INFORMATION ON DISPERSAL ABILITY AND SURVIVAL RATE IN THE SUGARCANE CLICK BEETLE *MELANOTUS OKINAWENSIS* ÔHIRA (COLEOPTERA: ELATERIDAE)

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Abstract

In estimating the population abundance by the mark-recapture method using male-attractant pheromone traps, the release of sterile males is preferable, because they do not increase the reproductive rate of wild females by increasing the mating rate. We estimated the influence of gamma radiation on males of the sugarcane click beetle *Melanotus okinawensis* ÔHIRA (Coleoptera: Elateridae) to determine an appropriate dose of gamma radiation in laboratory and field experiments. The hatchability of eggs was examined for 0, 50, 70, 90, and 150 Gy. No hatchings were observed in eggs laid by females which mated with males treated with doses of 70, 90 and 150 Gy. The longevity of adults in the laboratory was estimated with 0, 30, 50, 70, 90, 150, and 200 Gy. Analysis by the proportional hazard model indicated that irradiation significantly reduces the survival rate in the laboratory even if the dose is 30 Gy. Mean dispersal distance in the field was estimated with 0, 50, 90, and 150 Gy. Three hundred marked beetles for each dose were released at the center of Ikei Island on 1 and 3 April 2003. The estimates were 274, 219, 192, and 289 m, respectively, and we could not detect a significant influence of irradiation on the mean dispersal distance. Field survival rates were estimated using Jolly-Seber, Yamamura, and Yamamura B methods at Okinawa Prefectural Experiment Station in Naha for two doses of irradiation, 0 and 90 Gy; we could not detect significant differences between the two survival rates. The mortality added in the field was estimated to be much greater than the mortality caused by irradiation when we focus on the experiment within 12 days after release, if the dose of irradiation is lower than 90 Gy. It was therefore concluded that 90 Gy will be an appropriate dose for preparing sterile males to estimate population abundance and survival rate in the field within 12 days after release.

Key words: Sterile insect; gamma radiation; mark-recapture

**INTRODUCTION**

The sugarcane click beetle *Melanotus okinawensis* ÔHIRA (Coleoptera: Elateridae) is one of the most important pests of sugarcane in Okinawa and Kagoshima, Japan. Larvae (called wireworms) of this species injure underground buds, and impede continuous growth subsequent to harvest (Hokyo, 1980; Nagamine and Kinjo, 1981, 1990; Nakamori and Kawamura, 1997). This species requires two or three years to complete immature development and spends its entire life underground, except for a short period for flight and mating (Setokuchi et al., 1990). Adult emergence of *M. okinawensis* from the ground starts from early or mid-March, peak from early to mid-April and terminates around early May (Arakaki et al., 2008a, b, c). Adults mate and females lay eggs around the roots of sugarcane in this period (Yasuda et al., 1984). The mean longevity of wild adults collected from the field in early April was 49 and 40 days in females and males, respectively (Nagamine and Kinjo, 1981). Larvae are the damaging stage, feeding on underground buds and root systems of sugarcane. Mature larvae pupate, emerge in autumn, and remain underground as adults until the following spring (Nagamine and Kinjo, 1981). Female sex pheromone was identified as *n*-dodecyl acetate in...
M. okinawensis (Tamaki et al., 1986). Two control methods with pheromone substance, i.e., mass trapping and mating disruption, are potentially useful for controlling M. okinawensis. Arakaki et al. (2008a) evaluated the effect of the mass-trapping of male adults with pheromone traps by conducting a six-year experiment in Ikei Island. Arakaki et al. (2008c) evaluated the effect of mating disruption with pheromones by conducting a seven-year experiment on Minami-Daito Island. The abundance of M. okinawensis greatly decreased in both experiments.

Continuous monitoring of population parameters is indispensable to establish a successful control. The mark-recapture method is useful to estimate the abundance, survival rate, and dispersal ability of adult click beetles. Schallhart et al. (2009) recently used the isotope ratio as a mark for estimating the dispersal of Agriotes beetles. Population parameters of M. okinawensis were first estimated by Kishita et al. (2003). Many marked insects should be released to enhance the precision of estimates; however, we encounter practical problems during release, especially when we use insects reared in the laboratory or brought from other areas. When we release male adults and recapture them using sex pheromones, the released males may mate with wild females, potentially increasing the mean number of eggs laid by wild females by increasing the proportion of mated females. The release of insects becomes especially problematic in the final control phase where the abundance of wild insects becomes relatively small, and may disrupt the successful control of M. okinawensis.

We can avoid the problems caused by the release if we use sterile insects. Irradiation techniques, as well as mass-rearing techniques, are essential parts of the sterile insect technique (SIT), which is frequently used to eradicate insects (Dyck et al., 2005). SIT successfully eradicated the melon fly Bactrocera cucurbitae in Okinawa Prefecture by 1993 (Koyama et al., 2004). Similar procedures are now being applied to the sweetpotato weevil Cylas formicarius elegantulus and West Indian sweetpotato weevil Euscepes postfasciatus (Kuba et al., 2003). For E. postfasciatus, the influence of gamma-radiation on spermatogenesis was examined by Sakurai et al. (2000). Irradiation with 70 Gy of 14-day-old male adults of E. postfasciatus (seminal vesicles filled with sperm in this stage) achieved almost perfect sterilization. Currently, SIT is not applicable to M. okinawensis due to the difficulty of mass-rearing by their relatively long (two- and three-year) life cycles; however, irradiation techniques are equally applicable to M. okinawensis. In this paper, we first clarify the optimal amount of irradiation to achieve sterilization. Irradiation for sterilization may injure not only reproductive cells but also somatic cells (Sakurai et al., 1994, 2000). Hence we further examined the influence of irradiation on the survival rate of M. okinawensis males in the laboratory. The characteristics of the survival rate in the laboratory may be much different from in the field; hence, we next examined the influence of irradiation on the survival rate and dispersal ability of M. okinawensis in the field using mark-recapture methods.

**MATERIALS AND METHODS**

**Sterilization rate.** Larvae of M. okinawensis were collected in sugarcane fields on Okinawa Island in 2000, 2001 and 2002. Collected larvae were reared individually in plastic cups (220 ml) with expanded vermiculite with a piece of sweet potato (1 cm cube) at room temperature and under natural light conditions in Okinawa Prefectural Agricultural Experiment Station (OPAES), Naha City, Okinawa. Sweet potatoes were changed every two weeks until pupation (around December and November). They eclosed to adults about two weeks after pupation, and stayed in the soil until the following spring. One day before irradiation, the adults were sexed by differences in their antennae (Ôhira, 1988). Five different doses of gamma-rays (0, 50, 70, 90, and 150 Gy) from a cobalt-60 source were administered to males on 7 April 2003, at the Melon Fly Sterilization Facility of Okinawa Prefectural Plant Protection Center (OPPC), Naha city, Okinawa. After irradiation, a normal virgin female was confined with two treated males in a plastic cup (220 ml) for mating. Sports drink solution ‘Pokari-Sweat’ (Otsuka Pharmaceutical Company, Tokyo) impregnating a wad of cotton was supplied as food. A piece of wet tissue paper (4 cm²) was supplied as an oviposition substrate, because it is known that females preferably lay eggs on wet tissue papers (Nagamine and Kinjo, 1981). We counted the number of fresh eggs laid on the tissue paper every two days, and trans-
ferred them into separate plastic cups (60 ml). Hatchability was then examined every two days. We calculated the fiducial interval, which is sometimes inappropriately referred to as the 'exact confidence interval', to estimate the true quantity of hatchability (Clopper and Pearson, 1934).

**Effect of the irradiation on the male longevity.** Because of the long life cycle of *M. okinawensis* (Setokuchi et al., 1990), we cannot obtain a large number of males by rearing in the laboratory; therefore, we used collected wild males to examine the influence of irradiation on longevity. Males (approximately 800 beetles) were collected using 20 sex pheromone traps at Itoman City in the early season of their emergence from the ground (5 to 6 April 2003). The insects were stored in semitransparent plastic boxes (34×27×11.5 cm). Diluted sports drink solution impregnating tissue paper was supplied as food, and pieces of sugarcane leaves were supplied for shelter. On the day of irradiation, stored males were divided into batches of 20 males and were confined to plastic cups with tissue paper. Seven different doses of gamma-rays (0, 30, 50, 70, 90, 150 and 200 Gy) were administered to these wild males. In total, 120 males were irradiated for each dose. After irradiation, each male was reared individually in a plastic cup (60 ml) with a wad of cotton impregnated with diluted sports drink solution as food. One hundred males were reared for each treatment to estimate longevity. They were reared at 22°C and 14L10D photoperiod conditions. The wad of cotton with solution was changed once a week. The survival rate was recorded every day until all males had died.

Proportional hazard models are frequently used to analyze longevity in clinical experiments (Ohashi and Hamada, 1995). We analyzed longevity using a proportional hazard model, in which $S_t$ is the proportion of survived individuals in $i$th treatment at time $t$. Hazard, $h_t$, is defined by instantaneous mortality at time $t$, that is,

$$h_t = -\frac{dS_t}{dt} = -\frac{d\log(S_t)}{dt}. \quad (1)$$

The survival rate is then inversely described by

$$S_t = \exp\left(-\int_0^t h_u \, du\right). \quad (2)$$

We assume that the hazard is given by a multiplication,

$$h_t = h_i \exp(T_i), \quad (3)$$

where $h_i$ is the baseline hazard defined by the hazard in a population without irradiation, and $T_i$ is the effect of the $i$th dose of irradiation. By definition, we have $T_i = 0$ for the population without irradiation. This is a type of proportional hazard model, because hazard $h_t$ is always proportional to the baseline hazard $h_i$. We estimated $T_i$ by maximizing the partial likelihood (SAS Institute, 2008a).

**Sex pheromone trap.** The pheromone lure used for attracting male *M. okinawensis* was a polyethylene tube (60 cm length, 2 mm i.d.) that contained 1 ml dodecyl acetate (Tokyo Chemical Industry Co., Ltd., Tokyo). Purity was higher than 95%, and hence the lures were used without further purification. The tube lure was bent into a ring shape (9 cm diam.). A pheromone tube was attached to a funnel trap with crossed vases (15 cm diam.×38.5 cm ht.; Trécé Inc., Salinas, Calif., U.S.A.). Each trap was anchored with wire to a stick (about 1 cm diam.×60 cm ht.) in the ground (Arakaki et al., 2008a).

**Insects.** Male beetles were collected using sex pheromone traps at Itoman City three days before the release experiments. The insects were stored in semitransparent plastic boxes (34×27×11.5 cm). Diluted honey solution impregnated into tissue paper was supplied as food, and pieces of sugarcane leaves were supplied for shelter. One day before the experiments, the pronota and/or elytrae of beetles were marked with an oily fine-tip marker (Paint Marker; Mitsubishi Pencil Co., Ltd., Tokyo). Different marks were used to discriminate the different release dates and different doses of irradiation. From preliminary experiments, the marks were not lost even after insects were caught by traps.

**Influence on dispersal distance in the field.** Dispersal distance was estimated for four different doses of irradiation, 0, 50, 90, and 150 Gy, by gamma-rays from a cobalt-60 source at the Melon Fly Sterilization Facility of OPPC. Experiments were conducted in an agricultural area (81.4 ha) on Ikei Island (158 ha), Uruma City, Okinawa, Japan in April 2003. This island is about 12 km from Okinawa Island, isolated by the sea but connected by bridges (see Fig. 1 in Arakaki et al., 2008a). Sugarcane (26.9 ha) and tobacco (33.1 ha) were the main crops on this island in 2003. Funnel-vane
traps were set on the ground at 870 points in the agricultural area for the purpose of mass-trapping (Fig. 1). Among the traps in the agricultural area, 250 traps were set along a road in a lattice pattern to estimate the dispersal distance (Fig. 1). Three hundred marked beetles were released for each of the four doses on April 1 and 3 (2,400 beetles in total) at the center of the island (Fig. 1). The numbers of marked beetles recaptured by the 250 traps were counted on April 3 and 5. We tested the influence of irradiation on the proportion of the cumulative number of recaptured insects using the Cochran-Mantel-Haenszel test in which two releases were used as strata. We performed the test using JMP statistical software (SAS Institute, 2008b). Differences in the logarithmic distance of traps in which individuals are captured within two days after release were tested by ANOVA where two releases were used as blocks.

Underestimation of dispersal distance is likely when traps are used to record the dispersal distance of released insects, because they shorten the mean dispersal distance itself by intercepting organisms that should have dispersed further. The extent of underestimation may be especially large in our experimental field in which many traps (870 traps) were placed for the purpose of mass-trapping (Fig. 1). Yamamura et al. (2003) proposed a procedure to solve this problem by placing traps uniformly in a lattice pattern, and by assuming a random movement and a constant rate of settlement for organisms. This method is applicable if we recapture released insects for a sufficiently long period. Hence, we applied this method only for the first release where released insects were recaptured for four days. We did not apply the method to the second release, because the released insects were recaptured only for two days after the second release. The Microsoft Excel spreadsheet for this estimation is available at http://cse.niaes.affrc.go.jp/yamamura/Yamamura_et_al_2003_estimation.xls. The likelihood ratio chi-square test was applied to examine the effect of irradiation on mean dispersal distance.

**Influence on survival rate in the field.** In this experiment, we adopted a dose one level higher than the observed lowest dose for sterilization, to absolutely assure perfect sterilization. Survival rates were compared for two doses of irradiation: 0 and 90 Gy. Experiments were conducted in the field of OPAES. One thousand marked males for each treatment were released at the center of a sugarcane field (28.4 a) in the evening at four-day intervals (12, 16, 20, 24 April 2004). Newly sprouted knee-height stalks were growing in the sugarcane field during the experiments. Marked individuals were recaptured by four pheromone traps placed 5 m from the corners of the field, at two-day intervals.

For simplicity, we estimated the survival rate by assuming that the released insects were recaptured just before we examined the traps at four-day intervals using three methods: Jolly-Seber, Yamamura, and Yamamura B (Seber, 1982; Yamamura et al., 1992; Yamamura, 2003). We used multiple meth-

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**Fig. 1.** Arrangement of 250 traps (solid circles) used to evaluate dispersal distance. Open circles indicate traps used for mass-trapping. Arrow indicates the release point.
ods because they have complementary characteristics. The Jolly-Seber method is based on the restrictive assumption that the survival rate does not depend on the released population. The Yamamura method is based on different restrictive assumptions that the survival rate and the wild population size is kept constant during the experiment. The Yamamura B method is based on other restrictive assumptions in which the survival rate and the proportion of recapture is kept constant during the experiment; hence, the selection of best method changes depending on experimental conditions (Arakaki et al., 2008b). Released insects are continuously recaptured by traps, and hence these estimates include some biases even if other assumptions of the models are satisfied. Our current purpose is to estimate the influence of irradiation on the survival rate rather than absolute survival rate. Hence, bias will not largely influence our conclusion. We can estimate the SE of differences between the two survival rates from the square root of the sum of squares of SEs of two estimates of those rates. It can be judged that irradiation significantly influences the survival rate by $p < 0.05$ if the estimated difference $\pm 1.96 \times SE$ does not contain zero. The 90% confidence intervals of difference should be calculated to show the equivalent survival rate (Manly, 2001). We can calculate the 90% confidence intervals by the estimated difference $\pm 1.64 \times SE$.

RESULTS

Sterilization rate

The mean numbers of eggs ($\pm SE$) laid by females mated with males treated with 0, 50, 70, 90 and 150 Gy were 97.9±20.0, 83.9±17.4, 135±36.7, 202±40.1 and 130.4±29.3, respectively. Linear regression analysis of $\log_e$ (eggs$^{0.5}$) indicated no significant influence of dose ($p=0.39$).

The observed hatchability of eggs laid by females mated with untreated males ranged from 89.5 to 100% (Table 1). The 95% fiducial range was 92.8 to 95.7%. Small percentages of eggs hatched when males were treated with 50 Gy; however, no eggs hatched when males were treated with doses of 70, 90 and 150 Gy. The upper 95% fiducial limit was 0.3% with these doses at most (Table 1); hence, hatchability was shown to be sufficiently small if we used doses larger than 70 Gy.

Influence on survival rate in the laboratory

The observed mean longevity consistently decreased with increasing dose (Table 2). Analyses using the proportional hazard model indicated that irradiation significantly enhanced the hazard at all doses ($p$-value in Table 2); however, the differences between survival curves for 70, 90, and 150 Gy are not so clear (Fig. 2). The estimate of $T_i$ did not consistently increase from 70 to 150 Gy (Table 2) probably due to errors included in the estimation. The survival rates were greater than 90% within 12 days for all males, except for those with 200 Gy irradiation (85%; Fig. 2).

<table>
<thead>
<tr>
<th>Dose of irradiation (no. of replications)</th>
<th>0 Gy (9)</th>
<th>50 Gy (7)</th>
<th>70 Gy (8)</th>
<th>90 Gy (10)</th>
<th>150 Gy (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean hatchability of eggs (mean no. of eggs laid)</td>
<td>94.4 (97.9)</td>
<td>14.4 (83.9)</td>
<td>0 (135.0)</td>
<td>0 (202.2)</td>
<td>0 (130.4)</td>
</tr>
<tr>
<td>95% fiducial limit (%)</td>
<td>95UL 95.7 (15.6)</td>
<td>0.3 (0.2)</td>
<td>0.3 (0.3)</td>
<td>95LL 92.8 (10.0)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dose</th>
<th>Mean longevity (days) ± SE</th>
<th>$T_i$</th>
<th>SE</th>
<th>Wald chi-square</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Gy</td>
<td>36.1±1.4</td>
<td>——</td>
<td>——</td>
<td>——</td>
<td>——</td>
</tr>
<tr>
<td>30 Gy</td>
<td>26.1±0.9</td>
<td>0.751</td>
<td>0.248</td>
<td>9.2</td>
<td>0.0024</td>
</tr>
<tr>
<td>50 Gy</td>
<td>22.6±0.7</td>
<td>1.330</td>
<td>0.268</td>
<td>24.7</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>70 Gy</td>
<td>22.3±0.6</td>
<td>1.505</td>
<td>0.284</td>
<td>28.0</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>90 Gy</td>
<td>20.9±0.5</td>
<td>1.823</td>
<td>0.292</td>
<td>38.9</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>150 Gy</td>
<td>20.5±0.5</td>
<td>1.561</td>
<td>0.292</td>
<td>28.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>200 Gy</td>
<td>17.5±0.6</td>
<td>1.909</td>
<td>0.292</td>
<td>42.8</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Table 1. Influence of irradiation on the proportion (%) of hatched eggs laid by *M. okinawensis* females mated with males which were irradiated with four different doses of gamma-rays: 50, 70, 90, and 150 Gy. 95UL and 95LL indicate the upper 95% fiducial limit (in percentage) and lower 95% fiducial limit (as a percentage), respectively.

Table 2. Influence of irradiation on longevity in the laboratory. Parameter $T_i$ is estimated in the proportional hazard model. The $p$-value is for testing the null-hypothesis that the survival curve is the same as that for 0 Gy.
Influence on dispersal distance in the field

The proportion of the cumulative number of insects recaptured within two days after release was larger in the second release experiment (Table 3). We could not detect significant differences in the proportions of recaptured individuals from four different treatments (Cochran-Mantel-Haenszel chi-square = 3.44, df = 3, p = 0.329), although the proportion was largest at 0 Gy for both releases. The average distance of traps in which individuals were captured within two days after release was about 140 m (Table 3). We could not find a significant influence of dose on the average distance ($F = 0.412, df = 3, p = 0.745$), although the maximum distance of recaptured traps was shortest at 150 Gy for both releases. The estimate of the mean dispersal distance was about 240 m (Table 3). The likelihood ratio test indicated no significant influences of dose on the mean dispersal distance (likelihood ratio chi-square = 3.609, df = 3, p = 0.307).

Influence on survival rate in the field

Table 4 indicates that the three methods yielded similar estimates of the survival rate on average in our current experiment. Thus, the assumptions of the three methods seem to have been mostly satisfied in this experiment.

The differences in the average survival rates between the treatments of 0 and 90 Gy doses are estimated to be 0.008 for the Jolly-Seber method, 0.064 for the Yamamura method, and 0.017 for the Yamamura B method. We could not detect significant differences in the two survival rates for any of the three methods ($p > 0.05$). The estimated confidence intervals are −0.052 to 0.069 for the Jolly-Seber method, −0.018 to 0.147 for the Yamamura method, and −0.040 to 0.074 for the Yamamura B method. These differences in survival rates were estimated to be small, although not exactly zero.

DISCUSSION

Our purpose was to find the optimal dose of gamma-rays to obtain sterile males to estimate the population parameters (such as abundance and survival rate) in various fields by releasing sterile males in mark-recapture experiments. Sterilization should be complete so that released males do not induce practical problems by increasing the mating rate of females in the field; however, the estimates from mark-recapture experiments will be biased if released males have a lower survival rate or shorter dispersal distance due to the influence of irradiation. We showed that irradiation at 70 Gy induces

![Fig. 2. Survival rates of males in the laboratory (N=100) treated with seven different doses of irradiation: 0, 30, 50, 70, 90, 150 and 200 Gy.](image)

Table 3. Influence of irradiation on the proportion of recaptured individuals and the dispersal distance of male *M. okinawensis* in the field

<table>
<thead>
<tr>
<th>Dose (Gy)</th>
<th>First release April 1, 2003</th>
<th>Second release April 3, 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of males released</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>No. of males recaptured</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>Proportion of recaptured insects (%)</td>
<td>8.3</td>
<td>6.3</td>
</tr>
<tr>
<td>Mean dispersal distance of recaptured insects (m)</td>
<td>144</td>
<td>124</td>
</tr>
<tr>
<td>Maximum dispersal distance of recaptured insects (m)</td>
<td>568.4</td>
<td>500</td>
</tr>
<tr>
<td>Estimates of mean dispersal distance (m)</td>
<td>274</td>
<td>219</td>
</tr>
<tr>
<td>SE of mean dispersal distance (m)</td>
<td>57</td>
<td>45</td>
</tr>
</tbody>
</table>

*a* Calculated from the cumulative number of insects recaptured within two days after release.

*b* Calculated from the cumulative number of insects recaptured within four days after release.
sufficient sterilization for *M. okinawensis* males (Table 1); however, the proportional hazard model indicated that irradiation significantly reduced the survival rate in the laboratory even if the dose was 30 Gy (Table 2). In contrast, we could not detect significant differences in survival rates in the field (Table 4). The average survival rate per 4 days was around 24% for both irradiated and non-irradiated males. We also could not detect significant differences in the mean dispersal distance in the field (Table 3).

We thus reached apparently different conclusions on the survival rate between laboratory and field experiments. We should carefully examine the relation between two types of mortality: laboratory mortality and field mortality. Let, $h_i$ and $V_i$ be the hazard and survival rate for the $i$th dose at time $t$ in the field, respectively. In estimating the mean dispersal distance using the method of Yamamura et al. (2003), we implicitly assumed that the mortality is constant irrespective of age. That is, 

$$\eta_i = \tau_i,$$

where $\tau_i$ is the constant field hazard for $i$th treatment. The survival rate at time $t$ is then given by

$$V_i = \exp(-\tau_i t).$$  \hfill (4)

Field mortality includes mortality caused by irradiation and mortality added in the field. Using Eqs. (2) and (4), we can divide $V_i$ into the following two components, assuming that the added field mortality is independent of laboratory mortality.

$$V_i = \exp \left( -\int_0^t h_i(t) \, dt + \int_0^t h_i(t) \, dt - \tau_i t \right).$$  \hfill (5)

where the first term within the exponential, $-\int_0^t h_i(t) \, dt$, indicates the hazard by irradiation, while the second term, $-\int_0^t h_i(t) \, dt - \tau_i t$, indicates the hazard added in the field. Figure 2 indicates that the survival rate in the laboratory, $\exp(-\tau_i t)$, is above 90% within 12 days, except in the 200 Gy experiment. Hence, the cumulative hazard by laboratory mortality, $-\int_0^t h_i(t) \, dt$, is smaller than $-\log_{10}(0.9)=0.11$ within 12 days. Table 4 indicates that the survival rate per 4 days in the field, $\exp(-4 \tau_i)$, is around 24% within 12 days after re-
lease for both 0 and 90 Gy irradiation. Hence, the cumulative hazard by field mortality within 12 days, \( 12 \tau_e \), is around \(-(12/4) \times \log(0.24) = 4.28 \) within 12 days; therefore, the hazard added in the field is estimated to be larger than \( 4.28 - 0.11 = 4.17 \). The added field hazard is much greater than the hazard caused by irradiation if we focus on mortality within 12 days. Hence, we can conclude that the influence of mortality by irradiation is negligible when we use sterile males in mark-recapture experiments in the field within 12 days after release, if the dose is smaller than 150 Gy. We achieved sufficient sterilization at 70 Gy (Table 1), but the efficiency of sterilization may fluctuate around 70 Gy. Hence, we can conclude that 90 Gy will be an appropriate dose of irradiation.

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