is given by Kuno (1991):

$$s = \frac{\ln(\alpha)}{\ln(1 - p_t)}. \tag{9}$$

Equation (9) implies that a smaller sample size is associated with a higher inspection error. Sample size is also decreasing in p_t, reflecting that a smaller sample is required when the agency is prepared to tolerate higher infestation level in a lot. For the purposes of the current model, we assume that the agency fixes p_t and may vary sample size to achieve lower error probability α. Specifically, we assume $p_t = 0.5\%$.[16] With p_t fixed, Eq. (9) can be solved for different α's.

Next, we relate the costs of inspection to sample size. Larger samples require more inspection time and are thus more costly. We assume that during each minute, the inspector may examine a fixed sample of 60 cuttings. The maximum length of inspection is limited by 20 minutes, assuming that inspection beyond this time is impractical. Feasible inspection lengths and the associated sample sizes are shown in the first two columns of Table 5. The third column of Table 5 gives the cost of inspection of a given length, based on the actual PD inspection tariffs. The inspection tariff includes a fixed "base tariff" and a "per minute" rate. The last column of Table 5 presents the error probability α_l calculated for each sample size l using Eq. (9).

3.3. Model scenarios

We analyzed five scenarios. In the "Fixed allocation" scenario, every imported lot must be inspected with exactly five minutes; this scenario is assumed to replicate the current inspection policy when every lot has to be inspected. The total costs of inspection of all lots in this scenario, equal to 88,095

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[15] This assumption is roughly based on Temple et al.'s (2000) assumptions concerning scenarios of outbreaks for *T. palmi* and *B. tabaci*. In general, note that combined probability of high and medium scenarios of outbreaks of *B. tabaci* and *L. huidobrensis* is low (0.04) because impacts of these pest species are assumed to be limited by one year. For *T. palmi*, high impacts are unlikely because this is a quarantine pest of high concern and presumably both growers and PD would apply substantial efforts to minimize the spread of this pest had it become established in the Netherlands.

[16] The same detection threshold is set in New Zealand for inspection of imported nursery stock (Biosecurity New Zealand, 2006). EPPO recommends setting detection threshold for propagating materials to less than 1% (Anonymous, 2005). In general, detection threshold may vary depending on the commodity, pest, or the preferences of the agency.

Table 5
Relation between sample size, inspection length, sample costs, and error probability ($p_t = 0.5\%$)

Inspection length (l), minutes	Sample size (s), cuttings	Sample cost (c_l) (base tariff + per minute rate)[a], €	Error probability (α_l)
0	0	0	1.000
1	60	46.07	0.740
2	120	47.78	0.548
3	180	49.49	0.406
4	240	51.20	0.300
5	300	52.91	0.222
6	360	54.62	0.165
...	...	...	...
20	1,200	78.56	0.002

Source: MINLNV (2005).
[a] Base tariff = 44.36 euros; per minute rate = 1.71 euros.

euros (1,665 lots * 52.91 euros/lot), serve as a budget constraint in other scenarios. In "Optimal allocation" scenario, the model freely allocates the available budget. In "Small budget" and "Large budget" scenarios, the budget constraint of the "Optimal allocation" scenario is, respectively, reduced and increased by 50% to represent the situation when the available budget is very small or very large. Finally, the "Minimum proportion" scenario is identical to the "Small budget" scenario except that an additional constraint requiring inspection of at least 20% of lots of every pathway with five minutes is imposed. This scenario is introduced to analyze the implications of imposing the minimum inspection percentage on the optimal solution.

4. Results

The expected costs of pest introduction in the absence of import inspections are shown in the first row of Table 6. The values are obtained by a straightforward multiplication of the probabilities of introduction (Eq. (7)), when both α_l and ε_{ql} are equal to one, and the associated costs of introduction d_k. *A priori*, pathway B implies the largest expected costs of pest introduction, 0.859 million euros, because of a high estimated proportion of infested lots with *T. palmi*, the most damaging pest (see Table 2). The expected costs of pest introduction through each of the remaining pathways range from 0.657 to 0.775 million euros. The total expected costs of pest introduction from all pathways amount to 4.38 million euros.

Inspection of all lots with five minutes reduces the total expected pest costs to 1.31 million euros ("Fixed allocation" scenario, Table 6), or 30% of their pre-inspection level. However, if the same budget is allocated optimally, that is, under the "Optimal allocation" scenario, the expected pest costs decrease to 0.621 million euros, or 14% of their pre-inspection level. The largest reduction in the expected costs of pest introduction occurs for pathways B to F. This indicates that relatively more resources are allocated for inspection of lots of these pathways than of the pathway A. The reason is that each of the pathways B to F, *ceteris paribus*, has a higher proportion of infested lots or smaller number of imported lots compared to pathway A (see Table 2). Thus, for every euro of the available budget, inspection of an extra lot of the pathways B to F yields a greater reduction in the probability of pest introduction, and hence the expected pest costs, than inspection of a lot of the pathway A.

Table 6
Expected costs of pest introduction (1,000 euros)

Scenario	Expected pest costs, per pathway						Total pest costs	λ
	A	B	C	D	E	F		
No inspection	775	859	720	673	693	657	4,377	—
Fixed allocation	246	276	212	193	201	186	1,314	—
Optimal allocation	531	20	11	19	27	13	621	−17.92
Small budget	775	50	37	226	693	44	1,825	−48.67
Large budget	3	3	2	2	2	2	14	0.00
Minimum proportion	698	99	74	583	616	65	2,315	−32.93

How the available budget is allocated for inspection of lots of different pathways is demonstrated in Table 7. Table 7 indicates that in the "Optimal allocation" scenario, longer inspection times (14 and 15 minutes) are allocated to pathways with, *ceteris paribus*, smaller expected number of lots n_q or greater proportion of infested lots γ_{qk} (i.e., pathways C, B, and F). Smaller inspection times should apply to pathways whose inspection yields smaller reduction in the expected pest costs (pathways D and E), for every euro of available budget. Finally, less than 50% of lots along pathway A should be inspected with 9 minutes while the remaining share of lots should remain not inspected. Both a positive share of not inspected lots and a shorter inspection time for inspected lots explain why the expected costs of pest introduction for pathway A are higher than for other pathways.

Table 7
Length of inspection of every lot, in minutes (percentage of lots inspected with this length in parentheses)

Pathway	Scenario		
	Optimal allocation	Small budget	Minimum proportion
A	0 (54%)	0 (100%)	0 (80%)
	9 (46%)	—	5 (20%)
B	14 (100%)	11 (100%)	5 (20%)
	—	—	11 (80%)
C	15 (100%)	11 (100%)	5 (20%)
	—	—	11 (80%)
D	13 (100%)	0 (21%)	0 (77%)
	—	9 (79%)	5 (20%)
	—	—	8 (3%)
E	12 (100%)	0 (100%)	0 (80%)
	—	—	5 (20%)
F	14 (100%)	10 (100%)	5 (20%)
	—	—	11 (80%)

Note: Feasible lengths of inspection vary between 0 and 20 minutes. When the length of inspection is equal to zero for a certain pathway, then the percentage of lots of this pathway, indicated in parentheses, should not be inspected.

The results of the "Small budget" scenario indicate that a 50% decrease in the available budget increases the total expected costs of pest introduction to 1.83 million euros. In this scenario, lots from two pathways, A and E, remain completely not inspected (Table 7). In this scenario, the shadow price of inspection constraint is high $-\lambda = -48.67$ euros. Thus, a one-euro increase in the available budget would decrease the total expected costs of pest introduction by almost 49 euros compared to 18 euros under the "Optimal allocation" scenario.

Conversely, under the "Large budget" scenario, the total expected costs of pest introduction are negligible compared to their pre-inspection level because the available budget is large and all lots are inspected with 20 minutes. The shadow value of budget constraint is zero, indicating that the available budget is excessive; as a result, the agency would be better off reducing the inspection budget.

The total expected costs of pest introduction under the "Minimum proportion" scenario, equal to 2.32 million euros, are higher than under the "Small budget" scenario, because some of the resources are suboptimally allocated for the mandatory inspection of 20% of lots with five minutes (see Table 7).

4.1. Sensitivity analyses

We conducted the sensitivity analyses on five parameters in the "Optimal allocation" scenario. (Detailed results of the sensitivity analyses are available upon request.) An increase (decrease) in the size of the sample s (see Eq. (9)) that can be inspected during one minute of inspection makes inspection more (less) effective and hence decreases (increases) the probability of an inspection error (Eq. (9)). Thus, under a given budget, the inspection yields lower (higher) expected costs of pest introduction and shorter (longer) lengths of inspections. Even with a high, five-fold, increase in the size of a base sample, that is, from $s = 60$ to $s = 300$ cuttings, the marginal benefit of inspection was large, equal to five euros for every euro of the inspection capacity. When a lower (higher) detection threshold p_t is required, this increases (decreases) the error probability of inspection for a constant sample size (Eq. (9)). Consequently, both the length of inspection and the expected costs of pest introduction increase (decrease).

The model results appeared most sensitive to changes in the number of expected lots, n_q. Even small changes in n_q significantly influenced the expected pest costs. This result is due to the sensitivity of the assumed functional form of the probability of pest introduction (Eq. (7)) to changes in n_q (see footnote 13). Thus, a decrease (increase) in the expected number of lots from all the pathways lowers (raises) the probabilities and thus the expected costs of pest introduction and results in longer (shorter) inspection times. Furthermore, a simultaneous increase (decrease) in the expected number of lots from all pathways makes no inspection of a part or of all lots of pathway A that has the highest expected number of imported lots more (less) likely.

The numerical results are less sensitive to changes in the proportion of the infested lots, γ_{qk}, when γ_{qk} is higher (lower) than the expected costs of pest introduction and lengths of inspection increase (decrease), *ceteris paribus*. Finally, the changes in the costs of pest introduction, d_k, lead to proportional changes in the expected costs of pest introduction while leaving the inspection lengths unchanged.

5. Discussion and conclusions

The numerical results demonstrate that import inspection greatly reduces the expected costs of pest introduction. However, under limited inspection capacity, the optimal allocation of resources yields lower expected costs of pest introduction than when the same capacity is used to inspect all imported lots with a fixed length. Intuitively—and except for a coincidence—the optimal allocation will always be superior to the *a priori* imposed allocation when the latter is chosen without considering the expected pest costs associated with different pathways.

The results of the "Small budget" scenario suggest that when the budget is small (or when there are large differences in the probabilities of introduction or costs of introduction between pathways), the model is likely to produce corner solutions in which some pathways are completely not inspected. From the inspection agency's perspective, this is undesirable because: (i) pests may still be coming through pathways and stopping inspections forgoes important surveillance and monitoring goals of import inspection; and (ii) zero inspections of a certain pathway can make importers less diligent and thus lead to a decline of the phytosanitary quality of imported commodities through this pathway. The "Minimum proportion" scenario addresses this problem by imposing the minimum inspection percentage of lots from all the pathways. This comes at the cost of a moderate (+26%) increase in the expected costs of pest introduction relative to the "Small budget" scenario.

Sensitivity analyses suggest that the allocation of inspection effort remains consistent across pathways when the key parameters change in the same direction and magnitude. The assumption that the proportion of infested lots is constant has also contributed to the consistency of budget allocation results. This is because inspection of an extra lot from a pathway with *ceteris paribus* higher proportion of infested lots always yields a greater reduction in the probability of introduction than inspection of a lot of a pathway with lower proportion of infested lots. It may be more realistic to model the proportion of infested lots as varying between lots of, for example, various sizes (Surkov et al., 2007). However, this would require strong assumptions and additional data that we do not possess.

The objective of this article was to conceptually and empirically model import quarantine inspection policy under the capacity constraints. From a conceptual viewpoint, our results do not invalidate the results of earlier studies (e.g., Horan et al., 2002) but provide a more realistic approach to modeling the objectives of inspecting agencies under the binding capacity constraints. Rather than pursuing the unconstrained first-best allocation with marginal benefits equal to marginal costs, under capacity constraints, the inspecting agencies should allocate their resources to equalize the marginal costs of pest introduction across import pathways. The shadow value of the capacity constraint gives the marginal benefit of import inspection and allows assessing impacts of relaxation and tightening of the capacity constraints on the expected costs of pest introduction. The numerical results suggest that import inspection of CCs in the Netherlands has high marginal benefits, ranging from 18 to 49 euros for every euro of the available inspection capacity. Marginal benefit of inspection is high even with substantial variation in assumed inspection efficacy.

Because data on probabilities and costs of pest introductions are usually scarce, the numerical applications of the model can best be suited to pathways with large volumes of import and substantial historical records of intercepted pests, as was the case in this article. However, even if the data are limited, feasible assumptions (e.g., using the upper confidence intervals) can be made to represent the uncertainty associated with such parameters as the proportion of infested lots, the potential impact of a pest, or the number of pests possibly associated with particular pathways. When more information on a pathway is collected, these assumptions can be supported by actual data.

The model of import inspection presented in this article could be further extended in a number of directions. First, reactions of economic agents to actions of the inspecting agency,[17] that is, the lengths of inspection of certain commodities, could be included in the model. The importers of commodities may respond to longer inspection times by improving the phytosanitary standard of imported commodities or, which is also likely, directing imports to countries with less stringent phytosanitary regulations. Accounting for these feedback effects would allow obtaining useful and realistic insights into the impacts of import inspections on trade flows. Second, the "small country" assumption used in this article to calculate the costs of pest introduction could be relaxed. In an extended model, the costs of pest introduction may be calculated as losses for producers and consumers of the affected crops. Also, in such an extended framework, the impacts of pest introduction on prices of the affected crops can be analyzed. Third, a dynamic model of import inspection could be developed to more explicitly account for the impact of the allocation of inspection capacity in current time period on the likelihood and costs of pest introduction in future time periods.

This article suggests some implications for actual quarantine decision making. First, the conceptual model presents a novel scientific framework in which the budget allocation problems of the inspecting agencies can be evaluated. The empirical framework (with the appropriate extensions) can also be used to test *ex ante* the effectiveness and costs of new import inspection policies, for example, those allowed under the EU Directive 2000/29. Trade-offs in allocation of resources for import inspection between various commodities or pathways can also be analyzed. The framework can also be useful for other interested stakeholders (e.g., importers) to show the value and impact of import inspection. In summary, with appropriate extensions, the model presented in this article can be useful both for researchers involved in the area of economics of import quarantine and for policy makers seeking tools to evaluate the efficacy of import inspection policies.

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Appendix

Terminology (IPPC, 2006a)

Pest entry—movement of a pest into an area where it is not yet present, or present but not widely distributed and being officially controlled.

Pest establishment—perpetuation, for the foreseeable future, of a pest within an area after entry.

Pest introduction—the entry of a pest resulting in its establishment.

Consignment—a quantity of plants, plant products, and/or other articles, being moved from one country to another and covered, when required, by a single phytosanitary certificate. (A consignment may be composed of one or more commodities or lots.)

Lot—a number of units of a single commodity, identifiable by its homogeneity of composition, origin, etc., forming part of a consignment.

Notation

i = index of exporting countries ($i = 1, \ldots, I$).
j = index of commodities ($j = 1, \ldots, J$).
k = index of pests ($k = 1, \ldots, K$).
q = index of pathways ($q = 1, \ldots, Q$).
V_q = volume of import along the qth pathway.
d_k = present value of economic costs associated with introduction of the kth pest.
γ_{qk} = the proportion of import volume V_q infested with the kth pest.
α_{qk} = the probability that visual inspection of the lot following along the qth pathway fails to detect the kth pest.

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[17] We thank an anonymous reviewer for attracting our attention to this point.

h_k = conditions for survival of the kth pest in the importing country.
u_{qk} = the probability of introduction of the kth pest via qth pathway.
s_k = the probability of establishment of the kth pest after introduction.
p_{qk} = probability of introduction of the kth pest via the qth pathway.
D_q = total costs of pest introduction associated with the qth pathway.
b_q = budget for inspection of lots imported along the qth pathway.

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