Food Irradiation Research and Technology, Second Edition

Chapter · November 2007

DOI: 10.1002/9780470277638.ch9

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Chapter 13

PHYTOSANITARY IRRADIATION FOR FRESH HORTICULTURAL COMMODITIES: RESEARCH AND REGULATIONS

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Abstract: Irradiation is used to control and quarantine insects in exported fresh commodities. Insects vary in their tolerance to ionizing radiation. Generic radiation treatments of 150 Gy for fruit flies and 400 Gy for other insects were approved for all fresh horticultural commodities in the United States. Generic radiation treatments will accelerate commodity export approvals. By lowering the dose for specific commodities, costs will be reduced and quality will be maintained. Current issues for phytosanitary irradiation include the 1 kGy dose limit, labeling requirements, and prohibition by the European Union, Japan, Taiwan, and other countries. Codex Alimentarius, the US Food and Drug Administration (FDA), the US Department of Agriculture (USDA), the North American Plant Protection Organization (NAPPO), and the International Plant Protection Convention (IPPC) endorse irradiation as a phytosanitary measure and have published rules, standards, and guidelines to harmonize its use and facilitate trade.

Keywords: phytosanitary irradiation; ionizing radiation; quarantine pests; regulatory barriers; invasive pests; trade barriers

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Food Irradiation Research and Technology, Second Edition. Edited by Xuetong Fan and Christopher H. Sommers.

Published 2013 by John Wiley & Sons, Inc.

Introduction

A quarantine pest is a plant pest of potential economic importance to an area in which the pest is not yet present, or is present but not widely distributed and is being officially controlled. Quarantine or phytosanitary treatments eliminate, sterilize, or kill regulatory pests in exported commodities to prevent their introduction and establishment into new areas. Irradiation is a versatile technology to disinfest fresh and durable agricultural commodities of quarantine pests. Irradiation is broadly effective against insects and mites, cost competitive with other disinfestation methods (such as fumigation, heat, and cold), and fast. Irradiation generally does not significantly reduce commodity quality at the doses used to control insect pests, and may even extend shelf life. Additionally, irradiation can be applied to the commodity after packaging.

Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live (but sterile) insects may occur with the exported commodity, making inspection for the target pests redundant as a confirmation of treatment application and efficacy. This places an added level of importance on the certification procedures for irradiation facilities and proper documentation accompanying each shipment confirming treatment at approved doses. It also places an onus on researchers to ensure that the minimum absorbed dose approved for each quarantine pest has an adequate margin of safety.

The history of quarantine uses of irradiation and the relative tolerance of various arthropod groups have been reviewed by Rigney (1989), Heather (1992), Burditt (1996), and Hallman (1998, 2001). In this review we provide an update and synthesis of previous information, and discuss current trends in the use of irradiation as a phytosanitary treatment, with an emphasis on research methodology and the regulatory framework.

Developing Irradiation Quarantine Treatments

Insect Radiotolerance

Ionizing energy breaks chemical bonds within DNA and other molecules, thereby disrupting normal cellular function in the insect. Insect response to irradiation varies with the insect species and life stage, and the absorbed dose received by the insect. Tissues with undifferentiated, actively dividing cells are most susceptible to irradiation. Consequently, eggs are normally the most susceptible life stage and adults are the most

Table 13.1. Range of doses predicted to control various pest groups.

Pest group	Required response	Dose range (Gy)
Hemiptera	Sterilize adult or prevent generation turnover	50–200
Thrips	Sterilize actively reproducing adult	150–200
Tephritid fruit flies	Prevent adult emergence from larva	50–150
Bruchid seed weevils	Sterilize actively reproducing adult	70–300
Curculionid weevils	Sterilize actively reproducing adult	80–150
Scarab beetles	Sterilize actively reproducing adult	50–150
Stored product beetles	Sterilize actively reproducing adult	50–250
Stored product moths	Sterilize actively reproducing adult	100–600
Lepidopteran borers	Prevent adult emergence from larva	100–250
	Sterilize adult from late pupa	200–350
Mites	Sterilize actively reproducing adult	200–400
Nematodes	Sterilize actively reproducing adult	approx. 4000

Source: Modified from IPPC (2003a).

tolerant. Insect gonads and midgut contain mitotically active tissues, and irradiated insects are often sterile and stop feeding soon after treatment (Ducoff 1972; Tilton and Brower 1983; Koval 1994; Nation and Burditt 1994). The goal of a quarantine treatment is to prevent reproduction, and therefore the required response for a radiation treatment may be prevention of adult emergence (Follett and Armstrong 2004), or induction of adult sterility (Follett 2006a), or F_1 sterility (Follett 2006b, 2006c).

Arthropod groups vary in their tolerance to irradiation (Table 13.1). Among insects, Diptera (flies), Coleoptera (beetles), and Hemiptera (true bugs) tend to be less radiotolerant than Lepidoptera (moths and butterflies), although there is considerable variation among the species that have been tested within these groups. Estimates for Hemiptera (scales, mealybugs, aphids, and whiteflies) and Thysanoptera (thrips) are based on a small number of studies. Two of the most radiotolerant insects are the Indianmeal moth, *Plodia interpunctella*, and the Angoumois grain moth, *Sitrotroga cerealella*, both stored products pests (Ahmed 2001; Ignatowicz 2004). Several species of mites have been tested and appear to be relatively tolerant of ionizing radiation (Follett 2009). Nematodes are highly tolerant. Few studies have conducted the large-scale tests needed to confirm the efficacy of an irradiation dose predicted to give 100% mortality. Table 13.2 provides a list of quarantine insect pests that have been rigorously tested; much of this information is recent and will be used to update and revise approved irradiation treatment doses for specific pests. Most insects are sterilized at doses below 300 Gy.

Table 13.2. Insects for which large-scale confirmatory testing has been performed to establish treatment efficacy.

Species	Common name	Target dose	Stage	#Tested	Reference
Anastrepha ludens	Mexican fruit fly	100	L	101 794	Bustos et al. 2004
		69	L	95 000	Hallman and Martinez 2001
Anastrepha obliqua	West Indies fruit fly	100	L	100 400	Bustos et al. 2004
Anastrepha serpentina	Sapote fruit fly	100	L	105 252	Bustos et al. 2004
Anastrepha striata	Guava fruit fly	100	L	13 094	Toledo et al. 2003
Anastrepha suspensa		50	L	100 000	Gould and von Windeguth 1991
Bactrocera dorsalis	Oriental fruit fly	250	L	620 000	Seo et al. 1973
		150	L	173 000	Komson et al. 1992
		125	L	55 743	Follett and Armstrong 2004
Bactrocera cucurbitae	Melon fly	210	L	169 903	Seo et al. 1973
		150	L	93 666	Follett and Armstrong 2004
Bactrocera jarvisi	Jarvis' fruit fly	101	L	153 814	Heather et al. 1991
Bactrocera latifrons	Solanaceous fruit fly	150	L	157 111	T. Phillips (unpublished)
Bactrocera tryoni	Queensland fruit fly	75	L	24 700	Rigney and Wills 1985
		101	L	138 635	Heather et al. 1991
Ceratitis capitata	Mediterranean fruit fly	250	L	110 800	Seo et al. 1973
		218	L	70 400	Seo et al. 1973
		150	L	100 854	Bustos et al. 2004
		100	L	31 920	Follett and Armstrong 2004
		100	L	99 562	Torres-Rivers and Hallman 2007
Rhagoletis pomonella	Apple maggot	57	L	22 360	Hallman 2004b
Conotrachelus nenuphar	Plum curculio	92	A	25 000	Hallman 2003
Cylas formicarius elegantulus	Sweet potato weevil	150	A	62 600	Follett 2006a
		165	A	30 655	Hallman 2001
Euscepes postfasciatus	West Indian sweet potato weevil	150	A	50 000	Follett 2006a
Omphisa anastomosalis	Sweet potato vine borer	150	P	12 000	Follett 2006a

Table 13.2. (*Continued*)

Species	Common name	Target dose	Stage	#Tested	Reference
Cydia pomonella	Codling moth	200	L	132 000	Mansour and Mohamed 2004
Grapholita molesta	Oriental fruit moth	232	L	58 779	Hallman 2004a
Cryptophlebia illepida	Koa seedworm	250	L	11 256	Follett and Lower 2000
Ostrinia nubilalis	European corn borer	343	P	34 760	Hallman and Hellmich 2009
Pseudaulacaspis pentagona	White peach scale	150	A	35 424	Follett 2006c
Aspidiotus destructor	Coconut scale	150	A	32 716	Follett 2006b
Brevipalpus chilensis	False spider mite	300	A	8 042	Castro et al. 2004

Stage: L, larva; P, pupa; A, adult.

Methodology

The goal of irradiation as a phytosanitary treatment is to provide quarantine security for any regulated pests residing in or on the exported commodity. This is most often accomplished by preventing development to the reproductive stage or sterilizing the reproductive stage of the insect.

If multiple species on a commodity are regulated pests, irradiation studies begin by comparing the tolerance of the quarantine pests; then, in-depth studies focus on the most tolerant stage of the most tolerant species to arrive at a single dose providing quarantine security for the commodity. Typically, the most advanced developmental stage of the insect occurring in the commodity is the most tolerant when the goal is preventing adult emergence or reproduction. The most advanced stage may be the larva (or nymph), pupa, or adult. When larval development is completed in the host but the insect pupates outside the host, irradiation is applied to prevent adult emergence. In the case of tephritid fruit flies, preventing adult emergence is the desired response required for regulatory purposes because it prevents the emergence of adult flies that could be trapped and trigger regulatory actions, despite being sterile. When the insect pupates in the host, preventing adult emergence may be difficult, so adult sterility is the goal.

Often adults occur with the commodity. When the adult stage can occur in the commodity and is the most tolerant stage, the measure of treatment efficacy is the level of sterility. For sexually reproducing species, sterilizing one sex may be sufficient to prevent reproduction, but both sexes must be sterilized if mating status is unknown, as is usually the case. Males are often but not always more tolerant than females. Reciprocal crosses between irradiated and control males and females at several substerilizing doses are useful to determine the more tolerant sex (Follett and Lower 2000). In large-scale confirmatory tests, males and females should be mated before treatment, and females should have begun ovipositing. After irradiation treatment, surviving males and females are combined and allowed to mate and reproduce to determine the success of the dose. Adult females irradiated at a sterilizing dose will often oviposit (particularly if they were gravid when irradiated), but eggs will not hatch or hatching neonates do not develop. With asexual species the female is the focus of all tests. In rare cases irradiated insects will recover, so it is important to continue tests until all insects have died. Many insect species have life history attributes that complicate testing methods. For example, diaspidid scale insects are sessile (attached to the plant) and long-lived, and so experiments must use host material (e.g., pumpkin) that does not deteriorate after irradiation treatment and before the insects die. Some species require live host material to survive. The long-lived semi-sessile coccid scale, green scale (*Coccus viridis*) survives only on live host material such as gardenia, coffee, and hibiscus, which complicates testing because irradiation treatment causes rapid plant deterioration (Hara et al. 2002). Diapausing and nondiapausing strains of insects may have different tolerances to radiation and may require different bioassay methods (Hallman 2003).

To determine the most tolerant stage for a species, all stages are treated with a range of irradiation doses. Generally, five doses should be selected and five replicates of at least 30–50 insects should be used. In some cases, a single diagnostic dose is used to separate tolerance among stages or species. The ideal diagnostic dose causes only moderate mortality in the stage or species predicted to be most tolerant. This improves the chances that statistical tests can be used to separate mean responses among groups. Tests should be designed with the biology of the insect in mind, and insects should always be tested in the commodity of interest if possible. For example, pupae may be inherently more tolerant of irradiation than larvae, but because they occur only at the surface of the fruit, they may be easier to sterilize than larvae that feed at the center of the fruit where hypoxic conditions exist. If artificial inoculation is used, insects should be placed where they occur naturally or be allowed time to redistribute to preferred feeding sites in the commodity.

Accurate dosimetry is critical to the success of insect irradiation studies. The objective in research is to minimize the dose uniformity ratio (DUR), typically to keep it less than 1.2:1. Mehta and O'Hara discuss dosimetry in detail in Chapter 7. Dosimeters should be placed where the insects occur to accurately measure absorbed doses.

After dose response tests are completed, large-scale tests are conducted with the most tolerant life stage at a dose predicted to cause 100% mortality. The dose determined to provide quarantine security from testing large numbers of insects is often higher than that predicted from small-scale dose response tests to give 100% mortality. Insects are irradiated in the commodity after inoculation with a known number of insects or in naturally infested host material. For internal feeding insects naturally infesting the commodity, the number of viable insects treated is estimated by the number of insects successfully emerging in paired samples of untreated controls. Control mortality in this case cannot be determined. For artificial inoculation tests with a known number of test subjects, untreated control insects are always included in tests with irradiated insects so that mortality can be adjusted for natural variation and to guard against changes in experimental conditions over the course of testing that cause higher than normal mortality. Although control mortality ≤20% is desirable, higher mortality may be normal when using wild insects and naturally infested commodities.

Probit analysis is the standard method to evaluate dose response data, but other models (e.g., logit) should be used if they provide a better fit to the data (Robertson and Preisler 1992). These analyses are used to compare radiotolerance among life stages or species, and to help identify a target dose for large-scale testing. Covariance analysis is an alternative to compare response among stages or between species. Covariance analysis requires the slopes of the regression lines fitted to each group to be parallel, so the test of parallelism (nonsignificant stage or species by dose interaction effect) is tested before comparing stage or species effects (e.g., Follett and Armstrong 2004).

As mentioned, the actual dose to achieve quarantine security at a given level of precision may exceed the dose predicted from small-scale dose response tests. For example, the dose predicted to prevent emergence of adult melon flies treated in papaya from dose response data was 90 Gy (0 survivors in 900 tested insects) (Follett and Armstrong 2004); however, subsequent large-scale testing at 120 Gy resulted in 1 survivor out of 50 000 treated third instars and several partially emerged pupae. Increasing the dose for large-scale testing to 150 Gy resulted in 0 survivors in 96 700 treated insects and no partial pupal emergence (Follett and

Armstrong 2004). These results demonstrate the need for large-scale testing to verify a dose.

Varietal Testing

When the pest infests more than one host cultivar or variety, disinfestation studies should theoretically be carried out on the variety in which the pest is most tolerant to irradiation. For a given absorbed dose, pest response to irradiation in the host may vary depending on the milieu surrounding the pest. As mentioned, oxygen concentration is known to modify sensitivity to irradiation, and conditions producing hypoxia can increase radiation tolerance (Alpen 1998). Fruit flies have higher radiotolerance when treated in a nitrogen atmosphere compared with ambient air (Fisher 1997) and when treated in fruit compared with diet (Follett and Armstrong 2004). Radiation damage and mortality was less in codling moth larvae treated in 0.25% O_2 compared with 3% O_2 (Batchelor 1989). Varieties of a commodity with higher water content may have lower available oxygen, and insects infesting these varieties might show higher radiotolerance. Variety was shown to have a dramatic effect on egg hatch and larval development during irradiation studies with the Mediterranean fruit fly in nectarines (eight varieties) and plums (four varieties) (Kaneshiro et al. 1985), and a link with fruit moisture content was suspected but not measured. In the absence of comparative tests among varieties, the variety at greatest risk of infestation or the variety that makes up the greatest proportion of trade is used.

Probit 9 Efficacy and Alternatives

Postharvest commodity treatments for pests requiring a high degree of quarantine security are commonly referred to as probit 9 treatments. A response at the probit 9 level results in 99.9968% response. The USDA has used 99.9968% efficacy as the basis for approving many quarantine treatments against tephritid fruit flies. Probit 9, or 99.9968%, mortality is often incorrectly interpreted to mean that 3 survivors are allowed in 100 000 treated insects or 32 survivors in 1 million treated insects (Baker 1939) without regard to the precision associated with this level of survivorship. To achieve probit 9 mortality at the 95% confidence level, 93 613 insects must be tested with no survivors. Quantitative methods have been developed to calculate the number of test insects and confidence limits for other levels of precision and treatment efficacy, with and without survivors (Couey and Chew 1986). A probit 9 treatment usually provides adequate quarantine security (but see Mangan et al. 1997; Powell 2003), and developing such a treatment frequently proves to be the quickest and most easily accepted method for overcoming phytosanitary restrictions. Other countries (Japan, Australia, New Zealand) accept quarantine treatment efficacy at 99.99% (at the 95% confidence level), which is obtained by treating 29 956 insects with no survivors (Couey and Chew 1986). Japan and New Zealand require three replicates of 10 000 test insects with no survivors (Sproul 1976). The number of insects tested may need to be adjusted (increased) to account for control mortality (Follett and Neven 2006). For insects that are difficult to obtain in the field or rear in the laboratory, testing the efficacy of a potential treatment using lower numbers may be acceptable in certain cases. For example, an irradiation treatment of 300 Gy was accepted for the mango seed weevil, *Sternochetus mangiferae* (Federal Register 2002), a monophagous pest of mangos, based on evidence for its limited potential impact in the United States (Follett and Gabbard 2000) and cumulative data from several studies with a few thousand insects showing prevention of adult emergence at a target dose of 300 Gy (Heather and Corcoran 1991; Follett 2001) and sterilization at lower doses (Seo et al. 1973; Follett 2001). When low numbers of insects are used, the number tested without survivors can be used to calculate the level of quarantine security. When dose response or small-scale tests are used to predict an irradiation dose to control the pest, the lowest effective dose should be increased by 20–25% to add a margin of safety.

Landolt et al. (1984) pointed out that the probit 9 standard may be too stringent for commodities that are rarely infested or poor hosts. The *alternative treatment efficacy* approach measures risk as the probability of a mating pair or reproductive individual surviving in a shipment. The main quantitative argument for deviating from probit 9 treatment efficacy is low infestation rate of the commodity, but many other biological and nonbiological factors affect risk (Vail et al. 1993; Whyte et al. 1994; Follett and McQuate 2001). An advantage to using the alternative treatment efficacy approach is that fewer insects may be needed during development of quarantine treatments (Follett and McQuate 2001). The alternative treatment efficacy approach fits with the systems approach where multiple procedures are used to cumulatively provide quarantine security (Jang and Moffitt 1994, Follett and Vargas 2010). For example, irradiation of navel oranges within the range of doses providing probit 9 kill of tephritid fruit flies and other pests (150–400 Gy) causes pitting to the skin. In Hawaii, the oriental fruit fly and Mediterranean fruit fly are the main quarantine pests of citrus. Whereas 150 Gy is the approved irradiation dose for tephritid fruit flies, irradiation treatment at a dose of 30 Gy combined with cold storage at 2°C for 9 days provides high efficacy with minimal effects on quality (Follett unpublished data) and potentially could be combined with inspection, field control, and other mitigation procedures to give a high level of quarantine security. "Sharwil" avocado is a poor host for its main quarantine pest, oriental fruit fly. A multicomponent systems approach to reduce the risk on infestation in "Sharwil" avocados exported from Hawaii to the United States mainland is based on poor host status and low pest prevalence, and limiting shipments only to northern tier states during winter months when conditions are inhospitable to tropical fruit flies (Follett and Vargas 2009).

Maximum pest limit is another approach to quarantine security that focuses on survival rather than mortality and is closely related to the alternative treatment efficacy approach (Baker et al. 1990; Mangan et al. 1997). It is defined as the maximum number of insects that can be present in a consignment imported during a specified time at a specified location (Baker et al. 1990). A minimum sample size for inspection is determined from an estimate of the level of pest infestation, the efficacy of the postharvest treatment, and the maximum lot size assembled per day at a location. This level of inspection is predicted to detect infestation levels greater than the maximum level of permissible infestation with a certain probability and confidence limits (Baker et al. 1990).

Generic Radiation Treatments

A "generic" quarantine treatment is one that provides quarantine security for a broad group of pests. From a regulatory standpoint, "generic" can also refer to a treatment for a pest on all commodities it infests. A generic treatment for a group of insects could be applied at many taxonomic levels, for example, to all Diptera (flies), or to flies in the family Tephritidae (fruit flies), or to tephritid fruit flies in the genus *Bactrocera*. The rationale for generic doses is that information on radiotolerance for a subset of species within a group can be extrapolated to related species to arrive at an effective generic dose (Follett et al. 2007). Irradiation is the ideal technology for developing generic treatments because it is effective against most insects and mites at dose levels that do not affect the quality of most commodities. 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).

Initially, development of the generic dose concept has focused on tephritid fruit flies. The International Consultative Group on Food Irradiation (ICGFI) was the first group to formalize a recommendation for generic irradiation treatments (ICGFI 1991). In 1986, based on irradiation data for several tephritid fruit fly species and a limited number of other insect pests, they proposed a dose of 150 Gy for fruit flies and 300 Gy for other insects. Adoption of the 150 Gy dose for fruit flies was stymied by research suggesting that three tephritid fruit fly species in Hawaii required higher irradiation doses to prevent adult emergence from infested fruit (Seo et al. 1973). Based on the data presented by Seo et al. (1973), USDA-Animal Plant Health Inspection Service (APHIS) approved irradiation doses of 210, 225, and 250 Gy for the melon fly, Mediterranean fruit fly, and oriental fruit fly, respectively, for exporting fruits and vegetables from Hawaii (Federal Register 1997). The majority of economically important tephritid fruit flies come from four genera—(1) *Anastrepha*, (2) *Bactrocera*, (3) *Ceratitis*, and (4) *Rhagoletis*, and irradiation studies have been conducted with species in each of these genera. Although results from various irradiation studies with fruit flies have not always been consistent (reviewed by Rigney 1989; Burditt 1994, 1996; Hallman and Loaharanu 2002), the preponderance of evidence suggested that all the species in these genera could be controlled by doses at or below 150 Gy. Follett and Armstrong (2004) demonstrated that irradiation doses of 100, 125, and 150 Gy controlled *Ceratitis capitata*, *Bactrocera dorsalis*, and *Bactrocera cucurbitae*, respectively, which supported lowering the dose for Hawaii's fruit flies and paved the way for approval of the proposed 150 Gy generic dose for tephritids.

In 2006, low dose generic radiation treatments were approved for the first time. 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 ten specific plant pests, and doses for additional quarantine insect pests have been approved since (USDA-APHIS 2008; Follett 2009). The generic and specific radiation doses apply to all fresh agricultural commodities. 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 (Follett 2009). Hawaii uses the generic radiation treatments to export 12 million pounds of tropical fruits and vegetables to the United States mainland annually.

India is exporting mangos (*Mangifera indica*) and Thailand is exporting several types of tropical fruits to the United States using the generic radiation dose of 400 Gy. Vietnam is exporting dragon fruit (*Hylocereus undata*) to the United States also using the generic radiation dose of 400 Gy. Mexico received approval to export guavas (*Psidium guajava*) to the United States using 400 Gy, and mangos using a radiation dose of 150 Gy. Australia can export mangos, papayas (*Carica papaya*) and lychee (*Litchi chinensis*) 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 (ISPM) No. 28, Phytosanitary treatments for regulated pests (IPPC 2007), which will facilitate worldwide adoption.

Any country negotiating trade in fresh fruits and vegetables with the United States can use the low-dose generic radiation treatments (Follett et al. 2007). 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 systems and irradiated products. The trading partner agrees to adopt the USDA APHIS-approved generic irradiation treatments and approved irradiation treatments for other specific pests as part of the agreement.

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 (Follett 2009). Generic radiation doses also may lead to new opportunities for value-added products. Future research will focus on four areas. First, development of specific doses will be developed for quarantine Lepidoptera not covered by the generic treatments. 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 (e.g., Follett 2006a, Hollingsworth and Follett 2007).

Second, it may be practical to reduce dose levels for specific pests and commodities to shorten treatment time. 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 (e.g., Follett and Lower 2000, Follett 2006a, 2006c). 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.

Third, generic doses below 400 Gy should be developed for important groups of quarantine arthropods other than fruit flies (Follett 2009). After fruit flies, tortricid moths are probably the most significant internal-feeding pests of economic and quarantine concern for fruits and fleshy vegetables. Curculionid weevils are another important group of internal pests. Surface insects such as thrips, scales, and mealybugs are common interceptions on fresh commodities, and if numbers are sufficiently high can cause delay or rejection of consignments. Evidence is accumulating showing that all of these groups of insects are likely controlled at doses below 400 Gy, and development of generic doses for these insect groups would help lower the dose for many exported commodities (Follett 2009).

Finally, further research is needed on commodity tolerance and novel methods to reduce injury and extend shelf life (Kader 1986; Morris and Jessup 1994, Wall 2008, Follett and Weinert 2009). Commercial adoption of irradiation treatment requires an understanding of the radiotolerance limits of individual commodities and the multiple factors that mediate the phytotoxic threshold. Irradiation 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. 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). Since 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.

Information from research in these four areas will result in regulatory changes that facilitate trade by providing new or improved quarantine radiation treatments. 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 and Neven 2006). Lowering the radiation dose for specific pests or for the pests on a commodity will reduce treatment costs and help maintain commodity quality.

Regulatory Aspects of Irradiation

The establishment of national regulations for the use of irradiation as a phytosanitary treatment began in 1930 with a failed proposal to use X-rays for treating fruit exported from Formosa (Koidsumi 1930). Seven decades later, the International Plant Protection Convention (IPPC) adopted an international standard for the use of irradiation as a phytosanitary treatment (IPPC 2003a). The evolution of irradiation as a phytosanitary treatment from its disappointing start to international success was marked by a long history of national, regional, and international initiatives and several watershed events (discussed in the following text), including the official acceptance of irradiation as a "safe" treatment and the establishment of a regulatory and policy framework by the United States for the implementation of irradiation as a phytosanitary treatment.

Codex Alimentarius (Codex), the international organization responsible for establishing harmonized standards for food safety, adopted its Codex General Standard for Irradiated Food (CAC/RS 106-1979) in 1979. Although the standard does not specifically apply to phytosanitary treatments, it was the first international standard for irradiated food, and many phytosanitary treatments are for food commodities. The standard was subsequently revised in 1983 following the recommendations of the joint FAO-IAEA-WHO Expert Committee, and again in 2003 based on additional research indicating that the maximum absorbed dose could exceed 10 kGy when necessary to achieve a legitimate technological purpose (Codex 2003).

Associated with the General Standard is the Codex Recommended International Code of Practice for the Operation of Irradiation Facilities.

This was significant because it represented the first internationally harmonized guidelines on how to measure absorbed dose. It also describes relevant parameters in facilities, dosimetry and process control, good radiation processing practice, and product and inventory control (Codex 1984).

The Code includes two annexes: Annex A is related to dosimetry, indicating how to calculate the overall average adsorbed dose and explaining the concept of limiting dose values, routine dosimetry, and process control; Annex B gives some examples of technological conditions for the irradiation of certain items. Mango is one of the examples. It is noted that mangoes may be irradiated for three objectives: (1) control of insects, (2) to improve quality (extend shelf life), and (3) to reduce microbial load, using up to 1 kGy as an average dose.

It is significant that the Code focused on mangoes because the chemical treatment of mangoes became a serious political issue in 1982 after the US Environmental Protection Agency (EPA) announced a ban on the use of ethylene dibromide (EDB) because it was demonstrated to be a carcinogen (Ruckelshaus 1984). EDB was popular and widely used as a phytosanitary treatment at the time. The ban forced phytosanitary officials to seek alternative treatments for many commodities that were routinely treated for import and export, especially tropical fruits.

Political pressures and growing interest in the commercialization of irradiation for the treatment of food in the United States spurred the Food and Drug Administration (FDA) to open the regulatory door in 1986 by publishing 21 CFR 179.26, "Irradiation in the Production, Processing and Handling of Food." Among other things, this regulation authorized the use of irradiation up to 1 kGy for the disinfestation of arthropod pests in food, the use of up to 8 kGy for the control of microbial pathogens on seeds for sprouting, and up to 30 kGy for the microbial disinfestation of spices. This rule cleared the regulatory path for the USDA to authorize irradiation as a phytosanitary treatment on commodities for consumption.

European authorities have historically been among the most reluctant to accept irradiation as a treatment for foods, but also among the most active in supporting research on the safety of irradiation. Concerns are principally focused on health risks to food processing workers, possible long-term effects of consuming irradiated food (especially for children), and fears that food producers and processors will be less motivated to use good manufacturing practice to ensure the wholesomeness of food if they are able to rely on irradiation treatment to produce clean products. A very limited list of herbs, spices, and seasonings is currently authorized from approved facilities with mandatory labeling requirements. In 2001, the European Commission suggested that this list be considered complete and recommended further research on the effects of consuming irradiated food and identifying alternative treatments rather than expanding the possibilities for irradiation (European Commission 2001).

A similar situation occurs with Japan, where the use of nuclear technologies of any kind are perhaps more sensitive than for other countries for historical reasons. As do the Europeans, the Japanese allow and use irradiation for the treatment of food on a very limited and highly restricted basis. To date, the only phytosanitary treatment reported by Japan is for potatoes. A small proportion of Japan's potato production is treated for sprout inhibition (Furuta 2004).

USDA Regulations

The USDA had decided as early as 1966 that 150 Gy was the minimum dose to prevent adult emergence of three fruit flies: (1) oriental fruit fly, *B. dorsalis*; (2) Mediterranean fruit fly, *C. capitata*; and (3) melon fruit fly, *B. cucurbitae*; associated with papaya from Hawaii (Balock et al. 1966). In 1989, soon after FDA's regulations went into effect, the APHIS, the USDA Agency responsible for promulgating regulations dealing with quarantine treatments, published the first rule to allow the use of irradiation as a phytosanitary treatment. The rule specified a treatment of 150 Gy in order to ship fresh papaya from Hawaii to the mainland, Guam, Puerto Rico, and the Virgin Islands (Hawaii was later changed to 250 Gy).

Despite being limited to a specific commodity, origin, and domestic program (and despite the fact that no fruit was immediately shipped due to the lack of a treatment facility in Hawaii), this minor domestic regulation had major global impacts as a result of the regulatory and policy implications it represented for the phytosanitary community. By publication of this rule, the United States made clear its acceptance of irradiation as both a safe and effective phytosanitary treatment and, for the first time, APHIS approved a treatment that dealt with a complex of pests (fruit flies) rather than a single pest. At the same time, APHIS recognized the legitimacy of a nonmortality treatment (the required response was "inability to fly") and the possibility of detecting and accepting "live" quarantine pests in treated shipments (USDA-APHIS 1989).

Regulatory interest in irradiation peaked again in 1992 when the fumigant methyl bromide (MB) was listed in the Montreal Protocol as one of the substances that causes depletion of the ozone layer. The Montreal Protocol is an international treaty for the regulation of ozone-depleting substances in the atmosphere (EPA 1993). At the Meeting of the Parties to the Montreal Protocol held September 1997 in Montreal, Canada, it was agreed that the production of MB should be phased out by a certain percentage each year beginning in 1999. Developed countries were expected to phase it out completely by 2005 and developing countries by 2015 (EPA 1996).

Although the Montreal Protocol makes an exception for the use of MB as a quarantine treatment, the overall reduction in production of the fumigant over time has caused cost increases and reduced the availability of the compound with the net effect of making it increasingly less practical. The effect is not as immediate as was the ban on EDB, but the repercussions are just as significant because MB is also popular and widely used as a phytosanitary treatment for both food and nonfood items (e.g., cut flowers and wood products).

After 1995, rapidly increasing global trade pressures and the possible loss of MB as a fumigant for regulatory pest treatments made it imperative for practical treatment options to be explored. Unfortunately, the perception of public reluctance to accept irradiation and the relatively high initial costs associated with changing to irradiation as a preferred treatment technology made it less desirable than lower-cost alternatives. At the same time, technological advances, greater experience, and a growing body of research indicated that irradiation had increasingly greater potential as a treatment, or as an alternative treatment, for many quarantine pest problems.

It is in this light that APHIS decided in 1996 to expand its regulatory framework addressing irradiation treatment, develop comprehensive policy statements, and begin encouraging international harmonization while also updating its own treatments and approving new ones. In a Policy Notice of 1996 titled "The Application of Irradiation to Phytosanitary Problems," APHIS listed key positions and procedures, defined terms, offered research protocols, and proposed generic doses for nine fruit fly pests (USDA-APHIS 1996).

In response to a petition from Hawaii, APHIS further expanded its authorization in 1997 to add the possibility of treating fresh papaya, lychees, and carambolas from Hawaii at 250 Gy (Moy and Wong 2002). An irradiation dose of 250 Gy rather than 150 Gy was established after review of the data in Seo et al. (1973). Following this, APHIS also approved the irradiation of sweet potato (Federal Register 2004) and other commodities from Hawaii. Fruits and vegetables from Hawaii that are currently authorized for irradiation treatment include abiu, atemoya, banana, breadfruit, *Capsicum* spp., carambola, citrus, cowpea, *Cucurbita* spp., dragon fruit, eggplant, jackfruit, lychee, longan, mango, mangosteen, moringa, papaya, pineapple (other than smooth Cayenne), rambutan, sapodilla, sweet potato, and tomato, (Follett 2009).

Consistent with its Policy Notice, APHIS supplemented its authorizations for exports from Hawaii with regulations to also allow foreign imports by publishing a rule on Irradiation as a Phytosanitary Treatment for Imported Fresh Fruits and Vegetables (7 CFR 319.305). This updated regulation sets out specific standards for irradiation treatment that included a generic dose of 150 Gy for all tephritid fruit flies, and 400 Gy for all other insects except adults and pupae of Lepidoptera, and specific doses between 70 and 100 Gy for several *Anastrepha* and *Bactrocera* fruit flies, 300 Gy for the false red spider mite (*Brevipalpus chilensis*), 200 Gy for codling moth (*Cydia pomonella*), 250 Gy for koa seedworm (*Cryptophlebia illepida*) and litchi fruit moth (*Cryptophlebia ombrodelta*), 200 Gy for oriental fruit moth (*Grapholita molesta*), 92 Gy for plum curculio (*Conotrachelus nenaphur*), and 150 Gy for sweet potato weevil (*Cylas formicarius elegantulus*), West Indian sweet potato weevil (*Euscepes postfasciatus*) and sweet potato vine borer (*Omphisa anastomosalis*)(USDA-APHIS 2006). Specific doses for several additional insect species have been added since (USDA-APHIS 2008). Included also in this regulation are provisions that require the exporting country to establish Framework Equivalency Work Plans with APHIS demonstrating that the exporting country accepts irradiated commodities for import.

Regional and International Harmonization

The North American Plant Protection Organization (NAPPO), the regional organization responsible for setting phytosanitary standards recognized under the North American Free Trade Agreement (NAFTA), formally recognized the effectiveness of irradiation as a broad-spectrum quarantine treatment for fresh fruits and vegetables in 1989. In addition to NAPPO, other regional plant protection organizations that operate within the framework of the IPPC, including the European and Mediterranean Plant Protection Organization (EPPO), the Asia and the Pacific Plant Protection Commission (APPPC), the Comite de Sanidad Vegetal del Cono Sur (COSAVE), and the Organismo Internacional Regional de Sanidad Agropecuaria (OIRSA), endorsed irradiation as a quarantine treatment for fresh horticultural products at the Technical Consultation of Regional Plant Protection Organizations held in San Salvador in 1992 (FAO 1992).

At the NAPPO Annual Meeting in 1994, a roundtable discussion was organized on “The Application of Irradiation to Phytosanitary Problems.” NAPPO delegates from Canada, Mexico, and the United States provided enough encouragement for the NAPPO Executive Committee to agree on an initiative to elaborate a regional standard. The policies put forward by

APHIS in 1996 provided the framework for the development of “Guidelines for the Use of Irradiation as a Phytosanitary Treatment” that was adopted as a NAPPO standard (NAPPO 1997). This marked a significant step forward in international harmonization and became the springboard for creation of an international standard (IPPC 2003a).

Since 1993, the IPPC has prepared international standards for phytosanitary measures designed to promote international harmonization and facilitate safe trade by avoiding the use of unjustified measures as barriers. Standards adopted by the IPPC must be observed by members of the World Trade Organization according to the Agreement on the Application of Sanitary and Phytosanitary Measures (the WTO-SPS Agreement). Governments must provide a technical justification (generally a risk assessment) for measures that are inconsistent with international standard or for measures put in place in the absence of a standard (WTO 1994).

The Interim Commission on Phytosanitary Measures (ICPM), governing body of the IPPC, considered the global application of irradiation as a phytosanitary measure at its Third Session in 2001. A decision was made to create a working group with the purpose of developing an international standard for irradiation as a phytosanitary treatment, which was officially adopted in April 2003 (IPPC 2001, 2003b). The IPPC standard (International Standard for Phytosanitary Measures (ISPM) No. 18 *Guidelines for the use of irradiation as a phytosanitary measure*) describes specific procedures for the application of ionizing radiation as a phytosanitary treatment for regulated pests or articles. The document is organized like other IPPC standards, with sections including an introduction, scope, references, definitions and abbreviations, and an outline of requirements preceding the general and technical requirements. In addition, the standard includes an appendix providing scientific information on absorbed dose ranges for certain pest groups and another appendix providing guidance on undertaking research to develop irradiation treatments for regulated pests (IPPC 2003a).

Trade

The establishment of the NAPPO standard in 1997 opened new possibilities for the use of irradiation in trade between Mexico and the United States. Mexico has great potential because of the high volume of fruit and vegetable exports requiring phytosanitary treatments. Mexico also has trained personnel and significant experience with irradiation treatments. What may be more important is that Mexico already has a regulatory framework in place for sanitary and phytosanitary treatments that allows food to be irradiated for consumption and for importation (Verdejo 1997).

In 1998, a meeting was organized in Mexico to evaluate the capability of the country to initiate export markets for irradiated fruits and vegetables. Although it was recognized that Mexico had substantial potential for the export of irradiated fruits, especially mango, the producers opted instead to continue with treatments such as hot water dip that required a much lower initial investment in equipment and had no controversial implications for consumers. This attitude is changing, and Mexico is currently engaged in constructing new irradiation treatment facilities and has started exporting guavas to the United States. The United States has opened the door for shipments of irradiated commodities from not only Mexico but also all countries. As mentioned earlier, India, Vietnam, and Thailand are now exporting tropical fruits to the United States using generic dose treatments, and 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.

Based on the progressive regulatory directions established by the United States after 1980, many countries began to also consider legislation or regulations for irradiated food. More than 50 countries currently have regulations pertaining to irradiation as a treatment for food products and are treating or accepting treatment for at least one irradiated commodity (see Table 13.3). Although a large number of countries have approved irradiation as a treatment for food, few have large-scale commercial operations. This is due partly to regulatory barriers and partly to the lack of facilities and markets. Also, ensuring adequate throughput can be a substantial challenge given the seasonality of many agricultural products.

The situation is slightly less complicated with nonfood treatments. Commodities such as wood products, cut flowers, and bird seed that may also require phytosanitary treatments are not subject to the same degree of regulation associated with food products. As a result, regulatory frameworks for these treatments do not address health and safety concerns but rather emphasize the efficacy of the treatment, and the integrity of the treatment process and facility.

The evolution of regulatory frameworks for the adoption and implementation of irradiation as a phytosanitary treatment has been marked by numerous successes around the world. In the past, regulatory uncertainties have heightened anxiety among investors and producers who were already concerned about potential problems with public acceptance despite extensive information about the safety and effectiveness of irradiation. Today, the world has an international standard as a global

Table 13.3. Foods and food products authorized for irradiation for selected countries.

Country	Examples of food products authorized or treated with irradiation
Algeria	Potatoes
Argentina	Spices and dried vegetables, garlic, egg products, and dehydrated bovine serum
Australia	Breadfruit, carambola, custard apple, longan, litchi, mango, mangosteen, papaya and rambutan, herbs, spices, and herbal infusions
Bangladesh	Potatoes, onions, dried fish
Belgium	Feed for laboratory animals, spices, frozen frog legs, shrimp, aromatic herbs and teas, dehydrated vegetables
Brazil	Spices, dehydrated vegetables, fruits, vegetables, grain
Canada	Potatoes, onions, wheat flour and whole wheat flour, spices and dehydrated seasonings, mango
Czech Republic	Spices
Chile	Spices and condiments, dried vegetables, frozen food, potatoes, poultry meat
China	Spices, pepper, condiments and seasoning, dried fruits, nuts and preserved fruit, cooked meat foods of livestock and poultry, fresh fruits and vegetables, frozen packaged meat of livestock and poultry, grains, beans and bean products, garlic spice, dehydrated vegetables, and others
Croatia	Various tea herbs, chamomile, mixed spices, dry cauliflower and broccoli, paprika, liquid egg yolk, dry beef noodles
Cuba	Potatoes, onions, beans
Denmark	Spices
Ecuador	Banana flour, spices, animal feed, raw jelly, honey, tea herbs
Egypt	Fresh bulbs, tuber crops, dried garlic, dried onion, herbs and spices, dried onion
Finland	Spices
France	Laboratory animal food, spices, Arabic gum, dehydrated vegetables, cereal, poultry (frozen deboned chicken), frog legs, shrimp, dried fruit and vegetables, rice flour, strawberries, bovine serum
Germany	Spices
Ghana	Yam, maize
Hungary	Spices, onions, wine cork, enzymes
India	Pulses, dried seafood, fresh seafood, frozen seafood, spices and dry vegetables, seasonings, fresh mangos
Indonesia	Frozen seafood products (including frog legs), cacao powder, spices, food packaging, rice
Iran	Spices, dried fruits, nuts
Iraq	Spices
Israel	Spices, condiments, dry ingredients
Italy	Spices
Japan	Potato

(*Continued*)

Table 13.3. (*Continued*)

Country	Examples of food products authorized or treated with irradiation
Republic of Korea	Potato, onion, garlic, chestnut, mushroom (fresh and dried), spices, dried meat, shell fish powder, red pepper, paste powder, soy sauce powder, starch for condiments, dried vegetables, yeast-enzyme products, aloe powder, ginseng products, soybean paste powder, sterile meals
Malasia	Spices
Mexico	Spices, dried vegetables, chili, dried meat, fresh guava and mango
Moroco	Spices
Netherlands	Spices, frozen products, poultry, dehydrated vegetables, egg powder, packaging material
New Zealand	Breadfruit, carambola, custard Apple, longan, litchi, mango, mangosteen, papaya, rambutan, herbs, spices and herbal infusions
Norway	Spices
Pakistan	Potatoes
Peru	Spices, condiments, dehydrated products, medical herbs, flours, food supplements
Philippines	Spices (onion powder, garlic powder, cayenne powder, ground black pepper, Spanish paprika, dehydrated chives, ground anise, instant gravy, sausage seasoning, minced onion), frozen fruits (avocado, mango, macapuno, durian, ube, atis, buco, cheese, fruit cocktail), Solo papaya, Carabao mango, Cavendish banana
Poland	Spices, dried mushrooms, medical herbs
Portugal	Spices
South Africa	Cereal, dairy products, dehydrated foods, dehydrated vegetables, dried fruit, egg products, fish, fresh vegetables, garlic, health preparations, honey products, marinade, royal jelly, shelf-stable foods, soya mixtures, spices and herbs, Torulite yeast, vegetable powder
Syria	Chicken, cocoa beans, condiments, dates, fresh fish, dried fish products, mango, onions, licorice, spices
Thailand	Fermented pork sausage, sweet tamarind, spices, onions, enzymes, and fresh mango, rambutan, litchi, longan, mangosteen, pineapple
Turkey	Spices, dried seasonings and herbs, dried vegetables, meat and meat products, frozen fish and seafood, frozen frog legs, dried fruits
Ukraine	Spices
United Kingdom	Spices
United States	Spices, chicken, beef, fish, fresh fruits and vegetables, meals
Viet Nam	Spices, dragon fruit
Yugoslavia	Spices

Source: ICGFI (1991), Loaharanu (1997), Follett (2009).

reference point for the use of irradiation as a phytosanitary treatment, and the United States has put in place a regulatory framework demonstrating full acceptance of the technology. The uncertainties associated with potential regulatory barriers are substantially reduced, and the road is clear to realizing the full potential of irradiation as a phytosanitary treatment.

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