FORUM

Generic Radiation Quarantine Treatments: The Next Steps

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ABSTRACT In 2006, U.S. Department of Agriculture–Animal and Plant Health Inspection Service published a landmark rule providing generic radiation quarantine treatments. The rule approved radiation doses of 150 Gy for any tephritid fruit fly and 400 Gy for all other insects except the pupa and adult stages of Lepidoptera. The generic radiation treatments apply to all fresh horticultural commodities. Therefore, if a pest risk assessment demonstrates that no pupae or adult Lepidoptera are associated with a commodity, export approval can be forthcoming with no further research. Generic treatments are the culmination of decades of research but not an end point. Future research on quarantine and phytosanitary uses of radiation should focus on 1) development of specific doses for quarantine Lepidoptera not covered by the generic treatments, 2) reduction of dose levels for specific pests and commodities to shorten treatment time and minimize any deleterious effects of radiation treatment on commodity quality, 3) development of generic doses below 400 Gy for important groups of quarantine arthropods other than fruit flies, and 4) development of information on commodity tolerance and development of value-added irradiated fresh products that use generic radiation treatments. Generic treatments will facilitate safe trade between countries that have approved phytosanitary uses of radiation for fresh agricultural commodities.

KEY WORDS quarantine pest, postharvest phytosanitary treatment, irradiation, invasive species, ionizing radiation

World trade in agricultural commodities continues to grow. As agricultural trade expands, it increases the risk of introducing exotic insects into new areas where they may become plant pests. The establishment of new pests can be costly due to increased crop damage, control programs, and quarantine restrictions on trade. Quarantine treatments or systems exclude, sterilize, or kill regulatory pests in exported commodities to prevent their introduction and establishment into new areas. Because exclusion is the goal when dealing with quarantine pests, the tolerance for viable pests in the commodity is essentially zero (Follett and Neven 2006). Quarantine or phytosanitary treatments such as heat, cold, irradiation, and fumigation disinfest host commodities of insect pests before they are exported to areas where the pests do not occur. In some cases, commodities are exported and receive treatment at the port of arrival. Whereas development of heat, cold, and fumigation treatments involves generating data for each commodity and pest combination, radiation treatments are developed for a pest species irrespective of the fruit or vegetable host. This is possible because ionizing radiation penetrates commodities quickly, so treatment time is short and the required dose can be applied without changing the commodity's temperature; most commodities can tolerate irradiation at levels that control the pest (Morris and Jessup 1994, Thomas 2001, Wall 2008). Developing heat, cold and fumigation treatments, however, involves finding a balance between killing the pest and minimizing the adverse effects of the treatment process on commodity quality (Paull 1994).

Radiation Quarantine Treatment. The United States Food and Drug Administration has approved radiation doses up to 1,000 Gy (1 kGy) for preservation and disinfestation of fruits and vegetables (FDA 1986). Ionizing radiation breaks chemical bonds within DNA and other molecules, thereby disrupting normal cellular function in the infesting insect (Ducoff 1972, Koval 1994). Many tissues and functions of the insect may be disrupted by exposure to radiation (Vinson et al. 1969, Nation and Burditt 1994). Insects and other living organisms are able to repair molecular damage done by small amounts of ionizing energy (Alpen 1998), but large amounts are fatal or cause permanent sterility, and this is the basis for using irradiation to control insects in commodities. Radiotolerance can vary among the life stages of an insect, and between insect taxa. For example, Lepidoptera tend to be more radiotolerant than Diptera, Coleoptera, and Hemiptera, although there is considerable variation among the species that have been tested within these groups (Bakri et al. 2005). For individual species, radiotolerance normally increases with increasing developmental stage when the goal is to prevent successful reproduction (e.g., Follett 2008).

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Table 1. Irradiation doses approved for insects and insect groups by the USDA–APHIS

Scientific name	Common name	Dose (Gy)
Anastrepha ludens (Loew)	Mexican fruit fly	70
Anastrepha oblique (Macquart)	"West Indian fruit fly"	70
Anastrepha serpentina (Wiedemann)	"Sapote fruit fly"	100
Anastrepha suspensa (Loew)	Caribbean fruit fly	70
Aspidiotus destructor Signoret	Coconut scale	150
Bactrocera jarvisi (Tryon)	None	100
Bactrocera tryoni (Froggatt)	"Queensland fruit fly"	100
Brevipalpus chilensis Baker	"False red spider mite"	300
Conotrachelus nenuphar (Herbst)	Plum curculio	92
Copitarsia decolora Guenee	None	100
Cryptophlebia ombrodelta (Lower)	"Litchi fruit moth"	250
Cryptophlebia illepida (Butler)	"Koa seedworm"	250
Cylas formicarius elegantulus (Summers)	Sweetpotato weevil	150
Cydia pomonella (L.)	Codling moth	200
Euscepes postfasciatus (Fairemaire)	"West Indian sweetpotato weevil"	150
Grapholita molesta (Busck)	Oriental fruit moth	200
Omphisa anastomosalis (Guenée)	Sweetpotato vine borer	150
Pseudaulacaspis pentagona (Targioni Tozzetti)	White peach scale	150
Rhagoletis pomonella (Walsh)	Apple maggot	60
Sternochetus mangiferae (F.)	"Mango seed weevil"	300
Fruit flies in the family Tephritidae not listed above		150
Plant pests of the Insecta not listed above, except Lepidoptera pupae and adults		400

Sources: USDA–APHIS 2006. Treatments for fruits and vegetables. Federal Register 71 (18): 4451–4464, 26 June 2006. Rules and Regulations.

USDA–APHIS. 2008. Treatments for fruits and vegetables. Federal Register 73 (88): 24851–24856, 6 May 2008. Rules and Regulations.

Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live (but sterile or not viable) insects may occur with the exported commodity. The goal of a quarantine treatment is to prevent reproduction; therefore, the required response for a radiation treatment may be prevention of adult emergence (Follett and Armstrong 2004), induction of adult sterility (Follett 2006a), or F_1 sterility (Follett 2006b,c).

Generic Radiation Treatments. Generic treatments are the "holy grail" for quarantine entomologists. A generic treatment is a single treatment that controls a broad group of pests without adversely affecting the quality of a wide range of commodities (Follett and Neven 2006). Quarantine entomologists traditionally develop treatments for one pest and commodity at a time, and research often requires many years before an effective quarantine treatment is developed and eventually approved and adopted. Generic treatments for broad groups of pests and commodities would greatly shorten the process of gaining export approvals, saving time and resources. Although discussed for over two decades, until recently, generic radiation treatments never saw application due to limited scientific data. However, radiation—from an isotope source, such as cobalt-60, or x-rays—was ideal for developing generic treatments because it is effective against insects at doses that generally do not injure fresh commodities.

In 2006, low-dose generic radiation treatments were approved for the first time. U.S. Department of Agriculture–Animal and Plant Health Inspection Service (USDA–APHIS) approved generic doses of 150 Gy for tephritid fruit flies and 400 Gy for all insects except pupa and adult Lepidoptera (USDA–APHIS 2006). In the same ruling, APHIS also approved new minimum doses for 10 specific plant pests, and doses for additional quarantine insect pests have been approved since 2006 (USDA–APHIS 2008) (Table 1). The generic and specific radiation doses apply to all fresh agricultural commodities. The rationale for generic doses is that information on radiotolerance for a limited number of species can be extrapolated to related species to arrive at an effective generic dose (Hallman and Loaharanu 2002, Follett and Armstrong 2004, Follett and Neven 2006). A practical advantage of generic treatments is that if a new fruit fly species or other quarantine pest should invade a new area, exported products using radiation as a disinfestation treatment would not be interrupted because the generic doses also would apply to the new invasive species.

The availability of generic radiation treatments has stimulated worldwide interest in phytosanitary uses of this technology. Hawaii uses the generic radiation treatments to export 10 million pounds of tropical fruits and vegetables to the United States mainland annually (Table 2). India is exporting mangos (*Mangifera indica* L.) and Thailand is exporting several types of tropical fruits to the United States by using the generic radiation dose of 400 Gy. Vietnam is exporting

Table 2. Worldwide use of irradiation as a phytosanitary treatment for fresh fruits and vegetables, 2008

Exporting country or state	Fruit	Importing country	Dose (Gy)
Australia	Mango, papaya, litchi	New Zealand	250
Hawaii	Abiu, atemoya, banana, breadfruit, carambola, citrus, *Capsicum* spp., cowpea, *Cucurbita* spp. eggplant, dragon fruit, jackfruit, litchi, longan, mango, mangosteen, melons, moringa, papaya, pineapple, sapodilla, sweet potato, tomato	United States mainland	150 or 400
India	Mango	United States	400
India	Mango	Australia	400
Mexico	Guava	United States	400
Thailand	Lychee, longan, rambutan mango, mangosteen, pineapple	United States	400
Vietnam	Dragon fruit	United States	400

dragon fruit (*Hylocereus undata*) to the United States also using the generic radiation dose of 400 Gy. Mexico recently received approval to export guavas (*Psidium guajava* L.) to the United States by using 400 Gy and soon will be exporting mangos by using a radiation dose of 150 Gy. Indonesia, the Philippines, Peru, and South Africa plan to use generic radiation treatments to export horticultural crops to the United States in the near future. Australia is exporting mangos, papayas (*Carica papaya* L.) and lychee (*Litchi chinensis* Sonn.) to New Zealand after radiation treatment at 250 Gy, a generic dose developed for their specific quarantine pests (Corcoran and Waddell 2003). In 2009, the International Plant Protection Convention (IPPC) approved and annexed the generic dose of 150 Gy for all tephritid fruit flies to International Standards for Phytosanitary Measures No. 28, Phytosanitary treatments for regulated pests (IPPC 2007).

Any country negotiating trade in fresh fruits and vegetables with the United States can use the low-dose generic radiation treatments (Follett and Griffin 2006). In the United States, a framework equivalency work plan is a prerequisite, bilateral agreement identifying the key components and steps for establishing cooperation in irradiation. The purpose of the agreement is to develop a common understanding of capabilities, capacities, intents, and expectations before both countries invest resources in this effort, and to establish that each country must accept each other's systems and irradiated products.

The adoption of generic treatments would seem like the culminating event in the evolution of phytosanitary uses of irradiation; however, due to borderline quality problems with certain fruits and cost considerations when using the 400-Gy treatment, lowering the radiation dose for specific pests and commodities may be beneficial. Generic radiation doses also may lead to new opportunities for value-added products. This article discusses four areas of future irradiation research in light of the new generic treatments, including 1) developing radiation treatments for commodities with quarantine pests in the order Lepidoptera, 2) lowering dose levels below 400 Gy for specific commodities with a limited number of quarantine pests, 3) developing generic doses below 400 Gy for other important groups of quarantine pests, and 4) developing information on commodity tolerance and developing value-added fresh products for export. Information from this research will result in regulatory changes that facilitate trade by providing new or improved quarantine radiation treatments. Many of the examples used to illustrate each point come from Hawaii owing to the fact that Hawaii has been exporting to the U.S. mainland by using generic radiation doses for almost 10 yr, but the recommended research applies equally to any country exporting fresh commodities using radiation quarantine treatment.

Developing Specific Treatments for Quarantine Lepidoptera. The approved generic radiation treatment of 400 Gy excludes the pupa and adult stages of Lepidoptera (USDA–APHIS 2006). Typically, fresh commodities exported using irradiation that may contain pupae or adults of a lepidopteran quarantine pest must be inspected and found free of the pest before export is permitted, and the presence of these stages of the pest could result in rejection. Therefore, development of a radiation dose to control the pupa and adult stages of the lepidopteran pest would prevent potential rejections. For example, banana (*Musa* sp.) is approved for export from Hawaii to the U.S. mainland by using irradiation. The banana protocol requires inspection for pupae and adults of *Opogona sacchari* (Bojer) (Lepidoptera: Tineidae) and irradiation with a minimum dose of 400 Gy [to control tephritid fruit flies and green scale, *Coccus viridis* (Green)], or inspection for green scale and *O. sacchari* and irradiation with 150 Gy to control fruit flies (USDA–APHIS 2006). Hence, detection of pupae or adults of *O. sacchari* in a consignment will prevent export. Commercial treatment of fresh commodities can result in radiation doses 1.5–3.0 times the minimum dose. Bananas can show radiation injury at 600 Gy under certain conditions (Wall 2006), so lowering the minimum dose below 400 Gy would be beneficial. The required radiation dose could be reduced if treatments were developed for *O. sacchari* and green scale. Recent research suggests that *O. sacchari* pupae are sterilized at 150 Gy (Hollingsworth and Follett 2007), thus eliminating the need for inspection and the threat of rejection due to the presence of the pest. Irradiation studies with green scale suggest it may be controlled at a radiation dose of 250 Gy (Hara et al. 2002). Confirming this dose or a lower dose for green scale may permit reducing the dose for quarantine treatment of banana below 400 Gy.

Sweetpotato vine borer, *Omphisa anastomosalis* (Guenée) (Lepidoptera: Pyralidae), is another example of a quarantine pest that can occur with the exported commodity as a pupa, and therefore would be excluded from the 400-Gy generic treatment. Sweetpotato vine borer larvae develop inside the sweet potato [*Ipomoea batatas* (L.) Lam.] root and pupate behind "windows" just below the skin. The pupation chambers can be difficult to detect by visual inspection of the root, and therefore a quarantine treatment targeting the pupal stage is required when sweet potatoes are exported from Hawaii to the U.S. mainland (Follett 2006a). Because it is often difficult to prevent pupae from emerging as adults using irradiation, an effective treatment dose normally must prevent successful reproduction in adults. A radiation dose of 150 Gy applied to pupae was shown to prevent reproduction in adult sweetpotato vine borer (Follett 2006a).

The leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is a serious federal quarantine pest of tomatoes (*Lycopersicum* spp.) from Algeria, Chile, France, Italy, Morocco, and Spain. The larvae feed and develop between the epidermal layers of the leaves and fruit, forming mines. Pupation can be either in the soil, on the leaf surface, or within mines, and therefore *T. absoluta* pupae may occur with the exported fruit. Exporting countries must grow tomatoes in an area recognized as free of *T. absoluta,* or apply a preshipment methyl bromide treatment, or grow the tomatoes in accordance with an approved systems approach and have fruit inspected and free of *T. absoluta* (USDA–APHIS 2009). Because *T. absoluta* pupae may be present with fruit, the 400 Gy generic treatment cannot be used as an alternative mitigation measure without specific information on efficacy. Preliminary research on *T. absoluta* suggested that a radiation dose of 200 Gy applied to pupae might be sufficient to sterilize adult moths (Arthur 2004). If the efficacy of this dose can be confirmed through large-scale testing, irradiation would be an effective mitigation option for tomato export.

Lowering the Dose for Specific Pests and Commodities. The generic radiation doses can be lowered for specific pests and commodities if this is practical. If lowering the dose for a quarantine pest allows lowering of the dose for the commodity of interest, cost of treatment will be reduced, any quality problems will be minimized, and the capacity of the treatment facility may be increased owing to shorter treatment time. The 400-Gy generic radiation dose may be applied as "insurance" to avoid rejection of a consignment in case surface pests are found during inspection. If the commodity has minimal problems with surface pests and a small number of internal quarantine pests, developing specific doses for the internal pests may permit lowering the radiation treatment dose for the commodity.

Lychee exported from Hawaii to the U.S. mainland has five high-risk quarantine pests including three tephritid fruit flies—Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann); oriental fruit fly, *Bactrocera dorsalis* (Hendel), and melon fly, *Bactrocera cucurbitae* Coquillett—and two tortricid moths, *Cryptophlebia illepida* (Butler) and *Crytpophlebia ombrodelta* (Lower). When first approved, lychee could be exported after quarantine treatment only if the fruit were inspected and found free of *Cryptophlebia* spp.; hence, detection of *Cryptophlebia* larvae in a consignment would prevent export. The 150-Gy generic dose is approved for the fruit fly pests, but *Cyptophlebia* spp. are more tolerant of irradiation than the fruit flies. Research demonstrated that *C. illepida* was more radiotolerant than *C. ombrodelta,* and that a radiation dose of 250 was adequate to prevent adult emergence from late instar *C. illepida* (Follett and Lower 2000). The 250-Gy dose was approved for the two *Cryptophlebia* species (USDA–APHIS 2006). As a consequence, the fruit can be irradiated at 250 Gy instead of 400 Gy before export, and lychee fruit will not be rejected due to the presence of *Cryptophlebia* larvae.

Papayas exported from Hawaii to the U.S. mainland were routinely irradiated at a minimum dose of 400 Gy to control white peach scale, *Pseudaulacaspis pentagona* (Targioni Tozzetti), in addition to fruit flies because no information was available on the radiotolerance of white peach scale. Studies demonstrated that white peach scale is controlled at 150 Gy (Follett 2006a). Hence, a radiation treatment with a minimum absorbed dose of 150 Gy should provide quarantine security for white peach scale in addition to fruit flies on exported papaya. Lowering the dose significantly reduced costs of x-ray treatment of papaya, and because reducing the dose reduces the treatment time proportionally, the capacity of the treatment facility was increased. Recently, a new quarantine surface pest, the mealybug *Paracoccus marginatus* Williams & Granara de Willink, was discovered in Hawaii papaya, and so the commercial treatment dose was increased to 400 Gy to prevent rejections. Irradiation studies are needed with *P. marginatus* before dose levels can be lowered again from 400 Gy.

Hawaii grows several unique varieties of sweet potato, including a purple-fleshed type (Wall 2005). Hawaii was unable to export its sweet potatoes without quarantine treatment against *Euscepes postfaciatus* (Fairmaire) (Coleoptera: Curculionidae) and sweetpotato vine borer (federal quarantine pests), and sweetpotato weevil, *Cylas formicarius elegantulus* (Summers) (a quarantine pest for California and much of the southwestern United States) (Follett 2006a). A default dose radiation treatment of 400 Gy for sweet potatoes was approved (USDA–APHIS 2003) based on review of the literature for related species until research could be conducted to lower the dose. For 2 yr, industry used the 400-Gy dose to export sweet potatoes to the U.S. mainland. Subsequently, research showed that a radiation dose of 150 Gy was sufficient to control the sweet potato quarantine pests (Follett 2006a), and this dose was approved by APHIS and adopted by the industry. Lowering the dose resulted in lowering the cost of x-ray treatment by 60% and better returns to the growers and shippers.

Another means to lower radiation doses is by development of combination treatments. For example, Palou et al. (2007) demonstrated that Mediterranean fruit fly could be controlled in clementine mandarins with a radiation dose of 30 Gy and subsequent exposure to 1°C for 2 d, which is a significant reduction from both the approved generic radiation dose of 150 Gy and the standard cold quarantine treatments of 1.1–2.2°C for 14–18 d. Cold is a convenient combination treatment with irradiation for many commodities that are shipped with refrigeration as the cold treatment can be completed in transit. This approach may be applicable to other cold-tolerant commodities such as grapefruit, blueberries, and pome and stone fruits.

Generic Radiation Doses for Other Pest Groups. A generic treatment for a group of insects can be developed at any taxonomic level, e.g., to all Diptera (flies), or to flies in the family Tephritidae (fruit flies), or to tephritid fruit flies in the genus *Bactrocera.* A generic radiation dose is recommended after information has accumulated on effective quarantine radiation doses for a wide range of insects within the taxon or for the important economic species within the taxon (Follett and Neven 2006).

The generic dose for tephritid fruit flies of 150 Gy was based on data for 17 economically important species of *Anastrepha, Bactrocera, Ceratitis,* and *Rhagoletis* fruit flies (P.A.F. and Hallman, unpublished data; Follett and Griffin 2006). *Anastrepha, Ceratitis,* and *Rhagoletis* fruit flies are considerably less tolerant of irradiation than *Bactrocera* fruit flies; therefore, radiation doses $<$150 Gy may be sufficient to control

Table 3. Numbers of medium- and high-risk quarantine pest species in the major arthropod groups identified in pest risk assessments by USDA–APHIS–PPQ for subtropical and tropical fruits and vegetables exported to the United States by using radiation quarantine treatment

Exporting country or state	Commodity	Arthropod group[a,b]								
		Teph.	Curc.	Tort.	Cocc.	Dias.	Pseud.	Thrip.	Acari	Total
Hawaii	Abiu	2			2					4
	Atemoya	3			1		2			6
	Carambola	3								3
	Capisicum spp.	4								4
	Citrus	3								3
	Cowpea								1	1
	Cucurbita spp.	4								4
	Banana	3			1					5
	Bread-/jackfruit	3			2	1	4			11
	Eggplant	4								4
	Dragon fruit	3					3			6
	Litchi	2		3					1	6
	Longan	3		1			2		1	7
	Mango	2	1							3
	Mangosteen	2					3	1		6
	Melon	3								4
	Moringa				1	1	1			3
	Papaya	3							1	4
	Pineapple	3								3
	Rambutan	2			2		2	1		7
	Sapodilla	2					2			4
	Sweet potato		3				1			5
	Tomato	4								4
India	Mango	7	2		2	3				14
Mexico	Guava	7	2	1	1		6		2	23
Thailand	Litchi	2		2	2		3			9
	Longan	2		2	1		4			10
	Mango	7	3		2	2	6			20
	Mangosteen	3			2	2	7			14
	Rambutan	2		1		1	6			10
	Pineapple				1	0	2	1		4
Vietnam	Dragon fruit	3					3			6

[a] Full names of arthropod groups: Tephritidae, Curculionidae, Tortricidae, Coccidae, Diaspididae, Pseudococcidae, Thripidae, and Acari.
[b] Total number of medium- and high-risk pests may slightly exceed those listed under the various groups as all quarantine species may not fall into the groups listed (e.g., no columns for Aleyrodidae, or Lepidoptera other than tortricids). Commodities also may have regulated plant pathogens that are not listed here.

Anastrepha, Ceratitis, and *Rhagoletis* fruit flies. For example, a generic dose of 100 Gy might be sufficient for *Anastrepha,* and doses ranging from 70 to 100 Gy have already been approved for several species (Table 1; USDA–APHIS 2006, IPPC 2007).

Table 3 lists the numbers of medium- and high-risk quarantine pest species in the major arthropod groups identified in pest risk assessments by USDA–APHIS-Plant Protection Quarantine (PPQ) for subtropical and tropical fruits and vegetables exported to the United States by using radiation quarantine treatment. Tephritid fruit flies are the most pervasive quarantine pests, attacking 21 of the 24 fresh commodities listed. After fruit flies, tortricid moths are probably the most significant internal pests of economic and quarantine concern for fruit and soft vegetables (Table 3). Several irradiation studies have been done on tortricid moths suggesting control can be achieved at radiation doses between 120 and 200 Gy (IDIDAS 2007). A radiation dose of 200 Gy was shown to be sufficient to control codling moth, *Cydia pomonella* (L.) (Mansour 2003); *Ecdytolopha aurantiana* Lima (Arthur 2004); oriental fruit moth, *Grapholita molesta* (Busck) (Hallman 2004); and light brown apple moth, *Epiphyas postvittana* (Walker) (Dentener et al. 1990). Recent research on light brown apple moth suggests that adult emergence is prevented when fifth instars are irradiated at 150 Gy (P.A.F., unpublished data). Irradiation tests with *Cryptophlebia illepida* Butler indicated that 250 Gy prevented adult emergence from irradiated fourth and fifth instars, but 125 Gy was sufficient to cause sterility (Follett and Lower 2000).

Information on several other tortricid species is available from studies to develop sterilizing doses for sterile insect release programs (Bloem et al. 2003, IDIDAS 2007, Suckling et al. 2007). These studies concur that radiation doses ≤200 Gy are sufficient to sterilize females. A radiation dose of 200 Gy would probably suffice as a generic dose for tortricids, but detailed studies including large-scale validation tests on several additional pest species in the family is desirable before making a recommendation. A generic dose for the Lepidoptera as a whole might require a significantly higher dose, in the range of 500–600 Gy (Follett and Neven 2006), owing to the high radiotolerance of the Angoumois grain moth, *Sitotroga cerealella* (Olivier) (Ignatowicz 2004, Hallman and Phillips 2008), the most radiotolerant insect studied thus far.

Curculionid weevils are another important group of internal pests that soon may have sufficient information to propose a generic radiation dose. Studies are available for plum curculio, *Conotrachelus nenuphar* (Herbst) (Hallman 2003); sweetpotato weevil and *Euscepes postfasciatus* (Follett 2006a); and boll weevil, *Anthonomus grandis* Boheman (Davich and Lindquist 1962), suggesting a dose ≤150 Gy may be sufficient. Control of the closely related bruchid weevil, *Callosobruchus chinensis* L. (cowpea weevil), was achieved at 100 Gy (Gao et al. 2004). *Sternochetus mangiferae* (F.) seems to be an outlier (Table 1). A radiation dose of 300 Gy was approved for this quarantine pest of mangos based on data from several studies using a small number of insects (Follett 2002, USDA–APHIS 2006), but this dose can probably be lowered, as doses as low as 100 Gy have been shown to sterilize the weevil (Follett 2002). Due to the absence of an artificial diet and the cryptic feeding location in the seed, the large-scale studies needed to confirm a lower dose for *S. mangiferae* would be difficult and have not been attempted.

Several important groups of regulatory insects are surface pests such as thrips, scales, and mealybugs (Table 3), and these insects are likely controlled at doses below 400 Gy (Yalemar et al. 2001; Hara et al. 2002; Jacobsen and Hara 2003; Follett 2006b,c), but studies are limited. Surface insects are common interceptions on fresh commodities, and if numbers are sufficiently high can cause delay or rejection of consignments. Before generic treatments below 400 Gy can be recommended for a wider range of insect groups, information from coordinated research projects (e.g., IAEA 2004) and large-scale tests is needed on effective radiation doses for key pests in each of these groups. Based on the prevalence of quarantine pests in the various groups listed in Table 3, research toward the development of generic doses for the insect families Coccidae, Diaspididae, and Pseudococcidae (collectively 40% of species listed), or ideally all sternorrhynchous Hemiptera, would be particularly useful as it might facilitate lowering radiation doses for many subtropical and tropical fresh commodities.

Mites (Acari) are another important group of arthropods for additional research as they are not included in the 400-Gy generic treatment and are commonly encountered plant pests. The focus should be on pest mites in the families Tenuipalpidae, Tetranychidae, Eriophyidae, and Tarsonemidae. Few irradiation studies with mites have been attempted. The tenuipalpid *Brevipalpus chilensis* Baker, a quarantine pest of table grapes and other fruits exported from Chile, was sterilized at 300 Gy (Castro et al. 2004; Table 1); the tetranychids *Tetranychus cinnabarinus* (Boisduval) and *Tetranychus urticae* Koch were sterilized at 320 Gy (Ignatowicz and Banasik-Solgala 1999); and the eriophyid *Phyllocoptruta oleivora* Ashmead, an important fruit pest of citrus (*Citrus* spp.) in China, was sterilized at 350 Gy (Hu et al. 2004). These studies indicate that mites may generally be more tolerant of radiation than insects.

Commodity Quality and Unique Applications. Commercial adoption of radiation treatment requires an understanding of the radiotolerance limits of individual commodities and the multiple factors that mediate the phytotoxic threshold. Radiation may cause the breakdown of chemical compounds in the commodity, or affect its composition through slowed ripening. Many commodities tolerate the low doses required for insect disinfestation. Irradiation at <1,000 Gy has a minor effect on the nutritional composition and sensory attributes of a wide range of crops, including apple (*Malus pumila*), banana, blueberry (*Vaccinium* spp.), capsicums (*Capsicum* spp.), cucumber (*Cucumis sativus*), longan (*Dimocarpus longan*), lychee, mango, papaya, peach (*Prunus persica*), persimmon (*Diospyros virginiana*), rambutan (*Nephelium lappaceum*), strawberry (*Fragaria* spp.), and sweet potato (Mitchell et al. 1992, Morris and Jessup 1994, Thomas 2001, Wall 2008). However, at higher radiation doses (600–1000 Gy) certain fresh fruits and vegetables can show symptoms of phytotoxicity. Surface pitting, scald, and browning are typical external symptoms of radiation injury (Wall 2008). Cultivar differences, maturity, preharvest conditions, storage conditions, and interactions among these factors can modify radiotolerance and are often poorly understood. Research is needed on novel methods to reduce injury and extend shelf-life of radiosensitive crops such as combination treatments, ethylene inhibitors, edible coatings, and modified atmosphere packaging (Wall 2008). Because most fresh commodities traded between countries will initially make use of the 400-Gy generic treatment (due to the diversity of insect pests) quality studies should include responses to doses in the range of 400-1000 Gy.

Generic radiation treatments may allow for novel applications and products. Present regulatory guidelines for applying quarantine treatments are for single commodities only, as most quarantine treatment protocols are developed for single commodities. Generic radiation treatments were developed irrespective of commodity, and therefore, theoretically, could be applied to a mixture of fresh commodities as long as the technical objectives of the treatment are met. The first technical objective is to exceed the minimum dose to control the pests associated with the fruits in the mixture, whether it is 150 or 400 Gy. The second technical objective is not to exceed the maximum allowable dose of 1000 Gy, but practically speaking, the treatment should not exceed the maximum tolerable dose of the most radiation-sensitive fruit in the mixture.

Dose variation results during commercial radiation treatment because the ionizing radiation must penetrate to the center of a stack of boxes containing the commodity. Doses are typically higher on the outside of the stack and lower in the center of the stack. The degree of attenuation depends on the inherent density of the commodity and the bulk density of the packaged commodity. In a mixed fruit box, the different fruits might vary in size, shape, water content, and density, and so the pattern of radiation dosing may be more variable compared with treatment of a more uniform box of one type of fruit.

Follett and Weinert (2009) tested dose variation in boxes of single and mixed tropical fruits. Dose variation (ratio of maximum to minimum values) ranged from a low of 1.3 for papaya alone, to 1.37 for a mixture of papaya, longan, and banana. All treatments achieved the technical requirement of exceeding the 400-Gy minimum absorbed dose, and remaining below the 1-kGy maximum allowable dose. The lowest dose measured was for longan (432 Gy), and the highest dose measured was for the mango, rambutan, and longan mixture (650 Gy). Results showed that dose variation between fruit mixtures and single fruits is quite similar; therefore, that radiation treatment of loads of mixed fruit by using generic doses is technically feasible. Exporting mixed fruits in the same box may result in different ripening or senescence patterns for the fruits compared with having only a single fruit type in the box if an ethylene producer such as banana, papaya or mango is included in the mixture, and this topic warrants more research. Generic radiation treatments could lead to export approvals for value-added mixed fruit or vegetable gift boxes and other products which would diversify revenue for the produce industry.

Trade Facilitation. Low-dose generic radiation treatments will accelerate the approval of radiation quarantine treatments for specific crops and expedite new trade in fresh agricultural products. Developing radiation treatments for taxonomic groups or guilds of insects and groups of commodities rather than for individual pests and commodities helps avoid unnecessary research, and regulatory and trade bottlenecks (Follett et al. 2007). Lowering the radiation dose for specific pests or for the pests on a commodity will reduce treatment costs and help maintain commodity quality. The availability of generic dose treatments makes irradiation an attractive option compared with other quarantine treatments.

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