Supplemental Information:

Macaques can contribute to greener practices in oil palm plantations when used as biological pest control

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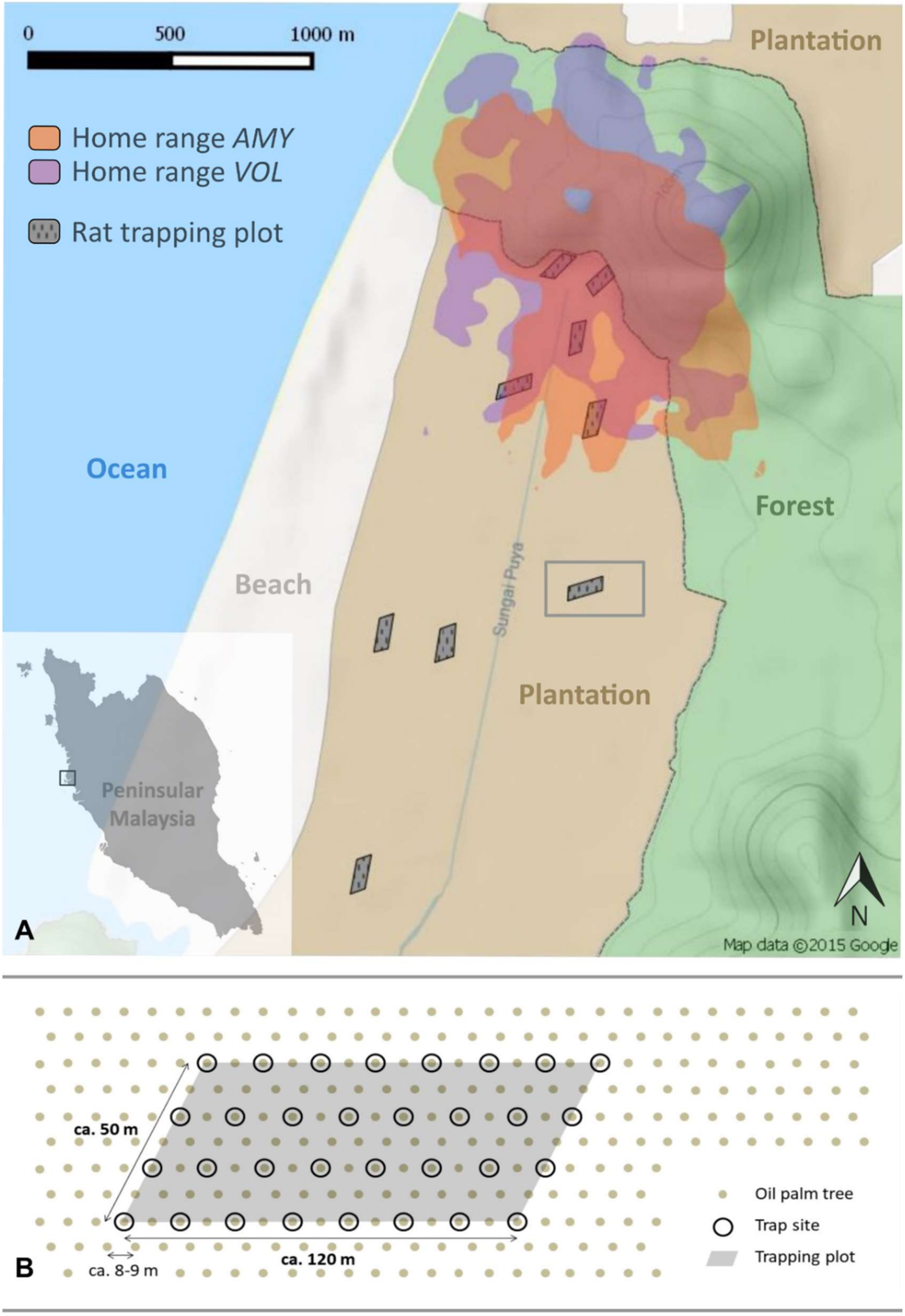

Figure S1. Study site at Segari Melintang Forest Reserve, Peninsular Malaysia (4°19-20' N, 100°34-36' E).

A) Home range areas of two groups of Southern pig-tailed macaques, based on GPS data taken from January to December 2017 for group *AMY* (orange) and October 2017 to September 2018 for group *VOL* (purple). The annual home ranges of group *AMY* and *VOL* were 92.7 and 96.6 hectare, respectively. The used plantation areas were 32.6 and 30.8 hectare for group *AMY* and *VOL*, respectively, accounting for 35 and 32% of their total home range areas. The home range overlap was 57%, with the total plantation area visited by pig-tailed macaques being 41 hectares. B) Experimental setup of our rat capture program. The trapping grid was based on single oil palm trees, with traps being placed at every second tree. Overall, each of the nine trapping plots was sampled twice over eight nights.

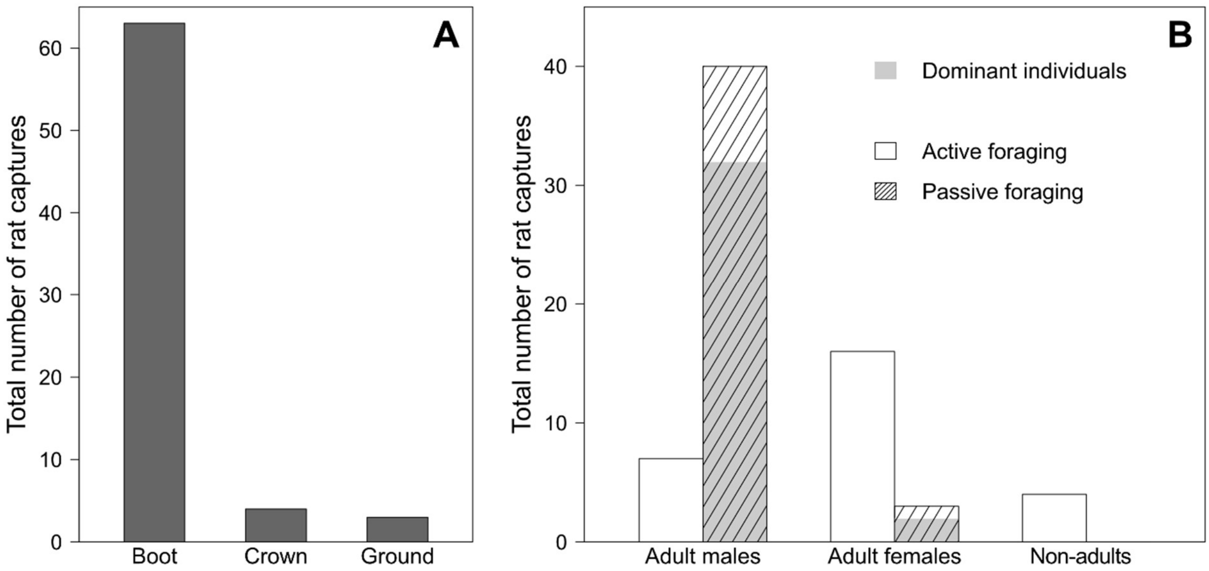

Figure S2. Rat catching behavior of two groups of Southern pig-tailed macaques.

The sample comprised a total of 70 observations, including *focal* and *ad libitum data* from group *AMY* and *VOL*. A) Number of rat captures in different foraging substrates, specifically, under persistent leaf bases (boots) from oil palm trunks, in crowns of oil palm trees, and on the ground. B) Number of rat captures using different hunting strategies, shown separately for adult males, adult females, and non-adult individuals. Rats that were captured by the dominant individuals are shown in grey. 'Active foraging' refers to actively searching for rats, for example, by removing boots from oil palm trees or lifting and manually inspecting piles of cut palm fronds on the ground. 'Passive foraging' implies sitting or standing beneath oil palm trees and waiting until rats, which were seeking shelter in cavities under boots, fell down because other macaques in the tree actively removed boots and uncovered them.

Supplemental Experimental Procedures

Study site

We conducted this study in the Segari Melintang Forest Reserve (SMFR), Perak, Peninsular Malaysia, and the oil palm plantations bordering its South-Western edge (4°19-20' N, 100°34-36' E) (Figure S1A). SMFR comprises 2,742 hectares, of which 408 hectares are strictly protected Virgin Jungle Reserve [S1]. The 420-hectare sized oil palm plantation area near Segari was established between 1980 and 1990 and is managed by a federal authority. The oil palm estate was accessible to macaques, with no major conflicts between wildlife and plantation workers being reported.

Study groups

We collected data on two habituated groups of wild, Southern pig-tailed macaques (*Macaca nemestrina*) from January 2016 to September 2018. We noted that also unhabituated macaque groups at our study site and at other oil palm estates use plantation area as foraging ground. Hence, it seems unlikely that habituation of macaques may have affected their behavior. To reduce habituation to humans other than researchers (for example, plantation workers or local residents), all researchers wore uniquely colored shirts for habituation purpose. As we could observe escape behavior by macaques when, for example, different colored raincoats were worn by researchers, we are confident that the macaques' response to the presence of plantation workers or local residents was different than their response to researchers.

Groups were followed from sunrise to sunset (7 a.m. to 7 p.m.). Both groups visited the plantation area bordering their forest habitat almost daily. Group size and composition differed between the groups and varied across time, as adult males emigrated or joined the group, some females and infants died or were born, and some individuals transitioned between age classes (for example, juveniles reached sub-adulthood and sub-adults reached adulthood) during the study. Group 1 (named *AMY*) consisted of 4 to 10 adult males, 12 to 19 adult females and 14 to 22 non-adult individuals. Group 2 (named *VOL)* consisted of 11 to 14 adult males, 19 to 21 adult females and 13 to 15 non-adult individuals. Adults are defined as fully grown individuals with adult morphology (such as anogenital swelling or elongated nipples in females, and prominent testes in males). Non-adult individuals comprise sub-adults (not yet fully grown or sexually active but already beginning to exhibit secondary sexual characteristics) and juveniles (weaned, but still range in frequent proximity to their behavioral mother).

Plantation usage pattern by pig-tailed macaques

We collected location data with a Garmin GPSMAP62s daily from January 2016 to September 2018 for group *AMY* and from October 2017 to September 2018 for group *VOL*. We took GPS waypoints every minute while following the macaques. We calculated the amount of time spent in the plantation for each day. We determined annual home range areas (January to December 2017 for group *AMY* and October 2017 to September 2018 for group *VOL*) using point Kernel Density Estimation (KDE) with 95% probability of use [S2]. This means that 95% of the recorded data points fall into the calculated home range area. We determined the size and ratio of the macaques' home range area lying within the oil palm plantation by calculating the overlay of the overall home range area polygon of the 95% KDE with the plantation area. Home-range analyses were conducted with the Home Range Analysis and Estimation (HoRAE) toolbox for the free GIS software OpenJUMP [S3]. We set cell size to 25 m and selected bandwidth using a rule-based ad hoc method designed to prevent under-smoothing [S4]. We used the Normal Gaussian Kernel-Function.

Impact of pig-tailed macaques on the oil palm yield

To assess oil palm fruitlet consumption rates of pig-tailed macaques, we collected 30-minute *focal animal data* (following [S5]) on 19 individuals (5 adult males, 9 adult females and 5 non-adults) of group *AMY* at the oil palm plantation from April to September 2015. We continuously recorded the number of all consumed oil palm fruitlets collected from attached fruit bunches, irrespective of their degree of ripeness. Oil palm seeds extracted from overripe and rotten fruitlets as well as ripe or unripe fruitlets collected from the ground were not considered for analysis, as those do not impact the harvest. Total observation time was 86 hours, individual observation times ranged from 3 to 6.9 hours (mean ± sd = 4.5 ± 1.1 hours).

On average, the annual oil palm yield amounts to 53.6 tons of fruits per hectare, given an average bunch weight of 25 kg [S6], a mean harvest of 15 bunches per tree per year [S7] and a planting density of approximately 143 palm trees per hectare [S6]. Thus, the annual yield in the macaques' overall plantation range of 41 hectares (Figure S1A) was estimated to amount to 2,197.6 tons of fruits. We estimated the annual oil palm fruit consumption by one group of pig-tailed macaques, considering the mean group composition of 10 adult males, 18 adult females and 16 non-adult individuals and a mean weight of 10 g per fruitlet [S7]. Specifically, we summed the mean individual consumption rates for males, females and non-adult individuals and the mean daily plantation visiting time of the groups. We then calculated the pig-tailed macaques' annual impact on the oil palm yield at our study site as follows:

$$Annual\ impact = \frac{Annual\ oil\ palm\ consumption}{Annual\ oil\ palm\ production} = \frac{\frac{Annual\ consumption\ rate}{group}}{\frac{Annual\ oil\ palm\ yield}{hectare} * Macaques'plantation\ range}$$

Feeding behavior of pig-tailed macaques at oil palm plantations

To assess the macaques' feeding behavior we collected 30-minute *focal animal data* from January 2017 to April 2018 on 35 individuals of group *AMY* (7 adult males, 14 adult females and 14 non-adults) and from March to August 2018 on 12 individuals of group *VOL* (5 adult males and 7 adult females) [S5]. Total observation time was 739 hours, individual observation times ranged from 5.6 to 18.9 hours (mean ± sd = 15.7 ± 2.8 hours). We continuously recorded the macaques' main activity and consumed food following a standardized ethogram of the macaques previously used by Ruppert *et al.* [S8]. For each rat that a macaque captured during the focal observations at oil palm plantations we described the capture strategy, including the substrate of foraging and any observed foraging behavior. We estimated rat size visually as big (> 60 g) or small (≤ 60 g) and marked the location via GPS. Rat catching events observed outside the focal observations were recorded as *ad libitum data* [S5]. We observed a total of 127 rat consumptions by macaques during the sampling period. For 70 of those events, we could observe the entire capture process, whereas 57 events were only spotted while the macaques were already eating the rat.

Assessment of rat abundance

<u>Rat capture program</u>: We assessed rat abundance in the oil palm plantation with a rat recapture program between April 2016 and May 2018. The total trapping area covered 100 hectares. As all trees in this area were planted at the same time, variation in tree height across the trapping area was negligible. Oil palm trees were harvested every 10 to 21 days, with plantation workers having only minor impact on the ranging behavior of our macaque groups. The macaques kept a minimum distance of about 50 m to workers but did not change direction or move back to the forest when encountering workers (A. Holzner, personal observation). To exclude a potential impact of the oil palm harvest on the rat abundance, we did not start rat trapping sessions within two days after plantation workers were observed in or close to the trapping area. We trapped rats in nine different, 0.6-hectare sized plantation plots, five within and four outside the established home range area of the pig-tailed macaque groups at the study site (Figure S1A). Each plot was trapped twice with a time gap of at least eight months. Trapping grids were based on the arrangement of oil palm trees (Figure S1B). In each trapping session, we set up 32 drop-door wire-mesh live traps (50 x 16 x 16 cm) on the ground in 4 straight lines with 8 traps each. We baited traps with oil palm fruits and set them daily for 8 consecutive days from 7 p.m. to 8 a.m. We determined sex and weight of captured rats and measured them for species identification. Measurements included body, tail and hind foot lengths [S9]. We marked rats using nail clipping on all feet according to predetermined sequences. This tagging method was preferred over toe clipping and metal ear tags, which can lead to chronic wounds or locomotion impairment and therefore increase predation risk for rats [S10]. For our study, nail clipping proved to be successful, as rats needed to be identified only for the 8-day period of one trapping session.

<u>Estimation of rat abundance</u>: Given that we observed low recapture rates (13 of 359 captured subjects were recaptured (3.6%), with recaptures occurring in 5 of 18 trapping sessions), commonly used techniques for population estimation, such as the Lincoln-Index [S11,S12] could not be applied to our data set. Thus, following Lehtonen and Mustonen [S13] and Royle and Nichols [S14], we considered the actual number of rat captures as a proxy for rat abundance, using a Poisson regression model. Each of the 32 traps in each trapping session was treated as one event. To avoid a potential impact of trap shyness which might lead to declining numbers of rat captures over the eight days of a trapping session [S15,S16], we summed the number of captured rats per trap over these eight days.

Rat species at the study site were *Rattus exulans*, *R. rattus*, *R. argentivener* and *R. tiomanicus* (identification follows Francis [S9], see above). Whereas the latter three are well described as pest species for oil palm plantations [S17–S19], no observation as pest species is available about *R. exulans*. This species is the smallest of the four [S19] and reported to be found in plantation areas close to forest edges (Hasber Salim, personal communication). In line with this, we could observe *R. exulans* more frequently in close proximity to the forest edge than deeper inside the plantation (58% of trapped rats within 100 m from the forest edge were identified as *R. exulans*, but only 26% within 101 to 300 m and only 4% at a distance of > 300 m from the forest edge). Moreover, the macaques' consumption rate of small rats was not proportionally higher at the forest edge (20% of consumed rats within 100 m from the forest edge could be identified as small rats, 25% within 101 to 300 m and 21% at a distance of > 300 m from the forest edge), indicating that *R. exulans* was most likely not or only in small quantities consumed by pig-tailed macaques. Given this data and considering the lack of evidence of *R.*

exulans being an oil palm pest, we excluded this species from further analyses. Finally, *R. argentiventer, R. rattus and R. tiomanicus* were pooled for analysis due to a lack of differences in the distribution patterns of these three species across the plantation (that is, within 100 m, 101 to 300 m and > 300 m from the forest edge, Pearson's chi-squared test, $\chi^2 = 1.45$, df = 4, p = 0.83).

Assessment of trapping environment: For each trap we investigated the following variables, which we expected to affect the abundance of rats.

Frequency of macaque visits: Due to the different positions of trapping plots within the home range of our study groups, the macaques visited trap sites with different frequencies. As rat species at the study site reach sexual maturity at an age of approximately 90 days [S20], we chose to take into account the frequency with which we observed macaques within 50 m of a trap site during the last 90 days prior to the sampling of the respective trapping plot. We chose the distance of 50 m according to the dispersion of the macaque groups around the recorded travelling routes. The frequency of macaque presence was based only on observations of group *AMY* as group *VOL* had not been fully habituated before the start of 2018. As most of the trapping sites within macaque range were also within the home range of group *VOL*, the lack of data on group *VOL* can be expected to make our estimates of macaque presence noisier and hence our analysis more conservative.

Distance to the forest edge: As plantation areas in close proximity to forests provide additional shelter and protection through close-by forest vegetation, rat abundance might differ according to an area's distance to the forest edge. Therefore, for each trap site, we measured the shortest distance to the forest edge in meters using GPS data.

Undergrowth: Previous work indicated a positive correlation between vegetation cover and rat occurrence at oil palm plantations [S21]. Due to the regular use of herbicides, undergrowth was generally low at the study site. Therefore, we chose a binary variable to assess undergrowth. We defined 'no undergrowth' as plantation areas without shrubs or other ground vegetation except grass up to 10 cm, whereas 'the occurrence of undergrowth' included areas with grass higher than 10 cm and scattered shrubs up to 1 m. This variable differed between trapping plots but was constant for the traps of the same plot across sessions.

Rainfall: Previous studies reported annual fluctuations in the abundance of *R. argentiventer*, *R. rattus* and *R. tiomanicus* [S22,S23]. Here, we used rainfall as a proxy to account for seasonal variation in rat abundance. This decision was based on the shifting dates of dry and monsoon seasons due to climate change [S24], which made the actual rainfall a better indicator of season than the sampling month. Following the reproductive cycle of the rats, we assessed the average rainfall during the last 90 days before the start of a trapping session.

Statistical analysis

To investigate the impact of macaques on the number of rat captures, we used a Generalized Linear Mixed Model (GLMM, [S25]) with Poisson error structure and log link function. As response variable we used the number of rats captured in a particular trap over the eight consecutive nights of one trapping session (N = 575 traps). We included the frequency of macaque visits as fixed effects test predictor, while rainfall, undergrowth, the distance to the forest edge and the trapping session (1 or 2) were included as fixed effects control predictors and trap site as random effect. To account for non-functioning traps, activated traps without captures and traps with recaptured animals or individuals of the species *R. exulans* (species excluded from analysis, see above), we included the number of nights a trap was active (log-transformed) as an offset term into the model [S26]. As the number of captured rats might be spatially autocorrelated beyond what is explained by the predictors, we also included a spatial autocorrelation term [S27,S28]. For that, we first fitted the model described above without accounting for autocorrelation and retrieved the residuals from it. For each data point we then calculated an autocorrelation term as the average of the residuals of all other data points, whereby the contribution of these residuals was weighted by the distance of the particular data points [S28]. The weighting function followed a normal distribution with a mean of zero and a standard deviation which maximized the likelihood of the full model with the autocorrelation term included [S29]. To facilitate model convergence and interpretation, we standardized all continuous predictors to a mean of zero and a standard deviation of one [S30]. We assessed model stability by excluding the levels of the random effects one at a time and comparing the estimates from the obtained models with the estimates from the model based on all data. This indicated no obviously influential cases. To rule out collinearity, we determined variance inflation factors (VIFs) for a standard linear model excluding the random effects (all VIFs < 2.2, [S31]). Overdispersion was no issue but there was an indication of underdispersion (dispersion parameter = 0.49), probably reflecting the small number of trapping cases observed in our dataset. To test the effect of the frequency of macaque visits, we compared the full model with a reduced model lacking only our test predictor (frequency of macaque visits) using a likelihood ratio test [S32]. We further tested the effect of our control predictors using likelihood ratio tests comparing the full model with reduced models lacking the control predictors one at a time [S32]. All statistical analyses were conducted in R version 3.4.4 (R Core Team 2018). The model was fitted using the function *glmer* of the package 'lme4' (version 1.1-19, [S33]) with the optimizer *bobyqa*. The auto-correlation term was calculated using an R function provided by Roger Mundry. VIFs were determined using the function *vif* of the package 'car' (version 3.0-2, [S34]). The full-null model comparison was derived using the R function *anova* with test argument 'test' set to 'Chisq' [S32]. Tests of individual fixed effects were derived using likelihood ratio tests using the R function *drop1* with test argument set to 'Chisq'. Confidence intervals were derived using the function *confint.merMod* of the package 'lme4' (version 1.1-19, [S33]).

The full vs. null model comparison revealed a significant influence of the frequency of macaque visits on the number of rat captures ($\chi^2 = 15.27$, df = 9, $p < 0.001$; n = 575). In summary, the full model revealed the following estimates and standard errors: Intercept: -3.57 ± 0.18; Frequency of macaque visits (test predictor): -0.72 ± 0.18 ($p < 0.001$); Distance to the forest edge (control predictor): 0.02 ± 0.12 ($p = 0.85$); Rainfall (control predictor): -0.28 ± 0.09 ($p < 0.01$); Presence of undergrowth (control predictor): -0.53 ± 0.21 ($p < 0.01$); Trapping session (control predictor): 0.50 ± 0.15 ($p < 0.01$); Autocorrelation term (control predictor): -0.56 ± 0.09 ($p < 0.001$).

Ethical note

We obtained permits to study Southern pig-tailed macaques from the Department of Wildlife and National Parks Peninsular Malaysia (permit holder: Dean of School of Biological Sciences, Universiti Sains Malaysia). No permits were required to capture rats of the genus *Rattus* ('pest species') outside of protected areas. We obtained permits to enter the forest reserve bordering the oil palm plantation from the Forestry Department Peninsular Malaysia (permit holder: Dr. Asyraf Mansor, School of Biological Sciences, Universiti Sains Malaysia). No written permit was needed to enter the plantations, but we informed the local management about the study. The study was conducted in line with Universiti Sains Malaysia's animal welfare requirements.

Author Contributions

Initial study idea: N.R.; Conceptual study design: A.H., N.R. and A.W.; Field data collection: A.H., F.S. and M.S.; Data analysis: A.H. and A.W.; Manuscript writing: A.H., A.W. and N.R.; Project logistics (for example, permit and grant applications, equipment acquisition): N.R., A.H., A.E., A.M. and S.A.M.S.; Contribution to study design, data analysis and/or interpretation of results: B.M.W., F.S., M.S., G.V. and H.K. All authors contributed to the draft and gave final approval for publication.

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