Efficiency of Export Plant Quarantine Inspection by Using Injury Marks

KOHJI YAMAMURA AND HAJIME KATSUMATA[1]

Laboratory of Population Ecology, National Institute of Agro-Environmental Sciences, Tsukuba, Ibaraki 305–8604, Japan

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ABSTRACT All apples (*Malus domestica*) and cherries (*Prunus avium*) exported from the United States to Japan undergo quarantine treatments such as fumigation and cold treatment to prevent the transport of codling moth, *Cydia pomonella* (L.). As an alternative to these treatments, a procedure called the systems approach has been proposed. This approach aims at achieving quarantine security by integrating several protection efforts such as integrated pest management (IPM), postharvest removal of infested fruits, and export sampling inspection of consignments. The inspection suggested in this approach has 2 novel characteristics: (1) the existence of injury marks such as worm holes as well as live insects is used as a basis for the decision to reject the consignment, and (2) the sampling inspection is repeated several times. We propose a method to estimate the efficiency of this plant quarantine inspection, by assuming there is a constant probability that a fruit with injury marks contains live insects. The hypothetical example shows that the efficiency of sampling inspection is considerably improved by using the existence of injury marks. It is, however, suggested that the sampling inspection is not as effective as the quarantine treatments even if the existence of injury marks is used.

KEY WORDS sampling inspection, export plant quarantine, proportion of infestation

SAMPLING INSPECTION IS one of the effective procedures to reduce the number of quarantine pests passing a port. In the Japanese import plant quarantine for fruit commodities, a sample is drawn at random from every consignment that arrives at port, and the consignment is accepted for importation only if the sample contains no live pests. This mode of inspection is called the zero-tolerance method. It is, however, impossible to prevent completely the introduction of quarantine pests by this kind of sampling inspection because there is a possibility that some infested fruits may be included in accepted consignments. Therefore, several types of fruit items that might be infested by serious pests are usually prohibited from importation to achieve quarantine security. As exceptions, apples (*Malus domestica*) and cherries (*Prunus avium*) from the United States are permitted for importation into Japan if they are appropriately treated by fumigation and cold treatment before export, although they might carry designated pests such as the codling moth, *Cydia pomonella* (L.).

A quarantine procedure called the systems approach has been proposed as an alternative to fumigation and cold treatment of apples and cherries (Hata et al. 1992, Jang and Moffitt 1994, Jang 1996). This approach has 5 distinct phases: (1) integrated pest management (IPM) practices in the field, (2) preharvest techniques to reduce the occurrence of pests on the produce, (3) postharvest removal of insect-infested or damaged fruits (4) inspection and certification of the packed fruit, and (5) shipping and distribution of the commodity. The systems approach aims at achieving total quarantine security by integrating the protection efforts conducted in each of these phases, but the effectiveness of this approach has not been fully evaluated. In this paper, we focus on the effectiveness of sampling inspection in phase 4 of the systems approach.

Export sampling inspection suggested in the systems approach has 2 novel characteristics: (1) the existence of injury marks such as worm holes as well as live insects is used as a basis for the decision to reject consignments, and (2) the inspection is repeated several times. We extend the method of Yamamura and Sugimoto (1995) to estimate the efficiency of this mode of export plant quarantine inspection. The method is applied to a hypothetical example of inspection for the codling moth.

Quarantine Inspection by Using Injury Marks. An injured fruit is defined as a fruit that has injury marks such as worm holes. An infested fruit is defined as a fruit that has 1 or more live insects. A typical export plant quarantine inspection by using injury marks is summarized as follows: (1) A sample of fruits is drawn from every consignment. (2) The consignment is rejected if the number of injured fruits in the sample exceeds a critical value. (3) The consignment is rejected if the sample contains 1 or more infested fruits. (4) Procedures 1–3 are repeated, and (5) The ac-

[1] Yokohama Plant Protection Station, Shin-yamashita Naka-ku, Yokohama, Kanagawa 231–0801, Japan.

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cepted consignment is exported. The sample is not returned to the consignment. The rejected consignments are discarded. The zero-tolerance method corresponds to a special case in which the 2nd procedure is missing.

Statistical Model. *Assumptions.* (1) The proportion of injured fruits varies depending on the production area and the year. A beta distribution approximately describes the probability distribution of the proportion of injured fruits in the production area of a given consignment. (2) Every consignment contains fruits that were drawn at random from the infinite population of the production area. (3) A sample is drawn at random from every consignment. The sample is not returned to the consignment. (4) There is a constant probability that an injured fruit contains live insects. Noninjured fruits do not contain live insects.

Let

k = the number of consignments inspected for exportation during a given period;

n_i = the number of fruits in the ith consignment $(i = 1,2, \ldots, k)$;

s_i = the number of fruits sampled from the ith consignment;

c_i = the maximum number of injured fruits permitted in the sample of the ith consignment;

r = the number of inspections;

q = the probability that an injured fruit contains live insects;

p = the probability of survival under a quarantine treatment;

X_i = the proportion of injured fruits in the production area of the ith consignment;

Y_i = the number of injured fruits in the sample drawn from the ith consignment;

V_i = the proportion of infested fruits in the production area of the ith consignment;

W_i = the number of infested fruits in the sample drawn from the ith consignment;

Z_i = the number of infested fruits exported through the ith consignment after the inspection;

T_i = the number of fruits exported through the ith consignment (either 0 or n_i);

μ_{before} = the average proportion of infested fruits before the export inspection;

μ_{after} = the average proportion of infested fruits after the export inspection; and

σ^2_{before} = the variance of V_i.

Single Sampling Inspection. The probability density of injured fruits (X_i) is

$$f(x) = \frac{1}{B(a,b)} x^{a-1}(1 - x)^{b-1}, \quad (0 \le x \le 1) \qquad [1]$$

where a and b are positive constants. $B(.,.)$ is a beta function. The mean and variance of X_i are given by $a/(a + b)$ and $ab/(a + b + 1)(a + b)^2$, respectively. Hence, μ_{before} and σ^2_{before} are given by $qa/(a + b)$ and $q^2\, ab/(a + b + 1)(a + b)^2$, respectively. The sample drawn from each consignment is equivalent to the sample drawn at random from the population of the production area. Hence, the conditional probability of Y_i for a given X_i is given by the binomial distribution

$$\Pr(Y_i = y|X_i = x) = \binom{s_i}{y} x^y (1 - x)^{s_i - y}.$$

$$(y = 0,1,2, \ldots, s_i). \qquad [2]$$

A consignment is accepted if the number of injured fruits in the sample (Y_i) is not larger than c_i and if all the injured fruits in the sample are non-infested fruits. The probability that all injured fruits are non-infested fruits is given by $(1 - q)^y$ for $Y_i = y$. Hence, the probability of acceptance of the ith consignment for a given X_i is

$$\sum_{y=0}^{c_i} (1 - q)^y \Pr(Y_i = y|X_i = x). \qquad [3]$$

The probability of infestation is qX_i for all the unexamined $(n_i - s_i)$ fruits. These infested fruits are exported only if the consignment is accepted. The expectation of the number of infested fruits is $(n_i - s_i)qX_i$ if the consignment is accepted, but it is zero if the consignment is rejected. Hence, the expectation of the number of infested fruits exported through the ith consignment for $X_i = x$ is given by multiplying $(n_i - s_i)qx$ and quantity 3. Then, we obtain $E(Z_i)$ by integrating it:

$$E(Z_i) = \int_0^1 (n_i - s_i)qx \sum_{y=0}^{c_i} (1 - q)^y \Pr(Y_i = y|X_i = x)$$

$$\cdot f(x)dx = (n_i - s_i)q \sum_{y=0}^{c_i} (1 - q)^y$$

$$\cdot \binom{s_i}{y} \frac{B(a + y + 1, b + s_i - y)}{B(a,b)}. \qquad [4]$$

The probability of acceptance of the ith consignment is given by the integration of quantity 3:

$$\int_0^1 \sum_{y=0}^{c_i} (1 - q)^y \Pr(Y_i = y|X_i = x) f(x)dx. \qquad [5]$$

$(n_i - s_i)$ fruits are exported if the consignment is accepted. Hence, the expectation of the number of fruits exported through the ith consignment is given by multiplying $(n_i - s_i)$ and quantity 5:

$$E(T_i) = (n_i - s_i) \int_0^1 \sum_{y=0}^{c_i} (1 - q)^y \Pr(Y_i = y|X_i = x) f(x)dx$$

$$= (n_i - s_i) \sum_{y=0}^{c_i} (1 - q)^y \binom{s_i}{y} \frac{B(a + y, b + s_i - y)}{B(a,b)}. \qquad [6]$$

In a sampling inspection where the sample is returned to the consignment after the examination, $(n_i - s_i)$ should be replaced by n_i in equation 6. The average proportion of infested fruits after inspection (μ_{after}) can be approximately expressed by a simple equation if k is sufficiently large:

$$\mu_{\text{after}} \approx \sum_{i=1}^{k} E(Z_i) \Big/ \sum_{i=1}^{k} E(T_i). \qquad [7]$$

The proportion of injured fruits will be sufficiently small for serious pests. Hence, we consider the limiting case, $b \to \infty$, in the following arguments. Then, equation 1 is approximately given by a gamma distribution with a shape parameter a and a scale parameter b:

$$f(x) = \frac{1}{\Gamma(a)} b^a x^{a-1} \exp(-bx), \qquad (0 \le x) \qquad [8]$$

where $\Gamma(.)$ is a gamma function. The mean and variance of X_i are given by a/b and a/b^2, respectively. Hence, μ_{before} and σ^2_{before} are given by qa/b and q^2a/b^2, respectively. Simultaneously, equations 2, 4, and 6 become the following equations when $b \to \infty$:

$$\Pr(Y_i = y | X_i = x) = \frac{(xs_i)^y \exp(-xs_i)}{y!}, \qquad (y = 0,1,2,\ldots) \qquad [9]$$

$$E(Z_i) = (n_i - s_i)\frac{qa}{b} \sum_{y=0}^{c_i} (1-q)^y \frac{\Gamma(a+y+1)}{\Gamma(a+1)y!} \cdot \left(1 + \frac{s_i}{b}\right)^{-(a+1)} \left(\frac{s_i}{b+s_i}\right)^y, \qquad [10]$$

$$E(T_i) = (n_i - s_i) \sum_{y=0}^{c_i} (1-q)^y \frac{\Gamma(a+y)}{\Gamma(a)y!} \cdot \left(1 + \frac{s_i}{b}\right)^{-a} \left(\frac{s_i}{b+s_i}\right)^y. \qquad [11]$$

Quarantine treatments such as fumigation or cold treatments may be used together with sampling inspections in the systems approach. Let us assume that live larvae are killed by the quarantine treatment with a constant probability of survival, p. Also assume that each infested fruit contains a single live larva. Then, if the quarantine treatment is conducted after the sampling inspection, the resultant expected number of infested fruits is given by a simple multiplication, $pE(Z_i)$. However, if a quarantine treatment is conducted before the sampling inspection, the resultant number of infested fruits may not be given by a simple multiplication, since the effectiveness of sampling inspection may change depending on the proportion of infested fruits. In this case, we should calculate $E(Z_i)$ by replacing q by pq.

Multiple Sampling Inspection ($r > 1$). We assume that the consignments are not intermixed between the successive inspections. We also assume that s_i and c_i do not change between inspections, for simplicity. If the sample size (s_i) is sufficiently smaller than the consignment size (n_i), the samples drawn in the successive inspections are almost mutually independent. Hence, the probability of acceptance is approximately given by the ^{r}th power of quantity 3. Then, we obtain

$$E(Z_i) \approx \int_0^{\infty} qx(n_i - rs_i)\left[\sum_{y=0}^{c_i} (1-q)^y \Pr(Y_i = y|X_i = x)\right]^r \cdot f(x)dx = (n_i - rs_i)\int_0^{\infty} qx \exp(-qrs_i x) \cdot \left[1 - \frac{\Gamma(c_i+1,(1-q)s_i x)}{\Gamma(c_i+1)}\right]^r f(x)dx, \qquad [12]$$

$$E(T_i) \approx \int_0^{\infty} (n_i - rs_i)\left[\sum_{y=0}^{c_i} (1-q)^y \Pr(Y_i = y|X_i = x)\right]^r \cdot f(x)dx = (n_i - rs_i)\int_0^{\infty} \exp(-qrs_i x) \cdot \left[1 - \frac{\Gamma(c_i+1,(1-q)s_i x)}{\Gamma(c_i+1)}\right]^r f(x)dx, \qquad [13]$$

where $\Gamma(c_i + 1, (1-q)s_i x)$ is an incomplete gamma integral (Wolfram 1996):

$$\Gamma(c_i+1,(1-q)s_i x) = \int_0^{(1-q)s_i x} t^{(c_i+1)-1} \exp(-t)dt.$$

The quantity of μ_{after} is given by equation 7 where $E(Z_i)$ and $E(T_i)$ are substituted by equations 12 and 13, respectively.

Comparison With Zero-Tolerance Method. The probability density of infested fruits is obtained by the transformation, $V_i = qX_i$, and hence it is approximately given by a gamma distribution with a shape parameter a and a scale parameter b/q:

$$g(v) = \frac{1}{\Gamma(a)}\left(\frac{b}{q}\right)^a v^{a-1} \exp\left[-\left(\frac{b}{q}\right)v\right]. \qquad (0 \le v) \qquad [14]$$

The distribution of W_i for a given V_i is given by a Poisson distribution:

$$\Pr(W_i = w | V_i = v) = \frac{(vs_i)^w \exp(-vs_i)}{w!}. \qquad (w = 0, 1, 2, \ldots) \qquad [15]$$

The consignment is accepted if $W_i = 0$. Hence, $E(Z_i)$ and $E(T_i)$ are given by the following equations by a similar argument described previously:

$$E(Z_i) = \int_0^{\infty} v(n_i - s_i)\Pr(W_i = 0|V_i = v)g(v)dv = (n_i - s_i)\frac{qa}{b}\left(1 + \frac{qs_i}{b}\right)^{-(a+1)}, \qquad [16]$$

$$E(T_i) = \int_0^\infty (n_i - s_i)\Pr(W_i = 0|V_i = v)g(v)dv$$

$$= (n_i - s_i)\left(1 + \frac{qs_i}{b}\right)^{-a}. \quad [17]$$

For a multiple inspection, we obtain the following equations:

$$E(Z_i) \approx (n_i - rs_i)\frac{qa}{b}\left(1 + \frac{qrs_i}{b}\right)^{-(a+1)}, \quad [18]$$

$$E(T_i) \approx (n_i - rs_i)\left(1 + \frac{qrs_i}{b}\right)^{-a}. \quad [19]$$

In a sampling inspection where the sample is returned to the consignment after the examination, $(n_i - s_i)$ and $(n_i - rs_i)$ should be replaced by n_i in equations 17 and 19, respectively.

Estimation of Parameters. From equations 8 and 9, we obtain

$$\Pr(Y_i = y) = \int_0^\infty \Pr(Y_i = y|X_i = x)f(x)dx$$

$$= \frac{\Gamma(a + y)}{y!\Gamma(a)}\left(1 + \frac{s_i}{b}\right)^{-a}\left(\frac{s_i}{b + s_i}\right)^{y}, \quad [20]$$

a negative binomial distribution with the mean $s_i a / b$ and variance $s_i a(b + s_i)/b^2$. We obtain the maximum likelihood estimates of a and b in a manner shown in the appendix of Yamamura and Sugimoto (1995). The maximum likelihood estimate of q, which is denoted by $\hat{q}$, is obtained by maximizing the conditional likelihood of W_i for a given set of Y_i:

$$\sqrt{\hat{q}} = \sum_{i=1}^{k} W_i \bigg/ \sum_{i=1}^{k} Y_i. \quad [21]$$

Example. We considered a numerical example of the sampling inspection for the codling moth. Although the parameters a, b, and q should be estimated by the maximum likelihood method based on equations 20 and 21, we do not have data for such estimation. Information developed by the Washington State Department of Agriculture showed that of the 41,397,020 apples inspected for export over a 5-yr period, 33 were found to be infested with codling moth larvae (Moffitt 1990). Hence, we estimated that $\mu_{\mathrm{before}} = qa/b = 33/41{,}397{,}020 = 8 \times 10^{-7}$. Moffitt (1990) examined the cull and off-graded apples from bins in the packagehouse, and found that 10 out of 171,448 culled apples were infested with codling moth larvae. These data yield an estimate, $q = 10/171448 = 5.8 \times 10^{-5}$. However, only a part of culled apples will have injury marks, and hence the actual value of q seems to be much larger than 5.8×10^{-5}. Thus, we first evaluated the effect of q on the proportion of infested fruits after the sampling inspection (μ_{after}) by using $q = 10^{-4}$, 10^{-3}, and 10^{-2}. In this calculation, we assumed $\mu_{\mathrm{before}} = 8 \times 10^{-7}$, $s_i = 10^4$, $(c_i/s_i) = 10^{-2}$, and $n_i = 10^6$. We also calculated μ_{after} for zero-tolerance method. Because we could not determine $\sigma^2_{\mathrm{before}}$, we calculated μ_{after} for various values of $\sigma^2_{\mathrm{before}}$. Equations 10, 11, 16, and 17 were used in these calculations. Figure 1 indicates that the sampling inspection by using injury marks is effective only if q is sufficiently small; that is, if the number of injured fruits is sufficiently larger than the number of infested fruits.

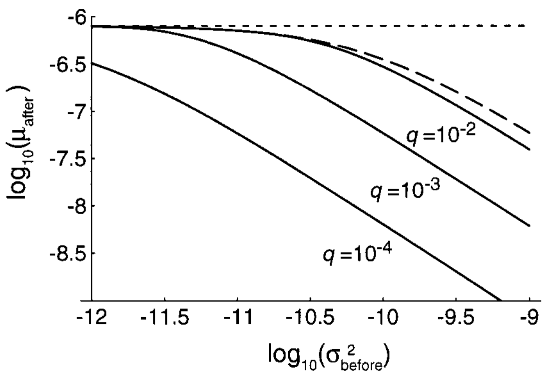

Fig. 1. Effect of the probability that an injured fruit contains live insects (q) upon the average proportion of infested fruits after the sampling inspection (μ_{after}). The curves are plotted against the logarithmic variance of the proportion of infested fruits before inspection ($\sigma^2_{\mathrm{before}}$). Solid curves indicate μ_{after} for the sampling inspection by using injury marks. The broken curve indicates μ_{after} for the zero-tolerance method. The dotted line indicates the average proportion of infested fruits before the sampling inspection (μ_{before}). $s_i = 10^4$, $c_i = 10^2$, and $n_i = 10^6$.

We next evaluated how difference in sampling scheme influences μ_{after}. Figure 2 indicates that the quarantine security will be considerably improved by using injury marks when the sample size (s_i) is small. Figure 3 indicates that the sampling inspection by using injury marks is effective only if the permitted proportion of injured fruits (c_i/s_i) is sufficiently small. The difference between $\log_{10}(\mu_{\mathrm{before}})$ and $\log_{10}(\mu_{\mathrm{after}})$ is 2 at most in Figs. 1–3. Hence, the survival rate is larger than 10^{-2} in most of these sampling schemes. However, the mortality of probit 9 (i.e., survival rate of $10^{-4.5}$) has been traditionally used as a standard of quarantine treatments (Landolt et al. 1984). If we want to obtain the probit 9 mortality only by a sampling inspection, an intensive sampling inspection using $s_i = 10^5$ and $c_i = 1$ is required (Fig. 4).

We evaluated the combined effect of a sampling inspection and a quarantine treatment that is conducted before the inspection, by replacing q by pq. Figure 5 indicates that the effectiveness of zero-tolerance method decreases with increasing degree of quarantine treatment; the effectiveness almost vanishes when $p = 10^{-2}$. The sampling inspection by using injury marks, on the contrary, does not lose its effectiveness even if a quarantine treatment is con-

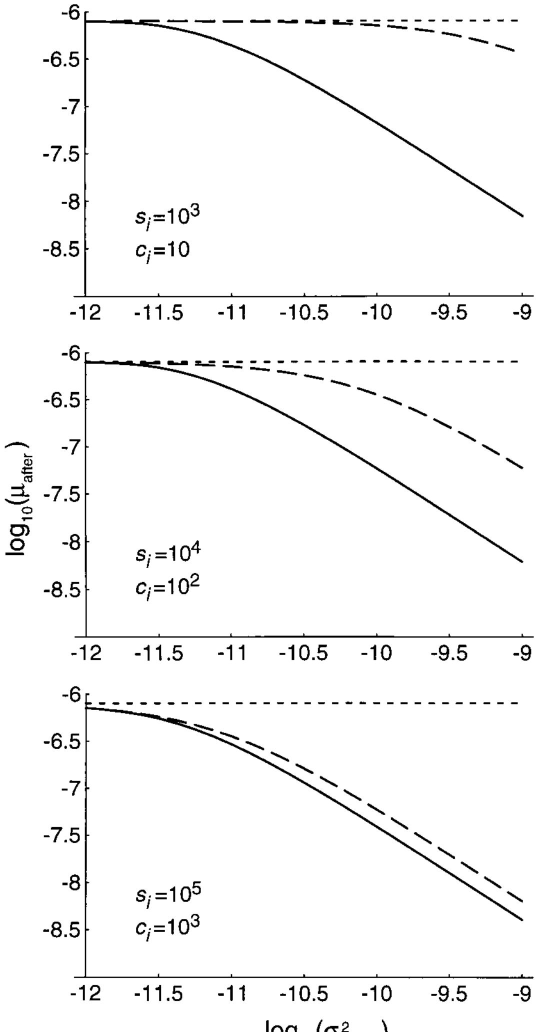

Fig. 2. Effect of the sample size (s_i) upon the average proportion of infested fruits after the sampling inspection ($\mu_{\rm after}$). Meanings of curves are as for Fig. 1. Percentage of injured fruits permitted for exportation is fixed at $(c_i/s_i) = 10^{-2}$. $n_i = 10^6$ and $q = 10^{-3}$.

ducted beforehand; the solid curves are almost the same for all p in Fig. 5.

The effect of the number of sampling inspections was evaluated by numerically integrating equations 12 and 13. We first integrated $[(n_i - rs_i) - E(T_i)]$ for equation 13 to improve the precision of numerical integration. Figure 6 indicates that $\mu_{\rm after}$ decreases with increasing number of inspections but that the decrease is not proportional to the number of inspections.

Discussion

All apples and cherries from the United States for Japan are currently exported after quarantine treat-

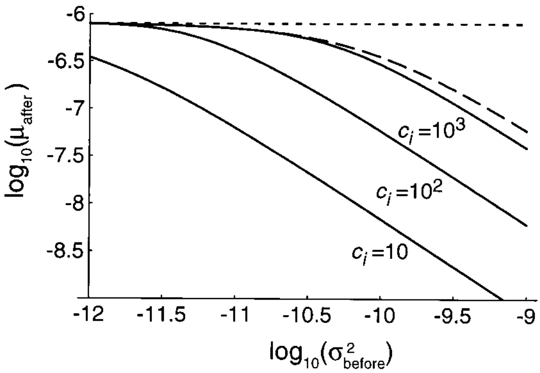

Fig. 3. Effect of the permissible number of injured fruits (c_i) upon the average proportion of infested fruits after the sampling inspection ($\mu_{\rm after}$). Meanings of curves are as for Fig. 1. $s_i = 10^4$, $n_i = 10^6$, and $q = 10^{-3}$.

ments such as fumigation and low-temperature treatment. Experiments, in which no survivor was observed in 3×10^4 insects treated, guarantee the efficiencies of these treatments because the probability of obtaining such an experimental result is <0.05 if the survival rate is larger than 10^{-4}; it ensures with 95.02% confidence that survival rate is less than 10^{-4} (Couey and Chew 1986). In contrast, Figs. 1 and 5 indicate that the survival rate under the usual sampling inspection is considerably larger than 10^{-4} even if injury marks are used. The difference between $\log_{10}(\mu_{\rm before})$ and $\log_{10}(\mu_{\rm after})$ is 2 at most, indicating that the survival rate under the sampling inspection is larger than 10^{-2} in this range of $\sigma^2_{\rm before}$. If we want to reduce the survival rate below 10^{-4} by a sampling inspection without quarantine treatments, an intensive sampling inspection will be required as shown in Fig. 4.

Various protection practices are conducted sequentially in the systems approach. If the mortality in each phase is mutually independent, we can estimate the total survival rate by multiplying the survival rate in

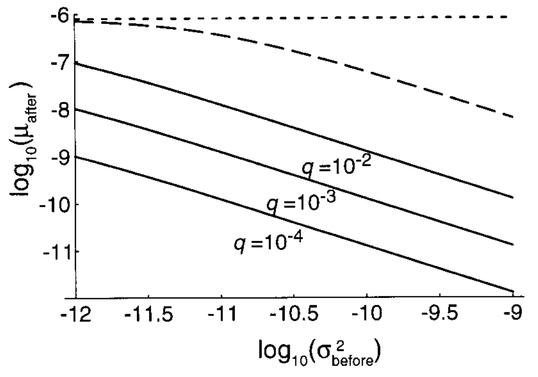

Fig. 4. Intensive sampling inspection having a probit 9 mortality, in which the average proportion of infested fruits after the sampling inspection ($\mu_{\rm after}$) is reduced by $10^{-4.5}$. Meanings of curves are as for Fig. 1. $s_i = 10^5$, $c_i = 1$, and $n_i = 10^6$.

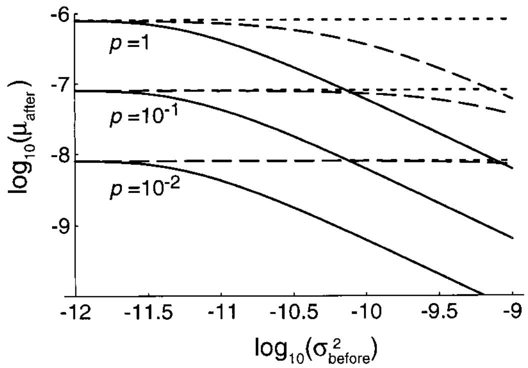

Fig. 5. Effect of the survival rate (p) of the quarantine treatment before sampling inspection upon the average proportion of infested fruits after the sampling inspection (μ_{after}). Meanings of curves are as for Fig. 1. $s_i = 10^4$, $c_i = 10^2$, $n_i = 10^6$, and $q = 10^{-3}$.

each phase. If there are some interactions between the mortality, however, the estimation becomes complicated. Mangan and Sharp (1994) reexamined the experimental results of multiple treatment from the literature to clarify the existence of interactions. The data of von Windeguth and Gould (1990) indicated no consistent interaction between the effects of gamma radiation and cold storage. However, synergetic effects were detected between the methylbromide treatment and cold storage reported by Seo et al. (1971) and between the hot water dip and cold storage reported by Couey et al. (1984). In contrast, Fig. 5 indicates the existence of antagonistic effects between quarantine treatments and the zero-tolerance method; the effectiveness of zero-tolerance method decreases with decreasing p. However, Fig. 5 indicates that the effectiveness of sampling inspection by using injury marks is not much influenced by p. Thus, a sampling inspection by using injury marks seems to be especially suitable for the systems approach because it does not lose its effectiveness even if quarantine treatments are used together. If the sampling inspection induces a survival rate of 10^{-2}, for example, we can achieve the probit 9 mortality by conducting together a quarantine treatment that has a survival rate of $10^{-2.5}$ because the multiplication yields the total survival rate of $10^{-4.5}$.

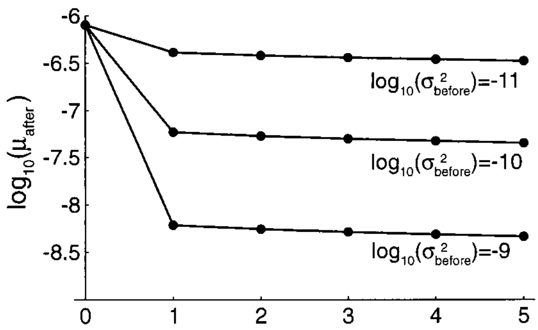

Fig. 6. Effect of the number of sampling inspections by using injury marks upon the average proportion of infested fruits after inspections (μ_{after}). $s_i = 10^4$, $c_i = 10^2$, $n_i = 10^6$, and $q = 10^{-3}$.

We do not yet have enough data to obtain accurate estimates of parameters. The quantity of X_i will fluctuate greatly year by year, and hence the maximum likelihood estimates of the parameters a and b should be calculated based on the data collected for a many years. The parameter q also may change depending on various factors such as the pest management practices and the climatic conditions. The parameter is very influential in determining the effectiveness of sampling inspection (Fig. 1). If such a variation is large, therefore, it may be preferable to calculate the weighted average of $E(Z_i)$ about q.

Although we calculated μ_{after} to evaluate the effectiveness of the export plant quarantine inspection in this paper, the expectation of the total number of infested fruits, $\sum_{i=1}^{k} E(Z_i)$, will be a more appropriate measure, if it is desired to evaluate the risk of quarantine pest invasion. If the quarantine pest species may be brought into the country through several fruit items, we should add all $E(Z_i)$ of those fruit items to obtain the estimate of the total number of insects passing the port. In the case of the codling moth, for example, $E(Z_i)$ of apples, cherries, nectarines and walnuts should be added. The quantity of $\sum_{i=1}^{k} E(Z_i)$ will increase with increasing k. Hence, the future risk of invasion by quarantine pests should be evaluated considering the future increase in the number of imported fruits.

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