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Effect of Irradiation on Queen Survivorship and Reproduction in the Invasive Fire Ant *Solenopsis invicta* (Hymenoptera: Formicidae) and a Proposed Phytosanitary Irradiation Treatment for Ants

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Abstract

We studied radiation tolerance in queens of the red imported fire ant *Solenopsis invicta* Buren (Hymenoptera: Formicidae) to identify a dose that prevents reproduction. Virgin or fertile queens were collected from Santa Fe and Formosa provinces in Argentina and reared in the laboratory in microcolonies. Virgin queens were irradiated at 0 (control), 70, 90, 120, or 150 Gy, and fertile queens were irradiated at 0, 60, 125, and 190 Gy, and then followed for 11 wk in the microcolonies to evaluate survival and reproduction. Virgin queens lay trophic eggs that do not hatch, whereas fertile queens lay eggs that hatch and develop into brood. In general, queen oviposition and survival decreased with increasing irradiation dose. For virgin queens, no eggs were laid by irradiated queens after the third week, whereas the control queens continued laying eggs throughout the 11-wk experiment. For fertile queens, only one larva and no pupae was observed in the 60 Gy treatment and no larvae or pupae were observed in the 125 and 190 Gy treatments, whereas a total of 431 larvae and 83 pupae were produced by untreated control queens during 11 wks. Survivorship of virgin and fertile queens was similarly reduced by irradiation treatment. These results with *S. invicta* are consistent with previous findings for three other invasive ants, *Wasmannia auropunctata* (Roger), *Pheidole megacephala* (F.), and *Linephithema humile* (Mayr), that are hitchhiker pests on fresh horticultural commodities. A radiation dose of 150 Gy is proposed as a phytosanitary treatment to prevent reproduction in ants.

Key words: red imported fire ant, invasive, quarantine, phytosanitary treatment, generic irradiation dose

Low dose ionizing radiation is used as a postharvest treatment to control quarantine pests in fresh agricultural commodities traded between countries (Follett and Griffin 2013; Follett 2014). The presence of hitchhiking insects, such as ants, on exported agricultural products can cause rejection, return shipment, or destruction of consignments, all of which are costly (Costa et al. 2005, Follett and Taniguchi 2007). The objective of an irradiation quarantine treatment is to prevent reproduction and thereby prevent the insect's introduction and establishment into new areas. Although most interceptions in the case of ants are sterile workers, reproductive queens may be found and thus ants pose a threat to agriculture in the importing country.

USDA-APHIS has approved generic radiation doses of 150 Gy for fruit flies in the family Tephritidae, and 400 Gy for all other insects except the pupa and adults stages of Lepidoptera which may require a higher dose (USDA APHIS 2006, Follett and Neven 2006). These generic radiation treatments apply to all fresh horticultural commodities. The 400 Gy generic dose was based on radiotolerance information for a wide variety of insect groups, but information was limited or nonexistent for several important groups of phytosanitary pests including ants (Follett and Griffin 2013). Research was needed to determine if the 400 Gy generic radiation dose was effective against ants and whether a lower dose might provide quarantine security.

We have developed radiation tolerance information for several of the world's most invasive ant species including the big-headed ant, *Pheidole megacephala* (F.) (Follett and Taniguchi 2007), the little fire ant, *Wasmannia auropunctata* (Roger) (Calcaterra et al. 2012), and the Argentine ant, *Linephithema humile* (Mayr) (Coulin et al. 2013). In each case queens received exposure to a series of ionizing radiation levels to identify a sterilizing dose. These studies suggested a radiation dose of ~100 Gy could sterilize ant queens. Information from additional economically important invasive ant species will provide support for a phytosanitary irradiation treatment for all ants.

The red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae), is a globally distributed invasive species from southern South America that has become a significant agricultural and quarantine pest in the southern United States, Australia, the Caribbean, Taiwan, southern China, and Macau (Ascunce et al. 2011). *S. invicta* is one of the world's five worst invasive ant species (Lowe et al. 2000). The native range of *S. invicta* includes parts of Brazil, Bolivia, Paraguay, and Argentina (Tschinkel 2006). It prefers open sunny areas, and causes economic losses by feeding on agricultural crops such as sunflowers, okra, cucumbers, soybeans, corn, and eggplant (Morisawa 2000).

Solenopsis invicta is a generalist and aggressive predator, and invasive colonies occurring at high densities can devastate most of the resident native species (Calcaterra et al. 2008, Briano et al. 2012, Brent and Vargo 2003). A mature colony of the red imported fire ant consists of 100,000 to 500,000 polymorphic workers, several hundred winged males and females (sexuals), one (monogyne form) or more (up to two thousand; polygyne form) reproductive wingless queens, and brood (eggs, larvae, and pupae; Brian 1979, Tschinkel 2006). Queens from polygyne colonies normally produce a high proportion of sterile males and thus the queens are less likely to be inseminated. As a result of the high number of new virgin queens, most new polygyne colonies are produced by budding of newly recruited or readopted queens (Porter et al. 1988). Therefore, queens collected in the wild may be virgin or fertile depending on social and physiological factors. Virgin queens lay (nonembryonated) trophic eggs that do not hatch, whereas inseminated queens lay fertile (embryonated) eggs that hatch and develop into brood; trophic eggs may serve as an important source of food for young larvae (Tschinkel 2006).

The objective of this study was to determine the radiation dose sufficient for the control of *S. invicta*. Unlike other disinfestation techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live (but nonviable or sterile) insects may occur with the exported commodity (Follett 2009). The desired response for ants is to sterilize reproductive females (queens) and prevent brood development (Follett and Taniguchi 2007, Calcaterra et al. 2012). *S. invicta* is not normally considered a phytosanitary pest, but will feed on plant parts including buds, developing fruits and seeds and therefore may occasionally be found in traded fresh produce. Information on *S. invicta* radiation tolerance, combined with information for several other invasive ant pests (Follett and Taniguchi 2007, Calcaterra et al. 2012, Coulin et al. 2013) will improve our knowledge of how radiotolerant overall ants are compared with other insects.

Materials and Methods

Collection of Colonies

In January 2014, 12 colonies of *S. invicta* were collected in Roldán (32.883°S, 60.883°W, 40 m altitude) at 50 km west from Rosario, Santa Fe, Argentina (Experiment 1—virgin queens), which is the southern limit of the known range of *S. invicta* (Pitts 2002). Additionally in November 2015, 23 colonies of *S. invicta* were collected from three sites 75 km apart in the eastern portion of Formosa province: Villa Escobar (26.617°S, 58.667°W, 60 m altitude), Herradura (26.483°S, 58.300°W, 59 m altitude), and Formosa (26°10′S, 59°09′, 55 m of altitude), Argentina (Experiment 2—fertile queens). The Formosa region is the likely source of the populations of *S. invicta* introduced in the United States (Ascunce et al. 2011). The Santa Fe and Formosa colonies of *S. invicta* represent distinct geographical populations along a south–north latitudinal gradient and were chosen to increase genetic diversity in queens used in the experiments.

The collection of virgin queens used in the first experiment was unexpected and reflects the difficulty in determining the physiological status of queens a priori in the field. Only the fertile queens used in the second experiment provided useful information for determining a radiation dose that prevents reproduction. We report results from the first experiment with virgin queens because it provides additional information on survivorship and fecundity after irradiation and supports the results from the second experiment with fertile queens. The methods used in the two experiments were identical except for slight variation in the irradiation treatments.

All colonies were collected by digging up *S. invicta* nests including queens, sexuals (winged males and females), workers, and brood from the ground and placing soil and ants into covered buckets coated with talc (to prevent escape). In the laboratory, ants were separated from soil by flotation (Banks et al. 1981) and transferred to plastic trays (25 by 40 by 7 cm) coated with talc. Ants were provided with a permanent source of water and sugar water and fed three times a week alternating with peanut butter, corn meal, hard boiled eggs, and sausage as in previous studies (Calcaterra et al. 2012, Coulin et al. 2013).

All wingless queens from each colony were placed individually in small black plastic containers (12 by 17 by 6 cm) with 10 workers (referred to here after as a microcolony) to care for and feed the queen, as in Calcaterra et al. (2012) and Coulin et al. (2013). Though the number of workers does not affect oviposition rate of individual queens (isolated from the colony), workers are necessary to rear brood (Tschinkel 2006). Each microcolony included a transparent glass tube (15 cm length by 1.5 cm diameter) half-filled with water and sealed with a cotton plug (to provide humidity), thereby leaving an area 5 by 1.5 cm for the queen and her progeny to settle and allowing free access for workers. Queens were fed as described above.

Microcolonies were kept in an incubator at 27 °C, 80% RH, and a photoperiod of 12:12 (L:D) h to provide optimal conditions for oviposition. This temperature is within the natural range of this species (25–32 °C, Porter 1988). All queens collected from Santa Fe were weighed to test for size bias among treatments because queens from large colonies are typically larger and have more developed ovaries than queens from small colonies, and thus their egg-laying rates may differ accordingly (Tschinkel 2006).

Fecundity Before Irradiation

All microcolonies were checked for 1 wk before irradiation under a 40× stereomicroscope for egg production to confirm whether they were actively reproducing. The number of eggs laid by individual queens was recorded. As a result, a total of 60 (Experiment 1—virgin) and 48 (Experiment 2—fertile) wingless queens from Santa Fe and Formosa respectively were selected to be irradiated. Brood, which have the potential to develop into reproductive females, have not been found in imported commodities during inspection and therefore were not tested. Early ant life stages are likely more susceptible to radiation than adults, as is invariably the case in other insects (Aldryhim and Adam 1999, Follett 2006, Follett and Griffin 2013).

Irradiation Treatment

All queens were randomly assigned to an irradiation treatment in each experiment, as in Follett and Taniguchi (2007), Calcaterra et al. (2012), and Coulin et al. (2013). For Experiment 1, 12 queens from the *S. invicta* colonies collected in Santa Fe were randomly assigned to each of five radiation treatments: 0 (control), 70, 90, 120, and 150 Gy. For Experiment 2, 12 queens from the *S. invicta* colonies collected in Formosa were randomly assigned to each of four treatments independent of their specific origin: 0 (control), 60, 125, and 190 Gy.

In both experiments, individual queens together with 5–10 workers were irradiated in the tubes where they were reared. Queens from the control treatments received the same manipulation and transportation as irradiated queens to avoid differences between treatments. Irradiation was carried out at the Comisión Nacional de Energía Atómica (Centro Atómico Ezeiza, Buenos Aires, Argentina) using a Gammacell-220 cobalt-60 irradiator (MDS Nordion, Ottawa, ON, Canada) with a dose rate 0.27 and 0.26 Gy per min (transit dose = 0.017 and 0.014 Gy) in Experiments 1 and 2, respectively. In both experiments, five dosimeters (Fricke ASTM E 1026-2013) were placed in separate empty glass vials to estimate the absorbed dose received by ants. In Experiment 1, measured dose for the 70, 90, 120, and 150 Gy treatments were 69.8, 90.5, 121.1, and 149 Gy, respectively, whereas in Experiment 2 measured dose (minimum–maximum) for the 60, 125, and 190 Gy treatments were 59–59.4, 125.6–126.4, and 188.7–188.8 Gy, respectively.

Fecundity and Survivorship After Irradiation

Within 12 h after irradiation, queens were transferred to new microcolonies and reared as described above. For both experiments the number of eggs, larvae, and pupae laid by individual queens was recorded weekly for 11 wks. As a reference for *S. invicta* developmental rate, egg-to-adult duration at 28 °C and 60% RH is normally ~27 d (6.6, 9.9, and 10.5 d for egg, larva, and pupa, respectively) in newly mated queens (Wang et al. 2015). Queen survivorship was also recorded weekly to determine the effect of radiation treatment on residual longevity.

Statistical Analysis

For both experiments, the mean weight of queens, and the mean number of eggs laid per queen (in microcolonies) during the week before irradiation and 11 wk after irradiation was analyzed using a generalized linear model (GLM) with Poisson distribution of residuals and log-link function corrected for overdispersion in STATISTICA v. 7.1 (StatSoft 2005).

Linear regression was performed on $\sqrt{x + 0.5}$ transformed data to predict the dose that would prevent egg laying. In Experiment 2, the total number of larvae and pupae produced per queen and queen survivorship data, which were not normally distributed and could not be made so with simple transformations, were analyzed using Kruskal–Wallis ANOVA test.

Results

Fecundity Before Irradiation

The total number of eggs laid during the week preceding irradiation treatment was similar among queens assigned to the different treatments in Experiment 1 (GLM Wald $\chi^2 = 1.13$, df = 4, $P = 0.89$), ranging from 105.9 ± 8.0 to 114.2 ± 11.8 eggs (mean ± SE), and in Experiment 2 (GLM Wald $\chi^2 = 1.79$, df = 3, $P = 0.618$), ranging from 92.8 ± 9.8 eggs to 119 ± 19.8 eggs. Thus, the queens chosen for irradiation in each treatment showed similar fecundity before both experiments. There was no significant difference in queen weights among radiation treatments in Experiment 1 (GLM Wald $\chi^2 = 1.56$, df = 4, $P = 0.816$; queen mean weight was 9.6 ± 1.1 mg [mean ± SD]).

Table 1. Residual longevity and fecundity (mean ± SE) of *S. invicta* virgin queens reared during 11 wk after irradiation

Irradiation dose (Gy)	No. queens	Survivorship (wk)	No. eggs/wk
0 (control)	12	8.00 ± 1.23a	10.64 ± 1.69a
70	12	8.83 ± 0.96a	4.87 ± 0.79b
90	12	6.75 ± 1.29a	3.8 ± 0.66b
120	12	6.17 ± 0.71a	3.40 ± 0.48b
150	12	5.25 ± 0.84a	2.79 ± 0.57b

Different letters in columns indicate significant differences among treatments ($P < 0.05$).

Experiment 1—Effect of Irradiation on Fecundity of Virgin Queens

Production of eggs in the microcolonies decreased after irradiation (Table 1). Irradiation had a significant effect on the mean number of eggs laid per queen (GLM Wald $\chi^2 = 28.3$; df = 4; $P = 0.0000$). Oviposition was 54.2, 64.3, 68, and 73.8% lower in the 70, 90, 120, and 150 Gy treatments compared with the control treatment (Table 1). Queens treated with a radiation dose of 120 and 150 Gy laid eggs only during the first week, whereas queens treated with 70 and 90 Gy laid eggs during the first and second weeks (Fig. 1). As no larvae were observed in either the control or irradiation treatments, we inferred post hoc that eggs in all treatments were nonembryonated (trophic eggs) laid by virgin queens. The linear regression equation describing the effect of dose on the mean number of trophic eggs laid per virgin queen was $y = -0.03x + 9.48$ ($R^2 = 0.26$; $F_{1,\,58} = 19.10$; $P = 0.0000$), and although the model had a poor fit to the data, the predicted radiation dose to prevent any egg laying was 297 Gy (253–342, 95% CL).

Effect of Irradiation on Survivorship of Virgin Queens

Differences in survival were not significant among treatments ($H = 6.155$, $n = 60$, df = 4, $P = 0.1878$; Table 1). However, virgin queen survivorship generally decreased with increasing radiation dose (Fig. 2). By the end of the 11-wk experiment, a total of 7, 8, 4, 0, and 0 queens survived in the 0, 70, 90, 120, and 150 Gy treatments, respectively.

Experiment 2—Effect of Irradiation on Fecundity of Fertile Queens

Production of eggs, larvae, and pupae in the microcolonies decreased markedly after irradiation (Table 2). Radiation had a significant effect on the mean number of eggs laid per queen (GLM Wald $\chi^2 = 41.8$, df = 3, $P = 0.0000$). Oviposition was 88.8, 88.7, and 82.3% lower in the 60, 125, and 190 Gy doses compared with the control treatment (Table 2). Queens treated with 60 and 190 Gy laid eggs only during the first week, whereas queens treated with a dose of 125 Gy laid eggs only during the first and second weeks (Fig. 3). The linear regression equation describing the effect of dose on the mean number of eggs laid per fertile queen was $y = -0.02x + 5.72$ ($R^2 = 0.24$; $F_{1,46} = 14.88$; $P = 0.0004$), and although the model had a poor fit to the data, the predicted radiation dose to prevent any egg laying was 269 Gy (208–331 Gy, 95% CL).

The production of larvae and pupae decreased significantly with irradiation treatment (Table 2). The number of larvae developing in the control treatment was significantly higher than that from irradiated queens ($H = 43.34$, $n = 48$, df = 3, $P = 0.0000$), and only one larva was observed in the 60 Gy treatment, while no larvae were observed in the 125 and 190 Gy treatments. The number of pupae developing in the control treatment was also significantly higher

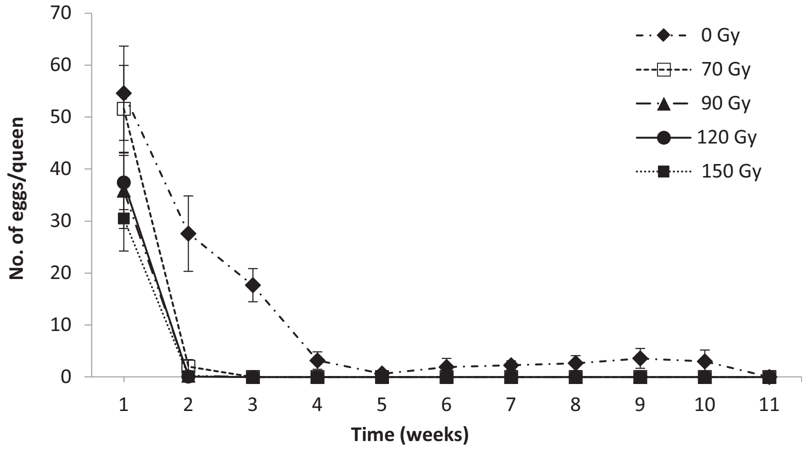

Fig. 1. Experiment 1: Mean (± SE) number of eggs laid per virgin queen during 11 wk after irradiation.

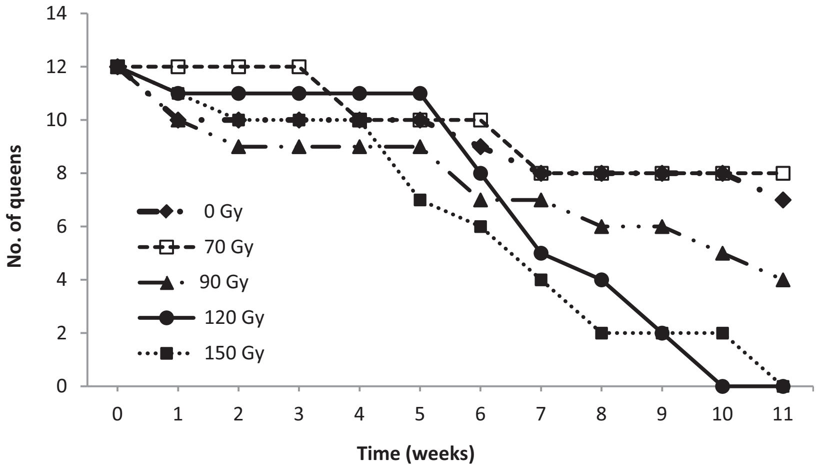

Fig. 2. Experiment 1: Number of live virgin queens during 11 wk after irradiation.

Table 2. Residual longevity and reproduction (mean ± SE) of *S. invicta* fertile queens reared during 11 wk after irradiation

Irradiation dose (Gy)	No. queens	Survivorship (wk)	No. eggs/wk	Total no. larvae[a]	Total no. pupae[b]
0 (control)	12	9.75 ± 0.18a	6.43 ± 2.01a	38.08 ± 9.89a	7.67 ± 2.57a
60	12	8.77 ± 0.79a	0.72 ± 0.72b	0.09 ± 0.09b	0b
125	12	4.58 ± 0.50b	0.73 ± 0.71b	0b	0b
190	12	3.67 ± 0.41b	1.14 ± 1.14b	0b	0b

Different letters in columns indicate a significant difference ($P < 0.05$).
[a] Number of larvae observed during the 11-wk period per queen.
[b] Number of pupae observed during the 11-wk period per queen.

than that from irradiated queens ($H = 27.9$, n = 48, df = 3, $P = 0.0000$; Table 2). A total of 92 pupae were produced by queens in the control treatment, while no pupae were produced by irradiated queens.

Effect of Irradiation on Survivorship of Fertile Queens

Inseminated queen survivorship decreased with increasing irradiation dose (Table 2). By the end of the 11-wk experiment, a total of 10, 8, 0, and 0 queens survived in the 0, 60, 125, and 190 Gy treatments, respectively (Fig. 4). All queens treated with a radiation dose of 125 Gy were dead at 9 wk, and all queens treated with a radiation dose of 190 Gy were dead at 7 wks, which was significantly lower queen survivorship than in the control treatment ($H = 30.03$, $n = 48$, df = 3, $P = 0.0000$).

Discussion

Irradiation had a strong effect on reproduction by *S. invicta*. There was little or no oviposition by irradiated queens in any treatment after the first week, and overall the mean number of eggs observed in the control treatment was two to six times higher than in the irradiation treatments. For fertile queens, a radiation dose of 60 Gy resulted in only one larva that did not develop further and no pupae, and a radiation dose of 125 Gy resulted in no larvae or pupae during

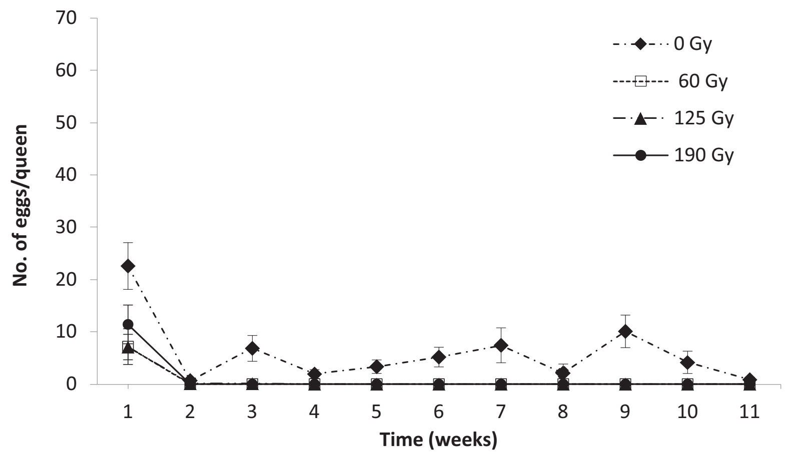

Fig. 3. Experiment 2: Mean (± SE) number of eggs laid per fertile queen during 11 wk after irradiation.

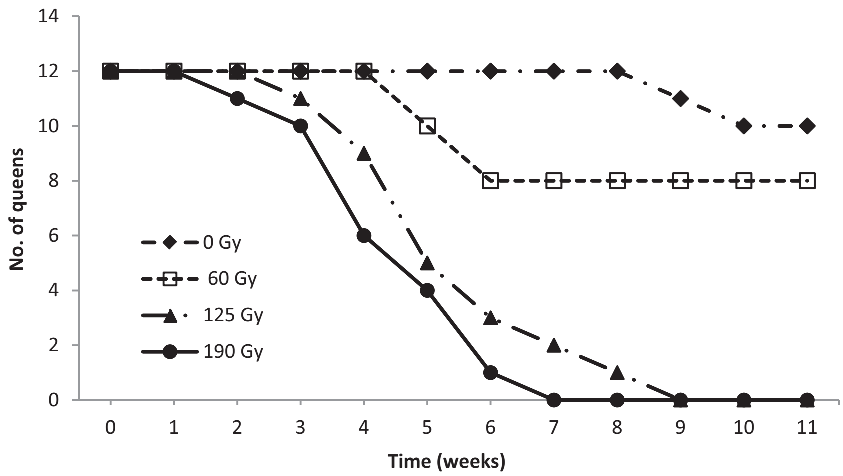

Fig. 4. Experiment 2: Number of live fertile queens during 11 wk after irradiation.

11 wk post irradiation. Thus, using no egg hatch as the desired criterion, irradiation treatment at 125 Gy is sufficient to sterilize *S. invicta* queens. If the less stringent criteria of no emergence of F1 adults is used (evidenced by no development to the pupal stage), irradiation treatment at 60 Gy would be sufficient to prevent reproduction.

Oviposition was generally lower in the microcolonies than levels expected for *S. invicta* colonies in nature, which was probably due to suboptimal laboratory rearing conditions as previously reported (Gavilanez-Slone and Porter 2014). The food sources in the microcolonies were selected to provide basic nutrition, not to replicate a natural diet. Some offspring in the microcolony may have been eaten by sibling larvae or by workers or the queen due to underfeeding. Despite reduced egg production in microcolonies, overall immature production by fertile *S. invicta* queens in unirradiated control treatments was higher than that observed in other studies with invasive ant species (Chang 1985, Calcaterra et al. 2012, Coulin et al. 2013). Similarly, survival from egg to larva was higher in *S. invicta* (59%) than that observed under similar conditions in *P. megacephala* (38%; Chang 1985), *L. humile* (41%; Coulin et al. 2013), and *W. auropunctata* (51%; Calcaterra et al. 2012). Radiation doses higher than 60–70 Gy stopped oviposition in fertile and infertile *S. invicta* queens independent of population source after the third week. A similar pattern was also observed in the invasive ants *W. auropunctata* (Calcaterra et al. 2012) and *L. humile* (Coulin et al. 2013). The lack of oviposition after the third week explains the poor fit of the linear regression model describing the relationship between oviposition and radiation dose, which can lead to an overestimation of the effective dose for quarantine control. Therefore, the development from egg to larva or pupa should be better estimators of the radiation tolerance of invasive ants to determine an effective dose for their control.

Postharvest quarantine treatments are typically validated by treating 30,000 or more insects with no survivors (Follett and Neven 2006). Lower numbers of insects may be acceptable during quarantine treatment development in certain cases, such as when the insect is difficult to rear in large numbers (Follett and Griffin 2013). In the United States, low replication irradiation treatments have been adopted for several regulatory pest species. A radiation dose of 250 Gy was approved for *Cryptophlebia illepida* (koa seedworm), an internal pest of lychee, longan, and rambutan fruit in Hawaii, after large scale testing with ~11,000 fifth-instar larvae (Follett and Lower 2000). The same dose was approved for a congener *Cryptophlebia ombrodelta* (litchi fruit moth) by demonstrating that *C. illepida* was more radiation tolerant in comparative tests with ~500 late instar larvae of each species (Follett and Lower 2000). A

Table 3. Minimum irradiation dose preventing reproduction in ant queens

Subfamily/species	Dose (Gy)	Reference
Dolichoderinae		
Linepithema humile	62	Coulin et al. 2013
Myrmicinae		
Wasmannia auropunctata	72	Calcaterra et al. 2012
Pheidole megacephala	90	Follett and Taniguchi 2007
Solenopsis invicta	60	Present study

radiation dose of 300 Gy was approved for *Sternochetus mangiferae* (mango seed weevil), a monophagous pest of mango fruit, after treatment of ~1,000 insects across several studies (Follett 2001). Due to the low replication in these studies, the radiation dose that was identified for further testing and eventually approved was two to three times higher than the lowest dose shown to provide control (no survivors), which provided a significant margin of safety. A radiation dose of 165 Gy was approved for *Sternochetus figidus* (mango pulp weevil) in Philippine mangos exported to the United States after treatment of 4,559 weevils at this dose resulted in no oviposition (Obra et al. 2014). This study with *S. figidus* used the stringent criteria for efficacy of no oviposition rather than no egg hatch, which strengthened the case for a 165 Gy irradiation treatment.

The desired response with irradiation treatment of ants is sterility of reproductive females (queens). Collecting and raising multiple independent ant colonies to provide queens for testing is not trivial and places limits on the number of insects that can be tested within a reasonable amount of time. Ants are a unique case in low replication quarantine studies because they are highly social: each queen must be collected with her colony in the field, and reared, irradiated and held for observations in a microcolony in the laboratory. Queens lay eggs but workers are required for brood care and the development from egg to larva to pupa, and so a level of social organization must be maintained to determine the effects of irradiation on reproduction. Therefore, each queen requires a major investment of time.

During dose response testing with *Pheidole megacephala* (Follett and Taniguchi 2007), *Wasmannia auropunctata* (Calcaterra et al. 2012), *Linepithema humile* (Coulin et al. 2013), and *Solenopsis invicta* (present study), a total of only 152 fertile queens in microcolonies were irradiated during a period of about 5 yrs. This is a small number of tested insects by quarantine treatment standards and therefore a significant margin of safety should be applied when making a general irradiation treatment recommendation for ants. Based on data for the four ant species listed above, a radiation dose of 150 Gy is recommended for ants (Formicidae), which is approximately 67% higher than the dose required to prevent reproduction in the most tolerant ant species tested to date, *Pheidole megacephala*, and more than 2x the dose required to prevent reproduction in the other three species tested (Table 3).

Most fresh commodities traded between countries using phytosanitary irradiation treatment are applying the 400 Gy generic dose due to the diversity of insect pests and the absence of specific approved treatments for all the pests (Follett 2014). For commodities with relatively few quarantine pests, applying lower doses may be possible. For example, longan, *Dimocarpus longan* Lour., rambutan, *Nephelium lappaceum* L., and papayas, *Carica papaya* L., can be exported from Hawaii to the U.S. mainland using the 150 Gy generic dose to control tephritid fruit flies (Follett 2009), and sweet potatoes, *Ipomoea batatas* (L.), can be exported using 150 Gy to control three internal pests of the roots (Follett 2006). However, these commodities are often treated with a radiation dose of 400 Gy as "insurance" against the possible presence of ants and other hitchhiking insects (Follett 2009, Calcaterra et al. 2012). Acceptance of the effectiveness of 150 Gy against ants would allow for more frequent use of the 150 Gy treatment for these and other commodities. Lowering the dose is desirable because any quality problems will be minimized, the cost of treatment will be reduced, and the capacity of the treatment facility may be increased owing to shorter treatment time (Follett 2009). Effective radiation doses below 400 Gy for other groups of regulatory pests such as weevils, thrips, and mealybugs are needed, and approving a dose for mites which currently have no treatment is vital to expanding the use of phytosanitary irradiation (Follett 2014).

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