FORUM

# The Case for a Generic Phytosanitary Irradiation Dose of 400 Gy for Lepidoptera That Infest Shipped Commodities as Pupae

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**ABSTRACT** The pros and cons of a generic phytosanitary irradiation dose against all Lepidoptera pupae on all commodities are discussed. The measure of efficacy is to prevent the F1 generation from hatching (F1 egg hatch) when late pupae are irradiated. More data exist for this measure than for others studied, and it is also commercially tenable (i.e., prevention of adult emergence would require a high dose not tolerated by fresh commodities). The dose required to prevent F1 egg hatch provides a liberal margin of security for various reasons. A point at issue is that correctly irradiated adults could be capable of flight and thus be found in survey traps in importing countries resulting in costly and unnecessary regulatory action. However, this possibility would be rare and should not be a barrier to the adoption of this generic treatment. The literature was thoroughly examined and only studies that could reasonably satisfy criteria of acceptable irradiation and evaluation methodology, proper age of pupae, and adequate presentation of raw data were accepted. Based on studies with 34 species in nine families, we suggest an efficacious dose of 400 Gy. However, large-scale confirmatory testing (≥30,000 individuals) has only been reported for one species. A dose as low as 350 Gy might suffice if results of more large-scale studies were available or the measure of efficacy were extended beyond prevention of F1 egg hatch, but data to defend measures of efficacy beyond F1 egg hatch are scarce and more would need to be generated.

**KEY WORDS** phytosanitary treatment, quarantine pest, ionizing radiation, phytosanitation

Phytosanitary irradiation (PI) is being used increasingly to disinfest fresh commodities of quarantine pests (Hallman 2011). One of the advantages of the technology compared with other treatments is that it has been very amenable to generic doses (one dose serves for a group of pests and commodities although not all have been tested for efficacy) that facilitate treatment development and application (Hallman 2012). Currently, two broad generic treatments (150 Gy for all Tephritidae and 400 Gy for all Insecta except pupal and adult Lepidoptera) are approved for use on imports to the United States and the 150-Gy dose for Tephritidae is accepted by the International Plant Protection Convention (IPPC). The Joint Food and Agricultural Organization/International Atomic Energy Agency Programme of Nuclear Techniques in Food and Agriculture (FAO/IAEA) has been instrumental in the development of PI and generic doses and currently has a 5-yr 12 nation cooperative research program to develop more generic treatment doses (IAEA 2009). In 2012, the IPPC issued a call for proposals for additional PI treatments including generic treatments for their treatment manual (IPPC 2011a,b). The proposed treatments undergo an evaluation process (Hallman et al. 2010). A parallel study to this one suggests a generic dose of 250 Gy for all eggs and larvae of Lepidoptera on all host commodities (Hallman et al. 2013).

The 400-Gy generic dose for Insecta does not include pupae and adult Lepidoptera because when it was developed it was uncertain whether all Lepidoptera quarantine pests in these stages would be controlled by that dose (APHIS 2005). Information available at the time indicated that up to 1 kGy might be needed for some pupae and adult Lepidoptera (Hallman 2012). Adult Lepidoptera are rarely of practical concern as quarantine pests. In most credible circumstances, adults would not be found except in commodities such as cut flowers and foliage, where there is a risk that adult moths may alight on the plants in the field at dawn and remain on them after harvest. However, it would be expected that routine harvesting, inspection, and packing would disturb and remove the adults. Adult Lepidoptera could also be found in boxes of packed commodity attracted to lights in packing facilities at night. Screening and other control techniques should eliminate this problem if it arises, ne-

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gating the need for a treatment. If there became a need for a PI treatment against adult Lepidoptera, the sterile insect technique (SIT) literature might be sufficient to support a generic dose, possibly >400 Gy (Bakri et al. 2005, Hallman and Phillips 2008).

Because some Lepidoptera (e.g., Crambidae, Gelechiidae, Pyralidae, Tortricidae) pupate on parts of fresh commodities that could be traded across quarantine boundaries, a generic dose for Lepidoptera pupae would be advantageous as a practical phytosanitary measure. Therefore, the objective of this study was to critically evaluate the literature on the effect of irradiation to late pupae that may be relevant to a generic PI dose for that group.

## Materials and Methods

Hallman (2000) suggested that the measure of efficacy for pupae should be reproductive sterility of the emerging adult and not prevention of adult emergence, because excessive doses not tolerated by most fresh commodities would be required to prevent adult emergence. Prevention of reproduction is an accepted endpoint for PI by the IPPC and other plant protection organizations (Hallman 2011).

The measure of efficacy must be precise; prevention of reproduction can be divided into a series of discernible thresholds. Examples of measures of efficacy in increasing order of development of the F1 generation are prevention of oviposition, egg hatch, development beyond successive instars, pupation, adult emergence, and development of eggs in the F1 adult. As the threshold in development increases, the dose to achieve it typically decreases. For example, doses to prevent development beyond the egg and first and fifth instars for *Ostrinia nubilalis* (Hübner) are 343, 289, and 233 Gy, respectively (Hallman and Hellmich 2009).

Many potentially useful research articles do not have as an objective the discovery of the minimum dose required to support a PI treatment but are directed toward SIT development. SIT data are often directly applicable to PI development but some differences are notable. The usual focus of SIT is prevention of reproduction by the male, whereas the focus of PI is prevention of establishment of a pest from a commodity, where both the males and females have been irradiated. It is unusual for mating between irradiated males and females to be reported in the SIT literature because that information is considered unimportant for SIT; however, prevention of female reproduction is frequently reported, which often may be accomplished with lower doses than those required to prevent male reproduction (Hallman 2000). Under the circumstances of PI, where both sexes will be irradiated, reproduction will be halted at or below the lower of the doses required to sterilize males and females.

Although in practice all SIT programs for Lepidoptera currently use insects irradiated as newly emerged adults, researchers often determine the dose required to reproductively sterilize pupae that are about to emerge as adults because it would be easier to irradiate and manage the insects as late pupae. However, pupae of Lepidoptera are notoriously variable in the length of the pupal stage, resulting in many pupae being irradiated before the adult is adequately developed (J. Carpenter, personal communication). Because irradiation interferes with continuing development, adults emerging from irradiated pupae that were not close to emerging as adults are often not acceptable for SIT.

Some of the literature on doses to prevent reproduction from late pupae is from studies to control stored product pests that are generally not quarantine pests, having been distributed worldwide long ago. We do not separate regulated from nonregulated pests for the purposes of this study but consider studies with late Lepidoptera pupae to be relevant to a generic PI dose for the order.

There is considerable literature on irradiation of insects and we attempted to access all relevant literature pertinent to Lepidoptera. The FAO/IAEA maintains an online database of literature on irradiation of organisms for SIT and PI (Bakri et al. 2005, IAEA 2012). As with any body of scientific literature, reports vary on soundness of methodology, accuracy in recording data, completeness in reporting, and logic of interpretation of results. It may not always be possible from the information given to understand exactly what was found or judge the soundness of the study. A liberal approach to this body of literature would be to accept all studies that meet minimal requirements of exposing late pupae to a series of doses of ionizing radiation and recording at least one dose that would prevent successful reproduction of the insect. An extremely conservative position would be to accept only those studies that report detailed dosimetry and demonstrate that the pupae used emerged within the next day or two after irradiation. We chose an intermediate level of soundness that tends to be somewhat liberal; we did not want to exclude studies that might point to a higher dose, because the risk of treatment failure can result in the establishment of invasive species. The generic dose would by necessity be near the high end of the dose range.

Hallman et al. (2010) argue that measures of efficacy for PI that involved the pupal and adult stages of most quarantine pests should prevent significant F1 development to provide a margin of security because there is no independent verification of efficacy for PI like there is for all other commercial treatments: dead insects soon after treatment. The lack of independent verification of efficacy means that any failure to achieve efficacy because of 1) subefficacious application of the treatment on a commercial scale, 2) factors that could affect efficacy but were not tested in the research supporting the treatment (Hallman et al. 2010), or 3) unexpected responses from species not tested (in the case of generic treatments) will not be detected. Heather and Hallman (2008) note that there have been failures in all major phytosanitary treatment categories that were only discovered by the presence of live insects after treatment. The develop-

**Table 1 Radiation doses absorbed by late pupal Lepidoptera to prevent oviposition, eclosion of the F1 egg, or development to the second instar**

| Species | Family | Dose in gray (no. pupae tested) to prevent | | | Reference |
|---|---|---|---|---|---|
| | | Oviposition | $F_1$ egg hatch | $F_1$ second instar | |
| *Diacrisia obliqua* | Arctiidae | 200 (216) | | | Khattak (1998) |
| *Hyphantria cunea* | Arctiidae | | 100 ([a]) | | Beratlief and Boguleanu (1973) |
| *Ostrinia nubilalis* | Crambidae | | 300 (400) | | Barbalescu and Rosca (1993) |
| *O. nubilalis* | Crambidae | | 343 (34,760) | 289 (9,468) | Hallman and Hellmich (2009) |
| *Neoleucinodes elegantalis* | Crambidae | 300 (50) | 200 (50) | | Arthur (2004) |
| *Stenoma catenifer* | Elachistidae | 300 (50) | | | Silva et al. (2007) |
| *Pectinophora gossypiella* | Gelechiidae | 450 (79) | 300 (50) | | Ouye et al. (1964) |
| *P. gossypiella* | Gelechiidae | | 200 (15) | | Qureshi et al. (1993) |
| *Tuta absoluta* | Gelechiidae | 200 (50) | 200 (50) | | Arthur (2004) |
| *Lymantria dispar* | Lymantriidae | | 200 (30) | | Godwin et al. (1964) |
| *Teia anartoides* | Lymantriidae | | 450 (15) | | Suckling et al. (2006) |
| *Agrotis ipsilon* | Noctuidae | | 200 ([a]) | | El Kady et al. (1983) |
| *Earias vittella* | Noctuidae | | 250 (15) | | Shantharam et al. (1997) |
| *Helicoverpa assulta* | Noctuidae | | 300 (60) | | Li et al. (2005) |
| *Helicoverpa zea* | Noctuidae | | 300 (62) | | Gross and Young (1978) |
| *Heliothis virescens* | Noctuidae | 650 (75) | 450 (75) | | Flint and Kressin (1967) |
| *H. virescens* | Noctuidae | | 300 (40) | | El Sayed and Graves (1969) |
| *Sesamia inferens* | Noctuidae | | 250 (82) | | Qureshi et al. (1975) |
| *Spodoptera frugiperda* | Noctuidae | | 175 (50) | | Noblet et al. (1969) |
| *S. frugiperda* | Noctuidae | 175 (50) | 125 (50) | | Arthur et al. (2002) |
| *Trichoplusia ni* | Noctuidae | | 300 (9) | | Toba and Kishaba (1973) |
| *Plutella xylostella* | Plutellidae | | 200 (20) | | Omar and Mansor (1993) |
| *P. xylostella* | Plutellidae | | 100 (30) | | Koo et al. (2011) |
| *Cadra cautella* | Pyralidae | 500 (90) | | | Cogburn et al. (1973) |
| *Chilo partellus* | Pyralidae | | 50 (25) | | Bughio (1992) |
| *Corcyra cephalonica* | Pyralidae | | 205 (10) | | Sehgal and Chand (1978) |
| *C. cephalonica* | Pyralidae | | 500 (50) | | Etman et al. (1990) |
| *Diatraea grandiosella* | Pyralidae | | 350 (2,000) | 300 (6,075) | Hallman et al. (unpublished) |
| *Diatraea saccharalis* | Pyralidae | | 350 (2,000) | 300 (5,350) | Darmawi et al. (1998) |
| *Eoreuma loftini* | Pyralidae | | 300 (474) | 250 (217) | Darmawi et al. (1998) |
| *Ephestia calidella* | Pyralidae | | 300 (125) | | Boshra and Mikhaiel (2006) |
| *Ephestia kuehniella* | Pyralidae | | 300 (120) | | Ayvaz and Tunçbilek (2006) |
| *Paramyclois transitella* | Pyralidae | | 300 (200) | | Hasaballa (1988) |
| *Plodia interpunctella* | Pyralidae | | 269 (600) | | Johnson and Vail (1987) |
| *P. interpunctella* | Pyralidae | | | 300 (45) | Ayvaz et al. (2008) |
| *Tryporyza incertulas* | Pyralidae | | 200 (16) | | TRGEP (1974) |
| *Amorbia emigratella* | Tortricidae | | 120 (128) | | Follett (2008) |
| *Cryptophlebia illepida* | Tortricidae | | 250 (620) | | Follett and Lower (2000) |
| *Cydia pomonella* | Tortricidae | | 200 (200) | | Hathaway (1966) |
| *Grapholita molesta* | Tortricidae | | 300 ([a]) | | Vasilyan et al. (1978) |
| *G. molesta* | Tortricidae | 300 (40) | 250 (40) | | Arthur (2011) |
| *Lobesia botrana* | Tortricidae | | 250 (10–12) | | Beratlief (1970) |
| *Thaumatotibia leucotreta* | Tortricidae | | 200 (20) | | Bloem et al. (2003) |
| *T. leucotreta* | Tortricidae | | 163 (500) | | J. H. Hofmeyr (unpublished data) |

[a] Number of pupae tested not given.

ment of methods to determine whether products have been irradiated (Arvanitoyannis et al. 2009, Crews et al. 2012) would only partially alleviate this risk; the most that those methods can ever be expected to determine is whether the proper minimum dose was absorbed, not whether the treatment is subefficacious because of a factor (e.g., low oxygen atmospheres [Hallman and Hellmich 2010]) that may reduce efficacy or a species not tested that is more radiotolerant than those species for which the generic dose was developed.

## Results and Discussion

Three measures of efficacy frequently appeared in the literature of irradiation of pupae of Lepidoptera: prevention of 1) oviposition, 2) F1 egg hatch, and 3) development beyond the F1 first instar. Of these three, there are far more data on prevention of F1 egg hatch than the other two. This fact makes prevention of F1 egg hatch the logical choice from the standpoint of available data for the measure of efficacy of a PI treatment of pupal Lepidoptera (Table 1). Prevention of F1 egg hatch also leaves a liberal margin of security between demonstrated efficacy and risk of successful reproduction, to compensate for the lack of independent verification of efficacy.

A generic dose should exceed the highest dose required to control the most tolerant species indicated in the literature to account for untested species that might be more tolerant. In practice, efficacious doses determined from some research results may be higher than seems reasonable, and where there is justification for suspecting a dose (e.g., contradiction by other studies), we argue that it may be omitted when determining the generic dose. This strategy was used in

developing a generic dose against tephritid fruit flies of 150 Gy where several studies, including large-scale studies, indicated that 150 Gy would be inadequate (Hallman and Loaharanu 2002, Hallman 2012, Hallman et al. 2013).

**Suggested Efficacious Dose of 400 Gy.** For prevention of F1 egg hatch from irradiated late Lepidoptera pupae, a dose of 400 Gy appears efficacious because it is supported by studies with 34 species in nine families (Table 1). Thirty-eight studies with 31 species in eight families directly support this dose by providing data that show that F1 egg hatch is prevented at <400 Gy. Because prevention of oviposition logically prevents egg hatch, the two studies with *Diacrisia obliqua* Walker (Khattak 1998) and *Stenoma catenifer* Walsingham (Silva et al. 2007) that found that doses ≤300 Gy prevented oviposition can also be used to support a generic dose of 400 Gy. Finally, the study with *Teia anartoides* (Suckling et al. 2006) apparently does not support a generic dose of 400 Gy because 400 Gy resulted in 0.07% hatch of F1 eggs. However, we assume that 400 Gy would be efficacious for reasons given below. Therefore, the total numbers of species and families with data supporting a dose of 400 Gy are 34 and 9, respectively.

The dose for a phytosanitary treatment should be as low as is defensible to minimize the risk of potential damage to treated commodities and the cost of treatment. By using measures of efficacy further developed than prevention of F1 egg hatch (e.g., prevention of F1 second instar, Table 1), an argument can be made for a generic dose <400 Gy. However, fewer data are currently available to support generic doses based on measures of efficacy further developed than prevention of F1 egg hatch.

Several studies report that 400 Gy would be marginally effective in preventing F1 egg hatch; other studies with the same species indicate that 400 Gy would suffice:

1. Cogburn et al. (1966) found that 150 late pupal *Sitotroga cerealella* (Olivier) produced "progeny" at 1.8% of the rate of nonirradiated control insects after irradiation with one kGy (progeny was not defined to stage of development except for being beyond the egg). This dose is much higher than the dose found to prevent reproduction in other studies with the insect (Table 1). After testing 15,264 adult *S. cerealella,* Hallman and Phillips (2008) found that eclosion of eggs laid by irradiated adults could be prevented with 443–505 Gy (target dose was 450 Gy; next lowest target dose was 400 Gy, which resulted in 0.09% egg hatch). Because pupal insects are considered more radiosusceptible than adults (Hallman et al. 2010), the dose for pupae could be expected to be <443–505 Gy.
2. Likewise, Cogburn et al. (1966) found that 450 Gy absorbed by 150 late pupae *Plodia interpunctella* (Hübner) did not prevent the production of "progeny," whereas Hallman and Phillips (2008) irradiated 22,083 adults and found that eclosion of eggs laid by the adults could be prevented with 336–388 Gy. In a smaller study, Johnson and Vail (1987) achieved complete sterilization with 269 Gy.
3. Flint and Kressin (1967) reported that a target dose of 450 Gy (dosimetry not given; next lowest dose was 350 Gy, which resulted in 0.3% F1 egg hatch for irradiated females, normal males) to late pupae were required to prevent F1 egg hatch of *Heliothis virescens,* but El Sayed and Graves (1969) reported that a target dose of 300 Gy would suffice.
4. Etman et al. (1990) reported that 500 Gy were required to prevent F1 egg hatch in *Corcyra cephalonica* late female pupae (dosimetry not given). At the next lowest dose observed, 400 Gy, 38.3% of F1 eggs hatched when only the female was irradiated. In contrast, Sehgal and Chand (1978) found no egg hatch at 205 Gy.
5. Suckling et al. (2006) found that a target dose of 450 Gy (dosimetry not given) was needed to prevent F1 egg hatch in late pupal *Teia anartoides;* at the next lowest dose (400 Gy) 0.07% of F1 eggs hatched (fate of the first instars is not given). These data are unusual in that F1 egg hatch at 100 Gy was 0.08%, implying that the slope of the dose–response relationship between 100 and 400 Gy (seven dose levels) is negligible and essentially equal to zero. The dose response for percentage survivorship of larvae hatching from those eggs was also found to have a slope of zero. We are not aware of data from any other insect that show a dose relationship that is this flat over such a large dose range (at least 300 Gy). At the very least, a dose–response relationship like this implies that most of the insects in the population are very susceptible to radiation (controlled at ≤100 Gy), with a very tiny fraction of the population being quite tolerant (requiring >400 Gy to control). Another explanation is that there was some chronic contamination with fertile material, which has been hypothesized for other studies. Nevertheless, Suckling et al. (2002) showed that even at a dose as low as 140 Gy, the F1 males back-crossed to fertile females produced no eggs. Data are not given for irradiated females, but it can be assumed that they will also be fully sterile in the F2 at 140 Gy; female sterility is usually achieved with an equal or lower dose than male sterility (Hallman 2000). The female of this species is flightless and unlikely to disseminate offspring.
6. Another relevant study is not included in Table 1 because it lacked a dose that completely prevented egg hatch. Follett and Snook (2012) found that 400 Gy (highest target dose used) applied to late pupae (289 females) of *Epiphyas postvittana* (Walker) resulted in one (1.7%) F1 egg hatching. However, at lower doses (300 and 350 Gy, respectively), lower percentages of F1 eggs hatched (0.5 and 0.003%), leading us to wonder whether the one F1 egg that hatched at 400 Gy was irradiated to a lower dose or the result of contamination with fertile material.

Figure 1 presents the results of all of the studies in a cumulative manner, showing that at 250 Gy, F1 egg hatch was prevented in most of the studies with only

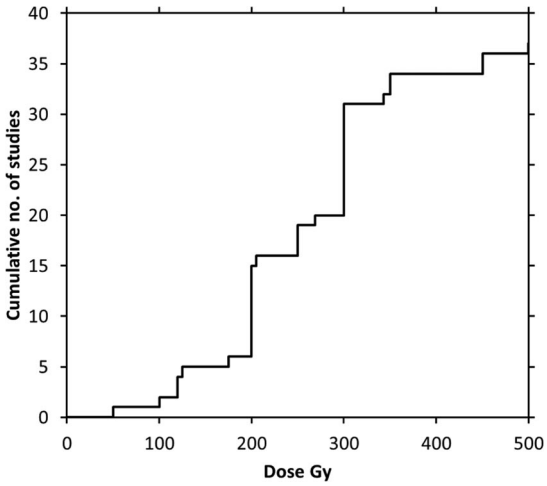


**Fig. 1.** Cumulative number of studies at minimum absorbed doses required to prevent F1 egg hatch when late Lepidoptera pupae were irradiated.

those few discussed above indicating that 350 Gy might not be sufficient. There are several factors that provide for a substantial margin of security that 400 Gy will be efficacious.

A generic dose of 400 Gy for Lepidoptera pupae is conservative because it is higher than needed for the great majority of the species studied (Fig. 1). Furthermore for each study there is a step-wise increment between the dose that provided complete prevention of F1 egg hatch and the next lowest dose below it that did not. It is probable that in some cases an intermediate dose would suffice. Also, there is an additional margin of security when the dose is applied commercially, because the procedure involves establishing that the minimum dose absorbed by the process load in the irradiation chamber is at least 400 Gy. The inherent margin of security arises because the product being irradiated receives a distribution of dose due in part to natural variation in the commodity (e.g., density) and also resulting from the design of the irradiation facility, which will have physical and operational conditions yielding variation in dose. In addition, the dosimeters and measurement procedure used will also have an inherent level of uncertainty. The application of commercial irradiation therefore involves taking these variations into consideration by first establishing the typical dose distribution within the process load, when applying the treatment in routine operation, and continually monitoring the process using a routine dosimetry system that has been validated. These measures are necessary to ensure the treatment is under control; the minimum dose delivered is efficacious while ensuring the maximum dose is less than that tolerated by the commodity.

Essentially, all insects present will receive >400 Gy, because the lowest dose that commercial applicators target will marginally exceed 400 Gy to ensure that no part of the load receives <400 Gy. Furthermore, the dose uniformity ratio (DUR) (maximum dose/minimum dose) for commercial applications is >1.15, meaning that most insects in a process load will absorb ≈460 Gy or often more, depending on the DUR of the irradiation system. In this way, therefore, a generic PI dose of 400 Gy will be efficacious against all pupae of Lepidoptera while providing a liberal margin of security.

Because irradiation results in cumulative damage to organisms over time, lower doses are generally required to achieve fatal effects later in development; in Table 1, for any given insect that has doses in more than one column, the dose decreases as the developmental milestone prevented advances. Therefore, even if some F1 individuals managed to hatch from eggs, they would most likely die in subsequent stages.

Furthermore, a phenomenon common to irradiation of Lepidoptera (inherited sterility) results in significantly greater sterility in the F2 generation than in the F1 generation (Carpenter et al. 2005). Any individuals that did happen to successfully complete the F1 generation would almost surely be reproductively sterile.

In conclusion, a generic dose of 400 Gy for all pupae of Lepidoptera may provide considerable security that it would prevent any pupae of the order occurring in irradiated commodities to successfully reproduce when all of the factors adding to this security are considered. Unfortunately, there is a lack of literature reporting large-scale testing for multiple species. Twenty of the 37 studies of egg hatch in Table 1 were done with 9–50 individuals at the efficacious dose. At the other end of the scale, two studies used 2,000 individuals and only one used a quantity that is often required to support a phytosanitary dose, at least 30,000 individuals (Hallman and Hellmich 2009).

It is recommended that researchers conduct trials comparing late pupae of various species for radiotolerance as measured by F1 egg hatch and test large numbers (≥10,000 pupae) of the most tolerant species. Some of the most tolerant species identified in this study include *Pectinophora gossypiella*, *Teia anartoides*, and species of Noctuidae and Pyralidae. Pyralidae is a key family because species commonly pupate in the portion of host plants that is exported.

The Technical Panel on Phytosanitary Treatments (TPPT) of the IPPC met recently to evaluate phytosanitary treatment proposals, including an earlier version of this proposal but at 350 Gy. The initial concerns raised at the TPPT included an insufficient number of large-scale studies (over several thousand individuals) and the issue that the treatment could allow adult Lepidoptera capable of flight. This in turn would raise the possibility that they could be found in survey traps for the insects and result in unnecessary regulatory action. This paper has reappraised all of the information related to the irradiation of Lepidoptera pupae and proposes a 400-Gy generic dose against pupae of all Lepidoptera (by preventing F1 egg hatch). The dose of 400 Gy is supported by the weight of evidence available and takes into consideration a margin of security when the data are reviewed. The number of studies taken together provide justification for a

400-Gy treatment, even though only one large scale study (>30,000 individuals) is available. As regards the argument against the treatment in terms of it possibly triggering unwarranted regulatory action due to finding correctly treated adult insects in surveillance traps in the importing country, the only way to prevent this outcome entirely using PI alone is to prevent the emergence of adults capable of flight. This measure would require a dose (>1 kGy) that would not be tolerated by fresh commodities. Currently, there are no reliable techniques for differentiating field-trapped adult Lepidoptera that have been reproductively sterilized via irradiation from feral adults, as there are with Tephritidae (J. Carpenter, personal communication). Recent developments in the detection of irradiated food at only marginally higher doses (Arvanitoyannis et al. 2009, Crews et al. 2012) open the possibility of a laboratory analytical technique to identify irradiated adults to prevent the launching of a regulatory response to a trapped insect, but more work is required to develop this strategy to practical implementation.

The IPPC (2003) guidelines for PI recognize the possibility that live target pests may be found post-treatment, because mortality will rarely be technically justified as the required response of PI. The guidelines note that it is essential that the irradiation treatment ensures target pests are unable to reproduce and state in addition, "that it is preferable that such pest(s) are unable to emerge or escape from the commodity unless they can be practically distinguished from nonirradiated pest(s)." The IPPC already allows for irradiated adults of three weevils to be present, although survey trapping is being done specifically to detect them in the environment and adult weevils may be present during irradiation treatment (IPPC 2011b). This is presumably because additional practical measures can be taken to minimize the risk of any live weevils from emerging or escaping from the shipped commodity. In the case of irradiated pupal Lepidoptera, the possibility of irradiated adults being found in survey traps is diminished not only because this would require weakened adults to emerge, escape from the commodity and be capable of flight, but also because it would mean that any additional measures to contain insects, such as commodity packaging, would have been breached. If the small but finite possibility of finding irradiated adult Lepidoptera capable of flight cannot be accepted, it is almost certain that PI will not be used widely as a treatment against pupae of Lepidoptera.

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