

# Can a Semiochemical-Based Trapping Method Diminish Damage Levels Caused by *Rhabdoscelus obscurus* (Coleoptera: Curculionidae)?

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Ann. Entomol. Soc. Am. 105(5): 693–700 (2012); DOI: <http://dx.doi.org/10.1603/AN12044>

**ABSTRACT** The New Guinea sugarcane weevil, *Rhabdoscelus obscurus* (Boisduval) (Coleoptera: Curculionidae), is an important pest of palms, ornamental nurseries, and sugarcane in the Pacific Islands. Without effective control methods, *R. obscurus* populations can cause major or complete loss of palm production in Guam and other Micronesian Islands. Moreover, *R. obscurus* has inflicted severe attacks on coconut trees on Guam. The role of monitoring is important in judging the dynamics of *R. obscurus* and recording area wide population trends. There is no precise research information available on the trap catch threshold levels relative to the damage caused by *R. obscurus*. Here we investigated the assessment of trap catch threshold levels and the potential for predicting *R. obscurus* larval damage by using adult pheromone trap captures. Spatial patterns of capture were studied in relation to subsequent larval damaged betel nut plants at various locations in Guam, United States, during 2010–2012. The generalized additive model was used to describe the effects of the treatment level (traps/ha), ranging from 0 to 12, and time on reducing the damage of *R. obscurus* to palms. We find that these two predictors are statistically significant, and the treatment level is demonstrated to be the crucial predictor for reducing the damage. There is no significant difference in effectively controlling the damage between the treatment levels of 9 and 12 traps/ha. At least 9 traps/ha is suggested for effectively controlling the damage based on results from the current study.

**KEY WORDS** binary response, response proportion, generalized additive model, palm, *Rhabdoscelus obscurus*

The New Guinea sugarcane weevil, *Rhabdoscelus obscurus* (Boisduval) (Coleoptera: Curculionidae), is a well-known pest of palms (*Hyophorbe lagenicaulis* (Bailey), *Pritchardia pacifica* (Seem & H. Wendl), *Phoenix roebelenii* O'Brien, *Archontophoenix alexandrae* (F. Muell.) H. Wendl. & Drude, *Roystonea regia* (Kunth) O.F. Cook, *Phoenix canariensis* Hort. ex Chaubaud, *Areca catechu* L. (*Cocos nucifera* L.), and ornamental nurseries throughout the world (Muniappan et al. 2004). In recent years the cultivation of ornamental nurseries and betel nut has increased markedly in the Pacific Islands. Therefore, *R. obscurus* have become an important pest insect. The larvae of this beetle feed on various species of palms, causing high mortality of the trees. In sugarcane growing regions they are an important pest of that crop, boring into the stems and causing substantial losses (Bianchi and Owen 1965). In coconuts they bore into the base of the trunk and can weaken the tree resulting in it being blown down in high winds. In betel nut they often bore near the

growing tip of the tree that can kill the tree (Reddy et al. 2011).

Trapping studies conducted over several years indicate that populations are high throughout Guam (Muniappan et al. 2004; Reddy et al. 2005, 2011). As a result, Guam and other Micronesian Islands are in the midst of a decline of palms as this weevil becomes a more serious pest. According to local growers and the Guam Department of Agriculture, thousands of palms in this region have been affected by *R. obscurus*. While some control methods occur, chemical application is both undesirable and expensive. Without appropriate effective control, weevil populations are likely to cause major or complete loss of palm production in Guam and other Micronesian Islands. Moreover, *R. obscurus* has inflicted severe attacks on coconut trees on Guam (Reddy et al. 2011). The role of monitoring is important in judging the dynamics of *R. obscurus* and recording area-wide population trends (Sallam et al. 2004).

The feeding habits of the larvae, which are cryptic in nature, and the nocturnal activity of the adults (Napompeth et al. 1972) make detection and control of infestations difficult (Robertson and Webster 1995). Pheromone-based mass trapping of adult borers of *R. obscurus* is an effective method of monitoring populations, and may also impact population densities (Sallam et al. 2007). In addition, pheromone and ethyl

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Table 1. Summary of study sites

Treatment details	Locations	Geographic locations
Treatment 1: (control/no traps)	Latte Heights	13° 29'30.43" N; 144° 50'35.60" E; 124.1 m, a.s.l. <sup>a</sup>
	Dededo	13° 29'47.09" N; 144° 50'56.43" E; 133.5 m, a.s.l.
Treatment 2: (1 trap/ha)	Inarajan	13° 15'15.49" N; 144° 43'18.03" E; 27.1 m, a.s.l.
	Yigo	13° 31'51.96" N; 144° 52'17.55" E; 134.7 m, a.s.l.
	Talofoto	13° 23'01.20" N; 144° 46'20.58" E; 6.7 m, a.s.l.
Treatment 3: (3 traps/ha)	Agat	13° 20'57.62" N; 144° 39'12.06" E; 74.4 m, a.s.l.
	Yoa	13°23'49.31" N; 144° 46'05.58" E; 70.0 m, a.s.l.
	Merizo	13° 15'02.50" N; 144° 43'02.28" E; 2.1 m, a.s.l.
Treatment 4: (6 traps/ha)	Barrigada	13° 28'01.01" N; 144° 48'02.73" E; 61.9m, a.s.l.
	Mongmong-Toto-Maite	13° 28'13.21" N; 144° 46'07.74" E; 19.2m, a.s.l.
	Mangilao	13° 26'58.57" N; 144° 48'44.27" E; 79.6 m, a.s.l.
Treatment 5: (9 traps/ha)	Malojloj	13° 19'23.58" N; 144° 45'53.11" E; 76.8 m, a.s.l.
	Agaa Heights	13° 28'09.62" N; 144° 44'49.04" E; 49.4 m, a.s.l.
	Asan	13° 28'17.17" N; 144° 42'29.07" E; 6.7 m, a.s.l.
Treatment 6: (12 traps/ha)	Santa Rita	13° 23'36.40" N; 144° 42'39.73" E; 147.2 m, a.s.l.
	Umatac	13° 17'54.65" N; 144° 39'52.10" E; 3.4 m, a.s.l.
	Tamuning	13° 30'04.69" N; 144° 46'15.53" E; 31.1m, a.s.l.
	Hagata	13° 28'35.77" N; 144° 44'18.85" E; 1.8 m, a.s.l.

<sup>a</sup> a.s.l., above sea level.

acetate lures have been effective in detecting invasions at even low population levels, so attention, in the recent past, has focused on synthetic semiochemical-based lures as a potential component of control of *R. obscurus* (Reddy and Guerrero 2004, 2010). Giblin-Davis et al. (2000) identified the pheromone of Hawaiian *R. obscurus* as 2-methyl-4-octanol and the equivalent pheromone compounds for Australian *R. obscurus* population as 2-methyl-4-octanol, (*E2*)-6-methyl-2-hepten-4-ol (rhynchophorol), and 2-methyl-4-heptanol, but 2-methyl-4-heptanol was not included in their trapping method for *R. obscurus* because it elicited no behavioral effect. The addition of ethyl acetate to the pheromone lures as a synergist significantly increased trap catches of *R. obscurus*, but did not help in controlling *R. obscurus* (Reddy et al. 2005). Additional studies conducted by Reddy et al. (2011) to improve the capture efficiency showed that 40 by 25-cm russet brown ground traps baited with pheromone lures and strapped to the trees are an efficient tool for catching *R. obscurus* in the field. Contrariwise, the authors further reported that indoors, black, but otherwise identical, traps were the most effective. However, there is no precise research information available on the trap catch threshold levels relative to the damage caused by *R. obscurus*.

Here we provide evidence on whether semiochemical-based lures, developed recently by Reddy et al. (2011), can reduce the damage caused by *R. obscurus*.

## Materials and Methods

**Study Sites and Time.** These experiments were carried out over the course of 2 yr, from 11 January 2010 to 13 December 2011. They occurred on the island of Guam (United States) at different locations as shown in Table 1. A large part of the land area of these locations is covered mostly by betel nut palm (*Areca catechu* L., family, Arecaceae (Palmae)), which was used for conducting these tests.

**Trap Type Used.** The russet brown ground traps with 40- × 25-cm size were constructed in our laboratory from a piece of white corrugated plastic board (Reddy et al. 2011). The lower outer edges of the ground traps were shielded with soil to prevent weevils from crawling under the traps. Because the adult has shown a preference for crawling down the tree to enter the trap (Reddy et al. 2005), traps were placed on the ground and secured to the host plants with an aluminum wire. Pheromone and ethyl acetate lures were suspended inside the traps on wires hung from the top. Two cut pieces of sugarcane, 12 cm long, were placed directly in the trap and replaced with fresh canes weekly. The inside bottom of the trap was treated with one 5-ml spray of carbaryl (2 ml/liter) to kill the attracted *R. obscurus*. Lures were changed at 4-mo intervals (Reddy et al. 2005).

**Semiochemical-Based Lures.** The pheromone and ethyl acetate lures (Product Code: P080K-inert plastic matrix in Food Grade Plastic Pouch, active ingredient 90% WW) were purchased from ChemTica Internacional S.A. (San José, Costa Rica), and were stored in a refrigerator until use. The pheromone lures ((*E2*)-6-methyl-2-hepten-4-ol and 2-methyl-4-octanol) (1:1) mixture in plastic pouch release devices are optimized for the Australian population of *R. obscurus*. The release rates and method of use of these lures were as previously described (Reddy et al. 2005).

**Treatment Details.** In each location, 1 ha area was identified and marked for conducting the experiments. Russet-brown colored ground traps with semiochemical-based lures were installed in each location in a single line spaced 60 m apart. The following treatments were deployed: T-1 (Control/No traps), T-2 (1 trap/ha), T-3 (3 traps/ha), T-4 (6 traps/ha), T-5 (9 traps/ha), and T-6 (12 traps/ha). Each treatment was replicated in three locations.

**General Trapping Method.** Traps with pheromone and ethyl acetate lures were placed on the ground and strapped to the betel nut trees as shown in Fig. 1.



Fig. 1. Trap type used in the current study. (Online figure in color.)

Trapped *R. obscurus* were counted and removed weekly. The traps were washed, rinsed, and new fresh cut sugarcane was added (Reddy et al. 2011).

**Sampling Method.** Damage in terms of larval holes were recorded monthly from within one hectare surrounding each trapping area by dividing the area into four 10 × 10 m quadrats. Within each quadrat, two random plants were chosen for recording the number of larval holes within that square. Sample universe is the field, four samples were taken at random, and the physical size of the unit was a 10 × 10 m quadrat. Therefore, eight plants/location/trapping areas represents total of 24 plants/3 locations/treatment.

**Data Analyses.** The generalized additive model (GAM; Hastie and Tibshirani 1990, Chambers and Hastie 1991) was used to analyze the effects of treatment level (traps/ha) and time (11 January to 13 December 2011) on the number of larval holes per palm; (ii) the effects of treatment level and time on the binary response of protection effect ( $y$ ), which is defined as:

$$y = \begin{cases} 1 & \text{if } x < 10 \\ 0 & \text{if } x \geq 10 \end{cases}$$

where  $x$  represents the number of larval holes per palm. Here, 10 larval holes are assumed to be the critical value for the protection effect. In the Discussion section, we will consider the feasibility of this assumption. For a given treatment level, there are in total eight palms at a location at a time point. The sum of the binary response of the protection effect is  $\sum y_i > 8$ . Thus, we can define the response proportion of the protection effect ( $p$ ) as:

$$p = \left( \sum_{i=1}^8 y_i \right) / 8$$

Here, the subscript  $i$  represents the  $i$ -th palm. It represents the proportion of palms whose larval hole number  $< 10$  at a locality. For a given trap density, there are totally eight palms at a locality at a time point. Response proportion reflects the protection effect of trap density.

For the analysis of the number of larval holes to two predictors, treatment level (traps/ha) and time, the following equation was built:

$$\ln(\text{Number}) = s(\text{Treatment}) + s(\text{Time})$$

Here, Number represents the number of larval holes per palm; Treatment represents the treatment level (traps/ha) at a specific time. Time represents the time span (days) from 11 January 2010;  $s$  is the smooth term. The generalized additive model is fit using the local scoring algorithm, which iteratively fits weighted additive models by back fitting. The back-fitting algorithm is a Gauss-Seidel method for fitting additive models, by iteratively smoothing partial residuals (Hastie and Tibshirani 1990). For inspecting whether the single predictor of treatment level (traps/ha) can significantly affect the damage of this pest insect to palms, the following equation was used:

$$\ln(\text{Number}) = s(\text{Treatment})$$

For the analysis of the response proportion to the two predictors, treatment level and time, the equation was built:

$$\text{logit}(p) = \ln\left(\frac{p}{1-p}\right) = s(\text{Treatment}) + s(\text{Time})$$

Here,  $p$  is the response proportion of protection effect as defined above.

To check whether the treatment level (traps/ha) is the crucial predictor for the response proportion of

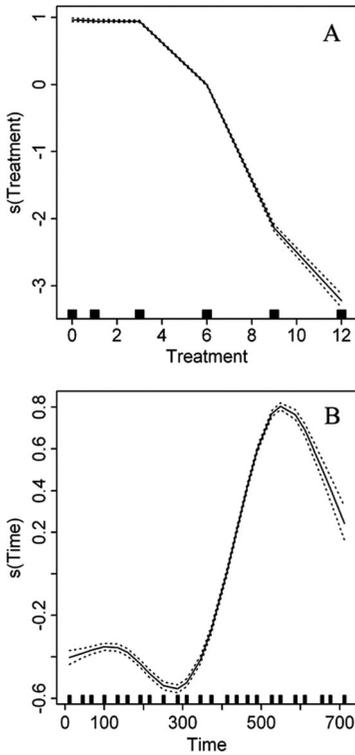


Fig. 2. The additive Poisson fit of the number of larval holes per palm to two predictors: treatment level (traps/ha) and time (days). The dashed curves are pointwise twice SE bands. The figures are plotted on the log scale, and each plot represents the contribution of that variable to the fitted log.

the protection effect, we used the GAM to analyze the relationship between the response proportion and the single variable of treatment level. That is:

$$\text{logit}(p) = \ln\left(\frac{p}{1-p}\right) = s(\text{Treatment})$$

The statistical software package of GAM based on R was used to carry out the fit of GAM. It is available and can be obtained at <http://cran.r-project.org/web/packages/gam/index.html>.

Results

The additive Poisson fit analysis of the data for 2 yr (2010 and 2011) indicated that the number of semio-

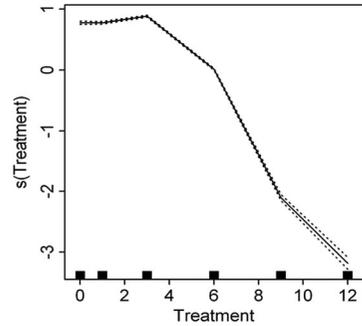


Fig. 3. The additive Poisson fit of the number of larval holes per palm to one predictor of treatment level (traps/ha). The dashed curves are pointwise twice SE bands. The figure is plotted on the log scale.

chemical-based traps and time can explain the number of larval holes per palm caused by *R. obscura* (Fig. 2; Table 2). The coefficient of determination (i.e.,  $r^2$ ) reaches 0.88 for a sample size of 3,024. When dropping the variable of time, Akaike information criterion (AIC) increases from 20,845 to 34,078 (approximately increasing 63.5%), and the coefficient of determination largely decreases. Figure 3 displays the GAM fit of the number of larval holes per palm to the single predictor of treatment level (traps/ha). It indicates that only using one predictor of treatment level is worse than using two predictors of treatment level and time to predict the number of larval holes per palm. Time also has a significant influence on the latter. From mid-October 2010 to the beginning of July 2011, the time predictor has an approximately linear positive effect on the number of larval holes per palm. Then the effect of time becomes negative from July 2011 onward. The above results imply that the absolute number of larval hole per palms cannot be perfectly described by the single predictor of treatment level (traps/ha) although its influence is significant. However, the above results do not consider the fact that every eight palms come from the same location at a time point. Thus, using the response proportion appears to be comprehensive because it is based on the count of location groups each made up of eight palms.

The additive logistic fit analysis of the data for 2 yr (2010 and 2011) also indicated that the number of semiochemical-based traps and time can explain the response proportion of the protection effect (Fig. 4; Table 3). These two predictors are also statistically

Table 2. The GAM fit of the no. of larval holes per palm

	df	Npar df	Npar Chisq	P(Chi)	AIC	$r^2$
Two predictors <sup>a</sup>						
(Intercept)	1				20,845	0.88
s(Treatment)	1	3	6,246.4	<2.2e-16		
s(Time)	1	3	5,378.9	<2.2e-16		
One predictor <sup>b</sup>						
(Intercept)	1				34,078	0.42
s(Treatment)	1	3	7,097.9	<2.2e-16		

<sup>a</sup> For the GAM model with two predictors: null deviance is 6,4287.45 on 3,023 df; residual deviance is 11,503.82 on 3015 df.

<sup>b</sup> For the GAM model of one predictor: null deviance is 64,287.45 on 3,023 df; residual deviance is 24,744.72 on 3,019 df.

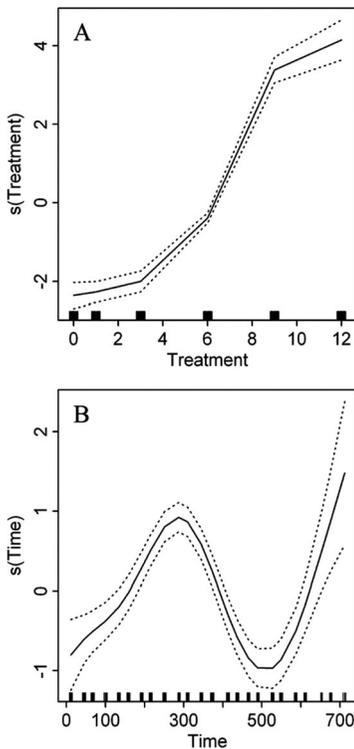


Fig. 4. The additive logistic fit of response proportion to two predictors: treatment level (traps/ha) and time (days). The dashed curves are pointwise twice SE bands. The figures are plotted on the logit scale, and each plot represents the contribution of that variable to the fitted logit.

significant, and they can explain 82% of the null deviance.  $r^2$  reaches 0.90 for a sample size of 378 (from 3024/8). When dropping the predictor of time, AIC only increases from 605 to 775 (increasing  $\approx 28\%$ ; see Table 3 for details). The coefficient of determination calculated by using a single predictor of treatment level (traps/ha) is equal to 0.85, which displays a good fit (Fig. 5). The response proportion at different treatment levels (from 1 to 12) can be estimated: 0.08, 0.09, 0.10, 0.13, 0.19, 0.35, 0.64, 0.87, 0.95, 0.97, 0.98, and 0.98. We find that the response proportion of the protection effect can exceed 0.90 when the treatment level = 9 traps/ha. Although the treatment level of eight traps/ha can make the response proportion approximate 0.90, conservatively, we suggest that at least nine

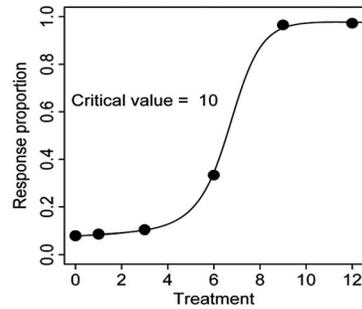


Fig. 5. The effect of treatment level (traps/ha) on response proportion (=the number of palms with larval hole number <10–8). The point each treatment level represents the mean of response proportions at the corresponding treatment level.

traps/ha are needed for diminishing the damage by *R. obscurus*. The Kolmogorov–Smirnov test (Xue and Chen 2007) was used to test whether there are significant differences in the response proportions among different treatment levels. There is no significant difference between 9 traps/ha and 12 traps/ha ( $D = 0.0278$ ;  $P$  value = 1). However, there is a significant difference between 9 traps/ha (or 12 traps/ha) and a lower treatment level such as 1, 3, and 6 traps/ha.

Discussion

Our results indicate that there was a positive relationship between amount of larval damage and trap catches in both years tested. This is predictable as larvae of *R. obscurus* are found within a single betel nut plant, rather than migrating between plants. Our results agree with Sallam et al. (2007) who reported an estimation of the exact number of traps required per hectare to influence the weevil population in a given area is not realistic. This is because numerous factors affect population trends among various seasons and locations, and borer movement is a dynamic progression as emigration and migration can occur among the adult weevils (Veitch 1917, Mungomery 1937, Sallam et al. 2007). Our results indicated that 9 trap/ha significantly reduced the larval damage by *R. obscurus* compared with other trap numbers used. There is also no significant difference between 9 and 12 traps/ha, so we recommend to use 9 traps/ha for the control of *R.*

Table 3. The GAM fit of the response proportion of protection effect

	df	Npar df	Npar Chisq	P(Chi)	AIC	$r^2$
Two predictors <sup>a</sup>						
(Intercept)	1				605	0.90
s(Treatment)	1	3	161.4	<2.2e-16		
s(Time)	1	3	169.9	<2.2e-16		
One predictor <sup>b</sup>						
(Intercept)	1				775	0.85
s(Treatment)	1	3	160.5	<2.2e-16		

<sup>a</sup> For the GAM model with two predictors: null deviance is 3,120.8 on 377 df; residual deviance is 570.34 on 369 df.

<sup>b</sup> For the GAM model of one predictor: null deviance is 3,120.8 on 377 df; residual deviance is 748.42 on 373 df.

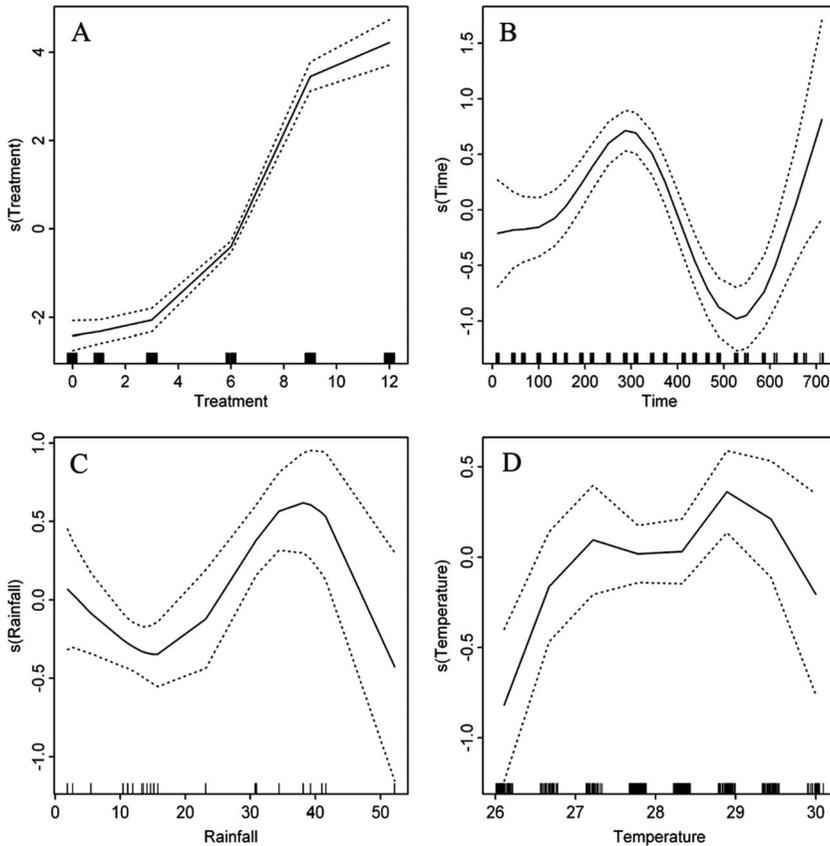


Fig. 6. The additive logistic fit of response proportion to four predictors: treatment level (traps/ha), time (days), monthly rainfall (cm), and monthly average air temperature ( $^{\circ}\text{C}$ ). The dashed curves are pointwise twice SE bands. The figures are plotted on the logit scale, and each plot represents the contribution of that variable to the fitted logit.

*obscurus*. Similar such results were obtained by Oehlschlager et al. (1995) in the case of *Rhynchophorus palmarum* (L.) where constant pheromone trapping in oil palm orchards over several months at a density of about 6 traps/ha resulted in significantly reduced trap catches over time and dropped the occurrence of red-ring disease, which is associated with weevil infestation. Sallam et al. (2007) recommended placing water traps at the edge of the fields or under the shade of trees adjacent to targeted paddocks. The authors suggested that the method should be adopted early in the season (November–December).

It has been demonstrated that temperature can notably affect the population dynamics of insects (Stige et al. 2007, Friedenberget al. 2008, Shi et al. 2011b). The monthly average air temperature in Guam during 2010–2011 ranged from 26.94 to 29.11 $^{\circ}\text{C}$  (see <http://www.nws.noaa.gov/climate/index.php?wfo=guam>). For most insects and mites, development rate increases approximately linearly over the range of 20–30 $^{\circ}\text{C}$  (Ikemoto 2005, Shi et al. 2011a). In addition, rainfall directly affects the relative humidity of habitat, which was demonstrated to have a significant influence on the development, survival, and reproduction of some insects and mites (Sánchez-Ramos et al. 2007, Pappas et al. 2008). Thus, we added two predic-

tors of monthly rainfall and monthly average air temperature to the response proportion model. After carrying out the GAM fit (Fig. 6), all four variables (i.e., treatment level, time, monthly rainfall, monthly average air temperature) were statistically significant. However, AIC only decreases from 605 (obtained from the GAM model with two predictors; see Table 3) to 594.5 (decreasing only 1.7%). That is to say, the effects of rainfall and temperature on the response proportion are so weak that we could neglect them.

In the response proportion model, we defined 10 larval holes as the critical value of the protection effect. In fact, this assumption is made for simplicity to use the GAM model. We also chose 6, 8, 12, and 14 as the critical values to test whether changing the original assumption of 10 can affect the conclusion that at least 9 traps/ha could effectively diminish the damage of *R. obscurus*. We found that the conclusion still holds under these assumptions of critical values (Fig. 7). Although the predicted response proportions at the treatment levels <9 traps/ha changes for these different critical values, especially at the treatment of 6 traps/ha, the predicted response proportions at the treatment levels of 9 and 12 traps/ha are still  $\approx 1$ . That is, at these two treatment levels, the damage of *R.*

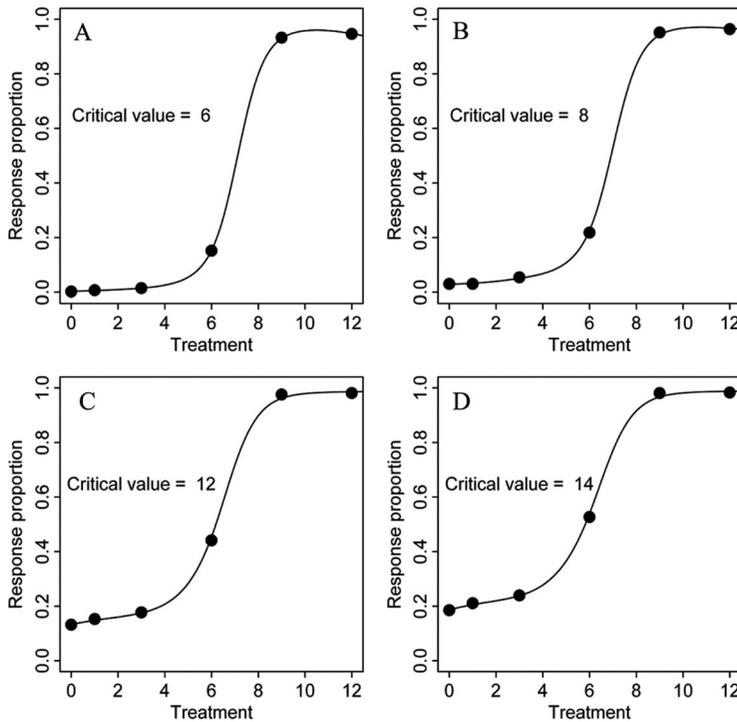


Fig. 7. The effects of treatment level (traps/ha) on response proportion under the assumptions of different critical values. The point each treatment level represents the mean of response proportions at the corresponding treatment level. The coefficients of determination ( $r^2$ ) based on these critical values are: 0.89, 0.88, 0.79, and 0.72, respectively.

*obscurus* is still predicted to be very minor. When the critical value is assumed to be smaller, the GAM model can fit the data better based on the coefficients of determination. For these critical values, the GAM model displays the superior fitting flexibility for the observations. The predicted values are very approximate to the means of the response proportions for any critical value. The critical values  $>14$  were not considered because the predicted response proportion at the treatment of 6 traps/ha is  $>0.5$ . That means, at such a treatment level, some palms should be living. However, we did not observe any living palms at such a treatment level. Thus, the critical value  $>14$  appears not to be sound. The conclusions in the Results section still hold for these critical values. Even though the critical value was smaller than 10, it would not diminish the crucial conclusions from the current study that 1) the treatment level and time are two important variables for describing the damage of *R. obscurus*, and the former is the crucial variable for the response proportion of the protection effect, and 2) at least 9 traps/ha are needed for effectively reducing the damage of *R. obscurus*.

#### Acknowledgments

This project was supported by FY 2009 Pacific Islands Area Conservation Innovation Grants (PIA-CIG) Program, Grant Agreement no. 69-9251-9-822, The Natural Resources Conservation Service–U.S. Department of Agriculture (NRCS–USDA) and USDA Hatch funds (Project no. GUA0561). In

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#### References Cited

- Bianchi, F. A., and R. P. Owen. 1965. Observations on *Rhabdoscelus obscurus* (Boisduval) and *Rhabdoscelus asperipennis* (Fairmaire) in Micronesia (Coleoptera: Curculionidae). Proc. Hawaiian Entomol. Soc. 19: 77–82.
- Chambers, J. M., and T. J. Hastie. 1991. Statistical models in S., pp. 249–307. Chapman & Hall, London, United Kingdom.
- Friedenberg, N. A., S. Sarkar, N. Kouchoukos, R. F. Billings, and M. P. Ayres. 2008. Temperature extremes, density dependence, and southern pine beetle (Coleoptera: Curculionidae) population dynamics in east Texas. Environ. Entomol. 37: 650–659.
- Giblin–Davis, R. M., R. Gries, B. Crespi, L. N. Robertson, A. H. Hara, G. Gries, C. W. O'Brien, and H.D.J.R. Pierce. 2000. Aggregation pheromones of two geographical isolates of the New Guinea sugarcane weevil, *Rhabdoscelus obscurus*. J. Chem. Ecol. 12, 2763–2780.
- Hastie, T. J., and R. J. Tibshirani. 1990. Generalized additive models, pp. 136–171. Chapman & Hall, London, United Kingdom.
- Halfpapp, K. H., and R. I. Storey. 1991. Cane weevil borer, *Rhabdoscelus obscurus* (Coleoptera: Curculionidae), a pest of palms in Northern Queensland, Australia. Principes 35: 199–207.
- Ikemoto, T. 2005. Intrinsic optimum temperature for development of insects and mites. Environ. Entomol. 34: 1377–1387.

- Mungomery, R. W. 1937. Progress report of sugarcane beetle borer investigations in north Queensland. Proc. Queensl. Soc. Sugar Cane Tech. 8: 49–62.
- Muniappan, R. J., J. Bamba, J. Cruz, and G.V.P. Reddy. 2004. Field response of Guam populations of the New Guinea sugarcane weevil, *Rhabdoscelus obscurus* (Boisduval) (Coleoptera: Curculionidae), to aggregation pheromones and food volatiles. Micronesica 37: 57–68.
- Napompethet, B., T. Nishida, and W. C. Mitchell. 1972. Biology and rearing methods of the New Guinea sugarcane weevil, *Rhabdoscelus obscurus*. Hawaii Agric. Exp. Sta., Honolulu, Hawaii, Tech. Bull., No. 85: 51.
- Oehlschlager, A. C., R. S. McDonald, C. M. Chinchilla, and S. N. Patschke. 1995. Influence of a pheromone-based mass-trapping system on the distribution of *Rhynchophorus palmorum* (Coleoptera: Curculionidae) in oil palm. Environ. Entomol. 24: 1005–1012.
- Pappas, M. L., G. D. Broufas, and D. S. Koveos. 2008. Effect of relative humidity on development, survival and reproduction of the predatory lacewing *Dichochrysaprasina* (Neuroptera: Chrysopidae). Biol. Control. 46: 234–241.
- Reddy, G.V.P., and A. Guerrero. 2004. Interactions of insect pheromones and plant semiochemicals. Trends Plant Sci. 9: 253–261.
- Reddy, G.V.P., and A. Guerrero. 2010. New pheromones and insect control strategies. Vitam. Horm. 83: 493–519.
- Reddy, G.V.P., Z. T. Cruz, J. Bamba, and R. Muniappan. 2005. Development of a semiochemical-based trapping method for the New Guinea sugarcane weevil, *Rhabdoscelus obscurus*. J. Appl. Entomol. 129: 65–69.
- Reddy, G.V.P., S. Balakrishnan, J. E. Remolona, R. Kikuchi, and J. P. Bamba. 2011. Influence of trap type, size, color, and trapping location on the capture of the New Guinea sugarcane weevil, *Rhabdoscelus obscurus* (Coleoptera: Curculionidae). Ann. Entomol. Soc. Am. 104: 594–603.
- Robertson, L. N., and D. E. Webster. 1995. Strategies for managing cane weevil borer. Proc. Aust. Soc. Sugar. Tech. 17: 90–96.
- Sallam, M. N., C. A. McAvoy, G. D. Puglisi, and A. M. Hopkins. 2004. Can economic injury levels be derived for sugarcane weevil borer, *Rhabdoscelus obscurus* (Boisduval) (Coleoptera: Curculionidae), in far-northern Queensland? Aus. J. Entomol. 43: 66–71.
- Sallam, M. N., D. R. Peck, C. A. McAvoy, and D. A. Donald. 2007. Pheromone trapping of the sugarcane weevil borer, *Rhabdoscelus obscurus* (Boisduval) (Coleoptera: Curculionidae): an evaluation of trap design and placement in the field. Aus. J. Entomol. 46: 217–223.
- Sánchez-Ramos, I., F. Álvarez-Alfageme, and P. Castañera. 2007. Effects of relative humidity on development, fecundity and survival of three storage mites. Exp. Appl. Acarol. 41: 87–100.
- Shi, P., T. Ikemoto, C. Egami, Y. Sun, and F. Ge. 2011a. A modified program for estimating the parameters of the SSI model. Environ. Entomol. 40: 462–469.
- Shi, P., L. Zhong, H. S. Sandhu, F. Ge, X. Xu, and W. Chen. 2011b. Population decrease of *Scirpophaga incertulas* Walker (Lepidoptera: Pyralidae) under climate warming. Ecol. Evol. 2: 58–64.
- Stige, L. C., K.S. Chan, Z. Zhang, D. Frank, and N. C. Stenseth. 2007. Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics. Proc. Natl. Acad. Sci. U.S.A. 104: 16188–16193.
- Veitch, R. 1917. The cane beetle borer in Australia. Colonial Sugar Refining, Agriculture Report 3: 1–15.
- Xue, Y., and L. Chen. 2007. Statistical models and R software, pp. 227–229. Tsinghua University Press, Beijing, China.

Received 20 April 2012; accepted 30 June 2012.