CHAPTER 4

DESIGNING OPTIMAL PHYTOSANITARY INSPECTION POLICY

A conceptual framework and an application

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Abstract. Optimal allocation of available resources to minimize quarantine risks related to international trade is a problem facing plant protection agencies worldwide. In this paper a model of budget allocation to minimize quarantine risks is developed. Theoretical conditions that budget allocation should satisfy are derived. These conditions imply that optimal allocation of resources is achieved when the marginal pest risks are equalized across risky pathways. Furthermore, an empirical model of budget distribution is developed. In the empirical model, the protecting agency wants to minimize the expected number of infested ornamental plants imported in a given country. The model is parameterized using data on import of ornamental commodities, the associated quarantine risks and costs of import phytosanitary inspections pertaining to the Netherlands.

The results of the empirical model suggest that under specific assumptions (such as constant risk) greater risk reduction can be achieved by allocating larger funds to inspection of riskier pathways, and less or no funds to less risky pathways. The protecting agency has to trade off the risks from pathways that vary in terms of risk.

Keywords: optimal inspection; quarantine pest; ornamental plants

INTRODUCTION

Phytosanitary import inspection is an important component of quarantine policies worldwide. In many instances, import inspection is the only real and last barrier where exotic quarantine plant pests brought in together with imported commodities can be intercepted. The inspection capabilities of the responsible agencies are, however, under a constant pressure of the ever-growing volumes of importing commodities. There is evidence that in some countries the resources of the

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quarantine agencies are already lagging behind the increasing volumes of import (National Research Council 2002; Everett 2000). In addition, the broad assortment and origins of incoming consignments diversify phytosanitary risks and complicate inspection tasks of responsible agencies.

The economic rationale calls for the best use of available inspection resources, including monetary and human resources. More attention should therefore be paid to development of inspection policies in which scarce resources are allocated optimally and risks associated with import of various commodities are minimized. The treatment of this issue in the economic literature so far has been limited. Relevant studies focus on economics of controlling and preventing biological invasions (e.g. Horan et al. 2002; Saphores and Shogren 2005; Barbier 2001; Olson and Roy 2002), which is a somewhat broader phenomenon. A most relevant study on the economics of import inspection is a recent paper (Batabyal and Beladi in press) in which queuing theory is applied to analyse optimal allocation of resources for inspection of cargo ships. The general feature of these studies is that, though they provide theoretical conditions for optimal resource allocation, numerical examples are lacking. As a result it remains unclear how these theoretical conditions may be translated into practical decision making.

This paper adds an applied focus to the problem of optimal allocation of quarantine resources. Specifically, the main question addressed in the current work is: how can available resources be allocated to inspection of imported commodities such that the phytosanitary risks associated with these imports are minimized? To answer this question, first, a theoretical model of optimal budget allocation is proposed. In this model, the decision maker – the Quarantine Agency of an importing country – faces a problem of resource allocation to minimize quarantine risks stemming from different pathways (defined as commodity–country combinations). Based on this theoretical model, the empirical model is then developed. In this model the Agency wants to minimize the number of infested plants imported into the country. Data from the phytosanitary import inspections of ornamentals imported into the Netherlands were used to parameterize the model. The results of the optimal budget allocation are then presented. The paper concludes with a discussion.

THEORETICAL MODEL

Consider an importing country H that imports j commodities from i exporting countries in period t. Each of the j commodities may host k quarantine pests, currently not present in H. The Quarantine Agency considers the presence of any of these pests inside H as equally (economically) unacceptable. The Agency thus has no specific aversion towards a specific pest and treats all pests equally. The latter assumption has a simplifying implication that the Agency applies the same quarantine measures to all ij pathways. The only phytosanitary measure applied by the Agency is the visual inspection of incoming consignments along each of the ij pathways. For inspection, a sample of a pre-defined size is taken from every consignment. If at least one specimen of a quarantine organism is found in a sample, the entire consignment is rejected for import. Otherwise, the consignment is freely imported.

Denote the quarantine risk associated with the *ij*th pathway in period *t* as $r_{ij}^{t} \geq 0$. (The superscript implies that risk is period-specific; however, as the discussion henceforth is confined to a single period *t*, the superscript will be omitted.) Assume that *r* is measured in units that the Agency deems appropriate to reflect the quarantine risk associated with imported commodities. In reality, *r* may be expressed, e.g., as the expected economic costs due to pest incursion, the probability of pest establishment in *H*, the number of infested plant units or any other 'real' risk metric. The total import quarantine risk in period *t* is given by $R_t=\Sigma_{ij}r_{ij}$, assuming that risks from different pathways are not correlated.

Developing its risk management policy (i.e. import inspection), the Agency realizes that no inspection measures can reduce risk to zero. Hence, the Agency may impose a risk threshold below which risk is considered acceptable; consequently, commodities satisfying this threshold are imported without inspection. The Agency may choose to set the *total* risk threshold $\overline{R}$ or *individual* pathway risk threshold $\overline{r}$[1]. In the former case, total risk from all commodities should be lower than or equal to $\overline{R}$, i.e. $R_t \leq \overline{R}$; likewise, in the latter case, pathways' risks should not exceed $\overline{r}$, i.e. $r_{ij} \leq \overline{r}$. It is, however, more difficult to maintain $R_t \leq \overline{R}$ than $r_{ij} \leq \overline{r}$ constraint because management efforts should change with fluctuation in the trade volumes (Bigsby 2001). With the individual pathway constraint, management effort is constant. Henceforth, we assume that the Agency imposes an individual pathway risk constraint $\overline{r}$. The inspection measures applied by the Agency are consistent with the imposed constraint; i.e., the sampling procedure is such that the acceptable level of risk is maintained.

Inspection and sampling are, of course, costly. To reflect this, an inspection budget $b_{ij} \geq 0$ is allocated to each pathway. As a result, the quarantine risk per pathway is a function of the allocated budget, i.e. $r_{ij}=r(b_{ij})$. Assume that $r'(b) <0$ and $r''(b)>0$, so that risk is decreasing with budget, but the marginal risk-reducing effect of an extra unit of budget is decreasing. In relation to visual inspection, this implies that an extra inspection effort reduces the quarantine risk; however, subsequent inspection efforts decrease risk less than proportionally, reflecting the increasing difficulties in pest detection.

We can now formulate the optimization problem of the Agency. The relevant objective is to minimize the inspection costs subject to the acceptable risk constraint. The minimization problem (model *MB*) therefore reads as:

$$\text{Minimize } B = \sum\nolimits_{ij} b_{ij} \tag{1}$$

subject to $r\,(b_{ij}) \leq \overline{r} \qquad \forall\ i,j,$

$b_{ij} \geq 0.$

Because the risk constraint may not be binding, the solution to (1) will be given by Kuhn-Tucker conditions (Chiang 1984). The first-order conditions (FOC) to this problem are given by $\frac{1}{\varphi_{ij}} = r'(b_{ij}) < 0$ and $r'(b_{ij}) = \bar{r}$, where φ is the Lagrange multiplier associated with the *ij*th constraint. The FOCs imply that the optimal budget allocation is the one that makes individual pathway risks exactly equal to the constraint; at the same time, for pathways with initial risks strictly below $\bar{r}$, the budget should optimally be zero. Note that the Agency with unlimited budget may alternatively insure itself from all risks above $\bar{r}$ by trivially applying the same inspection procedures for all pathways, irrespective of actual r_{ij}'s. The spending of resources in this case will be clearly suboptimal as pathways with risks strictly lower than $\bar{r}$ will be inspected.

More relevant for import quarantine decision making is the situation when the budget is limited. Note that although the budget itself may be sufficient (because in most cases importers pay inspection fees), the complete inspection of all pathways may be unfeasible, e.g., due to the lack of qualified employees or the lack of inspection premises. Thus, with limited budget *B* (in period *t*), the Agency solves the following program (model *MR*):

$$\text{Minimize } R_t = \sum_{ij} r\ (b_{ij}) \tag{2}$$

subject to $\sum_{ij} b_{ij} \leq B \quad \forall\ i,j,$

$b_{ij} \geq 0.$

The constraint in fact should be binding in the optimum because it is always preferable to spend the budget 'a little bit more' to reduce risk marginally. Hence, the FOC is given by $r'(b_{ij}) = \lambda$ implying that in the optimum budget should be allocated such as to equalize the marginal pest risks across all pathways. The Lagrange multiplier λ is the 'shadow price' (Chiang 1984) of the budget constraint; it shows how the total risk will decrease (because $r'(b_{ij}) < 0$) when the budget constraint is relaxed. The limited budget in this model implies that in the optimal solution not all pathways may be inspected at the level satisfying $\bar{r}$. As a result, quarantine risks from some pathways may exceed the acceptable level $\bar{r}$.

Altogether, the results of *MB* and *MR* models provide an indication of how the Agency should allocate its resources optimally. As was mentioned in the Introduction, most quarantine agencies worldwide face binding budget constraints. Hence, the empirical model presented in the next section is based on the *MR* model.

EMPIRICAL MODEL

To translate a conceptual MR model into an empirical one, firstly, we need to specify a concrete objective function to be minimized – i.e. assume a specific risk function *r*, and secondly, establish relations between the costs of inspections (i.e. b_{ij}) and their efficacy (i.e. $r'(b)$). Obviously, for the model to yield practical insights, assumed empirical specifications should resemble the actual import inspection practice.

Given our earlier assumption that the Agency has no bias against specific pests, the relevant objective function is to minimize the expected number of infested commodity units imported into *H*. For concreteness, assume that the imported commodity is the ornamental materials for propagation (for example, cuttings or small plants for propagation; hereafter, simply 'plant') of *j* ornamental species. We thus implicitly assume that each infested plant may lead to realization of a quarantine risk in *H* with constant and independent (of other infested plants) probability of success. Given the limited budget *B*, the objective of the Agency is to:

$$\text{Minimize } E(N)=\sum_{ij} N_{ij}(b_{ij}) \tag{3}$$

subject to $\sum_{ij} b_{ij} \le B$

$b_{ij} \ge 0$,

where $N_{ij}(b_{ij})$ is the expected number of infested plants imported along the *ij*th pathway after import inspection. Specifically, it is given by:

$$N_{ij}(b_{ij})=V_{ij}\,p_{ij}\,\alpha(b_{ij})\,, \tag{4}$$

where V_{ij} is the volume of plants imported along *ij*th pathway in period *t*, p_{ij} is the proportion of infestation with quarantine pests in the total population of ornamental plant *j* in country *i* and $\alpha(b_{ij})$ is the probability that inspection will fail to detect at least one infested plant in the infested consignment. The probability of inspection failure is assumed to be decreasing and convex in the inspection budget, i.e. $\alpha'(b)<0$ and $\alpha''(b)>0$. V_{ij} is defined as $\sum_{z=1}^{Z} h_z^{ij}$ where h_z^{ij} is the size of the *z*th consignment. The proportion of infestation p_{ij} is estimated according to the following formula:

$$p_{ij}=\frac{u_{ij}}{v_{ij}}\,p_{\inf}\,, \tag{5}$$

where v_{ij} is the total volume of commodity imported along the *ij*th pathway in periods preceding t, u_{ij} is the total volume of consignments found infested with quarantine pests during import inspection for the same periods, and $p_{\inf}$ represents the assumed percentage share of u_{ij} actually infested with quarantine pests (see section 'Data' for explanation).

The Agency may vary the intensity of visual inspection by taking larger samples, hence lowering the probability $\alpha(b_{ij})$ that an infested plant remains undetected. We assume that detection probability is independent of the pest type and the type of propagation material. Statistically, the probability of detecting an infested plant in a given consignment is a function of the proportion of infestation p_{ij} and the sample size s (when s is small relative to consignment size), assuming binomial distribution of infested plants. Because the proportion of infestation is always unknown, the common convention is to assume a certain critical level of infestation p_c below which a consignment is deemed free from quarantine organisms (e.g. Kuno 1991; Couey and Chew 1986). The resulting sample size is a function of this threshold and the acceptable level of error α. The exact formula is given by Kuno (1991):

$$s = \frac{\ln(\alpha)}{ln(1-p_c)}\,. \tag{6}$$

Equation (6) implies that s is decreasing in α, that is, a higher error probability is associated with smaller sample; also, s is decreasing in p_c reflecting that a smaller sample is required when the Agency is prepared to tolerate higher infestation level in a consignment. Equation (6) suggests that the pathway risk accepted by the Agency (i.e. $\bar{r}$) is a function of both α and p_c. For the purposes of the current model we assume that the Agency fixes p_c and may vary sample size to achieve lower error probability. Specifically, we assume p_c=0.005. This is a common maximum infection level required by quarantine agencies worldwide, e.g., in New Zealand (Ministry of Agriculture and Forestry 2006) and in the countries that are members of the European Plant Protection Organisation (EPPO 2005). With p_c fixed, equation (6) can be solved for different α's.

Next, we relate the costs of inspection and sample size. Obviously, larger samples require more inspection time and are therefore more costly. We assume that inspection time is measured in 15-minute intervals during which the inspector may examine a fixed number of plants (equal to the sample size). Within 30 minutes, the inspector may inspect a larger sample, and so on. His productivity is however diminishing. Data about the costs of inspection came from the Dutch Plant Protection Service (PD) that charges a fixed rate for every 15 minutes of inspection. The costs for 0-105-minute inspections, together with corresponding error levels and sample sizes, are shown in Table 1 below.

***Table 1**. Relation between sample size, error level α, inspection length and sample costs (p_c=0.005)*

Inspection length, minutes	Sample size, units	α	Inspection costs (‘15 minutes’ fee + ‘call out’ fee)*, euros
0	0	1,0000	0
15	300	0,2223	61.61
30	570	0,0574	83.28
45	825	0,0160	104.95
60	1065	0,0048	126.62
75	1260	0,0018	148.29
90	1434	0,0008	169.96
105	1587	0,0004	191.63

*callout fee: 39.94 euros, ‘15 minutes’ fee: 21.67 euros. Source: (Plantenziektenkundige Dienst 2005)

The chosen inspection lengths were based on presumption of the ‘reasonable’ length. One might argue that the inspection lengths longer than 60 minutes are unfeasible in practice; nevertheless, for completeness, longer inspection intervals were included. The second column shows the assumed sample sizes that can be inspected within a corresponding inspection time. Note that the sample size is a concave function of the inspection time. This reflects the assumed diminishing marginal productivity of an inspector. The α’s are obtained by solving (6) for fixed p_c and s. Examining the relation between the last two columns one finds that α is decreasing and convex in inspection costs (consistent with our earlier assumptions about $\alpha(b_{ij})$).

DATA

In the empirical model, nine pathways are considered: three countries each exporting three ornamental species (propagating materials) to the Netherlands. Countries are indexed as A, B and C for confidentiality reasons. The exact pathways are the following: country A, Chrysanthemum, Rose and Dianthus; country B, Chrysanthemum, Dianthus and Impatiens; and country C, Chrysanthemum, Yucca and Dracaena. (Henceforth, unique pathways will be referred to by the name of the underlying ornamental species only (i.e. Rose, Yucca, Impatiens and Dracaena); for the remaining pathways a letter denoting the country index will be added to the species name, e.g., DiathusA.) The chosen pathways give a representative sample of the important channels of ornamental materials for propagation imported into the Netherlands. So, for example, in 1998-2001, the six ornamental species chosen for the model accounted for more than 81 % of Dutch import of ornamental plants and propagating materials. (The total number of imported ornamental species for the same period was approximately equal to 1,200.) Chrysanthemum and Dianthus contributed with by far the largest shares: 66.8 % and 11.6 %, respectively. Remaining pathways’ shares vary between 0.3 % and 2.7 %. The exporting countries were selected as important suppliers of respective ornamental species. For example, country A accounted for 30 % of Chrysanthemum exports and 38 % of Rose exports; country B supplied 18 % of Dianthus and 43 % of Impatiens; finally, country C exported 11 % of Chrysanthemum and dominated the export of Dracaena with an 84 % share. At the same time, for non-unique pathways (e.g., Chrysanthemum), there is a significant variation in imported volumes between exporting countries (see next paragraph). This circumstance plus the differences in historical findings of quarantine organisms (see below) were the final criteria based on which the pathways were chosen. Data on import volumes and results of import phytosanitary inspections were obtained from the database of inspection reports composed by the PD inspectors in the period 1998-2001. It should be noted that information in the database was presented at the *lot* level, with a lot typically representing a collection of imported plants or plant materials of a given species coming from a given country. A c*onsignment*, on the other hand, may consist of different lots covered by a single phytosanitary certificate (FAO 2006). For the purposes of the data analyses we consider each lot in the database as a single consignment.

Table 2 presents both historical data on import volumes and findings of quarantine organisms[3] and input data for the model. Consider first historical import data. Consignment-wise, Dianthus and Dracaena were imported in largest numbers compared to other ornamental species. In terms of the average consignment size, Chrysanthemum is leading. Yet for both parameters, there is substantial intra-pathway variation. For the model, the average volume of import expected in a given period t along the ijth pathway, V_{ij}, can be obtained by a straightforward multiplication of the number of consignments and their average size. It is, however, unlikely that all consignments will have the same size. We chose a pragmatic approach to represent this variation in size splitting the historical distribution of consignment sizes into discrete intervals, represented by the lower 5 %, 5-25 %, 25-50 %, 50-75 %, 75-95 % and upper 95 % percentiles. The expected number of consignments of a specific size was thus split according to these percentiles. This transformation is not shown due to space limitations but can be obtained upon request. The important issue to keep in mind is that the increasing percentile implies a greater consignment size (i.e. lower 5 % percentile gives 5 % of the smallest consignments, 5-25 % percentile represents 20 % of consignments of larger size, etc.). For further reference, the total number of plants to be imported (calculated for average consignment sizes) is approximately 671 million.

Data on findings of quarantine pests reveal that consignments of Dianthus have the largest relative and absolute rejection rate. (It is assumed that: 1) inspection procedures applied were the same for all pathways, and 2) all infested consignments were detected.) Most notably, DianthusA has the highest rejection rate among all pathways, suggesting that the underlying pathway is the most risky from the quarantine perspective. The second highest rejection rate among ornamental species pertains to consignments of Chrysanthemum. Finally, consignments of Dracaena have the lowest positive rejection rate. The remaining pathways (i.e. Rose, Impatiens and Yucca) had a zero rejection rate suggesting that these are the safest pathways from a phytosanitary perspective.

***Table 2**. Data and parameter values for the model**

Parameter	**Ornamental species**					
	Chrysanthemum	Rose	Dianthus	Yucca	Dracaena	Impatiens
A						
Consignments imported during 1998-2001	2,375	153	2,909			
Average consignment size	703,996	62,278	56,078			
Consignments infested with a quarantine pest	6	0	60			
Expected number of consignments in the model[a]	600	125	700			
Estimated proportion of infestation p_{ij}[b]	4.97E-05	1.05E-07	3.65E-04			
B						
Consignments imported during 1998-2001	1,008		7,255			818
Average consignment size	7,743		34,318			30,023
Found infested with a quarantine pest	8		106			0
Expected number of consignments in the model[a]	150		1,815			210
Estimated proportion of infestation p_{ij}[b]	7.43E-05		2.02E-04			1.22E-7
C						
Consignments imported during 1998-2001	606			586	6,354	
Average consignment size	1,013,192			5,477	23,109	
Consignments infested with a quarantine pest	1			0	2	
Expected number of consignments in the model[a]	155			150	1,560	
Estimated proportion of infestation p_{ij}[b]	1.20E-06			9.33E-07	3.54E-05	

* 9 pathways (3 ornamental species coming from 3 countries) are represented

a) based on 2001 data

b) own estimation

The rejection rate of consignments is not sufficient to deduce the true proportion of infestation p_{ij} of a given pathway. Reliable data of the proportion of infestation can be obtained only when the exact number of infested plants in every consignment found infested is counted[2]. Unfortunately, such data were not available for our model. To estimate the proportion of infestation we used the following approaches. If no consignments of the *ij*th pathway were rejected during import inspection, p_{ij} was estimated using the upper 95 % confidence limit using formula $0.95 = 1 - (1 - p_{ij})^{v_{ij}}$ from Couey and Chew (1986), where v_{ij} is the total number of plants imported along the *ij*th pathway in 1998-2001.

When the number of rejected consignments was greater than zero, we used equation (5) to estimate p_{ij}. Parameters u_{ij} and v_{ij} in this equation were taken from data for 1998-2001 shown in Table 2. Parameter $p_{\inf}$ in the same equation was given by the mean of Triang (0.5 %, 10 %, 20 %) distribution where parameters represent the minimum, most likely and maximum values, respectively. This distribution is assumed to approximate the variation in the actual proportion of infestation in consignments found infested with a quarantine pest. Although difficult to justify empirically, both the distribution and chosen parameters were based on a number of considerations. The lower bound was set on the presumption that because infestation was detected, the infestation rate was at least 0.5 %, i.e. the level at which the quarantine inspection can detect infestation with reasonable confidence. The only evidence for the most likely value comes from Frey (1993). Examining the infestation rate of ornamental cuttings imported into Switzerland he found an average sample infestation rate of approximately 13 %, ranging from 2.3 % for Dianthus and 8 % for Impatiens to 15 % for Chrysanthemum. With large uncertainty we set the most likely value at 10 %. The choice of the upper bound was based on the idea that the phytosanitary quality of imported commodities is currently high. This is because: 1) the exporting countries' inspecting Agency would detect sufficiently low infestations, and 2) even if an infestation is missed by the export quarantine, the commodities are chilled during transportation and infestation rate at the time of import inspection is unlikely to exceed seeming reasonable 20 %. The estimated proportions of infestation (p_{ij}'s) are shown in Table 2.

RESULTS

Before discussing the results of the model, it is useful to estimate expected pest risks in the absence of import inspection. This will allow seeing the effect of import inspection better. Recall that in our model quarantine risk is measured as the expected number of infested plants entering the importing country. Straightforward application of equation (4) yields the required estimate. Thus, the expected number of infested plants in the absence of inspection is calculated as the product of the expected volume of imported plants and the estimated proportion of infestation associated with the given pathway. Parameter α is equal to unity in this case to reflect the absence of import inspection. The resulting risk estimates for different pathways are presented in Table 3 below.

Table 3. *Expected number of infested plants per pathway*[*]

Country	Ornamental species					
	Chrysanthemum	Rose	Dianthus	Yucca	Dracaena	Impatiens
A	23,905	<1	21,172			
B	265		23,112			<1
C	177			<1	1,289	

[*] Calculated as the summed product of p_{ij} (Table 2) and the average consignment size in each of consignment size categories

Table 3 shows that the largest number of infested plants is expected from Dianthus pathways, reflecting relatively high proportions of infestation and volumes (especially in terms of number of consignments). Large numbers of infested plants can be also expected from ChrysanthemumA pathway, reflecting mainly the large volume of incoming plants along this pathway. As can be expected, pathways with higher proportions of infestation and large volumes of import represent the largest quarantine threat. Pathways with estimated (very) low p_{ij} thus represent a lower quarantine risk. The total number of infested plants expected from all pathways is about 69,872. The average proportion of infestation is approximately equal to 0.0001 (69,872 / 671 million).

To obtain a plausible value for the constraint *B* we then ran the model for the situation that is assumed to reflect current inspection practices. Here, the Agency applies the same inspection treatment to all pathways. The inspection length is fixed at 30 minutes with an error level of approximately 5 % (see Table 1). The resulting costs of inspections are obtained by multiplying the corresponding inspection tariff (i.e. 83.28 euros) with the total number of consignments imported along all 9 pathways. The costs per pathway were defined only by the number of consignments to be imported along a given pathway. The resulting total inspection cost amounted to 455,125 euros. The expected number of infested plants after application of such a uniform inspection rule is approximately equal to 4,010. The efficacy of quarantine inspection is thus about 94.3 % (1 - 4,010 / 69,872).

It is the total inspection costs obtained in the model above (i.e. 455,125 euros) that were used as a constraint in the main optimization model. The model should thus allocate these funds freely to find the solution in which the expected number of infested plants imported into the country is minimal. Table 4 presents the results of the budget allocation between the pathways in the model.

***Table 4**. Budget allocation per pathway, after minimizing risk (1000 euros)*

Country	**Ornamental species**					
	Chrysanthemum	Rose	Dianthus	Yucca	Dracaena	Impatiens
A	85,67	-	86,30			
B	7,32		169,22			-
C	12,50			-	94,11	

In Table 4, the sum of all pathway budgets equals the value of the constraint, i.e. 455,125. The budget is thus fully used. The allocation of budget to pathways is, however, very different. First, note that no budget at all is allocated for inspection of Rose, Yucca and Impatiens. This is consistent with the very small quarantine risks that they pose (see Table 3). Among pathways with a positive budget allocation, the largest shares of total budget are allocated for inspection of DianthusB and Dracaena. The DianthusB pathway received a large allocation because of both a high number of infested plants expected and a large number of imported consignments. The large absolute inspection costs allocated for Dracaena pathway are explained mainly by the large expected number of imported consignments; the quarantine threat posed by Dracaena is much lower than, for example, by ChrysanthemumA (see Table 3). In general, the results of budget allocation presented in Table 4 are consistent with numbers presented in Table 3. Pathways with larger expected number of infested plants *ceteris paribus* receive larger budget allocation. To see *how* pathways budgets are allocated, let us inspect Figure 1.

Figure 1 shows the distribution of the inspection lengths for a given pathway for consignments of different sizes within the pathway. Figure 1 indicates that budget as a function of inspection time is allocated differently not only across pathways, but also across different consignment size categories within pathways. The general trend is that larger consignments receive lengthier inspection treatment than smaller ones. Furthermore, pathways with larger expected number of infested plants *ceteris paribus* are inspected with more time. Compare again results for DianthusB and Dracaena pathways. The consignments coming along the former pathway should be inspected with more time than consignments coming along the latter. This finding reflects the difference in quarantine risks between these two pathways and supports an earlier argument that Dracaena received large absolute budget allocation mainly because of the large number of imported consignments.

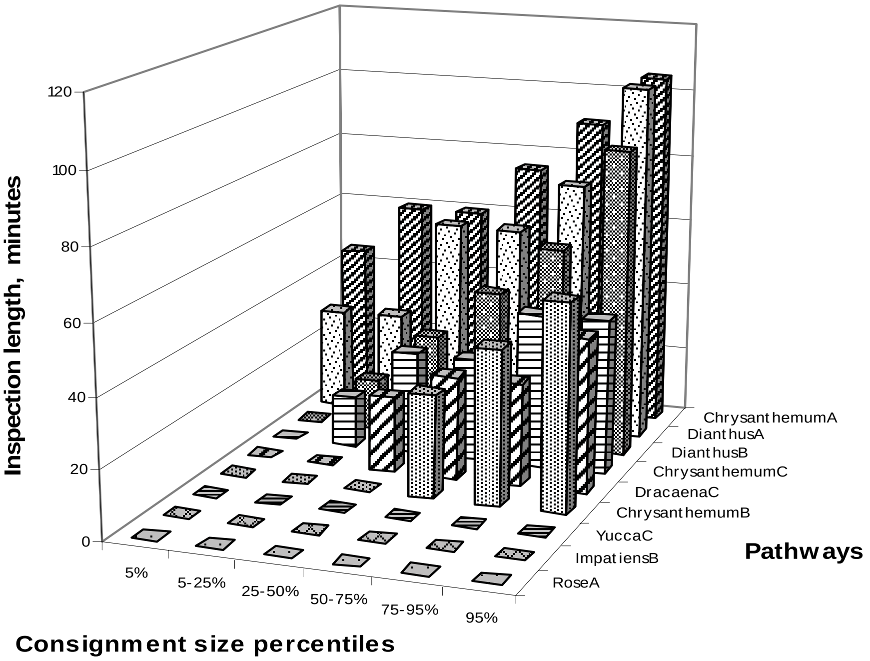

Figure 1. *Distribution of inspection times across pathways and sizes groups*

The expected number of imported infested plants in this model is equal to 380, suggesting that the Agency may reduce the initial risk by 99.4 %. This is due to allocation of larger budgets and longer inspection times for *a priori* more risky pathways. In fact, there is a redistribution of the common resources towards riskier pathways at the expense of pathways with comparatively lower risks. This explains why the reduction in the expected risk in this model is higher compared to the model in which all pathways are inspected with equal time and budget per inspection. On the other hand, some pathways (Rose, Yucca and Impatiens) remain completely uninspected implying that the Agency should bear the risk that some infested plants might be imported along these pathways.

It is worthwhile noting that obtained results remain stable when there is a change in the quarantine budget. An increase (decrease) in the total budget leads to an increase (decrease) in the average time of inspection of a pathway. The direction of budget distribution also remains consistent with observed trends: more risky pathways and larger consignments receive proportionally higher budgets. Another important result is related to the shadow price of the budget constraint. Recall from the theoretical model that the shadow price indicates the change of objective value had the constraint been changed by one euro. The shadow price in the model was equal to -0.0032, implying that the 312.5 euro increase in the total budget would lead to approximately 1 unit decrease in the expected number of infested plants. A 50 % increase (decrease) in the total budget resulted in shadow prices equal to -0.00032 (-0.0198). These results are in line with the premise that import inspection has high marginal efficacy with low budgets and low efficacy with high budgets (because it is more difficult to detect a marginal infested plant).

DISCUSSION

In this paper we presented a model of optimal allocation of budget resources to minimize import quarantine risks. The theoretical model implies that the available resources should be allocated so that the marginal pest risks are equalized across import pathways. The results of the empirical model suggest that pathways with larger expected risks *ceteris paribus* should receive a larger share of the budget and longer inspection treatment. Within pathways, larger consignments must be inspected more intensively than smaller ones. This finding reflects the implicit assumption that for a fixed proportion of infestation, larger consignments have more infested plants, and thus require more thorough inspection treatment (assuming that the probability of detecting a pest does not depend on the consignment size). The model output also suggests that some pathways with *a priori* low risks may remain completely uninspected. This finding is consistent with Horan et al. (2002, p. 1309), who noted that it is optimal to devote more resources to confront (quarantine) events that are considered more likely and to allocate few or no resources to confronting events that are considered less likely. Yet, it is obvious that the Agency should be prepared to bear some quarantine risks in this case (due to no inspections of certain pathways).

The main message from these results is that, with limited resources, the inspection of all risky pathways may not be optimal (let alone feasible). For quarantine policy making, this implies that the Agency should focus on, *ceteris paribus*, riskier pathways and leave other pathways uninspected or inspected with lower effort. Presumably, this is the current practice in many countries worldwide. A possible solution to alleviate the quarantine risks remaining along unchecked pathways would be for the Agency to rely on self-protection efforts of importers of risky commodities (or other interested stakeholders).

Some reservations related to the model setup and assumptions should be mentioned. The first reservation is related with data. Quantitative data related to quarantine risks are generally scarce (Gray et al. 1998) and the proportions of infestation are very hard to estimate at the low levels that are prevalent. However, the actual application of the model developed in this paper crucially depends on the availability and quality of the quantitative estimates. The procedure to estimate the proportion of infestation – a key factor influencing the optimal allocation of resources among different pathways – in the current work was indirect, implying that the estimates of p_{ij} may be biased. This bias may be in part due to a triangular distribution used to estimate the proportion of infestation in rejected consignments. Conceivably, this distribution gives only a limited approximation of the true proportion of infestation. Given that the exact computation of actually infested plants is almost infeasible, other non-parametric distributions with more parameters (for example, discrete) could be used as possible alternatives. Data on parameters in these distributions may come from experts.

The discussion in the previous paragraph underscores the importance of the proper account of uncertainty in estimating quarantine risks associated with different pathways. Another important characteristic that the model fails to address is the variability in quarantine risks (Gray et al. 1998). The model found the optimal solution based on the premise that the proportion of infestation of a given pathway is fixed. Specifically, it was expressed as the mean of the probability distribution $f(p_{ij})$ of the proportion of infestation. As a result, in the model every consignment is assumed to carry a positive number of infested plants, which is somewhat counterintuitive. In reality one would expect a very significant variation in the p_{ij} within the pathway, e.g., due to stochastic fluctuations or to variations in the quality of plants imported from different producers in the exporting country. This variation most probably takes the form that some of the consignments are completely free from quarantine organisms (after all, most consignments successfully pass import inspection) and others are infested with varying extent. A more realistic model should take this issue into account.

These shortcomings suggest clear avenues for improvement of the presented empirical model. Overall, we believe that the presented model is a useful step towards development of more effective quarantine inspection policy.

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NOTES

1. There is a third option: to minimize risks for specific pests (Bigsby 2001); we ruled this possibility out by assuming non-pest-specific risks
2. This is the approach adopted by e.g. Roberts et al. (1998) and Wearing et al. (2001) in the quantitative risk assessments of, respectively, fire-blight and codling-moth introductions via trade in fruits
3. We use the term ‘quarantine’ throughout the remainder of the paper to emphasize that the pest that caused the rejection of a particular consignment was not tolerated by the importing country. In reality, consignments in the database were rejected due to both quarantine and non-quarantine pests; however, for the purposes of the numerical model we consider all cases of rejections as due to quarantine pests. This is consistent with the set-up of the model, in which Agency considers all pests as equally damaging. For official definition of the quarantine pest see FAO (2006)

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