Exhibit 5, #32

FORUM

Accelerated Development of Quarantine Treatments for Insects on Poor Hosts

PETER A. FOLLETT AND GRANT T. MCQUATE

U.S. Pacific Basin Agricultural Research Center, USDA–ARS, P.O. Box 4459, Hilo, HI 96720

J. Econ. Entomol. 94(5): 1005–1011 (2001)

ABSTRACT The probit 9 standard for quarantine treatment efficacy (99.9968% mortality) was originally recommended for tropical fruits heavily infested with fruit flies and it centers on high mortality to achieve quarantine security. This standard may be too stringent for quarantine pests in commodities that are rarely infested or are poor hosts. The *alternative treatment efficacy* approach measures risk as the probability of a mating pair, gravid female, or parthenogenic individual surviving in a shipment. This will be a function of many factors including infestation rate and shipment volume. Applying the risk-based alternative treatment efficacy approach to pests on rarely infested or poor hosts will lower the number of required test insects needed for developing quarantine treatments; hence data for a quarantine treatment could be generated by testing 10,000 or fewer insects with no survivors, compared with 90,000–100,000 insects to demonstrate the traditional probit 9 efficacy. Several commodity/quarantine pest systems where this approach could be applied are discussed. This approach would save time and resources, and help farmers export their crop on a more-timely basis.

KEY WORDS *Bactrocera dorsalis, Cryptophlebia,* alternative treatment efficacy, quarantine treatment, pest risk management

AN OVERRIDING CONCERN for countries importing foreign commodities is the exclusion of exotic pests of potential economic importance that are not yet present or are not widely distributed in the importing country, so-called quarantine pests. Phytosanitary or quarantine treatments are often required to disinfest host commodities of economically important arthropod pests before they are moved through market channels to areas where the pest does not occur. In the past, the guiding principle in quarantine treatment research has been the probit 9 standard for treatment efficacy (Robertson et al. 1994). The probit 9 standard (99.9968% mortality) was initially recommended for tropical fruits heavily infested with fruit flies (Baker 1939). The probit 9 approach centers on high mortality of the treated pest population and, for heavily infested commodities, usually provides adequate quarantine security. However, this standard may be too stringent for commodities that are rarely infested or are poor hosts.

The *alternative treatment efficacy* approach measures risk as the probability of a mating pair, gravid female, or parthenogenic individual surviving in a shipment (Landolt et al. 1984). This will be a function of many factors including infestation rate, culling and other postharvest removal of infested fruit, shipment volume, shipping and storage conditions and the mortality these conditions exact on the pest, and other biological and nonbiological factors (Vail et al. 1993, Liquido et al. 1997). The probability of establishment after shipment will be a function of many additional factors including host availability and suitability of the climate (Landolt et al. 1984, Whyte et al. 1994). The main quantitative argument for deviating from probit 9 treatment efficacy is low infestation rate of the commodity. One practical benefit of reducing the required treatment efficacy is that fewer insects must be tested during quarantine treatment development.

Here, we synthesize a series of published equations that calculate the risk of infestation, the required treatment efficacy, and the necessary number of test insects during quarantine treatment development to ensure quarantine security. Quarantine pests of the tropical fruit rambutan (*Nephelium lappaceum* L.) and several other commodities are used to illustrate the approach and necessary conditions.

Calculating Pest Risk

The main criterion for defining risk is the probability of a potential mating pair or reproductive individual surviving in a regulated consignment of fruit. This will primarily be a function of infestation rate, shipment size, and the efficacy of the disinfestation treatment. The probability of finding one or more mating pairs is given by:

$$P = [1 - e^{-NFT/2}]^2, \qquad [1]$$

where N is the number of fruit in a shipment, F is the field infestation rate (per fruit), and T is pest survival after a postharvest treatment (Liquido et al. 1996, 1997). Equation 1 assumes a Poisson distribution of

surviving insects in fruit (i.e., frequency distribution for rare events [Sokal and Rohlf 1981, Couey and Chew 1986]). *NFT* is the average number of live pests in a shipment after a postharvest treatment.

If we assume the postharvest treatment (T) provides probit 9 efficacy (99.9968% mortality of the pest), we can calculate the frequency of live pest occurrence and the probability of having a mating pair in a single shipment or series of shipments. If probit 9 efficacy of a disinfestation treatment results in significant overkill, the efficacy of the treatment can be reduced to some extent, while still maintaining quarantine security. Assuming we are trying to prevent a mating pair from arriving in a single shipment, the equations to calculate the required treatment mortality (m) are as follows:

$$m = 1 - (NR/(i*n*s)), \quad [2]$$

$$NR = -2*(\log_e (1 - \sqrt{P})), \quad [3]$$

where i is the infestation rate (or the upper bound of 95% confidence interval for infestation rate determined in the field if this is available), n is the number of fruit in a shipment, and s is the natural survival rate of insects in fruit after harvest (Vail et al. 1993). NR is the number of fruit (N) multiplied by the infestation rate (R) and is a constant function of P (Vail et al. 1993). We conservatively set P, the probability of having one or more mating pairs, at 0.01 (99% chance of having < 1 mating pair) which makes $NR = 0.21$. (So, there is a 99% probability of the presence of <1 mating pair if an average of 0.2107 individuals survive in a given quantity of fruits based on the Poisson distribution [Vail et al. 1993]). If we assume that the survival rate (s) is 1.0, m becomes solely a function of infestation rate and shipment size. These are the main factors that have a direct effect on the probability of a mating pair surviving in a shipment, although other variables could modify or reduce the numbers. From these estimates, the required quarantine treatment efficacy can be calculated to ensure with 99% confidence that <1 mating pairs survives in a shipment. Equation 2 is only valid if ($NR/i*n*s$) is <1, which is not always satisfied if pest infestation is extremely rare (see discussion).

Estimates for the required treatment efficacy can be used to determine the number of insects that must be tested such that if no survivors are found, we will have 95% confidence that the probability of survivors meets the treatment efficacy or probit mortality level established. The equation to calculate the number of test insects (n) is as follows:

$$n = [\log(1 - C)]/\log(m), \quad [4]$$

where C = confidence level (between 0 and 1, arbitrarily set at 0.95), and m is the level of required mortality (between 0 and 1, from equation 2) (Couey and Chew 1986). The probit 9 standard requires that 93,613 insects ($C = 0.95$, $m = 0.999968$) be tested with no survivors. [Couey and Chew (1986) also give the equation for calculating the required number of test insects with one or more survivors.] This level of testing may not be practical for insect pests that rarely infest the host or if survivorship on the host is poor. With the alternative treatment efficacy approach, low infestability of the host is included in a probability equation and the number of required test insects can be reduced. When m, the required treatment efficacy, decreases so does the required number of test insects.

There are many quarantine insects on poor or rarely infested hosts that qualify for the alternative treatment efficacy approach, and significant resources could be saved by reducing the number of test insects required during quarantine treatment development. The rambutan pest system in Hawaii is used to illustrate in detail the application of the alternative efficacy approach and the calculation of pest risk.

Rambutan Infestation in Hawaii

Rambutan, *Nephelium lappacium* L., is an evergreen tree fruit native to west Malaysia and Sumatra and widely grown in Southeast Asia (Zee et al. 1998). Malaysia and Thailand currently are the major exporting countries. The fruit belongs to the Sapindaceae, a family that includes the lychee, *Litchi chinensis* Sonn., and longan, *Dimocarpus longan* (Lour.) Steud. In Hawaii, rambutan is the lead crop in a rapidly expanding tropical exotic fruits industry and exports of this fruit have begun.

The principal high-risk regulatory pests of rambutan are *Bactrocera dorsalis* (Hendel), *Ceratitis capitata* (Wiedemann), and *Cryptophlebia* spp., which are all internal feeders (USDA-APHIS-PPQ 1996). *Bactrocera dorsalis* and *C. ceratitis* adults lay groups of eggs beneath the surface of the fruit. The entire larval period is spent inside the fruit feeding on the pulp and the last instar leaves the fruit to pupate in the soil. Mature fruits are most susceptible to fruit fly attack, but the spinterns and thick pericarp of rambutan probably act as impediments to oviposition. Although adult 'sting' marks and multiple eggs can be found in rambutan fruits, seldom are *B. dorsalis* and *C. ceratitis* larvae observed inside fruit while the fruit is healthy and still on the tree (P.A.F., unpublished data).

Two species of *Cryptophlebia* (Lepidoptera: Tortricidae) attack rambutan in Hawaii: *Cryptophlebia illepida* (Butler), a native Hawaiian species known as the koa seedworm, and *Cryptophlebia ombrodelta* (Lower), an Australian import called the litchi fruit moth. Both species are regulatory pests of lychee and longan, but recently have also been found infesting rambutan (McQuate et al. 2000) and are a quarantine concern on this fruit. *Cryptophlebia* is multivoltine (Jones et al. 1997). Eggs are laid singly on the fruit surface and neonate larvae penetrate the skin and feed at the skin/pulp interface. Larvae may feed on the pulp or bore into the seed, and leave the fruit to pupate. Typically, only one larva is found feeding in a fruit (McQuate et al. 2000). No insecticides are applied to rambutan in Hawaii for control of fruit flies or *Cryptophlebia.*

While fruit flies and *Cryptophlebia* oviposit on rambutan fruits, actual damage from larval feeding is un-

Table 1. Required treatment efficacy and number of test insects for *B. dorsalis* and *Cryptophlebia* infesting rambutan in Hawaii using the alternative treatment efficacy approach (95% confidence that <1 mating pair survives in a shipment)

Pest	Infestation rate	95% CL (upper bound)	Shipment size (kg)	Shipment size (No. fruits)	Probability of ≥1 mating pairs with probit 9[a]	Treatment efficacy required[b]	Probit[c]	No. test insects required (0 survivors)[d]
B. dorsalis	0.0007	0.0009	20,000	500,000	5.1×10^{-5}	99.953	8.31	6,372
			10,000	250,000	1.3×10^{-5}	99.906	8.11	1,383
			2000	50,000	5.2×10^{-7}	99.532	7.59	639
Cryptophlebia	0.0011	0.0013	20,000	500,000	1.1×10^{-4}	99.968	8.40	9,076
			10,000	250,000	2.7×10^{-5}	99.935	8.21	4,607
			2000	50,000	1.1×10^{-6}	99.676	7.72	923

[a] From equation 1.
[b] From equations 2 and 3.
[c] From equations 2 and 3, and a probit table.
[d] From equations 2, 3, and 4.

common and larval survival to pupation when fruit are on the tree is rare (P.A.F., unpublished data). Laboratory tests and field surveys in Hawaii over the past several years confirm that rambutan and its close relatives, lychee and longan, are poor hosts for *B. dorsalis*, *C. ceratitis*, and *Cryptophlebia.* In a recent study, over 47,000 mature fruits of nine varieties of rambutan were harvested from orchards in Hawaii to assess natural levels of infestation by any internal feeding pests such as fruit flies and *Cryptophlebia* (McQuate et al. 2000). Fruits were held in perforated zip-lock bags with sand in the bottom to allow larval development and pupation, then removed and held for adult eclosion. Rambutan fruits in this study were infested by *B. dorsalis* and *Cryptophlebia* spp.; *C. capitata* was not observed. Over all varieties, infestation rates (number of adults emerging per fruit) for the quarantine pests were 0.0007 for *B. dorsalis* (33 adults emerged from 47,188 fruits) and 0.0011 (50 adults emerged from 47,188 fruits) for *Cryptophlebia* spp. The average number of adults emerging per infested fruit was 3.3 for *B. dorsalis* and 1.1 for *Cryptophlebia.*

To calculate pest risk during export shipments, estimates are needed for rambutan infestation rates, shipment size, and the efficacy of the disinfestation treatment. To be conservative, we determined 95% confidence intervals for these single point estimates of infestation rates and used the upper bound for further calculations of pest risk. Using the approach of Couey and Chew (1986) (Table 1) the upper bound of the 95% confidence limit was calculated as 0.0009 for *B. dorsalis* and 0.0013 for *Cryptophlebia.*

Realistic estimates for shipment size in terms of number of fruits can be determined using fruit weight data. In McQuate et al. (2000) rambutan fruit weights averaged from 34.0 g ('R-7') to 47.9 g ('R-156 Red'). Using these weights, a shipment of 20,000 kg would have ≈590,000 fruits of the small variety and 418,000 fruits of the large variety. Because rambutan varieties are usually mixed in a shipment, an estimate of 500,000 fruits in 20,000 kg is realistic. Shipments sizes of 2,000–10,000 kg are probably more realistic for the rambutan industry in Hawaii at this time, which would yield ≈50,000–250,000 fruits.

If we assume the postharvest treatment (T) provides probit 9 efficacy (99.9968% mortality of the pest), the frequency of live pest occurrence in a series of rambutan shipments, and the probability of having a mating pair in a single shipment for *B. dorsalis* and *Cryptophlebia* can be calculated (Table 1). At the largest shipment size, 500,000 fruits, the predicted frequency of occurrence (*NFT*) of live *B. dorsalis* is 0.014 (1 individual in 71 shipments), and at the smallest shipment size, 50,000 fruits, the frequency is predicted to be 0.0014 (1 individual in 714 shipments). At the largest shipment size, 500,000 fruits, the probability of >1 mating pairs surviving in a shipment is 0.000051 (5.1×10^{-5}) for *B. dorsalis* (1 mating pair in 19,608 shipments), and 0.00011 (1.1×10^{-4}) for *Cryptophlebia* (1 mating pair in 9091 shipments). In a shipment of 50,000 fruits, the probability of a mating pair in a shipment is reduced to 5.2×10^{-7} for *B. dorsalis* and 1.1×10^{-6} for *Cryptophlebia.* Therefore, in all cases, the probit 9 level of efficacy of the treatment provides a high level of overkill, and the probability of a having a mating pair of either of these two pests in a shipment of rambutan is extremely small.

The required quarantine treatment efficacy (m) can be calculated to ensure with 99% confidence that <1 mating pair survives in a rambutan shipment or series of shipments (Table 1). Using the upper bound of the 95% confidence interval for infestation rates determined in the field, less-than-probit 9 efficacy was required for a quarantine treatment for each of the shipment sizes considered. For example, in a shipment size of 500,000 rambutan fruits the required treatment efficacy to prevent the shipment of a mating pair for *B. dorsalis* is 99.953% mortality, which translates to probit 8.31, and the required treatment efficacy to prevent the shipment of a mating pair for *Cryptophlebia* is 99.967% mortality, which translates to probit 8.4.

Estimates for the required treatment efficacy can be used to determine the number of insects that must be tested during quarantine studies such that if no survivors are found, we will have 95% confidence that the probability of survivors meets the treatment efficacy or probit level established. For *B. dorsalis* and *Cryptophlebia* in rambutan under three shipment size con-

Table 2. Examples of other commodities that are rarely infested or poor hosts for quarantine pests

Pest	Commodity	Infestation rate (insects/fruit)	Shipment size (kg)	Shipment size (No. fruits)	Probability of ≥1 mating pairs with probit 9	Treatment efficacy required	Probit	No. test insects required (0 survivors)
Cryptophlebia	Longan[a]	1.4×10^{-3}	10,000	1,110,000	6.0×10^{-4}	99.986	8.56	21,397
Oriental fruit fly	Lychee[a]	5.6×10^{-3}	10,000	588,000	2.6×10^{-3}	99.994	8.83	49,927
	Avocadoes[b]	2.1×10^{-2}	9,000	40,000	1.8×10^{-4}	99.975	8.47	11,981
Codling moth	Nectarines[c]	9.2×10^{-6}	15,966	89,600	1.7×10^{-10}	74.437	5.65	10
	Sweet cherries[d]	1.8×10^{-8}	17,417	3,456,000	9.9×10^{-13}	—	—	
Western cherry fruit fly	Sweet cherries[d]	1.9×10^{-6}	17,417	3,456,000	1.1×10^{-8}	96.791	6.85	92
Peach twig borer	Prunes[e]	1.2×10^{-4}	20,320	627,200	1.4×10^{-6}	99.720	7.77	1,068

—, Not calculable from equations 2 and 3 due to extremely low incidence.
[a] G.T. McQuate, unpublished data.
[b] Liquido et al. (1995).
[c] Curtis et al. (1991).
[d] Source: Washington State Department of Agriculture F&V Inspection and USDA-APHIS.
[e] Yokoyama and Miller (1999).

ditions, the required number of test insects (n) ranged from 639–9,076 (Table 1). For example, to ensure quarantine security for *B. dorsalis* in a shipment of 500,000 rambutan fruits or less, 6,372 insects must be treated with the proposed treatment with no survivors.

Other Commodities that are Rarely Infested

Table 2 lists several additional crop/quarantine pest situations that would be amenable to the alternative treatment efficacy approach. Like rambutan, surveys have been conducted at harvest of the internal-feeding pests of lychee and longan in Hawaii, and the two quarantine pests infesting these fruits were *B. dorsalis* and *Cryptophlebia.* No insecticides are applied to lychee or longan in Hawaii. The infestation rate for *Cryptophlebia* in longan was 1.4×10^{-3} (14 adults emerged from 9,700 fruits), and the infestation rate for *B. dorsalis* in lychee was 5.6×10^{-3} (201 adults emerged from 35,722 fruits) (G.T.M., unpublished data). Using the alternative treatment efficacy approach, the required treatment efficacy for *Cryptophlebia* in a shipment of 1,110,000 longan (10,000 kg) would be 99.986%, and the number of insects required during large-scale testing of a quarantine treatment with no survivors would be 21,397. Likewise, the required treatment efficacy for *B. dorsalis* in a shipment of 588,000 lychee (10,000 kg) would be 99.994%, and the number of insects required during large-scale testing of a quarantine treatment with no survivors would be 49,927. For both *Cryptophlebia* in longan and *B. dorsalis* in lychee in Hawaii, the reduction in the required severity of a treatment and the number of required test insects using the alternative treatment efficacy approach compared with the probit 9 approach is substantial but not dramatic.

A more extreme case of an inherently poor host is codling moth in nectarines. Only three live codling moths (larvae) were found infesting 326,625 packed nectarines sampled from packinghouses in the San Joaquin Valley of California between 1985–87 for an infestation rate of 9.2×10^{-6} (Curtis et al. 1991). In a container load of nectarines with an estimated 89,600 fruits the required treatment efficacy for codling moth would be 74.437 (probit 5.65) and, therefore, a very limited number of insects (theoretically 10, but practically ≈200) would be required during large-scale testing of a quarantine treatment with no survivors.

The alternative efficacy approach can be extended beyond the consideration of quarantine pests on inherently poor hosts. For example, low infestation rate at harvest could be the result of effective pest management before harvest, as in the case of peach twig borer, *Anarsia lineatella* Zeller (Lepidoptera: Gelechiidae), in prunes and Western cherry fruit fly, *Rhagoletis indifferens* Curran (Diptera: Tephritidae) in sweet cherries. Peach twig borer is an occasional pest of fresh prunes in the San Joaquin Valley of California that is easily controlled with a dormant insecticide control program (Yokoyama and Miller 1999). The infestation rate of fresh prunes at harvest by peach twig borer was estimated at one larva per 8,501 fruit (Yokoyama and Miller 1999). At this level of infestation, the required treatment mortality to prevent a mating pair in a shipment is 99.72% (probit 7.76), and the number of required test insects during large-scale testing with no survivors is 1,068 (Table 2). Sweet cherry is a good host for Western cherry fruit fly and consequently multiple sprays with insecticides are necessary to suppress populations in the field. At pack out, the infestation rate of cherries for Western cherry fruit fly is extremely low: from 1997–99, 146 larvae of Western cherry fruit fly were detected during inspection of 75,730,574 cherries (infestation rate = 1.9×10^{-6}) for the Japan market (J. D. Hansen, USDA-ARS, Yakima, WA, personal communication). At this level of infestation, the required treatment mortality to prevent a mating pair in a large shipment (17,417 kg; 3,456,000 cherries) is 96.791 (probit 6.85), and the number of required test insects during large-scale testing with no survivors is theoretically 92 (Table 2).

Harvesting climacteric fruits (those that continue to ripen after harvest) such as avocadoes, papayas and bananas at a nonpreferred maturity stage can also reduce infestation rates to extremely low levels before a quarantine treatment is applied. Ripe avocado is an acceptable host for *B. dorsalis* in Hawaii but infestation can be greatly reduced by harvesting mature green fruit. The infestation rate in mature green avocadoes at harvest was estimated at 0.021 (Liquido et al. 1995) (Table 2), and an overseas shipping container contains ≈40,000 avocadoes; the estimated number of test insects required with no survivors during quarantine treatment development is 11,981. Other examples are melon fly, *Bactrocera curcurbitae* (Coquillet), in papaya, and *C. ceratitis* and *B. dorsalis* in banana. Papaya is a preferred host for melon fly in Hawaii if fruit are one-half ripe or more, but typically fruit are harvested at color break to one-fourth ripe and are rarely infested (infestation rate = 0.02; Liquido et al. 1989). Ripe bananas are preferred hosts for *C. ceratitis* and *B. dorsalis* in Hawaii but fruit harvested at the mature green stage are considered nonhosts (Armstrong et al. 2001). If harvest at a nonpreferred stage of maturity or pest management in the field is used to lower infestation levels of a pest as part of a quarantine security system before export, strict certification and inspection protocols are required to ensure the system is not compromised by human error or other unforeseen factors.

Discussion

Acceptance of the concept of pest risk management (i.e., probability of a mating pair in a shipment) for qualifying pests/commodities will often decrease the number of required test insects when developing quarantine treatments, thereby saving time and resources. Also, decreasing the time involved in developing a quarantine treatment will help farmers export their crop sooner, and allow researchers to develop quarantine treatments for other crops on a more-timely basis. Naturally low infestation rates determined for the primary internal-feeding regulatory pests of rambutan in Hawaii, *B. dorsalis* and *Cryptophlebia* spp., suggest that this crop/quarantine pest system is amenable to the alternative treatment efficacy approach. Other crop/pest systems also qualify for this approach. In crop/pest systems where infestation rates in the field have the potential to be high, various pest management tactics can be incorporated into a risk management system to arrive at low infestation rates at harvest (Landolt et al. 1984, Mangan et al. 1997), the so-called systems approach (Moffitt 1990, Jang and Moffitt 1994). For some highly infested fruit crops, preharvest pest management is actually critical to ensure that postharvest treatments causing the probit 9 level of mortality provide quarantine security (e.g., Mangan et al. 1997).

A high-temperature forced-air quarantine treatment was recently developed for rambutan to achieve probit 9 efficacy for *C. capitata* and *B. dorsalis,* and involved large-scale testing of vast numbers of eggs and first instars (T. Phillips, Oklahoma State University, unpublished data). For *B. dorsalis* alone, over 250,000 late eggs and first instars were tested with no survivors. This level of testing was far in excess of what was needed to ensure quarantine security for *B. dorsalis* in rambutan based on estimations of infestation rate (Table 1). With two fruit fly mass rearing facilities in Hawaii, probit 9 level testing for *B. dorsalis* was attainable using laboratory strains in a relatively short period of time (<6 mo). With quarantine pests such as *Cryptophlebia* for which mass rearing capabilities are not available, quarantine treatment development involves a more significant time investment. For example, we conducted extensive tests with fifth instar *Cryptophlebia* for irradiation and hot water immersion quarantine treatments; tests for each treatment were completed in approximately 2 yr, treating a total of 9,000–11,000 insects with no survivors (Follett and Lower 2000, Follett and Sanxter 2001). At this rate, data for a quarantine treatment for *Cryptophlebia* using the traditional approach of demonstrating probit 9 efficacy would require 15–20 yr (testing 90,000–100,000 insects).

The accuracy of predictive models can be dependent on model assumptions and assigned confidence levels. The assumption of a Poisson distribution for equation 1 is probably justified for poor or rarely infested hosts. Although multiple insects may reside in an individual fruit (a contagious distribution, as is the case with most fruit flies) at harvest, after fruit receive a quarantine treatment causing mortality in excess of 99.9%, the expectation is that rare survivors will be randomly distributed among fruit (Baker et al. 1990, Mangan et al. 1997). For insects with a contagious distribution on preferred hosts, models other than the Poisson may be more appropriate (Mangan 2000). The negative binomial distribution is also used to describe rare events; assuming this distribution, equation 1 would become $P = (\mathrm{NFT}/2)^2$. For rare events, predictions using the Poisson and negative binomial distribution are nearly identical.

The estimated values for m (equation 2) and n (equation 4) are dependent on the confidence level variables P and C, respectively. In calculating the required treatment efficacy, P was set conservatively at 99%. In calculating the required number of test insects, C was set at 95% because this is the confidence level traditionally used in discussing probit 9 (Couey and Chew 1986). Increasing the confidence level for either equation will result in a higher estimated number of required test insects during quarantine testing.

Equation 2 is not valid for $[i*n*s] < \mathrm{NR}$ because m will be negative; this can occur when the infestation rate (i) at harvest is extremely low and shipment size (n) is not extremely large. For example, sweet cherry is a poor host for codling moth (Table 2). In sweet cherries from the Pacific Northwest and California in 1997, four codling moth larvae were found in over 218 million inspected cherries exported to Japan, an infestation rate of 1.8×10^{-8} (J. D. Hansen, USDA-ARS, Yakima, WA, personal communication). In 1998 and 1999, no codling moth larvae were found in over 423 million inspected cherries. The largest single shipment

in 1999 was 17,417 kg, ≈3.5 million fruit. Assuming two shipments of 17,417 kg (7 million cherries) land at a destination in Japan with an average codling moth infestation rate (i) of 1.8×10^{-8}, and assuming survivorship (s) during transit is 1.0, [i*n*s] would be 0.126 and m, the required treatment mortality, calculated from equations (2) and (3) would be a negative number (−0.67).

A potentially useful element to a risk management system that has not been exploited up to now is shipment volume. This is illustrated with the different shipment sizes for rambutan shown in Table 1. In smaller shipments there are fewer insects and the probability of having infested fruits and surviving insects in the shipment is lower compared with larger shipments. As a result, the necessary level of mortality for a disinfestation treatment to ensure <1 mating pair survives is reduced. A maximum allowable shipment volume for a commodity (or group of commodities infested by a particular regulatory pest) could be part of an export regulation just as restrictions are now placed on the distribution of certain fruit imports (e.g., lychee fruits from Hawaii may not be distributed in Florida).

The alternative treatment efficacy approach estimates risk of pest survival and reproduction based on biological, ecological, quarantine treatment, and marketing or distribution data. Risk is defined as the probability of having one or more reproductive individuals in a shipment. With a reliable estimate for infestation rate, the level of quarantine treatment efficacy can be established within an acceptable level of risk. The level of treatment efficacy can be used in turn to calculate the number of test insects needed, as was shown here. In all cases, we considered only treatments yielding no survivors albeit testing involved smaller numbers of insects. In theory, estimates for the required treatment efficacy can be used to modify the disinfestation treatment if a higher level of pest survivorship is acceptable compared with survivorship in a treatment that gives probit 9 efficacy. For example, this might involve reducing the duration of a heat treatment, lowering the dose of an irradiation treatment, or raising the temperature of a cold treatment. This may be critical to the practical use of a disinfestation treatment if it negatively affects quality of the commodity, which is true for many disinfestation treatments for tropical fruits (Paull 1994, Follett and Sanxter 2000).

Acknowledgments

Paul G. Barr provided computer assistance and co-authored the statistical software, CQT_STATS. James Hansen provided data on infestation rates of Western cherry fruit fly and codling moth in sweet cherries. Constructive reviews of an early version of the manuscript by Shelby Fleischer, Patrick Vail, and Guy Hallman improved its focus.

References Cited

Armstrong, J. W. 2001. Quarantine security of bananas at harvest maturity against Mediterranean and oriental fruit flies (Diptera: Tephritidae) in Hawaii. J. Econ. Entomol. 94: 302–314.

Baker, A. C. 1939. The basis for treatment of products where fruit flies are involved as a condition for entry into the United States. USDA Circ. 551.

Baker, R. T., J. M. Cowly, D. S. Harte, and E. R. Frampton. 1990. Development of a maximum pest limit for fruit flies (Diptera: Tephritidae) in produce imported into New Zealand. J. Econ. Entomol. 83: 13–17.

Couey, H. M., and V. Chew. 1986. Confidence limits and sample size in quarantine research. J. Econ. Entomol. 79: 887–890.

Curtis, C. E., J. D. Clark, and J. S. Tebbetts. 1991. Incidence of codling moth (Lepidoptera: Tortricidae) in packed nectarines. J. Econ. Entomol. 84: 1686–1690.

Follett, P. A., and R. A. Lower. 2000. Irradiation to ensure quarantine security for *Cryptophlebia* spp. (Lepidoptera: Tortricidae) in sapindaceous fruits from Hawaii. J. Econ. Entomol. 93: 1848–1854.

Follett, P. A., and S. S. Sanxter. 2000. Comparison of rambutan quality after hot forced-air and irradiation quarantine treatments. HortScience 35: 1315–1318.

Follett, P. A., and S. S. Sanxter. 2001. Hot water immersion to ensure quarantine security for *Cryptophlebia* spp. (Lepidoptera: Tortricidae) in lychee and longan exported from Hawaii. J. Econ. Entomol. 94: 1294–1297.

Jang, E. B., and H. R. Moffitt. 1994. Systems approaches to achieving quarantine security, pp. 225–237. *In* J. L. Sharp and G. J. Hallman (eds.), Quarantine treatments for pests of food plants. Westview, San Francisco, CA.

Jones, V. P., C.H.M. Tome, and L. C. Caprio. 1997. Life table for the koa seedworm (Lepidoptera: Tortricidae) based of degree-day demography. J. Econ. Entomol. 90: 1291–1298.

Landolt, P. J., D. L. Chambers, and V. Chew. 1984. Alternative to the use of probit 9 mortality as a criterion for quarantine treatments of fruit fly (Diptera: Tephritidae) infested fruit. J. Econ. Entomol. 77: 285–287.

Liquido, N. J., R. T. Cunningham, and H. M. Couey. 1989. Infestation rates of papaya by fruit flies (Diptera: Tephritidae) in relation to the degree of fruit ripeness. J. Econ. Entomol. 82: 213–219.

Liquido, N. J., H. T. Chan, and G. T. McQuate. 1995. Hawaiian tephritid fruit flies (Diptera): integrity of the infestation-free quarantine procedure for 'Sharwil' avocado. J. Econ. Entomol. 88: 85–96.

Liquido, N. J., P. G. Barr, and V. Chew. 1996. CQT_STATS: biological statistics for pest risk assessment in developing commodity quarantine treatment. USDA-ARS Publ. Ser. (available at pbarr@pbarc.ars.usda.gov).

Liquido, N. J., R. L. Griffin, and K. W. Vick. 1997. Quarantine security for commodities: current approaches and potential strategies. USDA Publ. Ser. 199–04.

Mangan, R. 2000. Can pest management activities allow for alternatives to the "probit 9" quarantine treatment requirement? Proc. T-STAR Workshop X. Mitigating the Effects of Exotic Pests on Trade and Agriculture—Part A. The Caribbean. Homestead, FL, 1999.

Mangan, R. L., E. R. Frampton, D. B. Thomas, and D. S. Moreno. 1997. Application of the maximum pest limit concept to quarantine security standards for the Mexican fruit fly (Diptera: Tephtritidae). J. Econ. Entomol. 90: 1433–1440.

McQuate, G. P., P. A. Follett, and J. M. Yoshimoto. 2000. Field infestation of rambutan fruits by internal-feeding pests in Hawaii. J. Econ. Entomol. 93: 846–851.

Moffitt, H. R. 1990. A systems approach to meeting quarantine requirements for insect pests of deciduous fruits. Proc. Washington State Hortic. Assoc. 85: 223–225.

Paull, R. E. 1994. Response of tropical horticultural commodities to insect disinfestations treatments. HortScience 29: 988–996.

Robertson, J. L., H. K. Preisler, and E. R. Frampton. 1994. Statistical concept and minimum threshold concept, pp. 47–65. *In* Insect pests and fresh horticultural products: treatments and responses. Paull, R. E. and J. W. Armstrong, eds. CAB International, Wallingford, UK.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry. W. H. Freeman and Company, NY.

U.S. Dep. Agric.-APHIS-PPQ. 1996. Movement of rambutan fruit, *Nephelium lappaceum,* from Hawaii into other regions of the United States. Pest risk assessment, June. USDA.

Vail, P. V., J. S. Tebbetts, B. E. Mackey, and C. E. Curtis. 1993. Quarantine treatments: a biological approach to decision making for selected hosts of codling moth (Lepidoptera: Tortricidae). J. Econ. Entomol. 86: 70–75.

Whyte, C. F., R. T. Baker, J. M. Cowley, and D. S. Hart. 1994. A quantitative method for calculating the probability of pest establishment from imported plants and plant products, as a part of pest risk assessment. No. 4. N. Z. Plant Protection Centre Publications, Auckland, New Zealand.

Yokoyama, V. Y., and G. T. Miller. 1999. Host status of fresh prunes by potential quarantine pests in laboratory tests and evaluation of packinghouse culls. J. Econ. Entomol. 92: 485–489.

Zee, F.T.P., H. T. Chan, and C.-R. Yen. 1998. Lychee, longan, rambutan and pulasan, pp. 290–335. *In* P. Shaw, H. T. Chan, and S. Nagy (eds.), Tropical and subtropical fruits. Agscience, Auburndale, FL.

Received for publication 6 December 2000; accepted 11 April 2001.