FORUM

Fifty Years of Radiation Biology in Entomology: Lessons Learned from IDIDAS

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ABSTRACT The purpose of the International Database on Insect Disinfestation and Sterilization (IDIDAS: http://www-ididas.iaea.org/ididas/) website is to collect and share information about radiation doses for disinfestation and reproductive sterilization of arthropods and to perform a comparative analysis and quality assurance check on existing data. IDIDAS was developed based on a literature review and analysis of >2,750 references, published during the past five decades. In total, 309 species of arthropods, mostly of economic importance, from 196 genera, 84 families, 9 insect orders, and 2 arachnid orders, have been subjected to irradiation studies for purposes of (1) research, such as sperm precedence determination and parasitoid-host interaction studies, (2) disinfestation for quarantine or phytosanitary purposes or (3) different pest control applications, including the sterile insect technique (SIT) and biological control programs. Sensitivity to radiation among families, and in particular orders, varies sometimes over two orders of magnitude, with Arctiidae and Pyralidae (Lepidoptera) being the most radioresistant, requiring the highest sterilizing doses (100–300 Gy), and Acrididae (Orthoptera) and Blaberidae (Dictyoptera) the lowest (<5 Gy). Within Diptera, Coleoptera and Hemiptera radiation doses vary widely among families and range from 20 to 200 Gy. Soft Acari species belonging to Ixodidae are more sensitive than hard species of Argasidae and Tetranychidae mites. In general, most insect, mite, and tick families require a sterilizing dose of <200 Gy. Analysis of data shows that, with few exceptions, generic doses of radiation apply to species within the same genus, and thus, there is generally no need to develop radiation biology data for all species. Although the objective of this database is to present the optimum dose for research, disinfestation, or sterilization at the species level, there is some inconsistency in the recorded doses resulting from variation in many factors affecting sensitivity to radiation. Thus, this review highlights the need for further efforts to standardize experimental dosimetry and irradiation procedures for arthropods and provides a suitable platform for guiding future research in this area.

KEY WORDS arthropods, irradiation, sterilization, disinfestation, sterile insect technique

APPLICATIONS OF IONIZING RADIATION in entomology have three main purposes: (1) disinfestation of commodities for quarantine and phytosanitary purposes (Heather 1993, Hallman 2000), (2) pest control applications, such as in autocidal control known as sterile insect technique (SIT) (Knipling 1979, Hendrichs 2000, Tan 2000, Vreysen 2001), and in support of augmentative and classical biological control programs (Greany and Carpenter 1999), and (3) research applications, such as studies on sperm-precedence determination (Retnakaran 1970, Draz 1991) or on physiological interactions in host–parasitoid systems (Soller and Lanzrein 1996, Hoch and Schopf 2001). During the last five decades, these applications have been reviewed by several authors (Evans 1962, Grosch 1962, IAEA 1963, 1965, 1967, 1969, O'Brien and Wolfe 1964, LaChance et al. 1967, Proverbs 1969, Willard and Cherry 1975, Hooper 1989, Heather 1993, Burditt 1994, Hallman 1999, 2000, Hallman and Loaharanu 2002). However, most of these reviews were limited to a selected few species, a group of insects, or were for a particular purpose.

Records of radiation doses for reproductive sterilization and disinfestation of arthropods are scattered in published and manuscript sources worldwide and are difficult to locate and retrieve. Many journals and books published during the 1960s and earlier are not readily obtainable and are not included in other electronic bibliographic databases that usually cover literature only from 1970 onward. Furthermore, many theses, technical documents, and procedures and sterilization records of mass-rearing facilities were never published and therefore are not readily accessible. The International Database on Insect Disinfestation and Sterilization (IDIDAS) is intended to fill this void

The website for the International Database for Insect Disinfestation and Sterilization is http://www-ididas.iaea.org/IDIDAS/.

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by aiding the retrieval of information on doses of radiation used for research or in the control of pest insects and related arthropods.

In addition to facilitating checking and comparing existing data, the database gives regulatory authorities a comprehensive entry to the scientific literature to develop or corroborate disinfestation and sterilization treatments and provides researchers a basis for literature searches to plan experiments involving radiation. However, the comparison of radiosensitivity between insect species must clearly take into account the end result measured (sterilization of males and females, death, lethal dose [LD_{50}], death before eclosion, inability to reach the adult stage or reproduce, etc.), as well as the life stage irradiated.

This paper provides a brief background on the effects of radiation and describes the process undertaken to build IDIDAS database, as well as analyzing and interpreting the data collected with regard to radiation sensitivity in arthropods.

Mode of Action of Radiation for Reproductive Sterilization/Disinfestation

The most radiosensitive cells are those (1) with a high mitotic rate, (2) with a long mitotic future (i.e., under normal circumstances, will undergo many divisions), and (3) that are of the germ cell type. These generalizations, with some exceptions, have become known as the law of Bergonie and Tribondeau (Casarett 1968). In this regard, cells are most sensitive to radiation when they are dividing. That is the basis on which radiation is used to kill cancer cells. Cancer cells tend to divide more often than the other cells of the body. For a given dose of radiation, more cancer cells than normal cells are being killed. Thus, mitotically active reproductive cells (MARCs) are the most radiosensitive and show different killing and sterilization susceptibility according to developmental stages. Generally, earlier stages of spermatogenesis (spermatocytes and spermatogonia) are more radiosensitive than later stages (spermatids and spermatozoa) (Proverbs 1969). Susceptibility also changes according to mitosis phase. Dey and Manna (1983) found that chromosomes at spermatogonial metaphase and anaphase I are more sensitive to X-rays than they are at other stages. MARC sensitivity in female insects is further complicated by the presence of nurse cells that are subject to injury (LaChance and Leverich 1962). Nurse cells are extremely radiosensitive when they are undergoing endomitosis, a process involving chromosome replication without cell division wherein the chromosomes become polytene and have a huge nucleus of unraveled chromatin material (LaChance and Bruns 1963). Thus, females are, in general, more radiosensitive (Carney 1959, Galun et al. 1967, Hallman 2000). At the cytological level, sterilization is the result of the germ cell chromosome fragmentation (dominant lethal mutations, translocations, and other chromosomal aberrations), leading to the production of imbalanced gametes, and subsequently, inhibition of mitosis and the death of fertilized eggs or embryos.

Analysis of chromosomal aberrations performed in male progeny of gamma-irradiated males of Lepidoptera confirmed (Tothova and Marec 2001) that males are more able to survive with a higher number of chromosomal breaks than females. This may explain the markedly biased sex ratio of subsequent generations (F_1 generation) toward males, which are highly sterile. This phenomenon is known as inherited sterility or F_1 sterility (Bloem et al. 1999, Makee and Saour 1999, Carpenter 2000, IAEA 2002a).

Studies have shown that neither DNA content, chromosome number, nor chromosome arm number could be responsible for the differences in radiosensitivity (Jacquet and Leonard 1983), but there exists a relationship between average interphase nuclear volume (INV) and cell sensitivity to radiation. Apparently, the larger the nuclear volume, the greater the sensitivity (Sparrow et al. 1963, Casarett 1968). This relationship, determined in animals (vertebrate) and plants and used to predict their sensitivity to chronic irradiation, may be relevant in insects. Furthermore, radiosensitivity is most likely determined by other parameters including cell repopulation capacity, tissue and organ regeneration ability, and biological repair (Harrison and Anderson 1996). In fact, the expression of radiation damage depends on the relative rates of cell loss and cell proliferation of the basal cells.

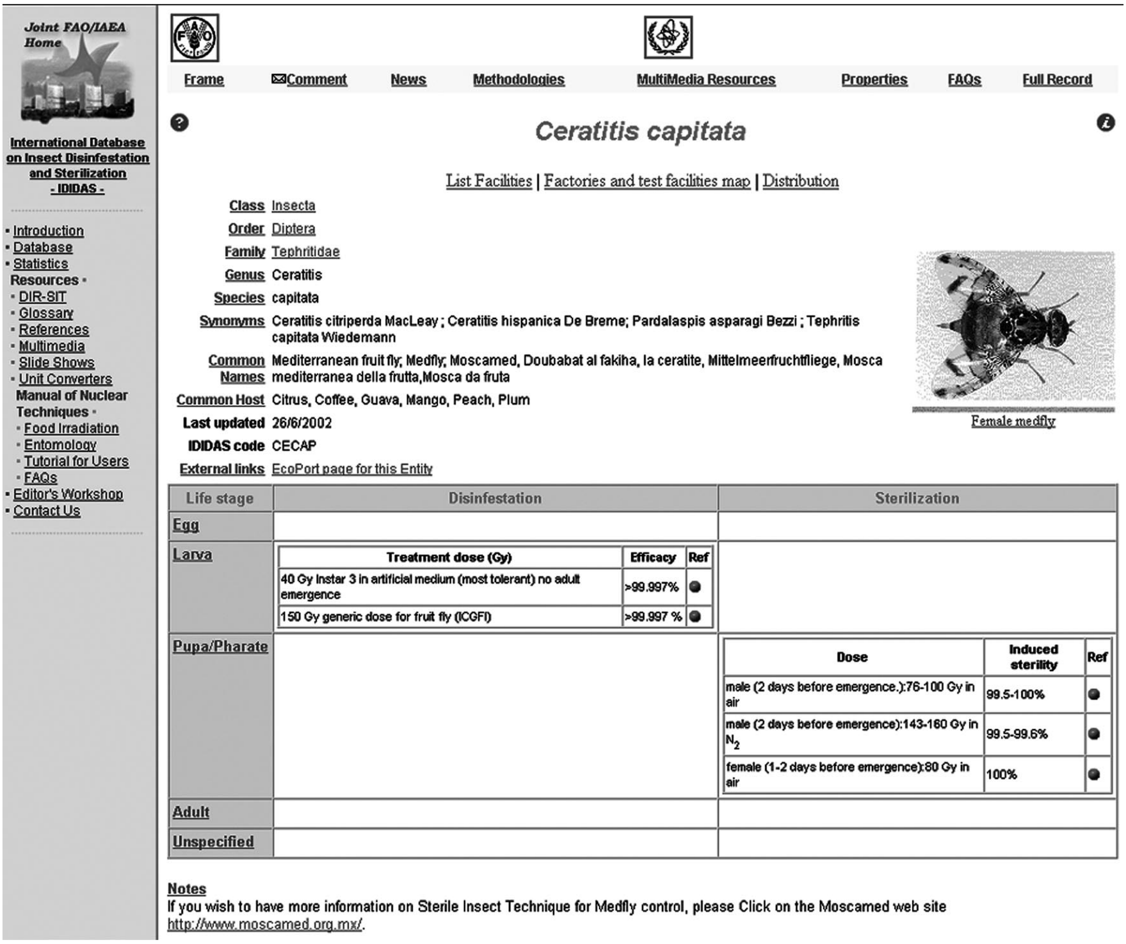
Beside the reproductive sterility induced by direct lesion of the genetic material (e.g., dominant lethal mutations) by radiation, it was reported (LaChance et al. 1967) that there are other causes of reproductive sterility that might have a cytological and/or physiological basis. These aspects will not be raised here because they are beyond the scope of this paper.

Some stem cells also occur in the midgut of adult insects and should be particularly sensitive to irradiation. In Coleoptera, and perhaps other insects, the midgut stem cells undergo continuing mitotic divisions in adults. Riemann and Flint (1967) showed that extensive damage to the midgut is the basic cause of the significant reduction in life span and mortality of irradiated boll weevils, which starve to death.

Somatic cells are less sensitive to radiation than stem cells, including gonial cells, as they are generally differentiated cells that have lost their ability to divide. This explains why a lethal dose must be higher dose than a sterilizing dose. The effect of radiation on somatic cells is expressed by the development of abnormalities, reduction of adult lifespan, flight ability, mating propensity, nutrition, and ultimately death of the insect.

Wholesomeness of Irradiated Insects and Food

A frequently raised question is whether the irradiation process makes biological material or food radioactive. The production of radionuclides in biological materials requires an extraordinary incident radiation of at least 10 million electron volts (MeV). This process cannot occur in biological materials irradiated with cobalt-60 (principal gamma energies of 1.17 and 1.33 MeV), Caesium-137 (principal gamma energy of



Joint FAO/IAEA Home

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Ceratitis capitata

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Class	Insecta
Order	Diptera
Family	Tephritidae
Genus	Ceratitis
Species	capitata
Synonyms	Ceratitis citriperda MacLeay ; Ceratitis hispanica De Breme; Pardalaspis asparagi Bezzi ; Tephritis capitata Wiedemann
Common Names	Mediterranean fruit fly; Medfly; Moscamed, Doubabat al fakiha, la ceratite, Mittelmeerfruchtfliege, Mosca mediterranea della frutta,Mosca da fruta
Common Host	Citrus, Coffee, Guava, Mango, Peach, Plum
Last updated	26/6/2002
IDIDAS code	CECAP
External links	EcoPort page for this Entity

Female medfly

Life stage	Disinfestation	Sterilization
Egg		
Larva	Treatment dose (Gy) / Efficacy / Ref: 40 Gy Instar 3 in artificial medium (most tolerant) no adult emergence / >99.997% / ● 150 Gy generic dose for fruit fly (ICGFI) / >99.997 % / ●	
Pupa/Pharate		Dose / Induced sterility / Ref: male (2 days before emergence.):76-100 Gy in air / 99.5-100% / ● male (2 days before emergence):143-160 Gy in N_2 / 99.5-99.6% / ● female (1-2 days before emergence):80 Gy in air / 100% / ●
Adult		
Unspecified		

Notes

If you wish to have more information on Sterile Insect Technique for Medfly control, please Click on the Moscamed web site http://www.moscamed.org.mx/.

Fig. 1. Example of a species datasheet.

0.66 MeV), electrons (generated by accelerators with energy <10 MeV), or X-rays (generated by a machine with energy <5 MeV) (FAO/IAEA/WHO 1999, IAEA 1999, 2002b, Codex 2003a). The quantum energies of the radiation emitted from these acceptable radioactive sources are well below the thresholds for photonuclear activation of any chemical element. Consequently, even at the highest doses imaginable for disinfestation or sterilization, no radioactivity can be induced by these sources in the food or insects exposed.

New international standards for the use of irradiation as a phytosanitary measure, recognized by Food and Agriculture Organization (FAO), World Health Organization (WHO), the International Consultative Group on Food Irradiation (ICGFI), and World Trade Organization (WTO), have recently been approved by the International Plant Protection Convention (ISPM 2003) and the Codex Alimentarius Commission (Codex 2003b). These standards were prepared and ratified internationally to achieve international harmonization of phytosanitary measures, with the aim to facilitate global trade and avoid the use of unjustifiable measures as barriers to trade.

Process of Data Compilation and Analysis

To develop IDIDAS (Fig. 1), an extensive review of the literature including conventional and nonconventional sources such as theses and proceedings of meetings published from the 1950s onward was undertaken covering two main areas: ionizing radiation for commodities disinfestation and arthropods sterilization. At present, there are >2,750 references in the database that can be searched using a comprehensive set of parameters.

Disinfestation for Quarantine and Phytosanitary Purposes. For disinfestation purposes, the dose depends on the efficacy required and other criteria for the treatment. To be effective, a quarantine treatment needs only to prevent establishment of invasive or exotic species in a new locality. A measure of the efficacy can be determined from the size of the experimental sample (Couey and Chew 1986). Criteria for effectiveness of a treatment to prevent establishment of a pest species in a new location may be sexual sterilization or physical disablement of adults, inhibition of development to the adult or to an intermediate immature stage, or rarely, immediate mortality. For the purposes of disinfestations, the lowest dose was determined as far as possible from references, and the efficacies were shown for immature and adult stages together with the criteria used and listed to meet specific parameters. Ideally, research data should give the maximum and minimum doses of irradiation applied experimentally. The experimental maximum becomes the operational minimum required to achieve the desired result. Where only sterilization studies have been done for a species, these can be used with caution for disinfestations purposes or for range-finding trials for disinfestation. Wherever possible, the stage relevant to the dosage is given together with host commodities, which might require disinfestation.

Sterilization for Area-Wide Pest Management. For sterilization purposes for those species where more than one absorbed dose for sterilization treatment was reported in the literature, a general procedure was adopted to select the dose required to achieve the desired level of sterility and to ensure good quality of the sterilized insects. The intent was to select a dose that minimized somatic damage, and thus, allowed normal insect behavior. The key parameters considered were mating performance, flight ability, longevity, fertility, and fecundity levels. The evaluation of these parameters is described in detail elsewhere (FAO/IAEA/USDA 2003). In the case of Lepidoptera (Carpenter 2000, IAEA 2002a), and to a certain degree, Hemiptera (Harwalkar and Rahalkar 1979), a substerilizing dose might be selected in view of the damaging high dose required to achieve sterilization. Such a dose results in inherited sterility in which a high level of sterility is achieved in males and females of subsequent generations.

Units of Radiation. For comparative purposes, old and discontinued units of radiation found in the literature (Roentgen equivalent physical [Rep], roentgen [R or r], and radiation absorbed dose [rad]) were converted to Gray (Gy), the new unit of radiation in the International System (SI). The conversions are as follow: 1 rad = 0.01 Gy and 1 R (or r) = $97.3\ 10^{-4}$ Gy (in water) (Attix 1986). Rep is considered to be approximately the same as Roentgen (K. Mehta, personal communication).

Directory of Insect-Rearing Facilities for SIT (DIR-SIT) and Database on Authorized Food Irradiation Facilities. Two other databases are included within IDIDAS: the DIR-SIT database, which provides information worldwide on biofactories mass rearing sterile insects for use in pest control programs, and the Database on Authorized Food Irradiation Facilities, which includes the main industrial irradiation facilities in the world. DIR-SIT is based on a questionnaire designed to obtain information on insect mass rearing, sterilization, quality control, and shipment of sterile insects. The questionnaire was sent to all facilities worldwide producing sterile insects (≈40) between June 2002 and March 2003. Thirty of them responded. The data provided served as the new database.

DIR-SIT is an interactive database open to the public, but only editors can add or update information related to their facility. This database includes data on insect production, irradiation, quality control, shipment of sterile insects, field release, and a list of SIT experts. The information in DIR-SIT can be searched extensively using various key words such as production size, species name, irradiation dose, and country name. The DIR-SIT database is a work in progress; further biofactories and features will be added in the future.

Authorized Food Irradiation Facilities Database. This database contains the "International Inventory of Authorized Food Irradiation Facilities," which is updated annually by International Consultative Group on Food Irradiation (ICGFI). This database presents the option of selecting a country that has an authorized food irradiation facility (-ies), based on criteria established by ICGFI and information obtained on such authorized facility (-ies) within that country. To be authorized, industrial irradiation facilities must be licensed, regulated, and inspected by national safety and health authorities. Documented dose mapping should be done after repairs, modifications, or adjustments in equipment or processes that affect the absorbed dose (Codex 1983).

Output

Insect and Arachnid Species in the Database. In total, over the past five decades, 309 species of arthropods, mostly of economic importance, found in 196 genera, 84 families, 9 insect orders, and 2 arachnid orders, have been subjected to irradiation studies for purposes of research, biocontrol, or pest control programs integrating the SIT or postharvest disinfestation. Of these insect species, 85 are Diptera, 78 are Coleoptera, 71 are Lepidoptera, 26 are Hemiptera, 24 are Acari, 10 are Thysanoptera, 6 are Hymenoptera, 5 are Dictyoptera, 2 are Araneae, 1 is Isoptera, and 1 is Orthoptera (Table 1).

Of 85 entries on Diptera species from 17 families and 29 genera, 34 species are Tephritidae, confirming the importance of this group in pest management and international trade in agricultural, and in particular, horticultural commodities.

As the compilation for IDIDAS progresses with new research and additional information becoming available, the list of species that have been subjected to radiation studies will continue to increase.

Irradiation of Organisms from Different Taxonomic Groups. Arthropods are more radioresistant than human and other higher vertebrates (Table 2) but less resistant than viruses, protozoa, and bacteria (Whicker and Schultz 1982, Blaylock et al. 1996, Harrison and Anderson 1996). One of the main reasons is that arthropods have a discontinuous growth during immature stages. This is encoded in Dyar's Rule: i.e., insects double their weight at each molt, and thus, their cells need to divide only once per molting cycle (Hutchinson et al. 1997, Behera et al. 1999). The high resistance to irradiation of most adult insects is attributed to the fact that they are composed of differentiated cells, which do not undergo replacement (Sullivan and Grosch 1953). Such cells are much more resistant to death or damage induced by irradiation

Table 1. Insect and arachnid orders, families, genera, and species subjected to sterilization and/or disinfestation currently available in IDIDAS

Class	Order	Family (genus, species)	Total
Insecta	Diptera	Tephritidae (6,34), Culicidae (3,14), Glossinidae (1,8), Muscidae (4,6), Oestridae (1,2), Agromyzidae (1,1), Calliphoridae (3,5), Drosophilidae (1,5), Anthomyiidae (1,2), Chloropidae (1,1), Piophilidae (1,1), Cuterebridae (1,1), Psilidae (1,1), Sarcophagidae (1,1), Sciaridae (1,1), Tachinidae (1,1), Ceratopogonidae (1,1).	17 families 29 genera 85 species
	Lepidoptera	Tortricidae (16,20), Pyralidae (13,21), Noctuidae (6,13), Gelecheiidae (4,4), Lymantiidae (2,2), Arctiidae (2,2), Bombycidae (1,2), Cossidae (1,1), Lyonetiidae (1,1), Pieridae (1,1), Plutellidae (1,1), Sphingidae (1,1), Thaumetopoeidae (1,1), Tineidae (1,1), Yponomeutidae (3,4).	15 families 54 genera 71 species
	Coleoptera	Curculionidae (19,26), Tenebrionidae (8,11), Scarabaeidae (5,5), Dermestidae (3,7), Laemophloeidae (1,3), Bruchidae (3,5), Anobiidae (3,4), Chrysomelidae (3,2), Bostrichidae (2,1), Cleridae (1,1), Coccinellidae (1,1), Cerambycidae (1,1), Lyctidae (1,1), Scolytidae (1,1), Silvanidae (2,3), Ptinidae (1,1).	16 families 54 genera 78 species
	Hemiptera	Aleyrodidae (3,4), Reduviidae (3,3), Aphididae (2,2), Coreidae (2,2), Delphacidae (2,3), Cicadellidae (1,1), Lygaeidae (1,1), Miridae (1,1), Pentatomidae (2,3), Pseudococcidae (2,2), Pyrrhocoridae (1,1), Coccidae (1,1), Diaspididae (2.2).	13 families 23 genera 26 species
	Hymenoptera	Apidae (1,1), Braconidae (2,2), Eulophidae (1,1), Formicidae (1,1), Pteromalidae (1,1).	5 families 6 genera 6 species
	Isoptera	Kalotermitidae (1,1).	1 family 1 genus 1 species
	Dictyoptera	Blaberidae (1,1), Blattellidae (1,2), Oxyhaloidae (1,1), Blattidae (1,1).	4 families 4 genera 5 species
	Thysanoptera	Thripidae (5,9), Phlaecothripidae (1,1).	2 families 6 genera 10 species
Arachnida	Acari	Ixodidae (4,6), Tetranychidae (2,7), Acaridae (4,5), Argasidae (2,2), Siteroptidae (1,1), Tenuipalpidae (1,1), Eriophyidae (1,1), Oligonychidae (1,1), Dermanyssidae (1,1).	8 families 17 genera 24 species
	Aranea	Pholocidae (1,1), Eresidae (1,1).	2 families 2 genera 2 species

than are dividing or undifferentiated cells. However, some stem cells do occur in the gonads and midguts of adult insects. The successful sterilization of certain insect species without reduction in their lifespan may indicate that cell replacement in the midguts is either not affected or is not of major importance to viability (Riemann and Flint 1967).

Sterilization Dose Levels. According to the database, radiation doses to achieve sterility in insects and related arthropods ranges widely between and within orders. The mean dose (Fig. 2) for sterilization ranges from 130 to 400 Gy in Lepidoptera, 30 to 280 Gy in Acari, 40 to 200 Gy in Coleoptera, 10 to 180 Gy in Hemiptera, 20 to 160 Gy in Diptera, 20 to 150 Gy in Araneae, 5 to 140 Gy in Dictyoptera, 100 Gy in Thysanoptera, and 4 Gy in Orthoptera. Acrididae (Orthoptera) and Blaberidae (Dictyoptera) were the most radiosensitive (<5 Gy). Willard and Cherry (1975) suggested that large long-lived adults are generally more radiosensitive than small short-lived adults. However, as stated above, the radiosensitivity is more related to the average interphase nuclear volume. It was reported (Galun et al. 1974) that soft ticks species belonging to Ixodidae are more sensitive than hard cuticle species of Argasidae, as well as Tetranychidae and Acaridae mites. In this order, the doses for sterilization may change depending on whether the tick is engorged with blood or not. For example, to achieve 100% sterility, male and female *Amblyomma americanum* L. require 9.70 Gy before engorgement and 24.25 Gy after engorgement.

The irradiation dose for sterilization of Hymenoptera species, which includes potential pests such as Formicidae species, sawflies, and Africanized bees, is not well documented, although species of *Bracon* F. (then called *Habrobracon* Ashm.) were among the

Table 2. Ranges of LD_{50} obtained from acute irradiation of organisms from different taxonomic groups

Group	Dose (Gy)	References
Bacteria, protozoa, viruses	100–10,000	Harrison and Anderson 1996
Insects	30–1,500	Whicker and Schultz 1982
Mollusks	50–500	Ravera 1967
Higher plants	1.5–>130	Harrison and Anderson 1996
Fish	4–100	Harrison and Anderson 1996
Amphibians	7–22	Harrison and Anderson 1996
Reptiles	3–40	Harrison and Anderson 1996
Birds	5–20	Harrison and Anderson 1996
Humans	3	Rice and Baptist 1974

The length of time for survival is usually set at 30 days for mammals, but longer times may be needed for other organisms.

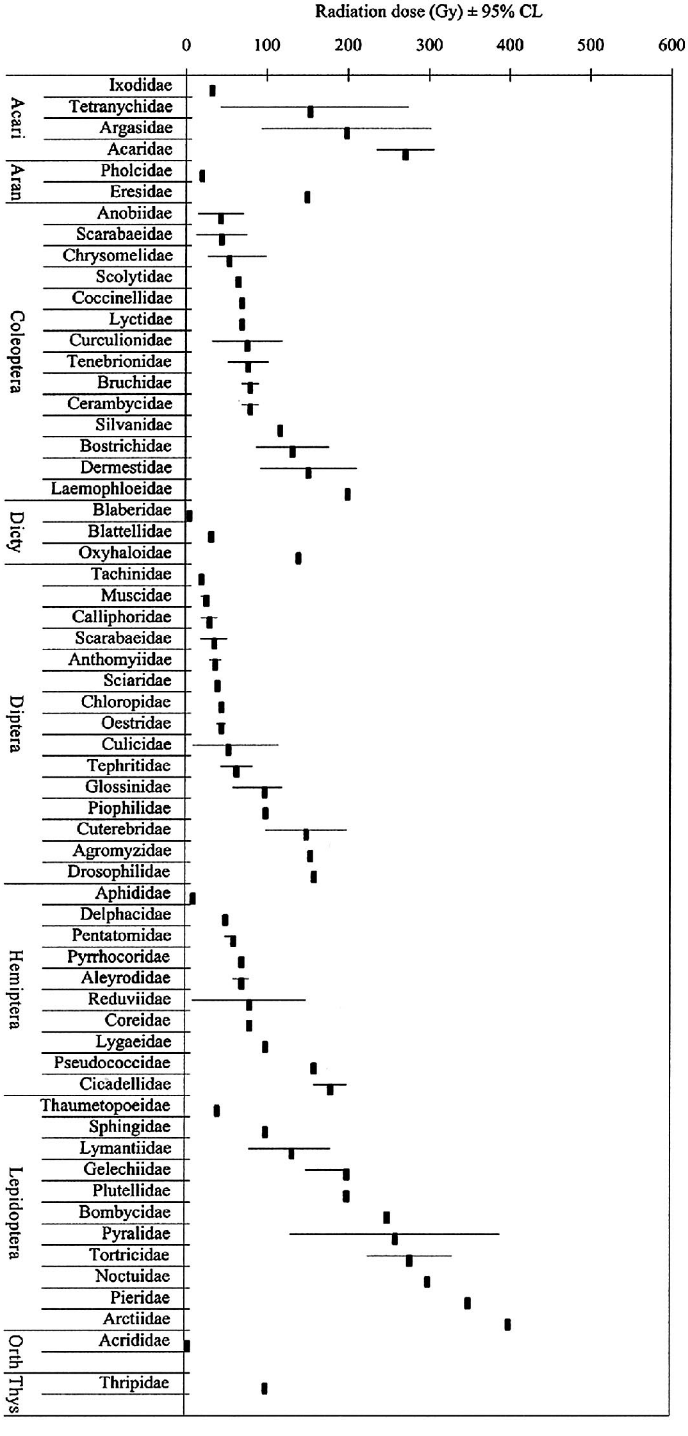

Fig. 2. Range of radiosterilization doses (mean ± 95% confidence level) for insects and related arthropods. Data are for in-air irradiation of males treated either as pupae or nymphs (mosquitoes and apple maggot fruit flies treated as adults). Other factors such as radiation source, temperature, dose rate, and level of sterility achieved were not necessarily consistent. Full references for data in this table are available from the IDIDAS website. Aran, Aranea; Dicty, Dictyoptera; Orth, Orthoptera; Thys, Thysanoptera.

most used species in radiobiology studies (Whiting 1961, Grosch 1965, Smith and Whiting 1966, Borstel 1967). Because of their complex social and mating behavior, SIT application to control social insects has so far been limited to a few laboratory experiments (Sakamoto and Takahashi 1981). For male honey bees, the sterilizing dose varies from 80 to 100 Gy (Lee 1958), and this is probably the only example in the literature. Most experimental irradiations of hymenopterans (e.g., the parasitic wasp *Bracon hebetor* Say) have been conducted in conjunction with relatively basic radiobiological investigations. For these reasons, the doses for sterilization or disinfestation of this group are not included in Fig. 2.

Doses shown in Fig. 2 represent irradiation doses administered under normal conditions for male pupae and nymphs (adults of mosquitoes and apple maggot fruit fly). Because differences in radiosensitivity between females and males insects have been reported (Hallman 2000), different doses might be required when female irradiation is the goal. For instance, female ixodid ticks (*Rhipicephalus appendiculatus* Neumann) are apparently more radioresistant than males (Purnell et al. 1972).

Disinfestation Dose Levels. The efficacy required for a disinfestation treatment (mostly immature stages) varies from country to country and according to whether the treatment is for quarantine or phytosanitary purposes. The highest efficacy likely to be required is 99.9968% at a confidence level (CL) of 95%. Other efficacies required may be 99.99% or even as low as 99.95%, each at a confidence limit of 95%. In 1986, a Task Force of ICGFI (ICGFI 1986) determined a generic dose of 300 Gy as the minimum needed to achieve quarantine security (99.9968% efficacy at the 95% CL) against any stage of any insect species in the absence of specific experimental data to show that a lower dose would be sufficient. This dose level has been widely validated subsequently for Insecta and most Acarina in publications cited in IDIDAS. The Task Force also identified 150 Gy as effective against any Tephritidae with a lower dose for certain species. These doses should be regarded as default dosages where actual efficacies could not be calculated reliably.

Limitations and Constraints

IDIDAS Taxonomic Challenges. The potential sources of error in any compilation of records such as this database are multiple. One of the main difficulties derives from taxonomy because this is an evolving science, and the names of many pest species have been revised during the past 50 yr. When reviewing the literature from the 1950s onward, old names and synonyms of species were encountered, and it was necessary to determine the updated names of species, genera and families. For example, the name *Bactrocera citri* (Chen) was used for *Bactrocera minax* (Enderlein), *Bactrocera (Tetradacus) minax* (Chen), and *Mellesis citri* Chen, which are known under the common name Chinese citrus fly. To add to this confusion, another species, *Bactrocera tsuneonis* (Miyake), was also called Chinese citrus fly by some authors. Another example of taxonomic revision is *Laspeyresia molesta* Busck, which changed to *Cydia molesta* (Busck) and to *Grapholita (Aspila) molesta* (Busck) (Komai 1999).

There are some records where the scientific name is a matter of taxonomic judgment, with a given species considered a member of one or another genus. This is confusing for someone not specialized in taxonomy and who may erroneously consider the organism as two different species (e.g., the Arctiid *Spilosoma obliqua* Walker [*Diacrisiae obliqua* Walker]). In this case, one of the names is added as a synonym and both names are searchable.

Fortunately, there were only a few cases where a choice between different "taxonomy schools" had to be made. Whenever possible, names accepted by the Entomological Society of America (ESA 1997), Commonwealth Agricultural Bureaux International (CABI 1972–2002), and the International Commission on Zoological Nomenclature (ICZN 2003) were adopted in the database. Other specialized systematic materials such as Mosquito Systematics were also consulted. The higher classification of insects adopted in IDIDAS is conservative. Thus, despite the current "splitting" of some families and subfamilies, these were mainly maintained lumped to aid retrievability. This has been done notably in the Pyralidae.

Organisms for irradiation should be defined for posterity by the placement of voucher specimens in an appropriately secure and curated collection. This is particularly important for groups subjected to frequent taxonomic changes such as the Tephritidae.

Conflicting Radiation Doses. The variation in the radiosensitivity between orders, families, and even genera within the same family of arthropods is expected. For example, within the Tephritidae, the mean radiation dose reported for *Ceratitis* MacLeay sterilization is similar to *Bactrocera* Macquart, but twice as high as those reported for the genera *Dacus* Fabricius and *Rhagoletis* Loew (Fig. 3). However, a variation of radiosterilizing dose for the same species beyond a reasonable range is unrealistic. One extreme example of inconsistent sterilization data in the literature is the case of *Sitophilus granarius* L. (Fig. 4), where the variation between the minimum and maximum doses reported in the literature is several-fold. Variation of a species' radiosterilizing dose might occur, and probably to a certain extent in response to external or internal factors. For example, in the case of the plum curculio, *Conotrachelus nenuphar* (Herbst), northern strains are more radiosusceptible than southern strains (Hallman 2003). Northern strains are univoltine and undergo obligate diapause as adults, whereas the southern strains are multivoltine and have a facultative diapause. Similarly, radioresistance differences reported in codling moth, *Cydia pomonella* L., populations originating from ecosystems at different altitudes, apparently having different background natural irradiation levels, have been attributed to genetic diversity in this species (Azizyan 2003).

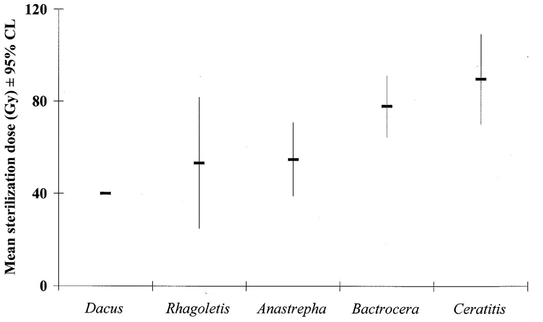

Fig. 3. Range of sterilization doses reported for Tephritidae genera. The range is based on the number of radiosterilized species within each genus. In the case of *Dacus*, data for only one species were found (*Dacus ciliatus* Low). Vertical lines represent the 95% confidence level of the mean (CL). Only doses of radiation of mature male pupae or adults irradiated in air were considered. Sources of irradiation are not comparable.

Besides these special genetic diversity cases, several other factors may be associated with inconsistencies in the literature of the reported sterilizing dose of a species, including the following:

- Physical Factors. These are the external factors involved when implementing irradiation and that might affect insect radiosensitivity. Such factors are the dose rate (Hooper 1975), temperature (Barbosa 1976), continuous (chronic) or fractionated (acute) irradiation (Mayas 1975, Tamhankar and Shantharam 2001), humidity, ventilation, dosimetry calibration, radiation types (electromagnetic and particulate radiations), and modified atmospheres (Ohinata et al. 1977, Fisher 1997).
- Biological Factors. These include such factors as insect gender, feeding condition, weight, diet, diapause (Carpenter and Gross 1989, Mansour 2003, Hallman 2003), developmental stages, and age at irradiation. Generally, adults are more radioresistant than pupae, which are more resistant than larvae, and fully grown pupae are more resistant to gamma irradiation than developing pupae (Ahmed et al. 1990, Dongre et al. 1997).
- Human Factors. These might also be a source of inconsistencies in reporting radiation doses for a species. For example these factors might involve the procedures followed for insect packing, which can significantly affect the level of hypoxia in the container of insects to be irradiated and thus the insect radiosensitivity (Hooper 1989, Fisher 1997). Other factors include operator skill for irradiator calibration, statistical analysis, sampling, evaluation of fertility or fecundity, data interpretation, and use of inconsistent terminology such as minimum, central, or maximum doses to describe the same treatment dose. Radiation dose for a species may also be adjusted to meet the requirement of the quarantine or SIT program objectives. That is, in certain preventive release or eradication programs, higher doses are used to achieve additional real or perceived security, whereas in suppression programs, lower doses are adopted. However, this adjustment should be based on the assessment of the risks.

All these factors should be recorded, harmonized, and made compatible with the treatment effectiveness. Unfortunately, these factors are often not specified in publications. In addition, there are conflicting reports on the way certain of these factors modify insect radiosensitivity (i.e., dose rate and diapause). Regular dosimetry, a component of quality control programs, is frequently neglected, and the dosimeter type is often not reported in the older literature. This raises doubt about the irradiator calibration and thus makes it difficult for any comparison between the findings of various authors. There is, therefore, an urgent need to harmonize the dosimetry system, which should be calibrated in accordance with international standards or appropriate national standards (ISO/ASTM 2003a, b, ISPM 2003) and according to documented standard operating procedures. For the radiation sterilization of live insects for use in pest management programs, harmonization has been initiated with the development of a standard dosimetry system (FAO/IAEA 2000) and the preparation of a standard operational procedure manual for quality control (FAO/IAEA/USDA 2003). The guidelines and standards for food irradiation are outlined by the Codex Alimentarius Commission adopted in 1983 and revised in 2003 (Codex 2003b), the Recommended Code of Practice for the Operation of Radiation Facilities used for the treatment of foods adopted in 1979 and revised in 1983 (Codex 1983), and the guidelines

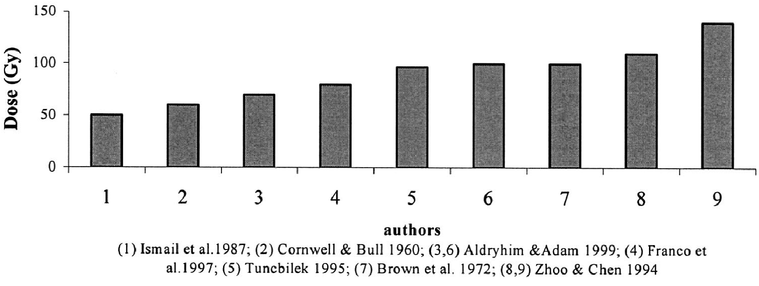

Fig. 4. Radiosterilization doses of the grain weevil, *S. granarius* L., according to different authors.

for the use of irradiation as a phytosanitary measure (ISPM 2003).

Bibliography and Other Resources. IDIDAS does not provide abstracts for all papers and reprints. Abstracts are included if available and if prior permission of the publisher has been obtained or where the database editor has prepared a summary. At present, a search of references is limited to author names and titles of citations. Pictures, drawings, and video clips are available for only a few records. Gradually, multimedia items will be added, based on voluntary contributions. The lists of hosts attributed to the arthropod species were retrieved from the literature and are not comprehensive. Only some of the most common hosts were reported.

Conclusion and Future Development

A database compiling radiation doses for arthropod sterilization and disinfestation has been developed to support researchers and regulators dealing with phytosanitary treatments and pest control program operators. Most insects and related arthropods require a sterilizing dose of <200 Gy. This dose for sterilization is close to the generic dose—150 Gy for fruit flies, 300 Gy for other species of insects and mites—recommended for commodity disinfestation through reproductive sterilization (ICGFI 1991, Hallman and Loaharanu 2002). This is more advantageous than killing the infesting insects, because, at low sterilizing doses, physical and chemical properties of commodities are better preserved (FAO/IAEA/WHO 1999).

The reported inconsistencies in the radiation doses for the sterilization of arthropod species reveal the need to harmonize the factors affecting the responses of arthropod to radiation and to set standards for radiation doses and dosimetry and for sterile insect quality control. In addition, research is needed to explain in more detail the way some physical factors such as dose rate and biological factors such as diapause affect radiosensitivity in arthropods.

IDIDAS is a work in progress and will continue to be refined as more information and feedback from users become available. It is expected that IDIDAS will stimulate further analysis of radiation entomology. These efforts will certainly have a great benefit on both pre- and postharvest control methods in term of reducing crop losses.

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References Cited

Ahmed, M.Y.Y., M.A.R. Daoud, E. S. El-Hawary, and S. A. Boshra. 1990. Susceptibility of the pupal stage of *Plodia interpunctella* Hubner to gamma irradiation as affected by radiation dose, age, sex and temperature, p. 1119. *In* F. Fleurat-Lessard and P. Ducom (eds.), Proceedings of the 5th Working Conference on Stored Product Protection, 9–14 September 1990, Bordeaux, France.

Aldryhim, Y. N., and E. E. Adam. 1999. Efficacy of gamma irradiation against *Sitophilus granarius* (L.). J. Stored Prod. Res. 35: 225–232.

Attix, F. H. 1986. Introduction to radiological physics and radiation dosimetry. Wiley, New York.

Azizyan, A. 2003. Study the comparative resistance of codling moth populations at different geographical regions to gamma irradiation. Progress Report. Research Contract ARM 11024/R1. Co-ordinated Research Program (CRP), IAEA, Vienna, Austria.

Barbosa, A. P. 1976. Interaction of gamma radiation and temperature on the determination of the sterilizing dose of some stored products pests. MSc thesis, Sao Paulo University, Escola Superior de Agricultura Luiz deq Ueiroz, Piracicaba, Brazil.

Behera, M. K., R. Behera, and B. Patro. 1999. Application of Dyar's rule to the development of *Macrosiphoniella sanborni* (Gill.) (Aphididae: Homoptera). Agric. Sci. Dig. (Karnal). 19: 179–182.

Blaylock, B. G., C. W. Theodorakis, and L. R. Shugart. 1996. Biological effects of ionizing radiation, pp. 39–50. *In* B. Amiro, R. Avadhanula, G. Johansson, C. M. Larsson, and M. Luning (eds.), Proceedings of the Symposium: Ionizing Radiation. The Swedish Radiation Protection Institute (SSI) and the Atomic Energy Control Board (AECB) of Canada, 20–24 May 1996, Stockholm, Sweden.

Bloem, S., K. A. Bloem, J. E. Carpenter, and C. O. Calkins. 1999. Inherited sterility in codling moth (Lepidoptera: Tortricidae): effect of substerilizing doses of radiation on insect fecundity, fertility and control. Ann. Entomol. Soc. Am. 92: 222–229.

Borstel, R. C. 1967. Genetic effects of chronic gamma radiation on *Habrobracon* sperm. Radiat. Res. 31: 615.

Brown, G. A., J. H. Brower, and E. W. Tilton. 1972. Gamma radiation effects on *Sitophilus zeamais* Mots., 1855 and *S. granarius.* J. Econ. Entomol. 65: 203–205.

Burditt, A. K. Jr. 1994. Irradiation, pp. 101–118. *In* J. L. Sharp and G. J. Hallman (eds.), Quarantine treatments of food plants. Westview Press, Boulder, CO.

[CABI] Commonwealth Agricultural Bureaux International. (1972–2002). Online abstracts database on entomology. CAB International Publishing, Wallingford, United Kingdom.

Carney, G. C. 1959. Differential response of male and female adults of *Trogoderma granarium* Everts towards sterilizing doses of gamma-radiation. Nature (Lond.). 183: 338–339.

Carpenter, J. E. 2000. Area-wide integration of lepidopteran F_1 sterility and augmentative biological control, pp. 193–200. *In* K.-H. Tan (ed.), Proceedings of the Conference, Symposium: area-wide control of fruit flies and other insect pests, 28 May–5 June 1998, Penerbit Universiti Sains Malaysia, Pulau Pinang, Malaysia.

Carpenter, J. E., and H. R. Gross. 1989. Interaction of inherited sterility and diapause in the corn earworm (Lepidoptera: Noctuidae). J. Econ. Entomol. 82: 1354–1357.

Casarett, A. P. 1968. Radiation biology. Prentice-Hall, Englewood Cliffs, NJ.

Codex. 1983. Recommended international code of practice for the operation of irradiation facilities used for the treatment of foods. CAC/RCP 19–1979, Rev. 1–1983. FAO, Roma, Italy.

Codex. 2003a. Recommended international code of practice for the radiation processing of foods. CAC/RCP 19–1979, Rev. 1–2003. FAO, Roma, Italy.

Codex. 2003b. General standard for irradiated food: CODEX STAN 106–1983, Rev. 1–2003. FAO, Roma, Italy.

Cornwell, P. B., and J. O. Bull. 1960. Insect control by gamma-irradiation: an appraisal of the potentialities and problems involved. J. Sci. Food. Agr. 11: 754–768.

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

Dey, S. K., and G. K. Manna. 1983. Differential stage sensitivity to x-rays in a bug *Physopelta schlanbuschi.* Natl. Acad. Sci. Lett. 16: 101–103.

Dongre, T. K., M. R. Harwalkar, S. P. Nene, and S. R. Padwal-Desai. 1997. Radio-sensitivity of different developmental stages of pulse beetle (*Callosobruchus maculatus*). J. Food Sci. Technol. 34: 413–415.

Draz, K.A.A. 1991. Sperm precedence for females mated with irradiated and normal males of caribbean fruit fly, *Anastrepha suspensa* (Loew). Isotope Rad. Res. 21: 147–152.

[ESA] Entomological Society of America. 1997. Common names of insects and related organisms, ESA Committee on Common Names of Insects. Entomological Society of America, Lanham, MD

Evans, H. J. 1962. Chromosome aberrations induced by ionizing radiation. Int. Rev. Cytol. 13: 221–321.

[FAO/IAEA] Food and Agriculture Organization/International Atomic Energy Agency. 2000. Gafchromic Dosimetry System for SIT, Standard Operating Procedures. IAEA, Vienna, Austria.

[FAO/IAEA/USDA] Food and Agriculture Organization/International Atomic Energy Agency/U.S. Department of Agriculture. 2003. Manual for "product quality control and shipping procedures for sterile mass-reared tephritid fruit flies," version 5.0. IAEA, Vienna, Austria.

[FAO/IAEA/WHO] Food and Agriculture Organization/International Atomic Energy Agency/World Health Organization. 1999. High-dose irradiation: wholesomeness of food irradiated with doses above 10 KGy. Joint FAO/IAEA/WHO Study Group, Technical Report Series 890. World Health Organization, Geneva, Switzerland.

Fisher, K. 1997. Irradiation effects in air and in nitrogen on Mediterranean fruit fly (Diptera:Teprhitidae) pupae in Western Australia. J. Econ. Entomol. 90: 1609–1614.

Franco, S.S.H., J. G. Franco, and V. Arthur. 1997. Determination of sterilizing dose of gamma radiation of Cobalt-60 for adults of *Sitophilus zeamais* Mots., 1855 (Coleoptera, Curculionidae) on maize. Ecossistema. 22: 120–121.

Galun, R., M. Warburg, and A. Avivi. 1967. Studies on the application of the sterile method in the tick *Ornithodoros tholozani.* Entomol. Exp. Appl. 10: 143–152.

Galun, R., M. Warburg, and S. Sternberg. 1974. The sterile-insect technique and its field applications, pp. 21–25. *In* Proceedings of a panel on the practical use of the sterile-male technique for insect control organized by the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture, 13–17 November 1972. IAEA, Vienna, Austria.

Greany, P., and J. E. Carpenter. 1999. Use of nuclear techniques in biological control of insects and weeds. Nuclear News. February: 32–34.

Grosch, D. S. 1962. Entomological aspects of radiation as related to genetics and physiology. Annu. Rev. Entomol. 7: 81–106.

Grosch, D. S. 1965. Biological effects of radiation. Bios. 36: 55–62.

Hallman, G. J. 1999. Ionizing radiation quarantine treatment against Tephritid fruit flies. Postharvest. Biol. Technol. 16: 93–106.

Hallman, G. J. 2000. Expanding radiation quarantine treatments beyond fruit flies. Agric. For. Entomol. 2: 85–95.

Hallman, G. J. 2003. Ionizing irradiation quarantine treatment against plum curculio (Coleoptera: Curculionidae). J. Econ. Entomol. 96: 1399–1404.

Hallman, G. J., and P. Loaharanu. 2002. Generic ionizing radiation quarantine treatments against fruit flies (Diptera: Tephritidae) proposed. J. Econ. Entomol. 95: 893–901.

Harrison, F. L., and S. L. Anderson. 1996. Taxonomic and development aspects of radiosensitivity, pp. 65–88. *In* B. Amiro, R. Avadhanula, G. Johansson, C. M. Larsson, and M. Luning (eds.), Proceedings of the Symposium: Ionizing Radiation, the Swedish Radiation Protection Institute (SSI) and The Atomic Energy Control Board (AECB) of Canada, 20–24 May, 1996, Stockholm, Sweden.

Harwalkar, M. R., and G. W. Rahalkar. 1979. Inheritance of sterility in *Dysdercus koenigii* F. (Hemiptera: Pyrrhocoridae). J. Nucl. Agric. Biol. 8: 121–123.

Heather, N. W. 1993. Irradiation as a quarantine treatment of agricultural commodities against arthropod pests, pp. 627–639. *In* Proceedings of the Symposium: management of insect pests: nuclear and related molecular and genetic techniques, 19–23 October 1992, Vienna, Austria.

Hendrichs, J. 2000. Use of the sterile insect technique against key insect pests. Sustainable Dev. Int. 2: 75–79.

Hoch, G., and A. Schopf. 2001. Effects of *Glyptapanteles liparidis* (Hym.: Braconidae) parasitism, polydnavirus, and venom on development of microsporidia-infected and uninfected *Lymantria dispar* (Lep.: Lymantriidae) larvae. J. Invertebr. Pathol. 77: 37–43.

Hooper, G.H.S. 1975. Sterilization of *Dacus cucumis* French (Diptera: Tephritidae) by gamma radiation. II. Effect of dose rate on sterility and competitiveness of adult males. J. Aust. Entomol. Soc. 14: 175–177.

Hooper, G.H.S. 1989. The effect of ionizing radiation on reproduction, pp. 153–164. *In* A. S. Robinson and G. Hooper (eds.), World crop pests, vol. 3A: fruit flies, their biology, natural enemies and control. Elsevier Publishers, New York.

Hutchinson, J.M.C., J. M. McNamara, A. I. Houston, and F. Vollrath. 1997. Dyar's rule and the investment principle: optimal moulting strategies if feeding rate is size-dependent and growth is discontinuous. Phil. Trans. Roy. Soc. Lond. Ser. B Biol. Sci. 352: 113–138.

[IAEA] International Atomic Energy Agency. 1963. Bibliographical series, no. 9: radioisotopes and ionizing radiations in entomology, vol. I (1950–1960). IAEA, Vienna, Austria.

[IAEA] International Atomic Energy Agency. 1965. Bibliographical series, no. 15: radioisotopes and ionizing radiations in entomology (1961–1963). IAEA, Vienna, Austria.

[IAEA] International Atomic Energy Agency. 1967. Bibliographical series, no. 24: radioisotopes and ionizing radiations in entomology, vol.III (1964–1965). IAEA, Vienna, Austria.

[IAEA] International Atomic Energy Agency. 1969. Bibliographical series, no. 36: radioisotopes and ionizing radiations in entomology, vol. IV (1966–1967). IAEA, Vienna, Austria.

[IAEA] International Atomic Energy Agency. 1999. Irradiation as a quarantine treatment of arthropod pests. Proceedings, Final Research Co-ordination Meeting organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, 3–7 November 1997, Honolulu, Hawaii.

[IAEA] **International Atomic Energy Agency. 2002a.** Evaluation of Lepidoptera population suppression by radiation induced sterility. Proceedings, Final Research Coordination Meeting organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, 28 May–2 June 1998, Penang, Malaysia.

[IAEA] **International Atomic Energy Agency. 2002b.** Natural and induced radioactivity in food. IAEA, Vienna, Austria.

[ICGFI] **International Consultative Group on Food Irradiation. 1986.** Irradiation as a quarantine treatment. Report: task force meeting, 17–21 February 1986, Chiang Mai, Thailand.

[ICGFI] **International Consultative Group on Food Irradiation. 1991.** Quarantine treatment of fresh fruits and vegetables. Report: task force meeting, 7–11 January 1991, Bethesda, Maryland.

[ICZN] **International Commission on Zoological Nomenclature [ICZN]. 2003.** Available online at http://www.iczn.org/.

[ISO/ASTM] **International Organization for Standardization/American Society for Testing and Materials. 2003a.** Standard guide for selection and calibration of dosimetry systems for radiation processing. Annual Book of ASTM Standards, vol. 12.02:19. ASTM, Philadelphia, PA.

[ISO/ASTM] **International Organization for Standardization/American Society for Testing and Materials. 2003b.** Standard guide for irradiation of insects for sterile release programs. Annual Book of ASTM Standards, vol. 12.02:19. ASTM, Philadelphia, PA.

[ISPM] **International Standards for Phytosanitary Measures. 2003.** Guidelines for the use of irradiation as a phytosanitary measure. FAO, Rome, Italy.

Ismail, I. I., M. A. Eweiss, S. R. Souka, and M. S El-Degwy. 1987. Effect of gamma radiation on the adult stage of the granary weevil *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). Bull. Entomol. Soc. Egypt, Econ. Ser. 16: 49–54.

Jacquet, P., and A. Leonard. 1983. Studies on the differential radiosensitivity of the male and female pronuclei in the mouse zygote, C4–08. *In* J. J. Broerse, G. W. Barendsen., and A. J. Van der Kogel (eds.), Proceedings, Congress: Radiation Research, Somatic and Genetic effects. The 7th International Congress of Radiation Research, July 3–8, 1983, Amsterdam, The Netherlands.

Knipling, E. F. 1979. The basic principles of insect population suppression and management. U.S. Dep. Agric. Handbook, no. 512. U.S. Government Printing Office, Washington, DC.

Komai, F. 1999. A taxonomic review of the genus *Grapholita* and allied genera in the Palaearctic region. Entomol. Scand. 55: 1–226.

LaChance, L. E., and A. P. Leverich. 1962. Radiosensitivity of developing reproductive cells in female *Cochliomyia hominivorax.* Genetics. 47: 721–735.

LaChance, L. E., and S. B. Bruns. 1963. Oogenesis and radiosensitivity in *Cochliomyia hominivorax* (Diptera: Calliphoridae). Biol. Bull. 124: 65–83.

LaChance, L. E., C. H Schmidt, and R. C Bushland. 1967. Radiation-induced sterilization, pp. 147–196. *In* W.W. Kilgore and R. L. Doutt (eds.), Pest control: biological, physical, and selected chemical methods. Academic, New York.

Lee, W. R. 1958. The dosage response curve for radiation induced dominant lethal mutations in the honeybee. Genetics. 43: 480–492.

Makee, H., and G. Saour. 1999. Nonrecovery of fertility in partially sterile male *Phthorimaea operculella* (Lepidoptera: Gelechiidae). J. Econ. Entomol. 92: 516–520.

Mansour, M. 2003. Gamma irradiation as a quarantine treatment for apples infested by codling moth (Lep., Tortricidae). J. Appl. Entomol. 127–141.

Mayas, I. 1975. The effect of fractionation of the sterilizing dose of gamma -rays on the emergence, fertility and competitiveness of the Mediterranean fruit fly, *Ceratitis capitata* Wied., pp. 145–152. *In* Proceedings, Symposium: The use of isotopes in pesticides and pest control, March 1974, Beirut, Lebanon.

O'Brien, R. D., and L. S. Wolfe. 1964. Radiation, radioactivity, and insects. Academic, New York.

Ohinata, K., M. Ashraf, and E. J. Harris. 1977. Mediterranean fruit flies: sterility and sexual competitiveness in the laboratory after treatment with gamma irradiation in air, carbon dioxide, helium, nitrogen or partial vacuum. J. Econ. Entomol. 70: 165–168.

Proverbs, M. D. 1969. Induced sterilization and control of insects. Annu. Rev. Entomol. 14: 81–102.

Purnell, R. E., J. D. Dargie, B. Gilliver, A. D. Irvin, and M. A. Ledger. 1972. Some effects of irradiation on the tick *Rhipicephalus appendiculatus.* Parasitology. 64: 429–440.

Ravera, O. 1967. The effect of x-ray on the demographic characteristics of *Physa acuta* (Gasteropoda: basommatophora). Malacologia. 5: 95–109.

Retnakaran, A. 1970. Preliminary results of radiation induced sterility of the male spruce budworm. Res. Notes. 26: 13–14.

Rice T. R., and J. P. Baptist. 1974. Ecologic effects of radioactive emissions from nuclear power plants, pp. 373–439. *In* L. A. Sagan (ed.), Human and ecological effects of nuclear power plants. Charles C. Thomas, Springfield, IL.

Riemann, J. G., and H. M. Flint. 1967. Irradiation effects on midguts and testes of the adult boll weevils *Anthonomus grandis,* determined by histological and shielding studies. Ann. Entomol. Soc. Am. 60: 289–308.

Sakamoto, C. H., and C. S. Takahashi. 1981. Biological effects of gamma radiation on Africanized bees. Apimondia Publishing House, Bucharest, Romania.

Smith, R. H., and A. R. Whiting. 1966. X-radiation sensitivity of *Habrobracon* oocytes at diakinesis. Genetics. 54: 364.

Soller, M., and B. Lanzrein. 1996. Polydnavirus and venom of the egg-larval parasitoid *Chelonus inanitus* (Braconidae) induce developmental arrest in the prepupae of its host *Spodopotera littoralis* (Noctuidae). J. Insect Physiol. 42: 471–481.

Sparrow, A. H., L. A. Schairer, and R. C. Sparrow. 1963. Relationships between nuclear volumes, chromosome numbers and relative radiosensitivities. Science. 141: 163–166.

Sullivan, R. L., and D. S. Grosch. 1953. The radiation tolerance of an adult wasp. Nucleonics. 11: 21–23.

Tamhankar, A. J., and K. Shantharam. 2001. Sterile insect technique (SIT) for control of spotted bollworm of cotton: field experiments confirm dose fractionation improves mating competitiveness of sterile males, pp. 250–252. *In* N. Ramamoorthy, M. Ananthakrishnan, and A. N. Nandakumar (eds.), Proceedings, Conference: Applications of Radioisotopes and Radiation Technology in the 21st Century, NAARRI International Conference, 12–14 December 2001, Mumbai, India.

Tan, K. H. 2000. Area-wide control of fruit flies and other insect pests. Penerbit Universiti Sains Malaysia, Pulau Pinang, Malaysia.

Tothova, A., and F. Marec. 2001. Chromosomal principle of radiation-induced F_1 sterility in *Ephestia kuehniella* (Lepidoptera: Pyralidae). Genome. 44: 172–184.

Tuncbilek, A. S. 1995. The effect of temperature upon the radiation susceptibility of *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). Turk. Entomol. Derg. 19: 27–35.

Vreysen, M.J.B. 2001. Principles of area-wide integrated tsetse fly control using the sterile insect technique. Med. Trop. 61: 397–411.

Whicker, F. W., and V. Schultz. 1982. Radioecology: nuclear energy and the environment. CRC, Boca Raton, FL.

Whiting, A. W. 1961. Genetics of *Habrobracon.* Adv. Genet. 10: 295–348.

Willard, W. K., and D. S. Cherry. 1975. Comparative radiosensitivity in the class Insecta. J. Theor. Biol. 52: 149–158.

Zhou, Y. X., and H. Chen. 1994. Study on sterile dosages of ^{60}Co-gamma rays for controlling the granary weevil. Acta Phytophyl. Sin. 21: 33–38.

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