Research

Introductory papers

Phytosanitary irradiation: An overview

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Abstract

This special issue of *Florida Entomologist* presents the accomplishments of the Coordinated Research Project (CRP): "Development of Generic Irradiation Doses for Quarantine Treatments" of the Joint Food and Agricultural Organization/International Atomic Energy Agency Programme on Nuclear Techniques in Food and Agriculture. The overarching objective was to develop generic phytosanitary irradiation (PI) treatments for groups of regulated phytosanitary pest species. Generic treatments are applicable to groups of regulated pest species although directly relevant research has been done on only a fraction of them. Good research practices were instilled in the participants to avoid problems that occurred with previous research, such as inadequate dosimetry, use of artificial infestation techniques without comparison to real-world situations, poor performance by the non-irradiated controls, and lack of large-scale confirmatory testing. New data was generated on 34 species in 10 families of insects, 3 families of mites and 1 family of snails. Several large-scale confirmatory tests were done supporting PI doses with the high degree of confidence necessary to gain regulatory approval of the treatments. Several new generic doses are supported by these articles, including generic doses for Lepidoptera (moths and butterflies), Pseudococcidae (mealybugs), and Curculionidae (weevils).

Key Words: dosimetry; large-scale confirmatory testing; quarantine treatment; radiation; phytosanitation; generic treatments

Resumen

Esta publicación especial de la Florida Entomologist presenta los logros del Proyecto Coordinado de Investigación (PCI): "Desarrollo de Dosis Genéricas de Irradiación para Tratamientos de Cuarentena" del Programa Junto de la Organización de Alimentos y Agricultura/ Organismo Internacional de la Energía Atómica sobre las Técnicas Nucleares en la Alimentación y la Agricultura. El objetivo fundamental fue desarrollar tratamientos genéricos fitosanitarios de irradiación (FI) para grupos de especies de plagas fitosanitarias regulados. Los tratamientos genéricos son aplicables a los grupos de especies de plagas reguladas aunque las investigaciones específicas pertinentes se ha hecho solamente para una fracción de ellos. Se inculcaron las buenas prácticas de investigación en los participantes para evitar los problemas que se produjeron con la investigación previa, como la dosimetría inadecuada, el uso de técnicas de infestación artificial y sin comparación con situaciones del mundo real, los malos resultados de los controles no irradiados, y la falta de una escala mayor de pruebas de confirmación. Se generaron nuevos datos sobre 34 especies en 10 familias de insectos, 3 familias de ácaros y una familia de caracol. Se realizaron varias pruebas confirmatorias a mayor escala que apoyaron la dosis FI con el alto grado de confianza necesario para obtener la aprobación reglamentaria de los tratamientos. Varias nuevas dosis genéricas son apoyadas por estos artículos, incluyendo las dosis genéricas para los Lepidoptera (mariposas y polillas), Pseudococcidae (cochinillas), y Curculionidae (gorgojos).

Palabras Clave: dosimetría; pruebas de confirmación a gran escala; tratamiento de cuarentena; radiación; fitosanidad; tratamientos genéricos

This special issue of Florida Entomologist presents the main accomplishments of the Coordinated Research Project (CRP) *Development of Generic Irradiation Doses for Quarantine Treatments* of the Joint Food and Agricultural Organization/International Atomic Energy Agency Programme on Nuclear Techniques in Food and Agriculture (FAO/IAEA 2016). The overarching objective of this CRP was to develop generic phytosanitary irradiation (PI) treatment doses for groups of regulated pests in international trade.

Irradiation is one of the newest phytosanitary measures used to prevent the introduction or spread of regulated pests. One of the characteristics of phytosanitary irradiation (PI) is that—unlike all other commercially used treatments—the effectiveness of irradiation against treated pest species is not measured solely on the basis of acute mortality, but also on preventing the successful development of the life stages—e.g., nonemergence of adults when larvae are irradiated—or the inability to reproduce—e.g., reproductive sterility of irradiated adults as when irradiated females lay eggs that hatch but these F_1 neonates die. The acceptance of live—but non-viable—pests during the inspection process was a paradigm shift for inspectors. Since the International Plant Protection Convention (IPPC) approved Guidelines for the Use of Irradiation as a Phytosanitary Measure (ISPM No. 18; IPPC 2003), enough commercial experience has been gained to confirm the efficacy and utility of PI, which is based on compliance with a whole process rather than only on a final inspection.

The PI technique is based on a solid scientific foundation resulting in great part from the 4 CRPs conducted since 1981 by the Joint Food and Agricultural Organization/International Atomic Energy Agency Program on

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Nuclear Techniques in Food Program through its Joint FAO-IAEA Division of Nuclear Techniques in Food and Agriculture. The FAO and IAEA had a pivotal role in the research that helped establish the 16 PI standards that are annexed to the IPPC International Standard on Phytosanitary Treatments for Regulated Pests (ISPM 28) and played the determining role for 6 of them: phytosanitary treatments (PT) numbers 1, 2, 3, 6, 14, and 19 (Table 1). For example, a recently adopted PT (19) was based on the research of Doan et al. (2012; 2016), who took part in the latest CRP.

Research on specific pest species or groups was conducted at institutions in various countries using practices that were adequate for the robust determination of treatment doses necessary for PI, including accurate, traceable dosimetry, acceptable pest-rearing methods and precise determinations of efficacy. Research to support irradiation treatment doses was central to the collaborative efforts, but efficacy under commercial conditions of oxygen stress, whether intentional or passive, was also tested for certain applications, as was the tolerance of specific commodities to irradiation treatment under various commercial conditions.

The papers published in this special issue of the *Florida Entomologist* present results obtained in the framework of this CRP during which 34 different pest species belonging to 10 families of insects, 3 families of mites, and 1 family of snails were studied. Confirmatory tests with very large numbers of insects were carried out for 13 insect species to validate treatment efficacy at statistical confidence levels commonly accepted internationally for phytosanitary security. Several generic and species-specific treatments have been developed by this coordinated research effort and will be submitted in response to the next IPPC call for treatment proposals.

Currently, virtually all commercial applications make use of generic PI treatments; i.e., treatments that apply for groups of pests and commodities (Hallman 2012). However, currently there are ~one million living arthropod species known to science, and the actual number has been estimated to be 2–30 million (Smithsonian Institution 2016). However, only a small fraction of these species are pests. Schwartz & Klassen (1991) stated: “It is generally assumed that there are more than 10,000 pest insects that cause losses. About 600 species are serious enough to warrant control measures each year…”. However in a fairly comprehensive book on destructive and useful insects in the USA, Metcalf et al. (1962) described ~1,400 pest arthropod species. Thus it seems likely that the estimate of 10,000 arthropod pest species cited above is too great and that the number in the world is roughly 2,000–3,000 species of which some are minor or sporadic pests and roughly 1,000 warrant control measures each year. A relevant variable is that the severity of damage caused by a pest species may vary greatly depending on local ecological factors. Many species cause little or no damage in the regions of their origins, but when transported to another continent or region they may present as very damaging. This phenomenon has been documented for many “adventive” or “invasive” species, whose intercontinental movement was facilitated by the surge in trade and tourism particularly since the Uruguay round of the General Agreement on Tariffs and Trade liberalized trade in agricultural and numerous other products (Klassen et al. 2002; Hulme 2009).

Also the number of food, feed, forestry and ornamental plant products traded commercially that are subject to attack by arthropods is large. Markle et al. (1998) described 691 food and feed crops that are traded in the USA; and tropical plant products are imported to augment domestic production, while temperate fruits are imported from the southern Hemisphere during the northern winter. It seems likely that perishable products derived from 1,500–2,000 plant species in the world are commercially significant and subject to attack by arthropods. Therefore, researching PI treatments against all insects and determining the radiation tolerance of all fresh commodities would be extremely time-consuming. However, research has generated a significant amount of literature in this area and a pragmatic approach has been used to propose generic PI treatments, some of which have been accepted for commercial trade within or between countries, and some of which have been accepted internationally e.g. the generic PI treatment for fruit flies of the family Tephritidae (IPPC 2007, Annex 7).

Generic treatments are not available for all pest groups of regulatory importance but they would be very useful. In addition, the growing volume of PI literature indicates that some of the accepted treatment doses may be larger than needed to ensure phytosanitary security. Research presented in this special issue was part of an international collaborative project directed at developing minimum doses for different pest species so that new species specific treatments—and more importantly, new generic treatments—could be established for various groups of pests. This approach has also provided additional support for treatment doses for existing generic PI treatments.

Commercial Use of Phytosanitary Irradiation

The number of irradiation facilities being established to provide PI on a commercial basis is increasing steadily, as is the number of countries involved in the export and import of produce irradiated for phytosanitary purposes. A brief summary of the experience of each country follows.

Table 1. List of radiation treatment annexes of ISPM 28: 2007.

Annex 01	PT 1 (2009):Irradiation treatment for *Anastrepha ludens*
Annex 02	PT 2 (2009): Irradiation treatment for *Anastrepha obliqua*
Annex 03	PT 3 (2009): Irradiation treatment for *Anastrepha serpentina*
Annex 04	PT 4 (2009): Irradiation treatment for *Bactrocera jarvisi*
Annex 05	PT 5 (2009): Irradiation treatment for *Bactrocera tryoni*
Annex 06	PT 6 (2009): Irradiation treatment for *Cydia pomonella*
Annex 07	PT 7 (2009): Irradiation treatment for fruit flies of the family Tephritidae (generic)
Annex 08	PT 8 (2009): Irradiation treatment for *Rhagoletis pomonella*
Annex 09	PT 9 (2010): Irradiation treatment for *Conotrachelus nenuphar*
Annex 10	PT 10 (2010): Irradiation treatment for *Grapholita molesta*
Annex 11	PT 11 (2010): Irradiation treatment for *Grapholita molesta* under hypoxia
Annex 12	PT 12 (2011): Irradiation treatment for *Cylas formicarius elegantulus*
Annex 13	PT 13 (2011): Irradiation treatment for *Euscepes postfasciatus*
Annex 14	PT 14 (2011): Irradiation treatment for *Ceratitis capitata*
Annex 19	PT 19 (2015):Irradiation treatment for *Dysmicoccus neobrevipes, Planococcus lilacinus* and *Planococcus minor*
Annex 20	PT 20 (2016): Irradiation treatment for *Ostrinia nubilalis*

AUSTRALIA

The first commercial trade between 2 countries of fresh produce irradiated for phytosanitary purposes was in late 2004 when Australia exported 19 t of irradiated mango (*Mangifera indica* L.; Sapindales: Anacardiaceae) to New Zealand. Volumes and types of fruits irradiated in Australia and exported to New Zealand steadily increased, and during the 2014-15 season the total volume of irradiated fruit was 988 t of mango, 430 t of tomato (*Lycopersicon esculentum* Mill.; Solanales: Solanaceae), 28 t of capsicum (*Capsicum* spp. L.; Solanales: Solanaceae), and 34 t of lychee (*Litchi chinensis* Sonn.; Sapindales: Sapindaceae).

Some 10 yr later shipments from Australia to the USA commenced, following the certification by the United States Department of Agriculture-Animal and Plant Health Inspection Service (USDA-APHIS) of the Steritech gamma irradiation plant located near Brisbane. The first shipments of Australian irradiated mango to the USA took place in Feb 2015. In mid-2015 there was also a first shipment of irradiated mandarin orange from Australia to Viet Nam. Since 2013, mango and capsicum from Queensland (28 and 26 t in 2012-13 and 2013-14, respectively) have been shipped to and marketed in fruit fly-free states of Australia following a ban on the insecticides, dimethoate and fenthion, which had been applied as postharvest phytosanitary treatments. In 2015, 28 t of table grapes [*Vitis vinifera* L. (Vitales: Vitaceae), 4 t of cherry (*Prunus avium* L.; Rosales: Rosaceae) and 2 t of plum (*Prunus* spp.; Rosaceae: Rosales) fruits irradiated in Australia were exported to Indonesia as part of trial shipments (Lynch & Nalder 2015). Australia also shipped 35 t of irradiated mango to Malaysia and this has continued in 2016. Viet Nam also received irradiated grape from Australia in early 2016.

P. R. CHINA

A large electron beam facility for PI with a treatment capacity of 100,000 tons per yr has been built in Pinxiang, Guanxi, P. R. China. It will irradiate imported fresh commodities from neighboring Viet Nam and other countries.

DOMINICAN REPUBLIC

In 2016 the Dominican Republic became the latest country to use PI to quickly solve a new phytosanitary problem after a Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), infestation resulted in a quarantine of fruits in the country. Mangoes were shipped to the Gateway America facility in Gulfport, Mississippi for PI and distribution to markets in the USA.

INDIA

Originally developed as a pilot facility to irradiate fresh agricultural products such as onion and potato, the Krushak Gamma Irradiation Centre in Lasalgaon has irradiated mango for export to the USA since 2007 (157 t). This comprised the first import by the USA of fruit irradiated for phytosanitary purposes in a foreign country (Hallman 2011). The exported quantity of irradiated mango in India has remained stable between 200–300 t most yr although it rose to 328 t in 2015 (Eustice 2016). This volume might significantly increase in future because of plans in India to build new irradiators that are nearer to large scale mango production areas.

MALAYSIA

In Aug 2015, the USDA announced amendments to USA fruit and vegetable regulations to allow the importation of fresh carambola (star fruit) (*Averrhoa carambola* L.; Oxalidales: Oxalidaceae), jackfruit (*Artocarpus heterophyllus* Lam.; Rosales: Moraceae), papaya (*Carica papaya* L.; Brassicales: Caricaceae), pineapple (*Ananas comosus* (L.) Merr.; Poales: Bromeliaceae), and rambutan (*Nephelium lappaceum* L.; Sapindales: Sapindaceae) fruits from Malaysia to the continental USA under the condition that they would be imported in commercial consignments and irradiated with a minimum dose of 400 Gy (USDA 2016) soon after arrival in the USA. The first trial shipments are expected in 2016.

MEXICO

In late 2007 Mexico and the United States signed agreements on PI treatments of fresh produce for export from Mexico. This country has since become the largest exporter of fruits irradiated for phytosanitary purposes and all of these irradiated products are exported to the USA (Table 2). There are 2 facilities that perform PI of fresh fruits. The main one is the Benebión Gamma Irradiation Facility near Matehuala, built for food irradiation and designed for PI treatments. The second plant is the Sterigenics-owned multipurpose gamma facility near Mexico City, which also irradiates non-food commodities, such as single-use medical devices.

The US Government allows irradiated carambola, fig, grapefruit, guava, mango, manzano pepper, pitahaya/pitaya, pomegranate, sweet lime, sweet orange, tangelo, and tangerine/mandarin orange to be imported into the USA (USDA 2016). All of these fruits except guava are irradiated with 150 Gy against tephritid fruit flies; guava fruits are irradiated with 400 Gy because other pests besides tephritid fruit flies are

Table 2. Quantities (t) of irradiated produce marketed in the continental USA.[1, 2]

Year	Origin						Total
	India	Mexico	South Africa	Thailand	Viet Nam	Hawaii	
2007	157	0	0	195	0	3,823	4,175
2008	276	262	0	2,440	121	3,915	7,014
2009	132	3,559	0	2,247	117	3,324	9,379
2010	94	5,672	0	1,540	754	5,746	13,806
2011	80	5,539	0	743	1,445	6,220	14,027
2012	217.5	8,349.5	16.5	937.5	1,764.5	4,296	15,581
2013	283	9,526	16.5	1,060.5	1,967.5	6,000[3]	18,853[3]
2014	265	10,119.5	0	843	2,293	6,500[3]	20,020[3]
Main product	Mango	Guava	Grapes	Longan	Dragon fruit	Sweet potato	

[1]Does not include quantities treated upon entry into the USA mainland.
[2]Data from Jeffers (2015a) and Food Irradiation (2015).
[3]Estimates include the new Pa'ina Hawaii facility.

considered to follow the guava phytosanitary pathway. The first irradiated mango fruit was shipped in Nov 2008, but today guava comprises the great majority of irradiated fruit shipments. In Jul 2015, the first shipments of figs to the US took place (Eustice 2016).

In 2015 Mexico received its first consignment of fruit irradiated (250 Gy) for phytosanitary purposes in the USA, i.e., peach (*Prunus persica* (L.) Batsch var. *persica;* Rosales: Rosaceae) from South Carolina and Georgia. More peach fruit is likely to be imported by Mexico during the 2016 season.

NEW ZEALAND

New Zealand was the first country to import fruit irradiated for phytosanitary purposes from another country (Australia). After the USA, New Zealand is currently the second largest market for irradiated produce. The first shipment took place in late 2004 when New Zealand imported 19 t of irradiated mango from Australia, and such trade has increased steadily to reach a total of 1,480 t during the 2014–2015 season. In 2014–2015 trade in irradiated tomato (430 t) and capsicum (28 t) from Australia commenced.

PAKISTAN

Over the past few yr, modest volumes of mango from Pakistan have been shipped to the USA and irradiated (400 Gy for scale insects and fruit flies) on arrival with electron beam technology. In 2014 and 2015, respectively, 14 and 85 t was irradiated.

In 2015, Australia amended its import regulations to enable the importation into Australia of fresh mango from Pakistan after irradiation with 400 Gy for fruit flies and mealybugs. This requirement was imposed by Australia as a condition for lifting its ban on fresh mango imports because of the presence of these pests in previous shipments.

PERU

Peru will begin shipping figs and pomegranates to the Gateway America PI facility in Gulfport, Mississippi for irradiation and distribution in the USA in 2016.

SOUTH AFRICA

Since 2012, small volumes of table grape have been irradiated at the gamma facility of HEPRO near Cape Town. The quantity doubled from 13 t in 2012 to 26 t in 2014. In 2014, persimmon (*Diospyros* spp.; Ericales: Ebenaceae) fruits were shipped to the USA and irradiated on arrival, and in 2015, the first shipment of South African lychee was irradiated on arrival in the US (Eustice 2016).

THAILAND

Being well equipped with irradiation facilities, Thailand was an early adopter of PI to boost exports of various tropical fruits, i.e., longan (*Dimocarpus longan* Lour.; Sapindales: Sapindaceae), mango, mangosteen (*Garcinia mangostana* L.; Malpighiales: Clusiaceae), and rambutan—all irradiated with 400 Gy—to the USA. Initially 195 t were shipped in 2007. The volume of trade reached 2,244 t in 2008 but subsequently trended downward to 843 t in 2014 (Jeffers 2015a).

UNITED STATES OF AMERICA

Commercial trade in phytosanitary irradiated commodities began in the USA. The first commercial uses of PI were 1 load of mango irradiated in Puerto Rico and sold in Florida in 1986 followed by a load of papayas irradiated in Hawaii and sold in California in 1987 (Hallman 2011). In 1995 the first continuous use of commercial PI began when fruit began to be shipped from Hawaii to be irradiated on the USA mainland and sold in commercial markets (Moy & Wong 2002). In 1999 guava began to be irradiated in Florida for shipment to other states followed by sweet potato and other fruits in subsequent yr. In 2000 an X-ray facility became operational in Hawaii to treat papaya and other tropical fruits that were shipped for sale in mainland USA; consequently the shipment of non-irradiated fruit to be processed on the mainland ceased. In 2014 that facility was responsible for irradiating approximately 6,500 t for shipment to mainland USA, mostly sweet potato.

In the period of 8 yr, from 2007 to 2014, the quantity of irradiated produce available on the US market has increased 5-fold to reach at least 20,000 t in 2014, half of which originated from Mexico (mostly guava), as shown in Table 2. Irradiation takes place outside of the USA for the vast majority of this irradiated fresh produce, but there are still small volumes being irradiated upon entry at USA ports. The USDA has 4 PI programs; (i) Preclearance (“offshore” irradiation at facilities outside of USA but dedicated to US imports); (ii) Port of Entry (fresh and suitably packaged imported commodities are irradiated soon after arrival in the USA); (iii) Domestic Quarantine (irradiation treatment for the domestic movement of commodities across quarantine boundaries, e.g. from Hawaii to the mainland), and; (iv) Exports , i.e., irradiation of fresh produce at facilities in the USA but for export of perishable commodities to another country.

In addition, PI has been used as a control measure to contain outbreaks of pests in the USA. For example in 2003, grapefruit and mandarin orange produced in a quarantined area in San Diego County, California were irradiated for shipment out of the area until the infestation of the Mexican fruit fly, *Anastrepha ludens* (Loew) (Diptera: Tephritidae), had been eradicated and PI was no longer necessary. More recently an outbreak of the oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), was discovered in southern Florida in Aug 2015, and small quantities of fresh produce were irradiated at a facility in Mississippi. Irradiation was also used on a consignment of infested dragon fruits (Harris 2015).

VIET NAM

Viet Nam has 2 facilities that have been used to irradiate fresh produce for export to the USA. The first shipments of irradiated dragon fruit to the US took place in 2008 when a total of 121 t was traded. In 2014, the volume reached 2,293 t (Jeffers 2015b). Recently authorities in both the USA and Australia approved irradiation as a phytosanitary treatment for lychee from Viet Nam. A first shipment of 2 t was sent to the US in May 2015 and other shipments amounting to 16 t were sent to Australia in Jun 2015 (Eustice 2016).

Irradiation Facilities

There are currently at least 13 irradiation facilities that regularly irradiate food for phytosanitary purposes (Table 3). All have been approved by the appropriate regulatory bodies including NPPOs (National Plant Protection Organizations). Ten of these facilities are multipurpose centers offering radiation processing services to food and non-food industries (e.g., food commodities and non-food commodities such as medical devices, pharmaceuticals and cosmetics). Food can be irradiated by 3 types of ionizing radiation: gamma rays, electron beams or X rays. Gamma irradiation facilities commonly use cobalt-60 as their source of ionizing radiation. The low doses and the even dose distribu-

Table 3. Phytosanitary irradiation facilities in the world in 2015.

	Country	Name
	Multipurpose service centers	
Gamma ray	Australia	Steritech
	Mexico	Sterigenics
	South Africa	Hepro
	Thailand	Thai Irradiation Center
		Synergy Health
	USA (Florida)	Sterigenics*
	Vietnam	An Phu
Electron beam	USA (Texas)	National Center for Electron Beam Research
	USA (Iowa)	Sadex
	Vietnam	Son-Son*
	Specialized food irradiation service centers	
Gamma ray	India	Krushak
	Mexico	Benebion
	USA (Hawaii)	Pa'ina
	USA (Mississippi)	Gateway America
Electron beam	P. R. China	Pinxiang*
X-ray	USA (Hawaii)	Calavo Growers, Inc.

*Currently not doing PI.

tion that PI requires can pose challenges to large scale multipurpose facilities especially those primarily designed to deliver larger doses to efficiently sterilize medical products. PI is easier to apply in gamma irradiators that have been designed for low (< 1 kGy) to medium dose (1–10 kGy) applications.

Gamma irradiation is the predominant technology in commercial use. Gamma rays can penetrate large bulky materials. Gamma irradiation is, therefore, suited to treating full pallet loads of products and delivering treatment doses that remain below a regulatory or technically-required maximum dose, while still ensuring that all parts of the product receive at least the minimum dose necessary to achieve the phytosanitary purpose.

Electron beam irradiation is offered in 4 of the facilities listed in Table 3. In contrast to gamma rays, accelerated electrons have relatively limited penetration, but depending on the depth of penetration required, electron energies can be varied from the keV to the MeV range, with 10 MeV being the highest permitted energy level. The comparative advantage of electron beam irradiation is that it the desired dose is achieved with extreme rapidity. Large pallets of products cannot be irradiated in 1 operation, and individual packages of commodities (with dimensions of typically of 10 cm each) must pass through the electron beam. However the technology offers the advantage of the radiation being electrically generated; electron beams can be switched off and do not present any radioactive hazard.

X-ray irradiation combines advantages of gamma irradiation (can be used to irradiate whole pallets at once) and electron beam irradiation (electrically generated). However—unlike the very energy efficient generation of an electron beam—the conversion of electrical energy into x rays is inefficient, with > 90% of the energy dissipated as heat. The increase in energy level permitted for X ray irradiation of food from 5 to 7.5 MeV, as currently permitted in the USA, would increase the efficiency of the process. Although there are few X ray facilities, 1 commercial X ray facility located in Hawaii irradiates produce at 5 MeV. Moosekian et al (2012) described the renewed interest in X ray irradiation and, although these authors focused on microbial aspects, X ray irradiation is also highly suitable for PI and is expected to be exploited to a greater extent in the future.

Given the unabated growth in the use of PI, several manufacturers of irradiation equipment have begun to adapt their machines to this particular application. For example, a double electron accelerator dedicated to PI has been recently finished in Pingxian, P. R. China, next to the border with Viet Nam which will irradiate fresh produce to be imported by P. R. China from Viet Nam and neighboring countries (Hénon 2014).

Few commercial irradiation facilities have been designed and located solely to serve the food trade. Most multipurpose facilities are built in an optimum location for irradiating a broad range of goods but not necessarily in the ideal places for fruit and vegetable growers and traders. Therefore, food producers and traders may be reticent to ship their product to a distant specialized contractor, especially if the perishable commodity has a short product life (e.g., ripe fruit) and additional transportation and treatment costs are required. A wide adoption of PI will therefore depend on the availability of affordable irradiation devices that can be located in or near fruit and vegetable packing houses or at locations where trade in fresh produce is concentrated (e.g., major ports) in the same way that other phytosanitary treatment facilities—such as hot water treatment tanks, cold storage facilities, and fumigation chambers—are purposely located for logistical and commercial reasons. Ultimately, the ideal solution would be to integrate PI technology into individual packing houses. This solution would allow full control by the packer and minimize time between harvest, packing, irradiation, and shipment, while containing costs and minimizing losses.

International Standards

In 1993 the European and Mediterranean Plant Protection Organization was the first international plant protection organization to approve PI treatments against several species of arthropods on fresh commodities (cut flowers), although this approval was never used and was rescinded in 2011 (EPPO 1993; 2016).

In Apr 2003, the publication by the IPPC of "International Standard for Phytosanitary Measure No. 18, Guidelines for the Use of Irradiation as a Phytosanitary Measure" (IPPC 2003) gave impetus to the worldwide interest in PI. This standard contains requirements such as the necessity to demonstrate the efficacy of the treatment, the need for dosimetry and dose mapping to ensure that the treatment is effective in the irradiation facility, the obligation for the NPPO to ensure that facilities are appropriately designed and that procedures are in place to conduct treatment with adequate record keeping and documentation. The last prescriptive part of the standard is an annex with a checklist for facility approval. Since this latter aspect is critical, it was the object of the Regional Standard for Phytosanitary Measure (RSPM) No. 9 "Approval of Irradiation Facilities" published by the Asia and Pacific Plant Protection Commission (APPPC) (FAO 2014). This new regional standard was largely based on the "Guidelines for the Audit and Accreditation of Irradiation Facilities used for Sanitary and Phytosanitary Treatment of Food and Agricultural Products". The latter guidelines were developed through an IAEA Regional Technical Cooperation project. The Codex Alimentarius Commission provided a general standard for irradiated food (FAO 2003b) and an international code of practice for facilities that irradiate food (FAO 2003a). Because of this overlap, both the ISPM No. 18 and the Codex requirements were incorporated into the RSPM No. 9 (FAO 2014).

ISPM No. 28 "Phytosanitary Treatments for Regulated Pests" (IPPC 2007) describes the requirements for submission and evaluation of the efficacy data and other relevant information for proposed phytosanitary treatments. One of the main purposes of this standard is international harmonization in order to enhance the mutual recognition of treatment efficacy by NPPOs and to facilitate trade. The particular phytosanitary treatments are provided in the annexes of ISPM No. 28, and are available in several languages. Treatments are added as annexes after they have been reviewed by the IPPC Technical Panel on Phytosanitary Treatments and officially adopted by the IPPC; and by July 2016 there were 21 such annexes and 16 were PI treatments (Table 1).

Regulations

In the USA, irradiation for disinfestation of arthropod pests in fresh commodities has been permitted by the Food and Drug Administration (FDA) since 1986 (FDA 1986). The maximum dose was set at 1 kGy though irradiation of food up to 10 kGy or even beyond 10 kGy for a stated technological purpose is regarded as safe (WHO 1999). Later, the FDA permitted the irradiation of fresh lettuce and spinach up to 4 kGy to control of foodborne pathogens and extend shelf-life (FDA 2008). This upper limit of 1 kGy has also been adopted in Australia for PI (FSANZ 2016).

In the USA the rule, "Irradiation Phytosanitary Treatment of Imported Fruits and Vegetables" (USDA 2002), has played an important role in facilitating the commercial development of PI. A subsequent rule established most of the PI doses currently accepted by the USA, including the generic dose of 400 Gy for all insects except the pupae and adults of Lepidoptera (USDA 2006), which is the PI dose used on the vast majority of shipments of irradiated produce.

In the European Union (EU) a framework Directive of 1999 set out the conditions for regulating food irradiation in EU member countries and described 4 purposes for which food irradiation may be used commercially; one being "to rid foodstuffs of organisms harmful to plant or plant products" (Anon 1999a). The implementing Directive (Anon 1999b), on the establishment of a European Community list of foods and food ingredients treated with ionizing radiation, would establish a list of foodstuffs authorized for commercial irradiation within the EU, but this list of foodstuffs has not yet issued. To date the Directive only includes dried aromatic herbs, spices and vegetable seasonings. Until the implementing Directive has issued, EU Member States may maintain existing authorizations concerning the treatment of foodstuffs in accordance with the implementing Directive.

Doses

The research to develop PI treatments and also the correct application of commercial PI depends on the ability of the research group or processor to: (a) measure the absorbed dose delivered to the sample / commodity, (b) determine the dose distribution patterns in the sample /product, and; (c) successfully monitor and control the routine radiation process. Each of these requirements relies on dosimetry; the measurement of absorbed dose. The essential process control parameter is the absorbed radiation dose, i.e., the quantity of energy (joules) imparted per unit mass (kilogram) and measured in grays (Gy). The product density affects the dose distribution and this is why dose mapping is used to determine the dose distribution and the minimum dose for a specific product density (e.g., carton of a fruit cultivar). Other factors, such as temperature, pressure and rate of application of dose, which may be regulated in other phytosanitary treatments, are not considered to affect the efficacy of PI. Therefore PI is easier to apply than most other treatments.

One external factor that must be considered is the oxygen content (i.e., molecular oxygen storage atmosphere or modified atmosphere packaging) of the commodities at the moment of irradiation, because the efficacy of PI is proportional to the molecular oxygen content. If a commodity is processed at low oxygen levels, it may require a greater irradiation dose than a commodity at the ambient oxygen level. The IPPC does not permit PI of commodities under low oxygen conditions unless research has established the efficacy of the irradiation dose under the same conditions. For example, Table 1 lists 2 PI treatments for *Grapholita molesta* Busck (Lepidoptera: Tortricidae), one is under the normal ambient atmosphere (20.95% oxygen) and the second is under hypoxia. It should also be noted that the USDA does not permit PI with oxygen partial pressures below 18 kPa—the partial pressure of oxygen in ambient normal air is 21 kPa.

GENERIC DOSES

PI is unique among phytosanitary treatments in its breadth of application. Most countries accept as established fact that the host commodity has little effect on the minimum efficacious dose and all PI treatments accepted by the IPPC (2007) are applicable to all species of fruits and vegetables. In practice, few commercial PI treatments target a single pest species but deliver the dose required to control the most resistant species of the pest species expected to be present on or in the commodity, because this dose will control all of the pest species that may infest the fruit or vegetable sample. This approach could be expanded further if more generic doses were developed like the 150 and 400 Gy treatments mentioned above. All 182 parties to the IPPC accept a dose of 150 Gy as the effective generic treatment against all Tephritidae species, and although all the parties to the convention have yet to agree, several including USA and those PI trading partners that allow PI accept a generic dose of 400 Gy against all insects except the pupae and adults of Lepidoptera.

Australia and New Zealand, like the USA, specify a minimum dose of 400 Gy against all insects except the pupae and adults of Lepidoptera as a biosecurity measure for imports of fresh commodities, but—unlike the USA—they also accept a minimum dose of 400 Gy against mites of the family Tetranychidae (MPI 2016). Furthermore, Australia and New Zealand do not allow PI as a technique against arthropods species that vector plant pathogens. Although PI prevents further development or reproduction of insects, a treatment dose of 400 Gy has not been shown to prevent disease transmission before the insect vectors die. In contrast, the USA does not exclude vector species.

The authorities in Australia and New Zealand maintain a regulatory list of fruits and vegetables that may be treated with irradiation, and allow commodities to be added on a case by case basis through a process of approval. PI treatments at the time of writing can only be used on apple (*Malus domestica* L.; Rosales: Rosaceae), apricot (*Prunus armeniaca* L.; Rosales: Rosaceae), bread fruit (*Artocarpus altilis* (Parkinson) Fosberg; Rosales: Moraceae), capsicum, carambola (star fruit), cherry, custard apple (*Annona reticulata* L.; Magnoliales: Annonaceae), 'honeydew' melon (*Cucumis melo* L. cv. 'honeydew'; Cucurbitales: Cucurbitaceae), litchi (lychee), longan, mango, mangosteen, nectarine (*Prunus persica* var. *nucipersica* [Suckow] C. K. Schneid.; Rosales: Rosaceae), papaya (paw paw), peach, persimmon, plum, rambutan, rockmelon (cantaloupe) (*Cucumis melo* var. *cantalupensis* Naudin), 'scallopini' summer squash (*Cucurbita pepo* L var. *clypeata*), strawberry (*Fragaria* × *ananassa* Duchesne; Rosales: Rosaceae: Rosoideae), table grape, tomato, and zucchini (courgette) (*Cucurbita pepo* L.; Cucurbitales: Cucurbitaceae).

Other countries accept generic clearance for the broad commodity class of fruits and vegetables (e.g., USA) and some countries are changing their commodity-specific regulations to allow the irradiation of broad classes of food materials. For example, India is currently introducing broad food classes, such as "fresh fruits and vegetables" in place of naming specific commodities in its food irradiation regulations.

New Zealand is also applying other generic PI doses to imports. Thus, New Zealand has accepted a generic dose of 500 Gy as a PI treatment against mites besides the Tetranychidae. Also, New Zealand has accepted—for the importation of only lychee and mango—a generic dose of 250 Gy against regulated pests including a wide variety of species from the insect orders: Coleoptera, Diptera, Hemiptera, Lepidoptera, and Thysanoptera. Malaysia has accepted a generic 300 Gy dose for Australian mango imports, and this treatment includes many of the same regulated pests as for Australian mango shipped to New Zealand—including the mango seed weevil, *Sternochetus mangiferae* (F.) (Coleoptera: Curculionidae). The reason that this generic dose is 300 Gy for Malaysia instead of 250 Gy as adopted by New Zealand is because the mango seed weevil can become established in Malaysia but not in New Zealand where the climate does not support mango production. Hallman (2012) discussed why the treatment dose against mango seed weevil was set at 300 Gy and not at a smaller dose that would suffice.

New Generic Treatments

Several new generic doses are proposed in this special issue (Table 4). A generic dose of 250 Gy for the family Pseudococcidae supported by large-scale studies with several species is proposed by Hofmeyr et al. (2016a). The pseudococcids comprise the third most important taxonomic group of quarantine pests, after Tephritidae and Lepidoptera. There are commodities of which only tephritids and pseudococcids are regulated pests, so a generic dose of 250 Gy against Pseudococcidae would allow that dose to be used in all of these instances.

A generic dose of 150 Gy is proposed for weevils of the main weevil family Curculionidae (Hallman 2016b). This dose would allow mangoes from areas that harbor 1 or more of the weevil species that infest mangoes to be treated with 150 Gy instead of with either 300 or 400 Gy, as is presently the case.

Hallman et al. (2016b) concluded that the generic doses of 400 and 500 Gy for the Tetranychidae and all other mite families, respectively—as accepted by Australia and New Zealand (MPI 2016)—although not supported by large-scale confirmatory testing, are probably sufficiently great to be phytosanitarily safe. Moreover, with large-scale confirmatory testing it might be possible to lower those doses somewhat.

Hallman (2016a) argued that the 400 Gy generic dose for insects other than pupae and adults of Lepidoptera could be lowered to 300 Gy with only a negligible increase in the phytosanitary risk. This dose would still leave a respectable margin of security because an analysis by MPI (2016) as well as other research indicates that non-lepidopteran insects can be controlled with ~250 Gy. Data from Hallman (2016a) also indicated that doses of ~250 and 200 Gy, respectively, might suffice for the families Diaspididae (Hemiptera; armored scales) and Agromyzidae (Diptera; leaf-miner flies).

Research conducted under the auspices of this CRP contributed to the proposals of generic PI doses of 250 Gy for lepidopteran eggs and larvae and 400 Gy for lepidopteran pupae (Hallman et al. 2013a, b).

SPECIFIC DOSES

Phytosanitary irradiation doses developed in experiments for individual quarantine pest species can be used to derive generic dose treatments for the corresponding group of organisms in the taxonomic hierarchy. For example, Bustos et al. (2004) determined specific doses for 4 species of the Tephritidae, and all 4 supported a generic dose of 150 Gy for that dipteran family.

Although the emphasis of the CRP as reported in this special issue is on generic doses, much of the research conducted can be used to support specific doses that could be used where only those species are present on commodities as regulated pests. Table 5 lists the pest species that were studied and presents the doses of irradiation found to meet the phytosanitary import requirements of each of these species. The dose given in the table is the lowest dose that achieved the measure of efficacy given in the table for all of the organisms irradiated at that dose. Where doses are associated with large numbers of treated organisms there is considerable confidence that the dose would serve

Table 4. Newly proposed generic dose treatments.

Treatment description	Minimum PI dose/Gy	Reference
Generic treatment for weevils of the main weevil family Curculionidae	150	Hallman 2016b
Generic dose for the family Agromyzidae	200	Hallman 2016a
Generic treatment for the family Pseudococcidae (mealybugs)	250	Hofmeyr et al. 2016a
Generic dose for the family Diaspididae	~250	Hallman 2016a
Generic PI dose for eggs and larvae of Lepidoptera	250	Hallman et al. 2013a
Revised generic dose for insects other than pupa and adult Lepidoptera (proposed to lower from 400 Gy)	300	Hallman 2016a
Generic treatment against mites of the family Tetranychidae	400	Hallman et al. 2016b MPI 2015
Generic PI doses for pupae of Lepidoptera	400	Hallman et al. 2013b
Generic treatment against all mites in addition to those of the family Tetranychidae (as accepted by Australia and New Zealand)	500	Hallman et al. 2016b MPI 2016

Table 5. Pest species that were studied in the Coordinated Research Project on "Development of Generic Irradiation Doses for Quarantine Treatments", 2009-2014, and the doses of radiation found to meet the phytosanitary import requirements of each of these species. Details are presented in the referenced articles.

Order Family	Genus species	Stage tested	Measure of efficacy: prevention of	Dose (Gy)	Number treated	Reference
Coleoptera						
Dermestidae	*Trogoderma granarium*	adult	F_1 progeny	100	102,700	Mansour 2016
Diptera						
Agromyzidae	*Liriomyza huidobrensis*	pharate adult	F_1 leaf mines	175	10,419	Ozyardimci et al. 2016
	Liriomyza sativa	pharate adult	F_1 leaf mines	174	10,583	Ozyardimci et al. 2016
	Liriomyza trifolii	pharate adult	F_1 leaf mines	166	10,280	Ozyardimci et al. 2016
Hemiptera						
Aleyrodidae	*Trialeurodes vaporariorum*	pharate adult	F_1 egg hatch	108	33,625	Van Nieuwenhove et al. 2016a
Diaspididae	*Aonidiella aurantii*	adult	F_1 1st instars	222	32,101	Khan et al. 2016b
	Aspidiotus destructor	adult	F_1 1st instars	224	51,101	Khan et al. 2016a
	Hemiberlesia lataniae	adult	F_1 1st instars	209	31,877	Van Nieuwenhove et al. 2016b
Pseudococcidae	*Dysmicoccus neobrevipes*	adult	F_1 2nd instars	231	31,750	Doan et al. 2016
	Exallomochlus hispidus	adult	F_1 progeny	120	200	Kuswadi et al. 2016
	Maconellicoccus hirsutus	adult	F_1 egg hatch	300	70	Seth et al. 2016a
	M. hirsutus	adult	F_1 adult emergence	100	70	Seth et al. 2016a
	M. hirsutus	adult	F_1 adult oviposition	60	70	Seth et al. 2016a
	Paracoccus marginatus	adult	F_1 egg hatch	200	70	Seth et al. 2016c
	P. marginatus	adult	F_1 adult emergence	70	70	Seth et al. 2016c
	P. marginatus	adult	F_1 adult oviposition	40	70	Seth et al. 2016c
	Phenacoccus solenopsis	adult	F_1 egg hatch	500	70	Seth et al. 2016b
	P. solenopsis	adult	F_1 2nd instars	200*	70	Seth et al. 2016b
	P. solenopsis	adult	F_1 adult emergence	100	70	Seth et al. 2016b
	P. solenopsis	adult	F_1 adult oviposition	70	70	Seth et al. 2016b
	Planococcus citri	adult	F_1 2nd instars	150	70,440	Hofmeyr et al. 2016c
	Planococcus ficus	adult	F_1 2nd instars	150	10,000	Hofmeyr et al. 2016c
	Planococcus lilacinus	adult	F_1 2nd instars	100	300	Doan et al. 2016
	Planococcus minor	adult	F_1 2nd instars	150	300	Doan et al. 2016
	Pseudococcus jackbeardsleyi	adult	F_1 2nd instars	150	167,810	Zhan et al. 2016
Liviidae	*Diaphorina citri*	adult	F_1 egg hatch	150	1,200	Hallman & Chapa 2016
Lepidoptera						
Crambidae	*Diatraea grandiosella*	pharate adult	F_1 2nd instars	300	6,075	Hallman et al. 2016a
	Diatraea saccharalis	last instar	adult emergence	75	108	Hallman et al. 2016a
	D. saccharalis	pharate adult	F_1 2nd instars	300	5,350	Hallman et al. 2016a
	Eoreuma loftini	last instar	adult emergence	161	59	Hallman et al. 2016a
	E. loftini	pharate adult	F_1 egg hatch	300	474	Hallman et al. 2016a
Noctuidae	*Grapholita molesta*	pharate adult	oviposition	300	40	Arthur et al. 2016b
	G. molesta	pharate adult	F_1 egg hatch	250	40	Arthur et al. 2016b
	Helicoverpa zea	last instar	adult emergence	166	2,197	Hallman 2016c
	Heliothis virescens	last instar	adult emergence	166	14,366	Hallman 2016c
	Spodoptera frugiperda	last instar	adult emergence	300	100	Arthur et al. 2016a

*Estimate from regression analysis; raw data not given.

Table 5. (Continued) Pest species that were studied in the Coordinated Research Project on "Development of Generic Irradiation Doses for Quarantine Treatments", 2009-2014, and the doses of radiation found to meet the phytosanitary import requirements of each of these species. Details are presented in the referenced articles.

Order Family	Genus species	Stage tested	Measure of efficacy: prevention of	Dose (Gy)	Number treated	Reference
	Trichoplusia ni	last instar	adult emergence	180	~60	Lopez-Martinez et al. 2016
	T. ni	pharate adult	F_1 egg hatch	400	~10	Lopez-Martinez et al. 2016
Tortricidae	*Thaumatotibia leucotreta*	last instar	adult emergence	150	3,200	Hofmeyr et al. 2016b
Sarcoptiformes						
Eriophyidae	*Aceria litchii*	adult	F_1 egg hatch	400	40	Arthur & Machi 2016
Trombidiformes						
Tenuipalpidae	*Brevipalpus phoenicis*	adult	F_1 egg hatch	300	210	Machi & Arthur 2016
Tetranychidae	*Tetranychus urticae*	adult	F_1 eggs	>200 <400	40	Arthur et al. 2016c
	T. urticae	adult	F_1 neonates	300	96	Machi et al. 2016
	Tetranychus desertorum		F_1 neonates	300	96	Machi et al. 2016
	Oligonychus ilicis		F_1 neonates	200	96	Machi et al. 2016
Stylommatophora						
Helicidae	*Cornu aspersum*	adult	F_1 egg hatch	75	757	Hallman 2016d

*Estimate from regression analysis; raw data not given.

as a PI treatment dose. However, it is possible that the effective dose could be smaller than that given; smaller doses may not have been assayed. Where small numbers of organisms—i.e., small in relation to the requirement of probit 9 level of security—were studied it is possible that a larger dose might be needed to achieve a high level of efficacy. Of course, it is also possible that a smaller dose may be efficacious if it has not already been shown to fail.

FACTORS THAT MAY AFFECT EFFICACY

Factors such as molecular oxygen content, temperature, dose rate, and host commodity have been hypothesized to affect the efficacy of PI with conflicting observations in the literature (Hallman et al. 2010). Among these factors, only the presence or absence of oxygen has been shown conclusively to impact PI treatment. Since ionizing radiation creates free radicals, high oxygen tension can enhance the effects of radiation; conversely when oxygen content is reduced, an intended level of efficacy may require a larger dose. Consequently, plant protection organizations only allow PI of commodities in low-oxygen atmospheres when adequate efficacy data for the treatment dose is available at the specified oxygen level (IPPC 2007; USDA 2016). Although some research has shown that this is not a problem for tephritid fruit flies (Hallman 2004; Follett et al. 2013) definitive research is needed to resolve this issue for this important group of quarantine pests. Also, Follett et al. (2013) did the research using larvae reared on diet and inserted into holes bored to the centers of papaya fruits, which introduced untested assumptions. Irradiation in hypoxic atmospheres seems to be a greater concern for quarantine pest species other than tephritids (Hallman & Hellmich 2010).

Dose rate has been hypothesized to affect PI efficacy; i.e., a faster dose rate leads to increased efficacy because it overwhelms radiation damage repair mechanisms (Hallman et al. 2010). Therefore, dose rate effects are of interest when electron beams are used in PI as they apply the dose much more quickly than cobalt-60 sources. The hypothetical risk is that PI doses determined using electron beam machines would be insufficient when applied in cobalt-60 facilities, and that doses determined with cobalt-60 machines would result in an increased risk of commodity damage when applied in electron beam facilities. Although data are still scarce, there is no evidence to date of these effects being significant at the dose rates used commercially.

Effects on fresh produce

Irradiation may deposit energy into the treated product in a non-uniform manner. To ensure that all parts of a load receive at least the minimum PI dose prescribed, some parts must receive doses of radiation that are much larger than the minimum. In certain cases, the dose uniformity ratio (DUR; maximum dose/minimum dose) can be as high as 3 or even 4. The DUR depends on factors such as the nature and energy of the radiation, the distance between the source and the load, and the dimensions and density of the load. Process loads that are large non-homogeneously assembled and that have non-uniform densities tend to have wide variations in their dose distributions, whereas homogenous loads of uniform densities have fairly uniform and symmetrical dose distributions.

Applying radiation to standard well-packed pallet loads is economical because large volumes of the commodity can be treated at once with minimum handling and risk of damage; however, the DURs for such loads are large and much of each load will receive considerably more dose than the minimum PI treatment dose. While this ensures that the product is correctly processed, it is desirable to limit the maximum dose as much as possible. Not only would this ensure that radiation energy is not being wasted, it also avoids the risk of affecting the quality of the produce in some undesirable way or of exceeding the legal maximum dose. Consequently, it is necessary to assess the effects on sensory quality of the highest doses that may be encountered in practice in a particular facility. For example an irradiator with a DUR of 3 that delivers a PI dose of 150 Gy would need to ensure that all parts of the consignment received at least 150 Gy and this would mean having to deliver 450 Gy to the part of the consignment that receives the maximum dose. Fortunately most fresh fruits and vegetables tolerate radiation better than they tolerate other commercial treatments (Heather & Hallman 2008). It is noteworthy that Ozyardimci et al. (2016) showed that irradiation with doses up to 1.0 kGy applied to shelled peas had only very limited effects on the content of vitamin C, total carotenoids, protein secondary structures, and sensory properties. Moreover the quality of irradiated lychees and mangoes is superior to the quality of either cold or heat-treated fruits, respectively. Irradiation is thus increasingly being used to assure premium quality fruit for consumers. The fact that a variety of fresh commodities have been subjected to commercial phytosanitary irradiation and yet marketed successfully implies that fresh commodities have broad tolerance of the relatively low doses of radiation required for phytosanitary irradiation.

There is abundant research showing the multiplicity of factors that affect the sensory impact of irradiation on fresh fruit and vegetables. As an example, the tolerance of citrus to low dose PI was shown to depend on dose, species, cultivar, and fruit maturity (Miller et al. 2000). Paradoxically, while Australia, Pakistan, and India are now shipping mangoes to the USA, Thailand has not been able to do so because of the unusual radiosensitivity of the 'Nam Dok Mai' variety, the most sought after cultivar of Thai mango.

Irradiation can retard the speed of ripening, and fruits that are commercially harvested before they are ready to be eaten, such as papaya, mango, and many other tropical fruits, may not ripen as quickly as non-irradiated fruit so it may be necessary to adapt harvesting schedules and procedures when using PI. In adjusting the harvesting of fruits and vegetables, it is important to clearly understand that some commodities have a climacteric phase when they produce large quantities of the ripening hormone, ethylene. Climacteric species include apple, apricot, avocado (*Persea americana* Mill.; Laurales: Lauraceae), banana, breadfruit, cherry, guava (*Psidium guajava* L.; Myrtales: Myrtaceae), jackfruit, kiwi (*Actinidia deliciosa* C. F. Liang & A. R. Ferguson; Ericales: Actinidiaceae), mango, papaya, peach, plum, sugar apple and tomato (Quisqualis 2016). In contrast non-climacteric fruits lack a ripening phase when substantial quantities of ethylene are produced, and they must have ripened on the plant by the time of harvest, because they tend not to ripen further after they have been harvested. Non-climacteric species include most capsicum cultivars, carambola, cashew (*Anacardium occidentale* L.; Sapindales: Anacardiaceae), citrus, grape, longan, lychee, melon, pineapple, strawberry and rambutan (Quisqualis 2016).

Delaying the harvest of the fruit or vegetable until it has reached an advanced stage of physiological maturity should ensure that the fruit or vegetable is ripe for the market. Indeed, a somewhat delayed harvest alone should result in improved quality. The fact that papaya, mango, and guava have been irradiated commercially in different countries for many yr while in the "mature-green" stage indicates the ability of these climacteric fruit species to tolerate PI and be delivered ripe for sale.

A comprehensive study of the effect of PI on nutritive quality of fruits and vegetables was conducted in Australia, which indicated that doses of ≤ 1 kGy do not present a safety or nutritional risk to consumers (FSANZ 2014). The only case for mild concern was the moderately reduced vitamin C content, which was observed in some cultivars of some fruit species after irradiation. However, in the majority of these cases the vitamin C content of irradiated fruit remained in the range of natural variation, and when the effects of these changes were compared to consumption patterns it was evident that the changes were unlikely to impact total dietary vitamin C intake.

Sensory evaluation can extend beyond the physical sciences and include consumer preference studies. A recent study by McDonald et al. (2012) showed that consumer liking of commercially irradiated peaches was not different from untreated peaches at 13–27 d after harvest, even though trained sensory evaluators and instrumental texture data showed a softening effect from irradiation at 0.9 kGy.

The Joint FAO/IAEA Programme on Nuclear Techniques in Food and Agriculture is developing an annotated database on tolerance of fresh commodities to ionizing radiation. This database will help facilitate international use of irradiation and related technologies, which may be used by industry to determine the feasibility of using PI (IAEA 2016).

Research Needs

Research is necessary to develop and validate generic PI treatments for pests not covered by the currently accepted treatments. Research is also needed to ensure that commercial PI treatments deliver the correct dose, but at levels not greatly in excess of the minimum required. For example, establishing 250 Gy (and not 400 Gy) as a generic dose for all insects except pupae and adults of Lepidoptera is an achievable goal, and this dose is small enough to remove the need to develop additional PI doses for subgroups or species within this major group. Hallman (2012) and the MPI (2015) indicate that 250 Gy seems adequate for all insects except pupae and adults of Lepidoptera, while not being large enough to create a serious obstacle to commercial implementation for the great majority of fresh commodities. Comparing the radio tolerance of a number of species of the same group and then carrying out large-scale confirmatory testing on the most tolerant one(s) is an approach that could accelerate the development of generic treatments.

Applied phytosanitary treatment research (as well as applied research in general) should be conducted in a manner as close to the natural setting for which it is designed to be applied in order to reduce the possibility of creating particular conditions that might affect efficacy. Hallman et al. (2010) discussed the approval process for PI treatments by the IPPC, and explained why some proposals were not accepted. These deficiencies include using artificial infestation of fruits with diet-reared insects and poor performance of the non-irradiated control.

The confidence in commercial PI is based on 3 pillars: (i) confidence in the research that supported the doses used, (i) confidence in the doses delivered in the irradiation facilities, and (iii) safeguarding after treatment. Phytosanitary irradiation does not have a post factum independent verification of efficacy as all other phytosanitary treatments do. If live insects are found in an irradiated consignment, it could certainly be useful to know if the insect was irradiated and even at what dose. The test would have to be irradiation specific, quick, and economical. The fact that such a test does not exist has not prevented PI from being successfully used for many yr. Certification of commercial application of PI is more rigorous than for any other phytosanitary treatment. The PI system that has been adopted gives a much higher level of confidence in the final result, and this confidence essentially removes the need for final inspection as a means of verifying adequate treatment application. This approach could serve as a model for other phytosanitary treatments (Hallman 2016c).

Conclusions

In generating the irradiation data and the manuscripts presented in this special issue the participants adhered to the following guidelines:

- Participants used research methodology shown to be appropriate in previous investigations that formed the bases of those PI treatment proposals that were accepted by the IPPC and avoided the mistakes in other proposals that were rejected by this body of experts (Hallman et al. 2010). In addition when conducting phytosanitary irradiation investigations, the participants gave greater consideration to the reproductive biology—and in some instances to the radiation biology—of the studied species than is required in investigating other phytosanitary treatments. This was so because invariably the goal was not acute mortality—as it is with all other phytosanitary treatments—but the prevention of further development and/or reproduction; this required enhanced entomological insights.
- A series of assumptions about the results being applicable to "real world" situations are made by researchers when applied research is conducted, some acknowledged but others not. In these phytosanitary investigations such assumptions had to be stated.
- The crucial importance of determining the dosimetry with methods that provide accuracy and precision was emphasized, because dosimetry was fundamental to establishing the treatment doses. Deficiencies or errors in determining dosimetry, or the failure to report the appropriate data would cause regulatory officials to question the validity of the treatments.
- The necessity to "finish the job" by conducting large-scale confirmatory tests was a high priority. As a result the PI doses for a number of the pest species studied were adequately supported and allowed generic doses to be proposed.
- Valid comparisons of irradiated cohorts with non-irradiated controls were fundamental to ensuring that the observed responses were due to radiation treatment and not to other factors. To serve as valid controls, the non-treated insects must develop and/or reproduce within normal expectations.
- Artificial rearing or infestation should be used only if it has been proven not to affect efficacy. Failure to meet this condition has resulted in the rejection of some proposed treatments (Hallman et al. 2010).
- Statistical analyses of the data used for estimating doses required for efficacy may not be as reliable as previously thought because the models tend to be imprecise at the extreme level of efficacy required of phytosanitary treatments (West & Hallman 2013). Therefore, large-scale confirmatory tests involving > 30,000 individual insects are needed to provide the necessary level of confidence in proposed treatment doses.
- It is well established that radiation tolerance increases as the development of an insect progresses through its life stages. Therefore, the most advanced developmental stage that can be present on/in the shipped commodity is the stage that should be tested in PI studies. Consequently, it is not necessary to assess the radiation tolerance of earlier developmental stages of the life cycle.
- The initial commercial applications of PI in the US and New Zealand benefited from the open-mindedness of food authorities who made science-based rules (Roberts & Hénon 2015). This early open-mindedness resulted in the regulatory flexibility that permitted the initially tentative commercial implementation of PI and its subsequent steady expansion in several different countries. This trend is expected to continue as PI can be used to overcome many present and future plant quarantine problems, and to stanch the global spread of inherently invasive pest species through commercial trade of perishable commodities.
- Finally, the participants in this CRP sought to identify the smallest efficacious doses for PI, not only because the use of small but efficacious doses reduces treatment costs, but also because it avoids negative effects on the nutritional qualities of irradiated fresh produce, plus unwanted changes in them of aroma, taste and "mouthfeel". Consequently to date there has been no significant adverse consumer reaction to the sale of irradiated fresh produce.

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