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The inequities of human-elephant coexistence: Deterrent strategies and crop protection costs in Thailand

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Abstract

Living near elephants imposes challenges for farmers, yet studies often overlook how farmers combine deterrent strategies and how the costs of crop protection are distributed within communities. This study evaluates variation in deterrent strategies, elephant-caused economic loss and the financial and social costs of crop protection in Ruam Thai Village, bordering Kuiburi National Park in Thailand. We used household surveys and farmer interviews to determine the types and combinations of deterrents used across farms growing different crop species and varying in plot size, and to assess farmers' financial investment in deterrents and night guarding effort in relation to distance to the protected area, elephant encounter frequency and elephant-caused yield loss. Farmers growing pineapple (a preferred food for elephants) used the most deterrents, including the highest frequency of night guarding and firecracker use. However, no deterrent strategy fully protected farms from economic loss. Financial investment in deterrents was associated with elephant encounter frequency and elephant-caused yield loss, suggesting farmers are caught in a ‘mitigation treadmill’ where protective investments escalate alongside damage, without resolving the underlying conflict. Night guarding effort was greatest among farmers closest to the protected area border and among those reporting the highest elephant-caused yield loss. These results demonstrate that the costs of human-elephant coexistence are unevenly distributed, leaving the most exposed farmers to bear the burden of these escalating defensive expenditures. Coordinated, community-led crop protection strategies are essential to interrupt this cycle, reduce inequities, and increase socio-economic resilience in human-elephant landscapes.

Introduction

Human-wildlife conflict poses a growing challenge to human well-being and wildlife conservation worldwide (Nyhus 2016). Negative interactions between people and wildlife can involve crop consumption and livestock depredation, property damage and risks to human safety, often requiring communities to adapt livelihood practices, invest in protective measures or endure persistent economic, psychological and social costs (Mayberry et al. 2017). In Asia, these conflicts are exacerbated by rapid agricultural expansion in and around remaining wildlife habitat. Asian elephants (*Elephas maximus*), an endangered species requiring vast, connected ranges, are particularly affected by habitat fragmentation (de Silva et al. 2023). The cultivation of palatable crops draws elephants into human-dominated areas, increasing negative human-elephant interactions, commonly described as human-elephant conflicts (HEC) and associated damage (Köpke et al. 2024). Persistent HEC erodes tolerance of elephants and prompts widespread adoption of reactive deterrent strategies that can have adverse effects on elephants, humans and long-term coexistence (Van de Water and Matteson 2018).

Elephant deterrents include physical barriers that restrict farm entry, aversive audio-visual and olfactory cues known to be disliked by elephants, and other interventions that discourage elephants from accessing agricultural areas (Davies et al. 2011; Mchome et al. 2025). In practice, however, farmers rarely rely on a single technique. They often combine active deterrents requiring human deployment, such as voice, firecrackers and vehicle horns, with passive measures that operate more independently,

such as electric fences, trenches, motion-sensor spotlights and alarm systems (Shaffer et al. 2019; Montgomery et al. 2022). Farmers' deterrent strategy – the quantity and type of deterrents used – can vary widely in cost, maintenance requirements and perceived effectiveness (Denninger Snyder and Rentsch 2020). Deterrents are often deployed in combination and can interact in their effects (Davies et al. 2011), so understanding how deterrent strategies and elephant-caused economic loss vary across crop species and plot sizes is important for evaluating farm-level crop protection measures.

Beyond crop loss, preventing elephant-caused crop damage imposes substantial financial and social costs on farmers. Owing to elephants' size, strength, and cognitive capacity, deterrent effectiveness can decline over time as elephants habituate to repeated exposure or discover weaknesses in physical barriers, especially where ongoing maintenance is limited (Shaffer et al. 2019; Mchome et al. 2025). Consequently, many farmers rely on night guarding, which involves active supervision of the farm throughout the night, as the most reliable strategy (Sitati et al. 2005; Gross et al. 2019). Night guards use active deterrents to address elephant presence and prevent crop damage, but doing so requires repeated overnight vigilance and sustained labour. As a result, this practice affects farmers' physical, psychological, and social well-being through ongoing risks during elephant encounters, lack of sleep, chronic stress and social isolation (Barua et al. 2013; Nyumba et al. 2020; Sampson et al. 2021; Owen et al. 2024). Spatio-temporal crop damage assessments can identify HEC patterns and hotspots, but they do not capture the financial investments, labour demands and social burdens farmers absorb while trying to prevent damage before it occurs. More broadly, the costs of human-wildlife coexistence are often unevenly distributed within and among affected communities, creating what has been described as "coexistence inequality" (Jordan et al. 2020). Previous studies have shown that greater elephant exposure is associated with greater impacts from elephants (Prins et al. 2022; Saif et al. 2020). Saif et al. (2020), for example, incorporated crop and property damage, mitigation expenditure and guarding time into an assessment of tangible costs, but less is known about how financial and social burdens of preventing these costs are distributed within affected communities.

Thailand, which hosts the largest wild elephant population in Southeast Asia, has recently experienced severe and increasing HEC (Sukmasuang et al. 2024). Between 2014 and 2023, 234 elephant casualties (166 deaths and 68 injuries) were recorded, with most incidents resulting from electrocution, road accidents and gunshots (Supanta et al. 2025). During the same period, 360 human casualties (189 deaths and 171 injuries) were recorded, with casualties increasing from 23 in 2014 to 51 in 2023 (Supanta et al. 2025). In southwestern Thailand, rural communities bordering Kuiburi National Park (KNP) frequently encounter elephants in farmland throughout the year (Kochprapa et al. 2023; Owen et al. 2024), and Ruam Thai Village has been the main HEC hotspot in the region for over 25 years (Srikrachang and Srikosamatara 2005). Previous studies in farms bordering KNP found that crop damage differed across crop types, but no part of the agricultural landscape is exempt from HEC (Kochprapa et al. 2023). Building on this work, understanding hidden costs of HEC in Ruam Thai Village and other human-elephant landscapes requires examining which deterrent strategies are associated with lower elephant-caused economic loss and the financial and social costs farmers bear to implement and sustain them.

This study examined variation in deterrent strategies and elephant-caused economic loss across agricultural contexts, and the financial and social costs of crop protection in relation to elephant exposure and impact in Ruam Thai Village. Specifically, we aimed to: (1) compare deterrent strategies and elephant-caused economic loss across farms growing different crop species and varying in plot size, and (2) assess how the financial and social costs of crop protection, measured as financial investment in deterrents and night guarding effort, vary in relation to elephant exposure and impact variables, including distance to the protected area (PA), elephant encounter frequency and elephant-caused yield loss. We predicted that deterrent strategies would differ by crop species and plot size, with the most deterrents used in pineapple farms, and that greater elephant exposure and impact would be associated with higher investment in deterrents and greater night guarding effort. Together, these aims evaluate farm-level crop protection outcomes and how the financial and social burdens of crop protection are distributed, providing evidence for multidimensional, context-specific coexistence strategies in human–elephant landscapes.

Study area

KNP (969 km²) is part of the Kaeng Krachan Forest Complex, a UNESCO World Heritage Site in southwestern Thailand. KNP hosts approximately 237–350 elephants and HEC has persisted in farms bordering the park since it was gazetted in 1999 (Department of National Parks, Wildlife and Plant Conservation 2025).

Ruam Thai Village (738 households and 2,007 residents; Department of Provincial Administration 2025) in Prachuap Khiri Khan province shares its north and west borders with KNP (Fig. 1). The village was established in 1978 when the Provincial Administrative Organization (PAO) enacted a land distribution scheme to eliminate communist settlements from the region (Sirichakkaraset et al. 2025). The Royal Forest Department granted a 30-year lease to the PAO, which distributed approximately 21,875 rai (8,649 acres) of national forest land to people who relocated as part of the Ruam Thai Demonstration Cooperative Village scheme (Wongsawaddiwattana and Pattaratuma 2005). At this time, the region was designated a “red zone” because of military activity to address communist settlers, so Ruam Thai Village’s first settlers consolidated houses in a central zone for safety and conducted agricultural activities in land closer to the forest that would eventually be gazetted as KNP in 1999 (Sirichakkaraset et al. 2025). The geo-political history that separated homes and farms exacerbates present-day HEC, as agricultural land is unoccupied at night when crop foraging attempts are most frequent. Today, pineapple (*Ananas comosus*) is the most commonly cultivated crop, followed by rubber (*Hevea brasiliensis*), mango (*Mangifera indica*), jackfruit (*Artocarpus heterophyllus*) and oil palm (*Elaeis guineensis*). Each of these species is attractive to elephants and several are targeted at all stages of maturity, meaning elephant encounters are persistent throughout the year rather than following a seasonal trend (Kochprapa et al. 2023).

Methods

Household survey

We conducted a 25-question survey among Ruam Thai Village farmers (N = 239) between 11 October and 12 December 2021 (Ethics approval number 03868e). Only one adult (≥ 18 years old) from each randomly selected household was surveyed. Participation was restricted to those who farmed land located within 2 km of the PA border. Surveys required approximately 30 minutes to complete and trained enumerators were present to provide clarification if requested.

The survey focused on respondents' farm-level cropping practices, experiences with elephants, deterrent strategies and elephant-caused yield loss. Respondents provided information for up to three plots, including cultivated crop species, plot size (rai), deterrents deployed, and average annual economic loss. Plot size is reported in rai (1 rai = 0.16 ha = 0.395 acres). All monetary values were recorded and reported in Thai Baht (USD 1 = 33.48 THB; Bank of Thailand 2021).

Deterrent options included night guarding, electric fence, firecrackers, gunshots, spinning lights/spotlights, siren system, bottle fence and trench (Fig. 2). Average economic loss (THB) was reported using ordinal categories, namely: no loss (0), low loss (< 25,000) and high loss (≥ 25,000).

Pineapple farmer interview

Interviews were conducted between 19 July and 14 October 2022 with randomly selected farmers (N = 71) in Ruam Thai Village whose farms were located within 2 km of the PA border to quantify the financial and social costs of crop protection in pineapple farms. Financial costs were measured as investment in deterrents (THB/rai/harvest) and social costs as night guarding effort (proportion of nights spent guarding).

The interview had two sections: 1. Open-ended and multiple choice questions about respondents' demographics and experiences with elephants and alternative crop cultivation, and 2. Itemised expenses (planting, maintaining and harvesting pineapple, including investment in deterrents and losses from elephants) and revenue from their most recent harvest cycle. Only one adult was interviewed per household.

Responses from both sections were used to assess how farmers' financial and social costs are influenced by elephant exposure and impact variables, including distance to the PA (m), elephant encounter frequency and elephant-caused yield loss. To calculate distance to the PA, farmers indicated the location of their farm on a map and the interviewer measured the distance to the PA border. Elephant encounter frequency was recorded as a categorical response ranging from never to every night. Yield loss was quantified by combining elephant-caused crop damage (THB/rai/harvest) with total yield sold (THB/rai/harvest) to estimate farmers' potential yield in the absence of elephant-caused damage. Elephant-caused yield loss was then calculated by dividing elephant-caused crop damage by the estimated potential yield.

Data analysis

As individual respondents with multiple plots could report data on up to three farms, analyses were conducted at the plot level. Analyses were restricted to respondents who completed at least one farm profile. To ensure sufficient sample sizes for comparative analyses between crops, species that were reported in fewer than 10 farm plots were excluded from analyses.

Continuous predictors were z-standardised prior to modelling, whereas categorical predictors were not transformed. Collinearity among predictors was evaluated using correlation matrices and variance inflation factors (VIF) and highly collinear combinations (VIF > 5) were not included in the same model. Model fit was evaluated using simulation-based residual diagnostics in DHARMa. Predictor significance was evaluated using Chi-squared likelihood ratio tests via Anova() in the car package. Model outputs were visualised using ggplot2. All statistical analyses were conducted in R version 4.0.3 (R Core Team 2020) and RStudio version 2024.12.1 (Posit Team 2025).

Farm characteristics, deterrent strategies and economic loss

To assess how farm characteristics shape deterrent strategy, crop species and plot size were analysed in relation to two variables: 1. The presence or absence of each deterrent, and 2. The total number of deterrents used. Seven individual deterrent types (Fig. 2; Online Resource 1, Table S1) were coded as binary variables (present/absent) and the total number of deterrents was calculated by summing the number of deterrents reported for each farm profile.

Binary deterrent-use variables were analysed using binomial generalised linear mixed models (GLMMs), fitted with glmer() from the lme4 package (Bates et al. 2015). The number of deterrents was analysed using a negative binomial GLMM, fitted with the glmmTMB() function in the glmmTMB package, to account for overdispersion (Brooks et al. 2017).

Prior to model fitting, we detected a significant association between crop species and plot size (one-way ANOVA, $F(4, 246) = 7.6$, $p < 0.001$). Therefore, models included crop species, plot size and their interaction, and participant ID was included as a random intercept to account for repeated measures.

Patterns of elephant-caused economic loss were then analysed across farm characteristics and deterrent strategies. Economic loss was treated as a categorical response variable with three levels (no loss, low loss, high loss), and analyses were conducted separately for each crop species due to collinearity between crop species and plot size. We fitted multinomial logistic regression models using the multinom() function from the nnet package (Venables and Ripley 2002).

Economic loss in each crop species was evaluated using two reduced models: (1) farm-level predictors (plot size and number of deterrents) and (2) individual deterrent predictors (presence/absence of each deterrent). Participant ID was not included as a random effect due to model complexity. Predictor

significance was evaluated using Chi-squared likelihood ratio tests and post hoc pairwise comparisons using estimated marginal means with Tukey-adjusted tests and Bonferroni correction.

Financial and social costs of crop protection in relation to elephant exposure and impact

To assess the financial and social costs of crop protection, financial investment in deterrents (THB/rai/harvest) and night guarding effort (0–100%) were modelled in relation to distance to the PA, elephant encounter frequency, and proportion of elephant-caused yield loss. Financial investment in deterrents was analysed using a linear model with log10-transformed investment and distance, whereas night guarding effort was analysed using a quasibinomial generalised linear model (GLM) with a logit link function. The same exposure and impact predictors were included as fixed effects in both models and their significance was evaluated using Chi-squared Type II likelihood ratio tests. Given the relatively small sample size, both analyses were conducted using additive models without interaction terms (Zuur et al. 2009).

Results

Farm characteristics, deterrent strategies and economic loss

After applying predefined exclusion criteria, the final household survey dataset comprised 305 plots managed by 223 farmers (as some participants cultivated more than one plot) across five crop species (Tables S2 and S3). Night guarding was the most frequently reported deterrent (65.6%), followed by electric fences and firecrackers. Spinning lights/spotlights and bottle fences were reported at intermediate frequencies, while siren systems and trenches were rare, and gunshots were not reported.

The predicted number of deterrents used was highest in pineapple farms and lowest in oil palm farms (Fig. 3a). A similar pattern was evident for night guarding (p = 0.015; Fig. 3b), with the highest predicted probabilities in pineapple farms and the lowest in oil palm farms.

There was a significant interaction between crop species and plot size for the number of deterrents used (p = 0.014; Fig. 3a; Table S4). Specifically, the number of deterrents increased with plot size in pineapple, rubber, mango and jackfruit farms, whereas in oil palm farms, deterrent quantity decreased with plot size.

Firecracker use also varied by crop species, with a significant interaction between crop species and plot size (p = 0.010; Fig. 3c). Firecracker use increased with plot size in pineapple farms, but remained low for other crop species. No significant interactions were detected between farm characteristics and the use of electric fences, siren systems, spinning lights/spotlights, bottle fences or trenches.

The number of deterrents was significantly associated with economic loss in all five crop species (pineapple: $\chi^2(2, n = 157) = 42.50$, $p < 0.001$; rubber: $\chi^2(2, n = 62) = 10.95$, $p = 0.004$; mango: $\chi^2(2, n = 46) = 21.70$, $p < 0.001$; jackfruit: $\chi^2(2, n = 29) = 10.47$, $p = 0.005$; oil palm: $\chi^2(2, n = 11) = 6.31$, $p = 0.043$; Table S5). However, the directionality of this relationship varied by crop species (Fig. 4; Table S6). For pineapple, farms experiencing high losses used the greatest number of deterrents. In mango farms, more deterrents were used in low-loss farms than in high-loss farms and no-loss farms.

Financial and social costs of crop protection in relation to elephant exposure and impact

Most farmers (83.1%) invested in deterrents, though expenses varied widely among farmers (Table S7). Half of the interviewed farmers (50.7%, n = 36) reported modest deterrent expenses between 1–500 THB/rai/harvest, while two farmers reported expenses exceeding 10,000 THB/rai/harvest.

Farmers' financial investment in deterrents was positively associated with the elephant-caused yield loss ($\chi^2(1) = 8.24$, $p = 0.004$; Fig. 5a; Table S8). Deterrent investment was also associated with elephant encounter frequency ($\chi^2(5) = 13.55$, $p = 0.019$; Fig. 5b). Model-estimated deterrent investment was lowest among farmers who reported never encountering elephants.

Night guarding was practiced by 69.0% of pineapple farmers (M = 33.0%; SD = 43.0%), and guarding effort varied widely among farmers. Nearly one-third of farmers (31.0%) did not guard at all, while 26.8% guarded their crops every night. Among remaining farmers, guarding effort was typically low, with 35.2% guarding on ≤ 20.0% of nights, and only 7.0% engaging in intermediate levels of guarding (20.1–99.9% of nights).

Night guarding effort increased with yield loss ($\chi^2(1) = 11.22$, $p < 0.001$; Fig. 6a; Table S8) and declined with greater distance to the PA ($\chi^2(1) = 5.06$, $p = 0.024$; Fig. 6b). Night guarding effort was not significantly associated with elephant encounter frequency ($\chi^2(5) = 10.00$, $p = 0.075$).

Discussion

Our results show that no deterrent strategy reported by farmers fully protected farms from economic loss across crop species. Farmers experiencing greater exposure and impact also bore greater financial and social costs of crop protection, underscoring the need for HEC mitigation strategies that simultaneously reduce crop damage and the unequal burdens of preventing it.

Farm characteristics, deterrent strategies and economic loss

Crop protection tactics differed markedly across farm types. Pineapple farms were guarded with more deterrents than mango, jackfruit, rubber and oil palm farms, and were more likely to be protected by night

guarding and firecrackers. This may be because mango and jackfruit are primarily targeted seasonally, when fruit is mature, whereas pineapple can be consumed at all stages of its growth cycle. In addition, night guarding and firecrackers are likely more viable in low-growth pineapple plantations, where elephants are more visible to night guards than in plantations with tall, perennial crops such as mango, jackfruit, rubber and oil palm. Conversely, oil palm farms used the fewest deterrents and had the lowest probability of night guarding presence, likely because mature oil palm trees are comparatively less vulnerable to elephant foraging (Kochprapa et al. 2023).

Deterrent quantity co-varied with economic loss across crop species, with farms experiencing high or low loss using more deterrents than no-loss farms. Sitati et al. (2005) similarly found positive associations between several mitigation methods and crop damage, suggesting a reactive pattern of deterrent deployment. This suggests that rather than resolving the underlying conflict, farmers may find themselves caught on a 'mitigation treadmill,' continually increasing crop protection efforts in response to previous loss just to keep pace with escalating threats. Under these conditions, greater deterrent quantity does not guarantee reduced losses, consistent with previous evidence that combining or intensifying deterrent measures does not necessarily improve crop protection outcomes (Davies et al. 2011; Gross et al. 2019). Similarly, few significant relationships emerged between individual deterrent types and farms reporting no elephant-caused economic loss. Night guarding and firecrackers were used significantly more in pineapple farms reporting high and low loss than farms reporting no loss. This may reflect increased crop damage from trampling when elephants are confronted with multiple active deterrents, a pattern documented in other regions (Davies et al. 2011; Gross et al. 2019; Sitati et al. 2005). Although these patterns indicate that current deterrent strategies did not fully prevent elephant-caused economic loss, they do not demonstrate that deterrents lacked effectiveness entirely, as our study could not quantify the additional crop losses that may have occurred in their absence.

A limitation of this study is that farmers self-reported elephant-caused yield loss because crop damage could not be independently enumerated. Previous studies comparing farmer reports with field-based assessments have found both broad agreement in estimates of crop damage and substantial discrepancies in perceived impacts from elephants (Hoffmeier-Karimi and Schulte 2015; Kiffner et al. 2021). Future studies should combine standardised crop damage enumeration with long-term, field-based evaluations of individual deterrents and combined strategies, using comparative designs with appropriate controls to distinguish observed crop loss from loss prevented by deterrents (Sitati et al. 2005; Kiffner et al. 2021).

Unequal financial and social costs of human-elephant coexistence

The financial and social costs of crop protection were unevenly distributed across farmers experiencing differing elephant exposure and impact, providing an example of within-community inequality in how the costs of coexistence are shared (Jordan et al. 2020). Farmers reporting higher elephant-caused yield loss invested significantly more in deterrents whereas investment was lowest among farmers who never

encountered elephants. This aligns with findings from other human-elephant landscapes, where greater elephant exposure was associated with greater tangible costs (Saif et al. 2020). Investment in high-cost deterrents may reduce crop damage in some cases, but additional crop protection measures act as defensive expenditures – investments required to mitigate potential losses without enhancing agricultural output. These expenditures increase expenses without increasing revenue, thereby reducing or potentially eliminating profit for a given harvest cycle (Fath and Imron 2023). Moreover, the most effective deterrent strategies are often more costly, restricting their adoption to farmers with sufficient financial resources and leaving economically insecure households more vulnerable to elephant-caused crop damage (Nyirenda et al. 2018; Köpke et al. 2023, 2024). Under these constraints, farmers appear to substitute capital-intensive deterrents with labour-intensive alternatives, shifting from financial costs to social costs when further investment in deterrents becomes untenable.

As such, night guarding was the most commonly used deterrent in Ruam Thai Village, but guarding effort was concentrated among farmers closest to the PA and experiencing the greatest elephant-caused yield loss. These findings align with other studies that suggest farmers living closest to the PA are disproportionately affected and should therefore be prioritised in regional coexistence strategies (Köpke et al. 2024; Prins et al. 2022). Although night guarding may reduce financial expenditures, it imposes substantial social costs on farmers, including disrupted livelihoods, reduced school attendance and performance, diminished physical and mental health, exposure to illness and disease and social isolation (Barua et al. 2013; Nyumba et al. 2020; Sampson et al. 2021; Owen et al. 2024). These cumulative burdens exacerbate socio-economic vulnerability, erode tolerance of elephants and weaken support for conservation (Van de Water and Matteson 2018). In some contexts, they are linked to increased poaching, retaliatory killings and calls for “problem” elephant removal (Gunaryadi et al. 2017; Menon and Tiwari 2019). Therefore, identifying farmers who bear the greatest financial and social burdens of coexistence is central to designing support strategies that reconcile human well-being with long-term conservation of Asian elephants.

Fostering socio-economic resilience through Adaptive Coexistence Networks

To address inequities in human-elephant landscapes and break the mitigation treadmill, coexistence strategies must move beyond reactive, farm-level mitigation toward coordinated, community-level crop protection (Shaffer et al. 2019). This transition depends on recognising unequal exposure, investment and effort in the current system, wherein farmers most affected by HEC absorb financial and social costs that ultimately contribute to shared protection. Communal guarding represents a viable pathway to enhance crop protection outcomes and redistribute these defensive costs, provided it is grounded in meaningful participation, transparency and locally appropriate burden-sharing (Gunaryadi et al. 2017; Gross et al. 2019; Sheil and Akampurira 2026). Presently, individual farmers guard their own farm, but communal guarding would station rotating groups of farmers at habitual elephant crossings. Guards would use pre-planned tactics and welfare-informed safeguards to guide elephants towards known

retreat routes, with the goal of minimising escalation and unintended consequences for crops, farmers and elephants (Davies et al. 2011; Sekar et al. 2026).

Building on our findings, we propose Adaptive Coexistence Networks (ACNs) as a conceptual model to coordinate locally-led, community-level crop protection in human-elephant landscapes. ACNs are structured around three components: (1) collective governance, which formalises a shift from individual to communal crop protection and redistributes tangible and intangible costs of coexistence; (2) shared knowledge systems, which integrate local ecological knowledge with systematic monitoring of elephant movements and crop damage; and (3) coordinated response, which employs early warning technologies to support guarding teams. By integrating these three components, ACNs move mitigation beyond reactive deterrent deployment toward collaborative crop protection. Conservation technologies, such as acoustic detection devices and unmanned aerial vehicles (drones), have improved HEC mitigation by alerting people to elephant presence, reducing response time and directing elephants out of agricultural areas (Zeppelzauer et al. 2015; Hahn et al. 2017). More recently, AI-integrated camera trap networks have been used as “early warning systems” to detect individual elephants entering farms (Rastogi et al. 2025), an important step towards deploying deterrent strategies tailored to the elephants’ demographic- and individual-level characteristics.

Beyond improving crop protection, ACNs may generate social benefits by transforming crop defence from an isolated household burden into a shared community practice. Communal guarding could redistribute labour and strengthen social cohesion among farmers, provided that responsibilities are locally owned and sustainable (Sheil and Akampurira 2026). These benefits are central to socio-economic resilience, as coexistence strategies may become more legitimate, durable and fair when people feel better supported and less dependent on individual endurance.

Importantly, ACNs must consider elephant well-being and landscape connectivity. Acute, antagonistic interactions with humans can elevate glucocorticoids (Vijayakrishnan et al. 2018) and chronic disturbance may reduce reproductive potential through stress-related suppression of reproductive hormones (Tang et al. 2020). Accordingly, HEC mitigation within ACNs must align with elephant cognition and behaviour and emphasise spatial and temporal consistency to clearly communicate zone restrictions to elephants while facilitating continued use of established pathways and corridors (Mumby and Plotnik 2018; Songhurst et al. 2016). Beyond crop protection, long-term detection data collected by guarding teams could inform landscape-level management decisions, simultaneously addressing immediate impacts and structural drivers of HEC.

Although ACNs can redistribute the burdens of crop protection, they should be embedded within broader coexistence strategies that reduce the need for defensive action over time. Long-term human-elephant coexistence requires solutions that reduce defensive costs and generate proactive benefits for people, elephants and ecosystems (Shaffer et al. 2019). For example, cultivating alternative (less palatable) crops has effectively reduced crop damage and disincentivised elephant presence in agricultural areas (Owen et al. 2024). Similarly, beehive fences have deterred farm entry, while reducing the need for

antagonistic human-elephant interactions and generating socio-economic benefits for farmers (Van de Water et al. 2020). Future studies evaluating crop protection measures should move beyond conventional deterrent assessment metrics (affordability, short-term effectiveness) to apply a One Well-being approach (Van de Water et al. 2024) that bases coexistence strategy selection on social, economic and ecological consequences for humans, elephants and ecosystems.

This study demonstrates that current deterrent strategies impose uneven burdens on farmers while failing to reliably prevent elephant-caused crop damage. Rather than asking only which deterrents are most effective, our findings highlight the need to ask who bears the financial, labour and social costs of making coexistence possible. We propose ACNs as a pathway for redistributing these burdens through collective governance, shared knowledge and coordinated response, while also strengthening social support, local agency and adaptive decision-making. Future coexistence strategies should therefore move beyond farm-level deterrent deployment toward multidimensional coexistence strategies that reduce crop loss, protect elephant well-being, maintain landscape connectivity and build equitable socio-economic resilience in human-elephant landscapes.

Declarations

Ethics approval

Data collection involving human subjects was approved by Miami University's Institutional Review Board (Protocol ID: 03868e, 11 June 2021). Informed consent was obtained from all participants.

Competing interests

The authors have no competing interests to declare.

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Author Contribution

Study design and methodology: AO, AvdW, RL, KM; data analysis and visualisation: AO, AvdW, RL, KM; writing and editing: AO, AvdW, RL, KM; funding acquisition: AO, AvdW; supervision: KM.

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Data Availability

The data that support the findings of this study are available from the corresponding author (AO) upon request.

References

1. Bank of Thailand (2021) FM_FX_001_S3: Rates of exchange of commercial banks in Bangkok Metropolis (2002–present) [Data set]. Bank of Thailand, Bangkok, Thailand. https://app.bot.or.th/BTWS_STAT/statistics/BOTWEBSTAT.aspx?language=eng&reportID=123. Accessed 2 March 2026
2. Barua M, Bhagwat SA, Jadhav S (2013) The hidden dimensions of human–wildlife conflict: Health impacts, opportunity and transaction costs. Biol Conserv 157:309–316. https://doi.org/10.1016/j.biocon.2012.07.014
3. Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48. https://doi.org/10.18637/jss.v067.i01
4. Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Mächler M, Bolker BM (2017) glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J 9:378–400. https://doi.org/10.32614/RJ-2017-066
5. Davies TE, Wilson S, Hazarika N, Chakrabarty J, Das D, Hodgson DJ, Zimmermann A (2011) Effectiveness of intervention methods against crop-raiding elephants. Conserv Lett 4:346–354. https://doi.org/10.1111/j.1755-263X.2011.00182.x
6. de Silva S, Wu T, Nyhus P, Weaver A, Thieme A, Johnson J, Wadey J, Mossbrucker A, Vu T, Neang T, Chen BS, Songer M, Leimgruber P (2023) Land-use change is associated with multi-century loss of elephant ecosystems in Asia. Sci Rep 13:5996. https://doi.org/10.1038/s41598-023-30650-8
7. Denninger Snyder K, Rentsch D (2020) Rethinking assessment of success of mitigation strategies for elephant-induced crop damage. Conserv Biol 34:829–842. https://doi.org/10.1111/cobi.13433
8. Department of National Parks, Wildlife and Plant Conservation (2025) [Wild elephant populations in protected areas, fiscal year 2025]. DNP Data Catalog. https://catalog.dnp.go.th/dataset/dnp09_11_01/resource/ac95287d-2940-43e0-be7a-e92f373f530c. Accessed 3 March 2026
9. Department of Provincial Administration (2025) Population statistics by administrative area (monthly reports) [Data set]. Ministry of Interior, Thailand.

https://stat.bora.dopa.go.th/stat/statnew/statMONTH/statmonth/#/mainpage. Accessed 16 February 2026

10. Fath H, Imron MA (2023) Modelling the emergence of financial well-being on the adoption process of mitigation measures in human-elephant conflict. J Industrial Eng Educ 1:136–170
11. Gross EM, Lahkar BP, Subedi N, Nyirenda VR, Lichtenfeld LL, Jakoby O (2019) Does traditional and advanced guarding reduce crop losses due to wildlife? A comparative analysis from Africa and Asia. J Nat Conserv 50:125712. https://doi.org/10.1016/j.jnc.2019.125712
12. Gunaryadi D, Sugiyo, Hedges S (2017) Community-based human-elephant conflict mitigation: The value of an evidence-based approach in promoting the uptake of effective methods. PLoS ONE 12:e0173742. https://doi.org/10.1371/journal.pone.0173742
13. Hahn N, Mwakatobe A, Konuche J, de Souza N, Keyyu J, Goss M, Chang'a A, Palminteri S, Dinerstein E, Olson D (2017) Unmanned aerial vehicles mitigate human–elephant conflict on the borders of Tanzanian parks: A case study. Oryx 51:513–516. https://doi.org/10.1017/S0030605316000946
14. Hoffmeier-Karimi R, Schulte B (2015) Assessing perceived and documented crop damage in a Tanzanian village impacted by human-elephant conflict (HEC). Pachyderm 56:51–60. https://doi.org/10.69649/pachyderm.v56i.371
15. Jordan NR, Smith BP, Appleby RG, van Eeden LM, Webster HS (2020) Addressing inequality and intolerance in human–wildlife coexistence. Conserv Biol 34:803–810. https://doi.org/10.1111/cobi.13471
16. Kiffner C, Schaal I, Cass L, Peirce K, Sussman O, Grueser A, Wachtel E, Adams H, Clark K, König HJ, Kioko J (2021) Perceptions and realities of elephant crop raiding and mitigation methods. Conserv Sci Pract 3:e372. https://doi.org/10.1111/csp2.372
17. Kochprapa P, Savini C, Ngoprasert D, Savini T, Gale GA (2023) Spatio-temporal dynamics of human–elephant conflict in a valley of pineapple plantations. Integr Conserv 2:95–107. https://doi.org/10.1002/inc3.23
18. Köpke S, Withanachchi SS, Pathiranage R, Withanachchi CR, Gamage DU, Nissanka TS, Warapitiya CC, Nissanka BM, Ranasinghe NN, Senarathna CD, Dissanayake HR, Perera ENC, Schleyer C, Thiel A (2023) Human-elephant conflict in the Sri Lankan dry zone: investigating social and geographical drivers through field-based methods. GeoJournal 88:5153–5172. https://doi.org/10.1007/s10708-023-10913-7
19. Köpke S, Withanachchi SS, Perera ENC, Withanachchi CR, Gamage DU, Nissanka TS, Warapitiya CC, Nissanka BM, Ranasinghe NN, Senarathna CD, Dissanayake HR, Pathiranage R, Schleyer C, Thiel A (2024) Factors driving human–elephant conflict: statistical assessment of vulnerability and implications for wildlife conflict management in Sri Lanka. Biodivers Conserv 33:3075–3101. https://doi.org/10.1007/s10531-024-02903-z
20. Mayberry AL, Hovorka AJ, Evans KE (2017) Well-being impacts of human-elephant conflict in Khumaga, Botswana: Exploring visible and hidden dimensions. Conserv Soc 15:280–291. https://doi.org/10.4103/cs.cs_16_132

21. Mchome GJ, Mariki SB, Smit JB, Majige LM, Hassan SN (2025) Assessing the efficacy of multiple elephant deterrents in the Kilombero Valley, Tanzania. Trop Conserv Sci 18:1–15. https://doi.org/10.1177/19400829251381934
22. Menon V, Tiwari SKR (2019) Population status of Asian elephants *Elephas maximus* and key threats. Int Zoo Yearbook 53:17–30. https://doi.org/10.1111/izy.12247
23. Montgomery RA, Raupp J, Mukhwana M, Greenleaf A, Mudumba T, Muruthi P (2022) The efficacy of interventions to protect crops from raiding elephants. Ambio 51:716–727. https://doi.org/10.1007/s13280-021-01587-x
24. Mumby HS, Plotnik JM (2018) Taking the elephants' perspective: Remembering elephant behavior, cognition and ecology in human-elephant conflict mitigation. Front Ecol Evol 6:122. https://doi.org/10.3389/fevo.2018.00122
25. Nyhus PJ (2016) Human–wildlife conflict and coexistence. Annu Rev Environ Resour 41:143–171. https://doi.org/10.1146/annurev-environ-110615-085634
26. Nyirenda VR, Nkhata BA, Tembo O, Siamundele S (2018) Elephant crop damage: Subsistence farmers' social vulnerability, livelihood sustainability and elephant conservation. Sustainability 10:3572. https://doi.org/10.3390/su10103572
27. Nyumba TO, Emenye OE, Leader-Williams N (2020) Assessing impacts of human-elephant conflict on human wellbeing: An empirical analysis of communities living with elephants around Maasai Mara National Reserve in Kenya. PLoS ONE 15:e0239545. https://doi.org/10.1371/journal.pone.0239545
28. Owen A, van de Water A, Sutthiboriban N, Tantipisanuh N, Sangthong S, Rajbhandari A, Matteson K (2024) The role of alternative crop cultivation in promoting human-elephant coexistence: A multidisciplinary investigation in Thailand. Diversity 16:519. https://doi.org/10.3390/d16090519
29. Posit Team (2025) RStudio: Integrated development environment for R. Posit Software, PBC, Boston, USA. https://www.posit.co/
30. Prins HHT, Liefting Y, de Jong JF (2022) Marginal farmers carry the burden of damage caused by Asian elephants *Elephas maximus* in Bardiya National Park, Nepal. Oryx 56:73–81. https://doi.org/10.1017/S0030605319001431
31. R Core Team (2020) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/
32. Rastogi S, Bhattacharyya S, Vimal K, Dinerstein E, Shah WA, Nagano Y, Hirari S, Gulick S, Lee A, Sekar N (2025) Promoting human–elephant coexistence through integration of AI, real-time alerts, and rapid response. Conserv Sci Pract 7:e70186. https://doi.org/10.1111/csp2.70186
33. Saif O, Kansky R, Palash A, Kidd M, Knight AT (2020) Costs of coexistence: understanding the drivers of tolerance towards Asian elephants *Elephas maximus* in rural Bangladesh. Oryx 54:603–611. https://doi.org/10.1017/S0030605318001072
34. Sampson C, Rodriguez SL, Leimgruber P, Huang Q, Tonkyn D (2021) A quantitative assessment of the indirect impacts of human-elephant conflict. PLoS ONE 16:e0253784.

https://doi.org/10.1371/journal.pone.0253784

35. Sekar N, Bhatt T, Deomurari A, Sharma S, Kumari P, Kayina A, Somanathan E (2026) Effects of organized guarding on mortality from human–elephant conflict in northeast India. Conserv Biol 40:e70204. https://doi.org/10.1111/cobi.70204
36. Shaffer LJ, Khadka KK, Van Den Hoek J, Naithani KJ (2019) Human-elephant conflict: a review of current management strategies and future directions. Front Ecol Evol 6:235. https://doi.org/10.3389/fevo.2018.00235
37. Sheil D, Akampurira E (2026) Supporting interventions to lessen human–wildlife conflict. People Nat 8:1100–1116. https://doi.org/10.1002/pan3.70314
38. Sirichakkaraset S, Emphandhu D, Phongkhieo NT (2025) Fostering sustainable growth through creative community-based tourism (C-CBT): A case study of Ban Ruam Thai village in Kui Buri National Park, Thailand. Humanities. Arts Social Sci Stud 25:631–646. https://doi.org/10.69598/hasss.25.3.276209
39. Sitati NW, Walpole MJ, Leader-Williams N (2005) Factors affecting susceptibility of farms to crop raiding by African elephants: Using a predictive model to mitigate conflict. J Appl Ecol 42:1175–1182. https://doi.org/10.1111/j.1365-2664.2005.01091.x
40. Songhurst A, McCulloch G, Coulson T (2016) Finding pathways to human–elephant coexistence: A risky business. Oryx 50:713–720. https://doi.org/10.1017/S0030605315000344
41. Srikrachang M, Srikosamatara S (2005) Elephant crop raiding problems and their solutions at Kui Buri National Park, Southwestern Thailand. Nat Hist Bull Siam Soc 53:87–109
42. Sukmasuang R, Phumpakphan N, Deungkae P, Chaiyarat R, Pla-Ard M, Khiowsree N, Charaspet K, Paansri P, Noowong J (2024) Review: Status of wild elephant, conflict and conservation actions in Thailand. Biodiversitas 25:1479–1498. https://doi.org/10.13057/biodiv/d250416
43. Supanta J, Poolkhet C, Yindee M, Manatchaiworakul W, Wongtawan T (2025) Human–elephant conflict in Thailand over the past decade (2014–2023): occurrence, geographical distribution, and temporal trends. Animals 15:1304. https://doi.org/10.3390/ani15091304
44. Tang R, Li W, Zhu D, Shang X, Guo X, Zhang L (2020) Raging elephants: effects of human disturbance on physiological stress and reproductive potential in wild Asian elephants. Conserv Physiol 8:coz106. https://doi.org/10.1093/conphys/coz106
45. Van de Water A, Matteson K (2018) Human-elephant conflict in western Thailand: Socio-economic drivers and potential mitigation strategies. PLoS ONE 13:e0194736. https://doi.org/10.1371/journal.pone.0194736
46. Van de Water A, King LE, Arkajak R, Arkajak J, van Doormaal N, Ceccarelli V, Sluiter L, Doornwaard SM, Praet V, Owen D, Matteson K (2020) Beehive fences as a sustainable local solution to human-elephant conflict in Thailand. Conserv Sci Pract 2:e260. https://doi.org/10.1111/csp2.260
47. Van de Water A, Garaï ME, Burnett MM, Henley MD, Di Minin E, Streicher JP, Bates LA, Slotow R (2024) Integrating a One Well-being approach in elephant conservation: evaluating consequences of management interventions. Ecol Soc 29:15. https://doi.org/10.5751/ES-15193-290315

48. Venables WN, Ripley BD (2002) Modern applied statistics with S, 4th edn. Springer, New York. https://doi.org/10.1007/978-0-387-21706-2
49. Vijayakrishnan S, Kumar MA, Umapathy G, Kumar V, Sinha A (2018) Physiological stress responses in wild Asian elephants *Elephas maximus* in a human-dominated landscape in the Western Ghats, southern India. Gen Comp Endocrinol 266:150–156. https://doi.org/10.1016/j.ygcen.2018.05.009
50. Wongsawaddiwattana C, Pattaratuma A (2005) Reform land use patterns of people at Ruamthai Demonstration Cooperative Village, Kui Buri district, Prachuap Khiri Khan Province. Kasetsart J Soc Sci 26:33–41
51. Zeppelzauer M, Hensman S, Stoeger AS (2015) Towards an automated acoustic detection system for free ranging elephants. Bioacoustics 24:13–29. https://doi.org/10.1080/09524622.2014.906321
52. Zuur AF, Ieno EN, Walker NJ, Saveliev AA, Smith GM (2009) Mixed effects models and extensions in ecology with R. Springer, New York. https://doi.org/10.1007/978-0-387-87458-6

Figures

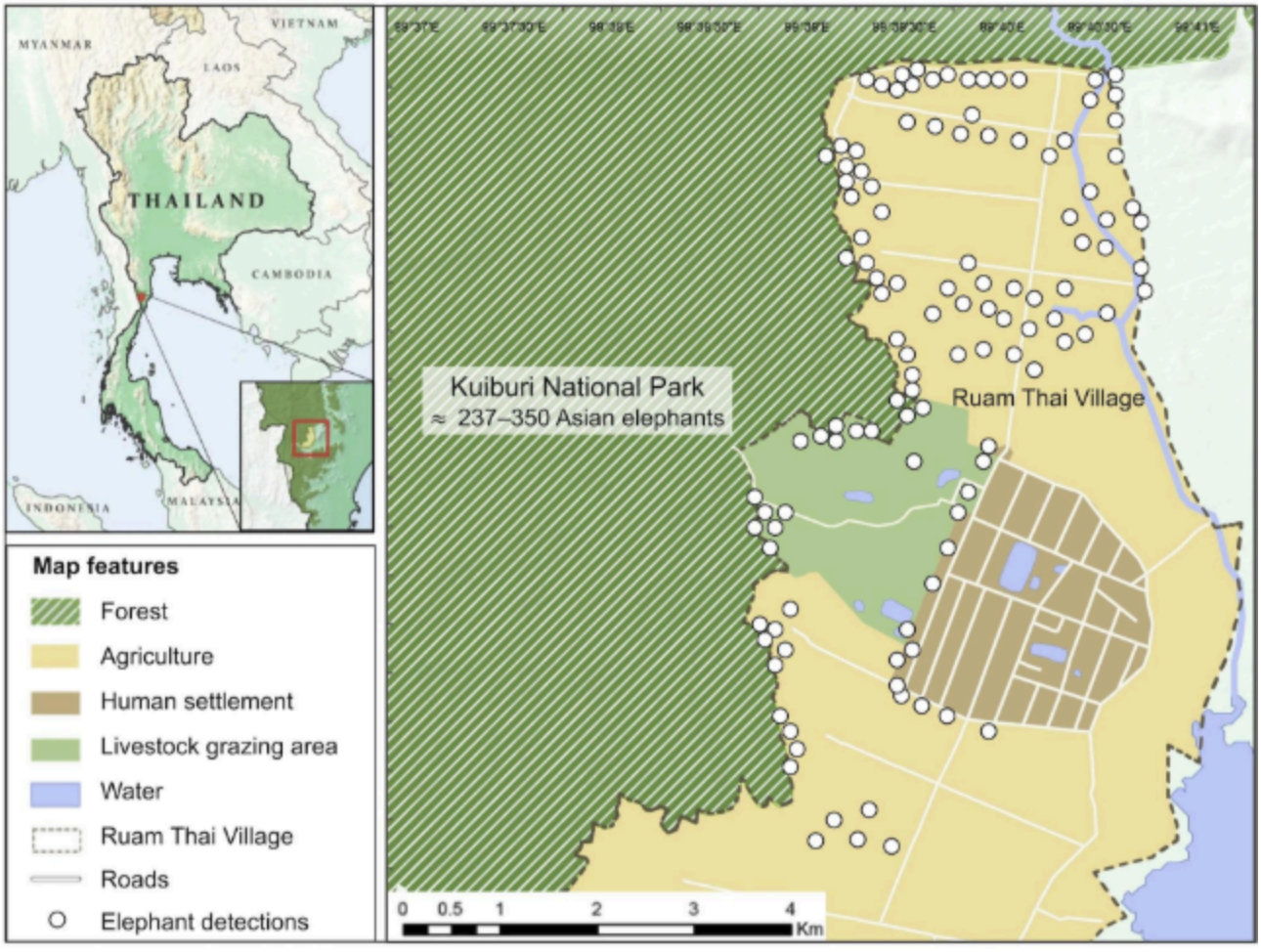


Figure 1

Location of Kuiburi National Park in Prachuap Khiri Khan, southwestern Thailand (left) and land-use layout of Ruam Thai Village (right). Human settlement is consolidated in a central location, leaving forest-adjacent agricultural plots unsupervised and increasing exposure to elephant-caused crop damage. Elephant detection locations (white circles) represent approximate regions, rather than exact coordinates, as identified by elephant response rangers and farmers during unpublished participatory mapping exercises in October 2023

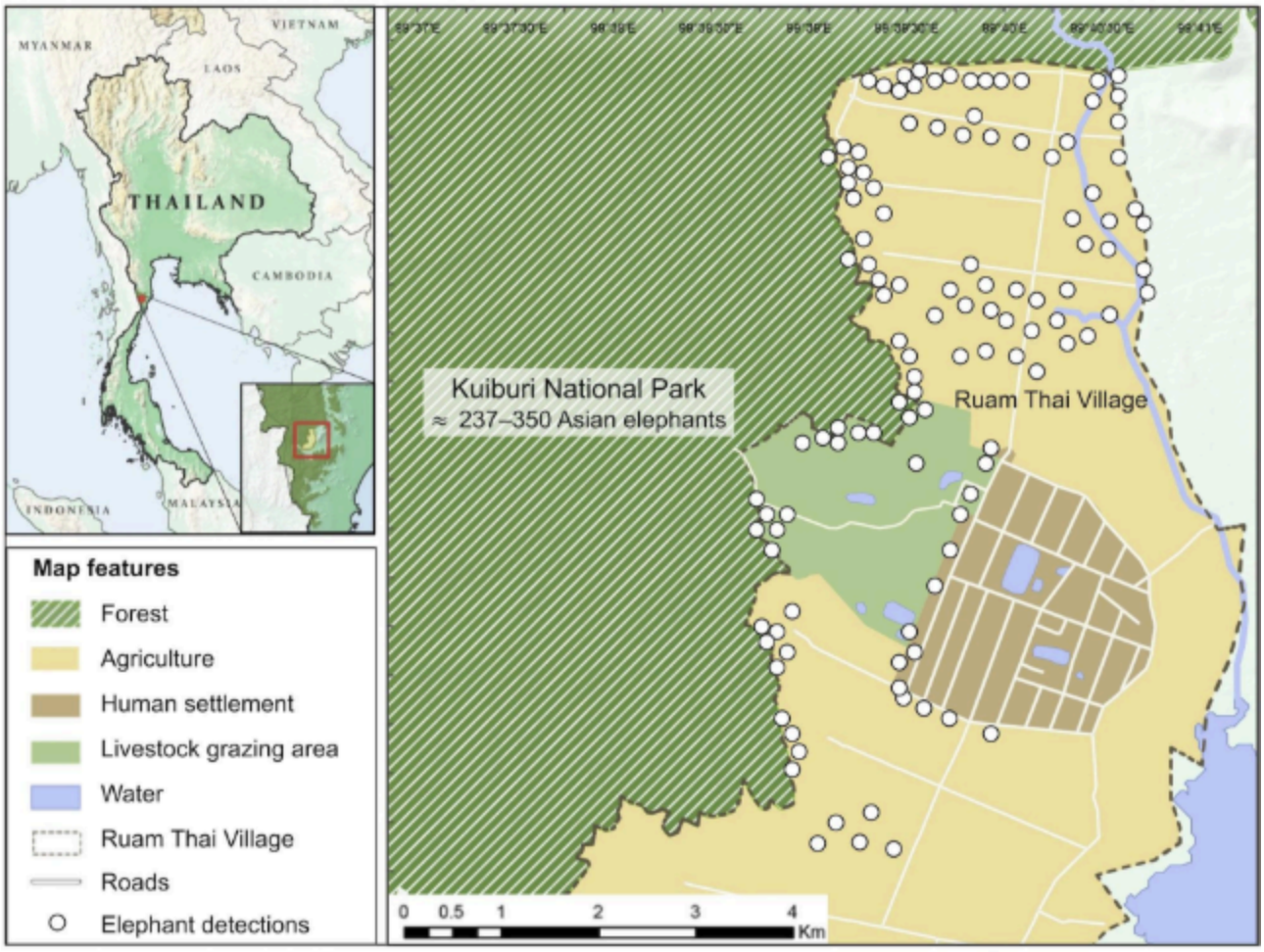


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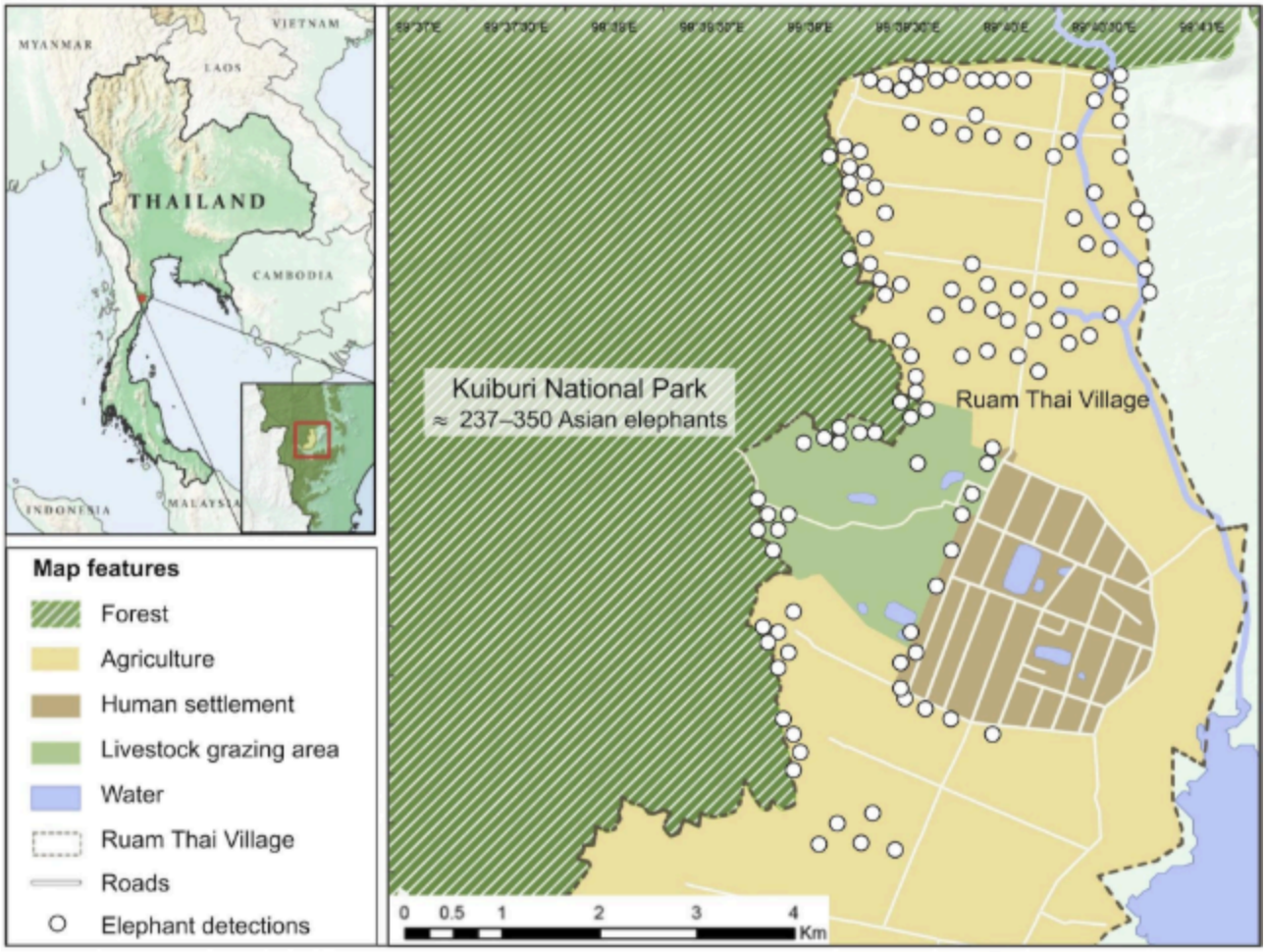


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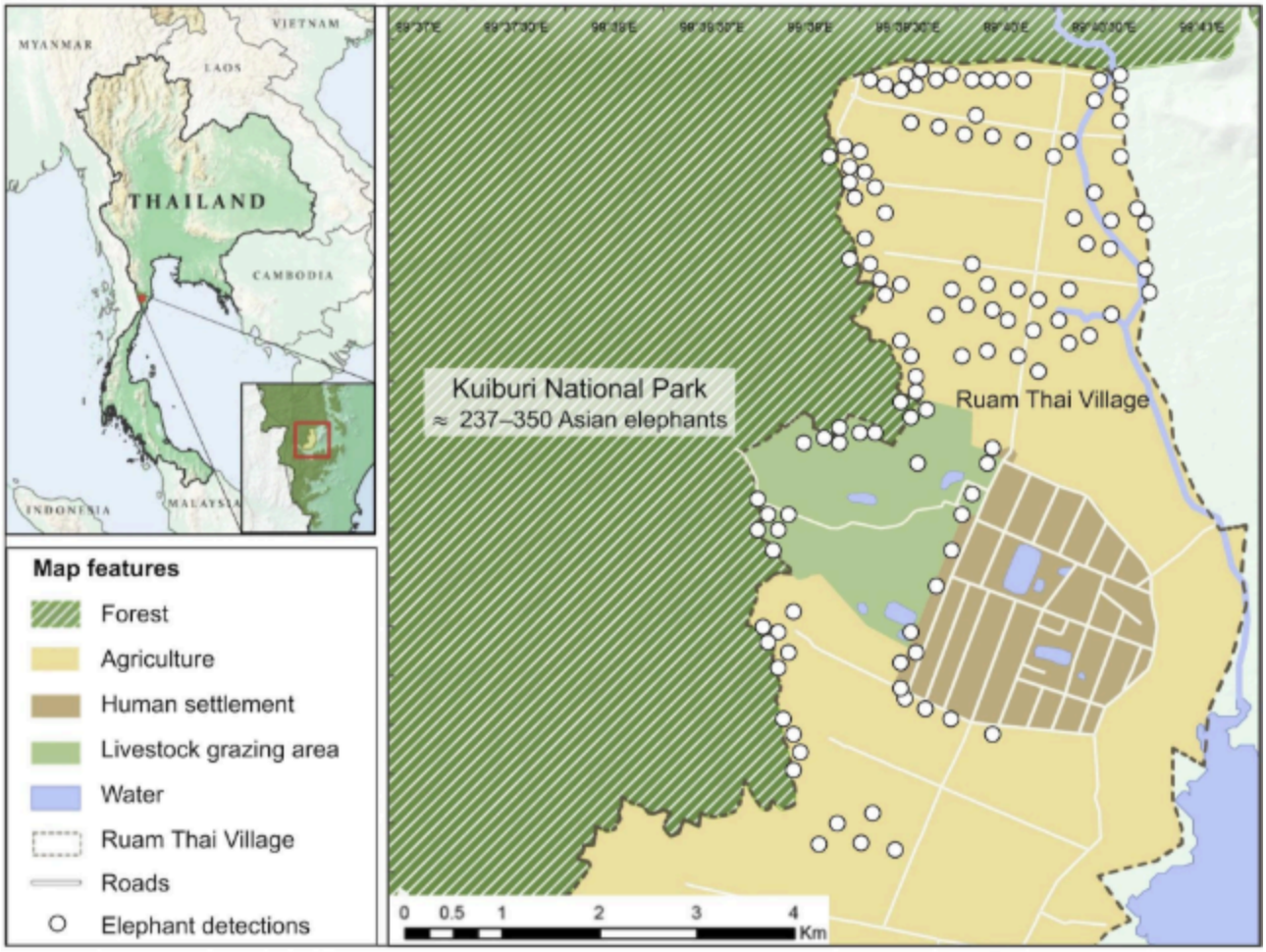


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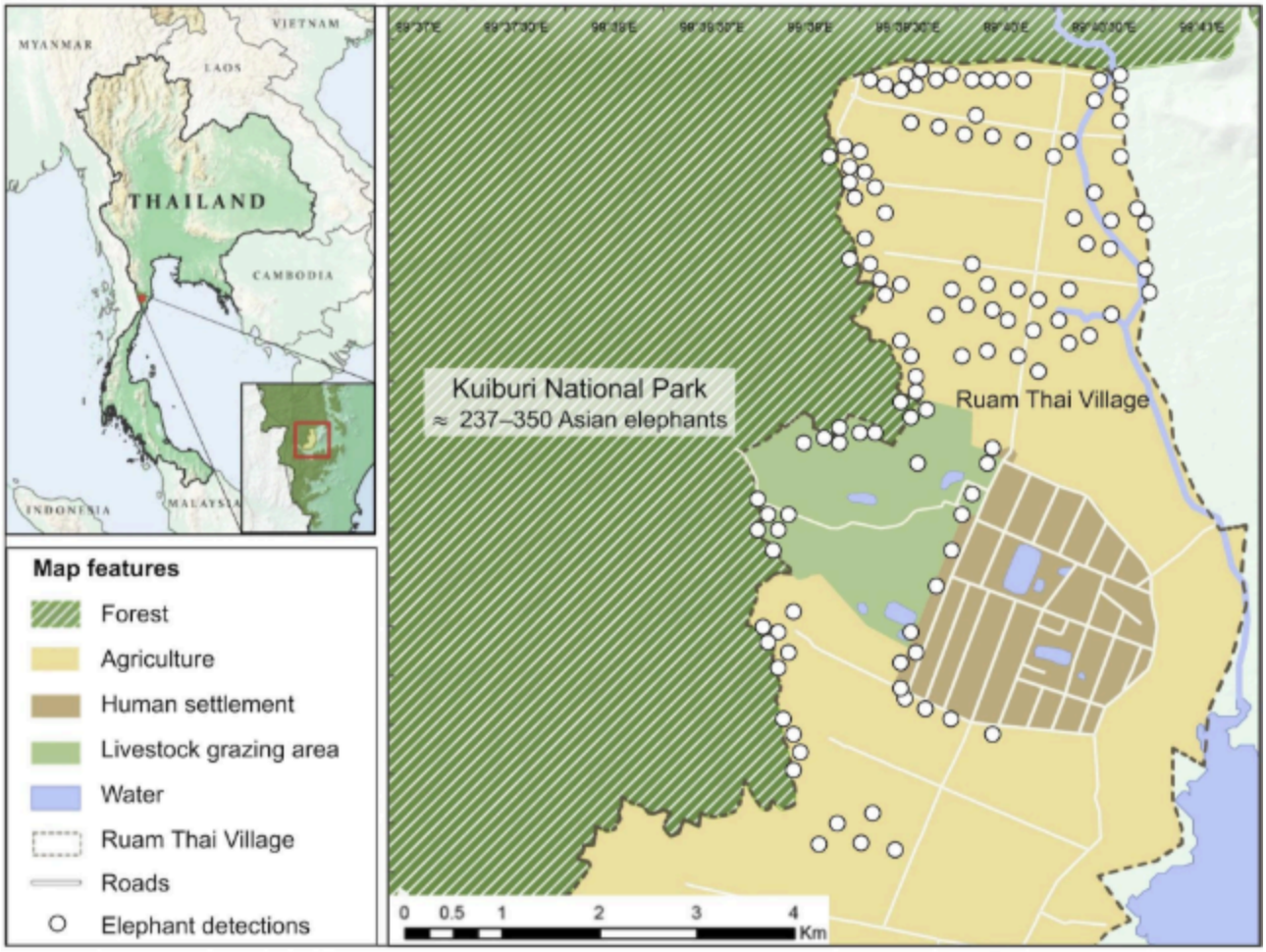


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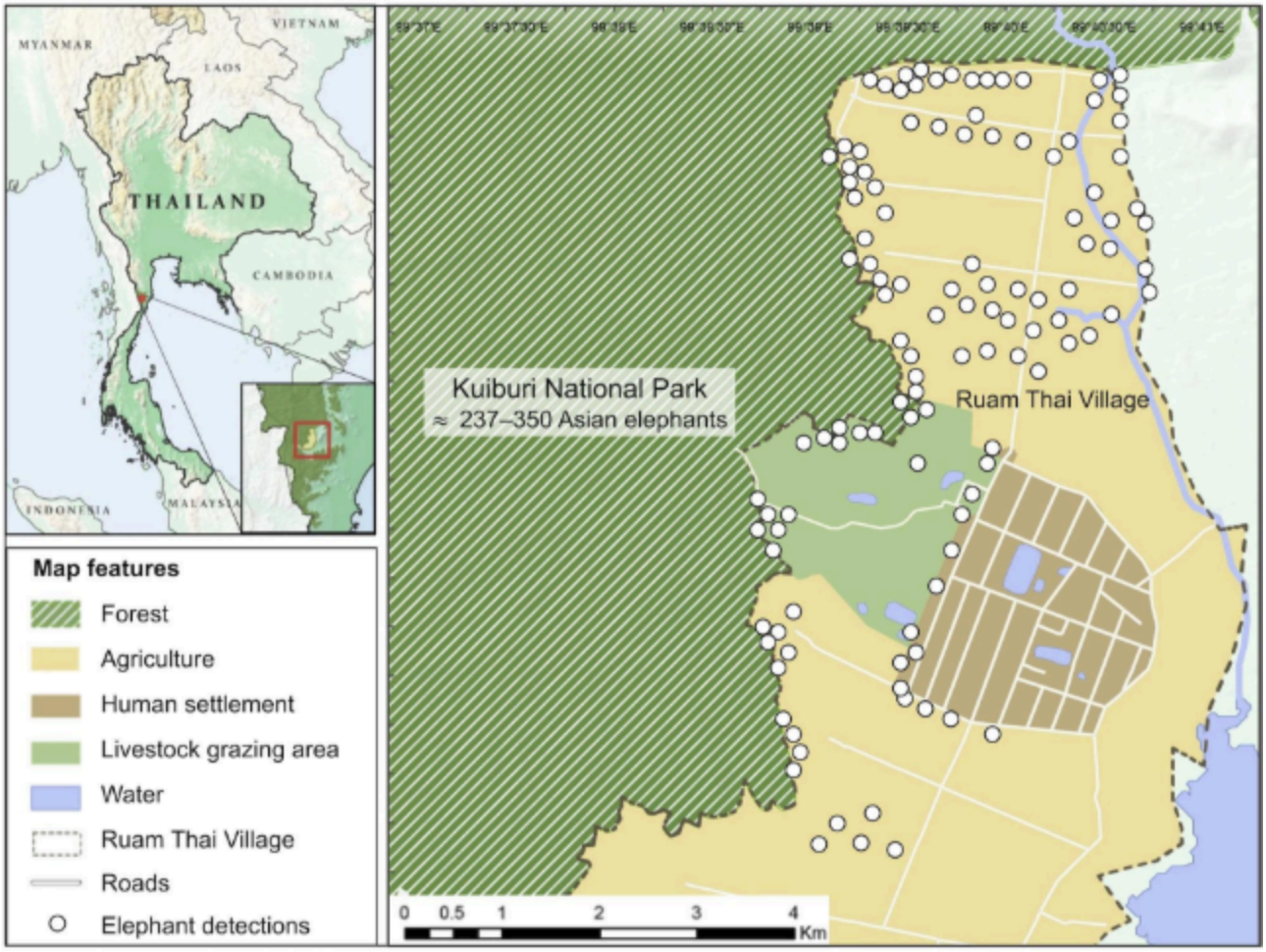


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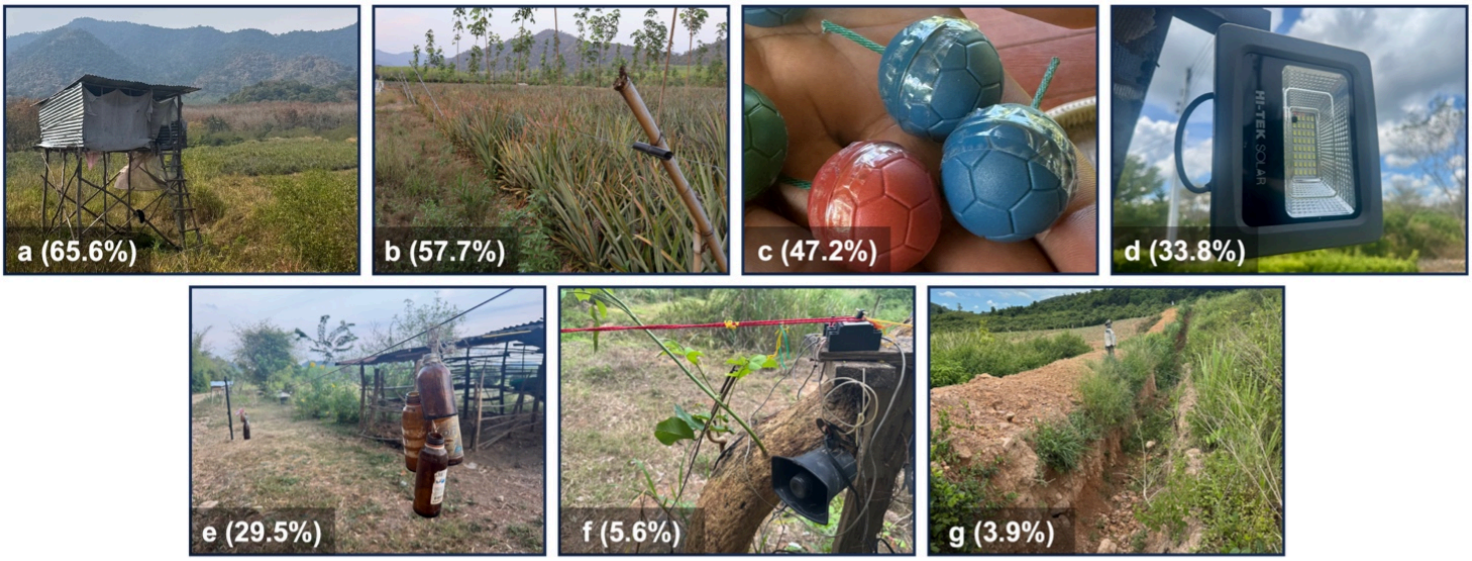


Figure 2

Deterrents used by farmers in Ruam Thai Village. (a) night guarding, (b) electric fence, (c) firecrackers, (d) spinning lights/spotlights, (e) bottle fence, (f) siren system and (g) trench. Percentages indicate the proportion of farm profiles (N = 305) in which each deterrent was reported. Percentages exceed 100% in total because deterrent use was not mutually exclusive. Gunshots were included as a survey response option but were not reported

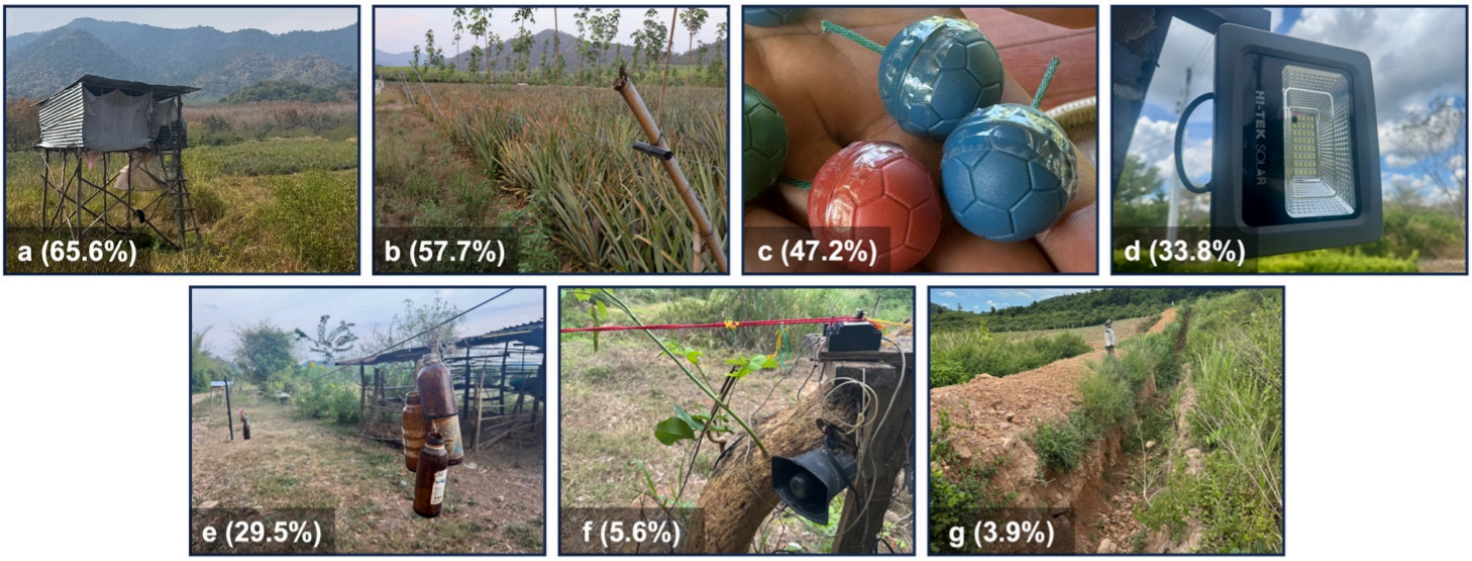


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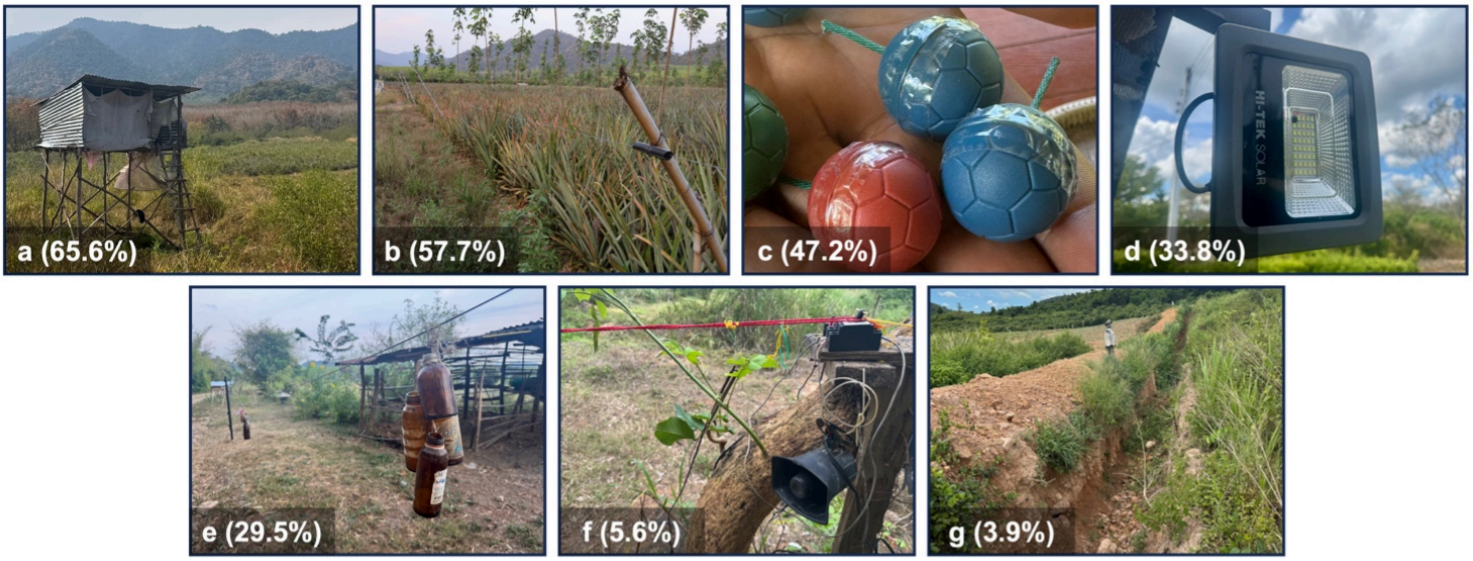


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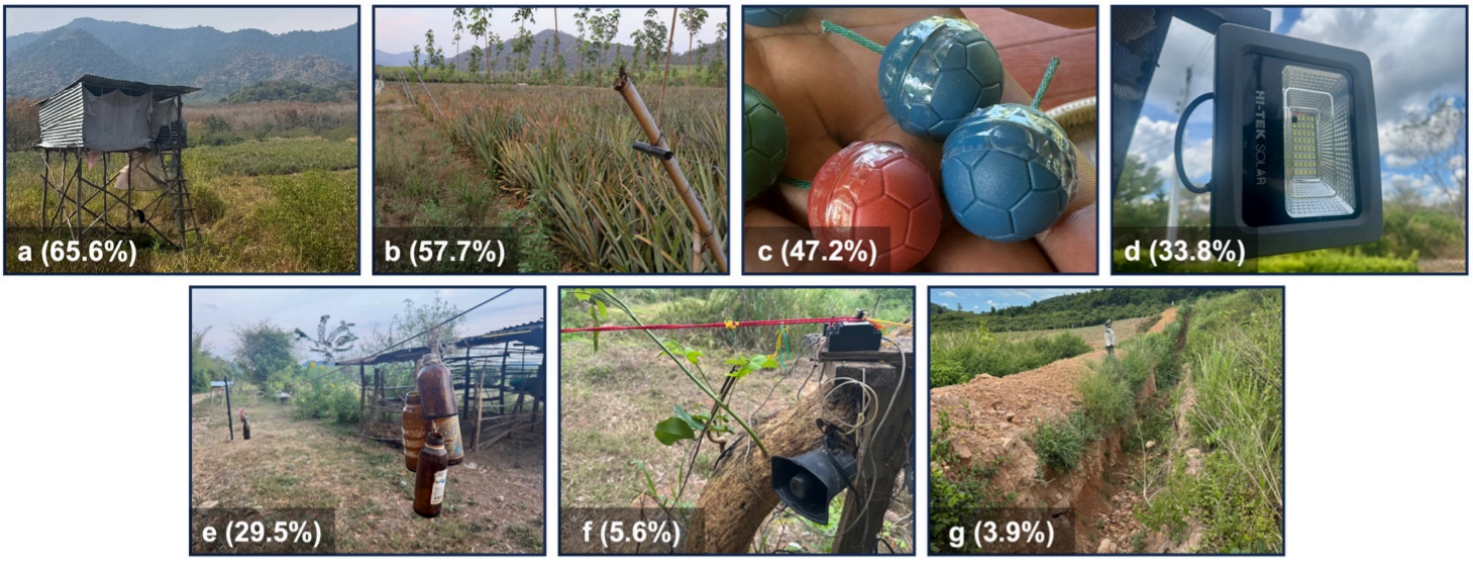


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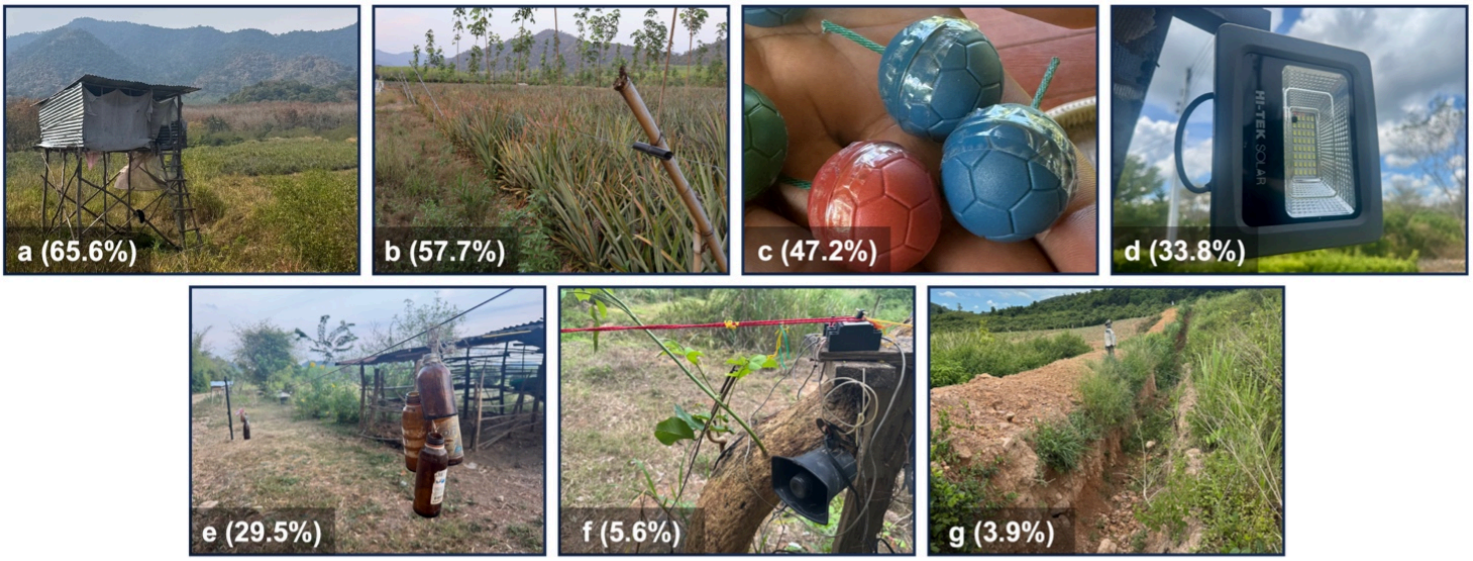


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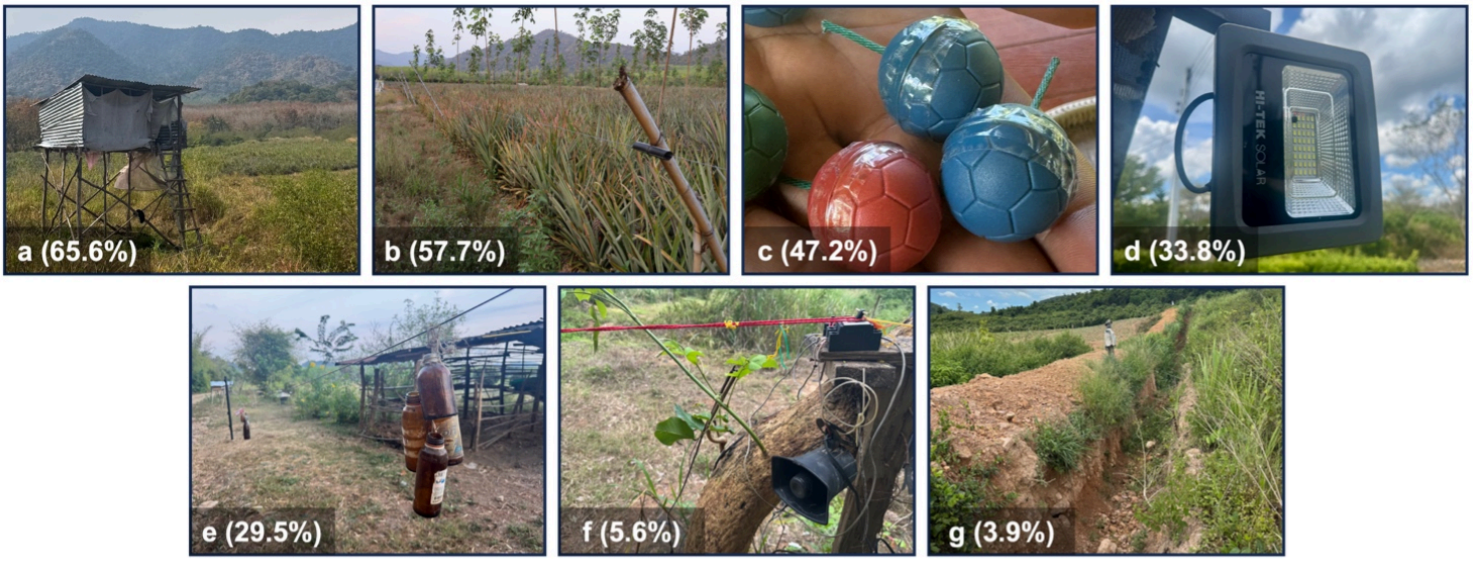


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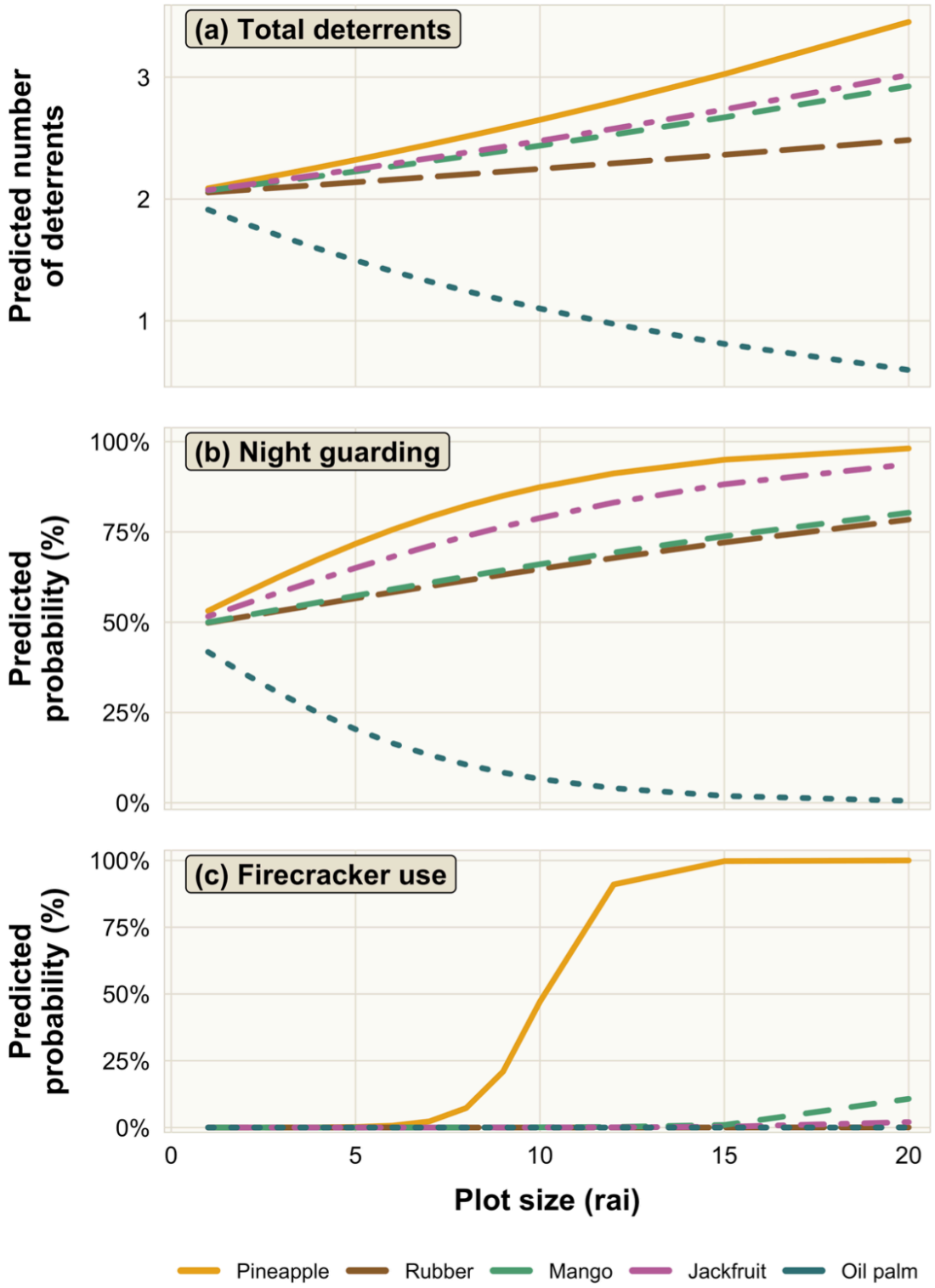


Figure 3

Model-predicted relationships between deterrent use and plot size (rai) across pineapple, rubber, mango, jackfruit and oil palm farms: (a) Predicted number of deterrents used. (b) Predicted probability of night guarding. (c) Predicted probability of firecracker use. Lines show predictions from crop species × plot size interaction models. Confidence intervals are omitted for clarity and reported for each model in Table S4

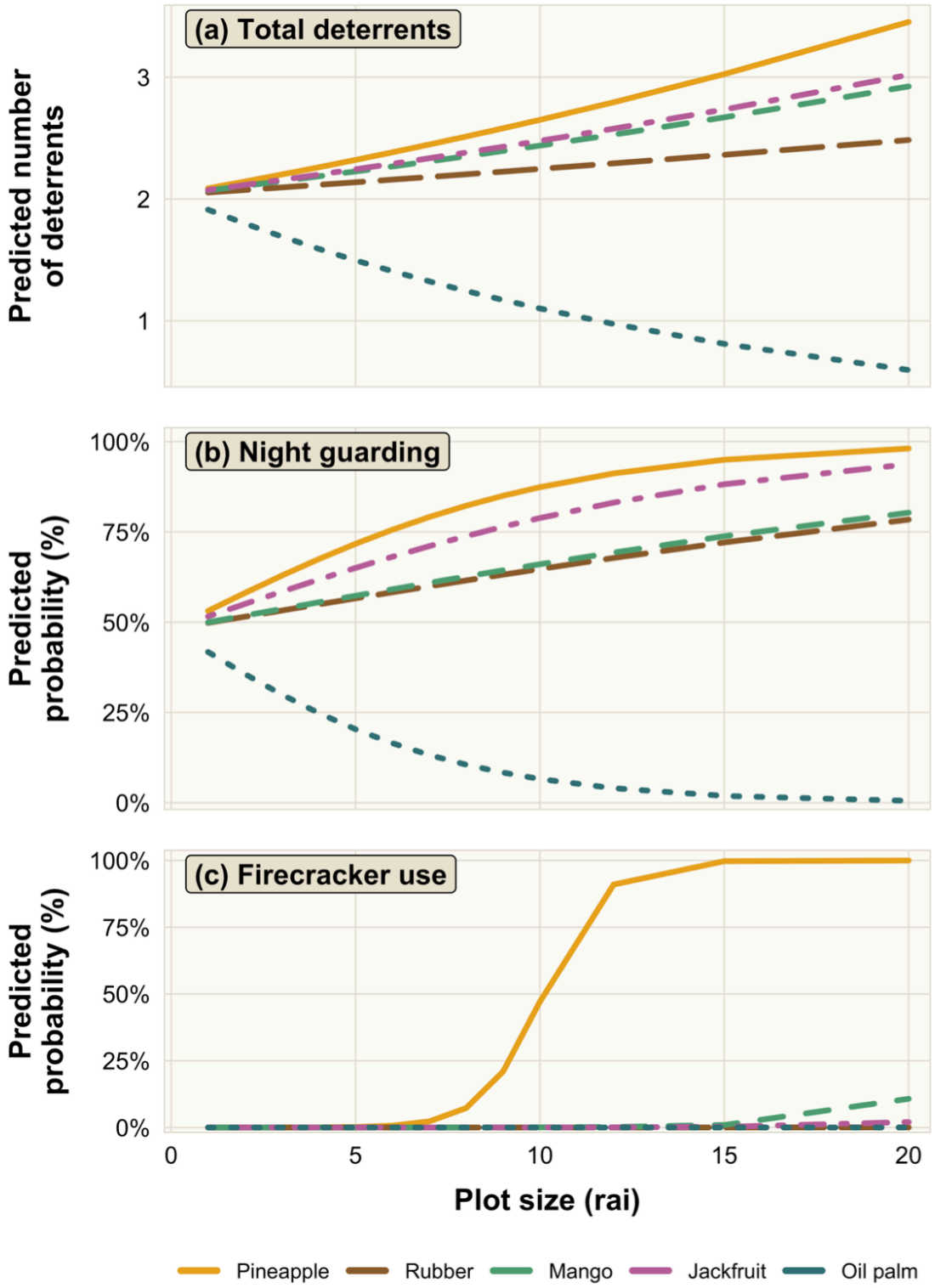


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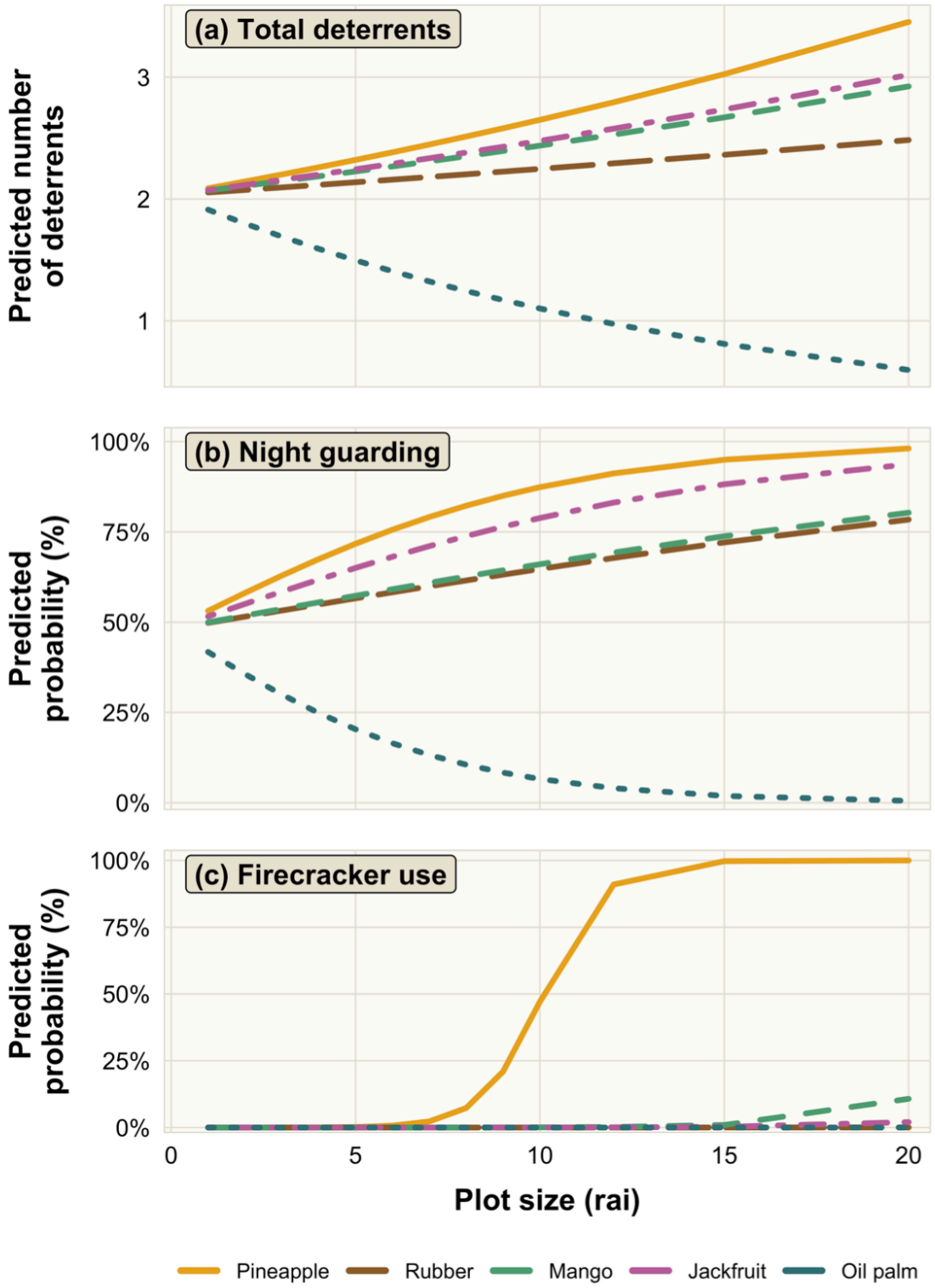


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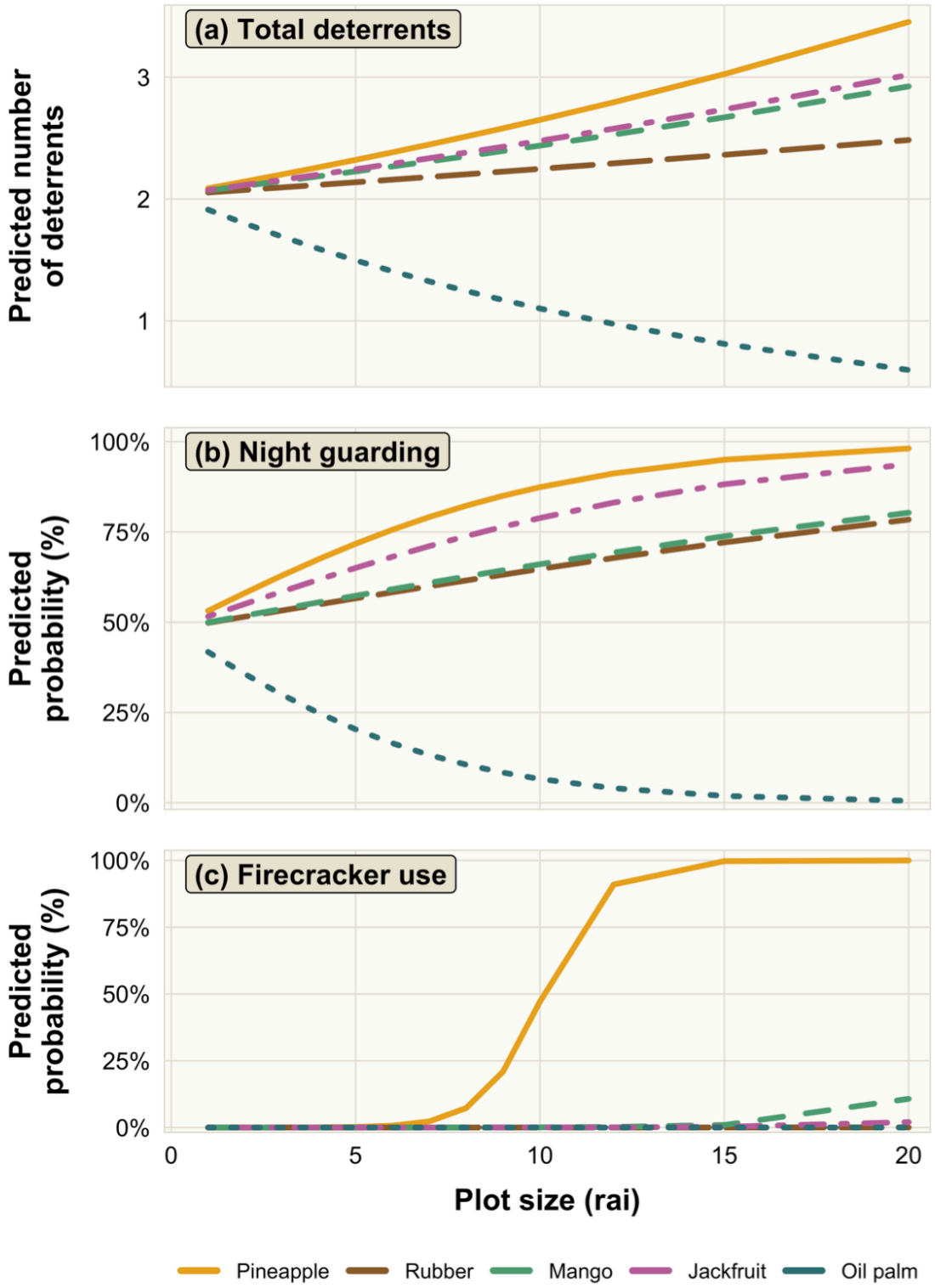


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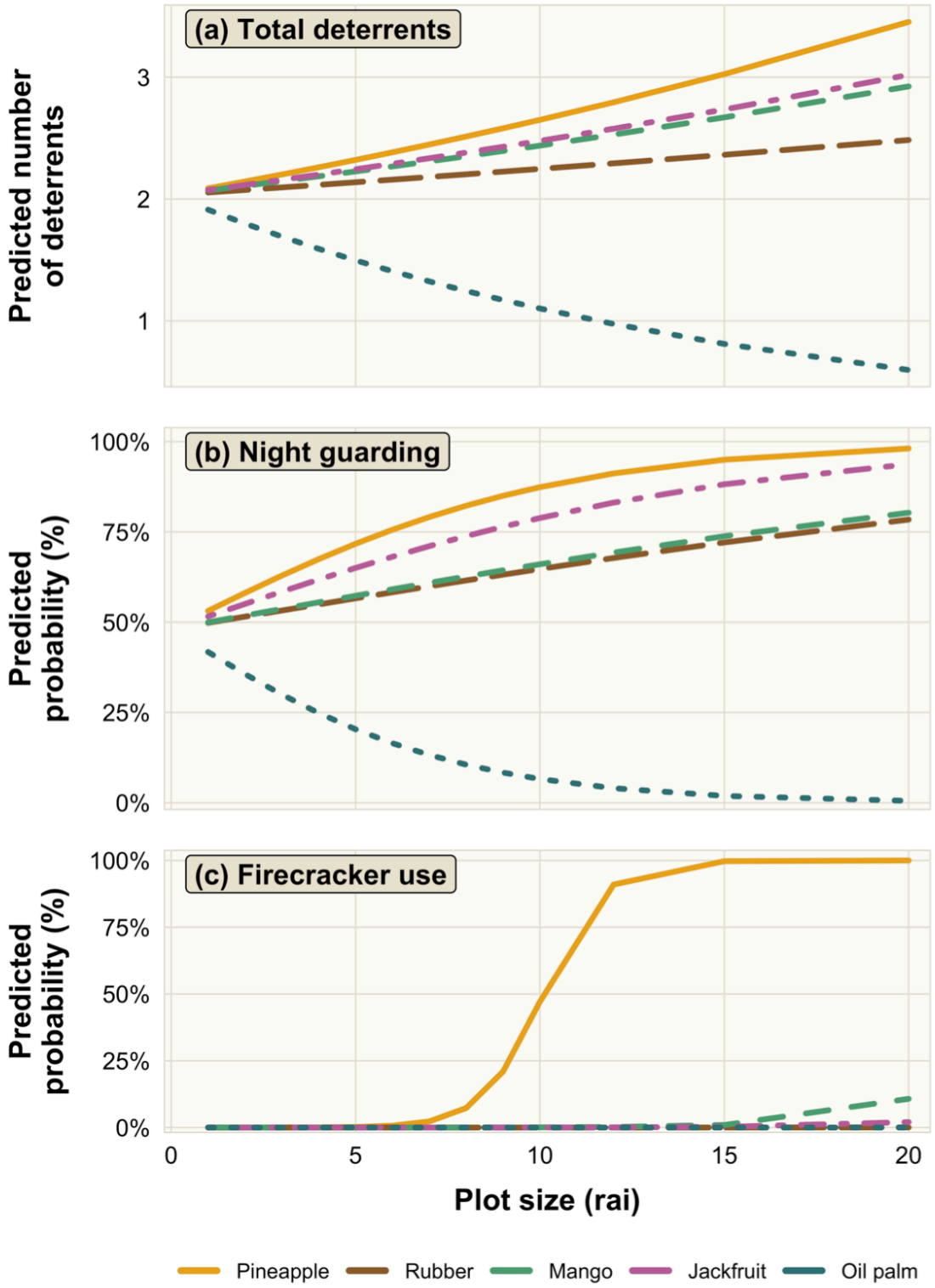


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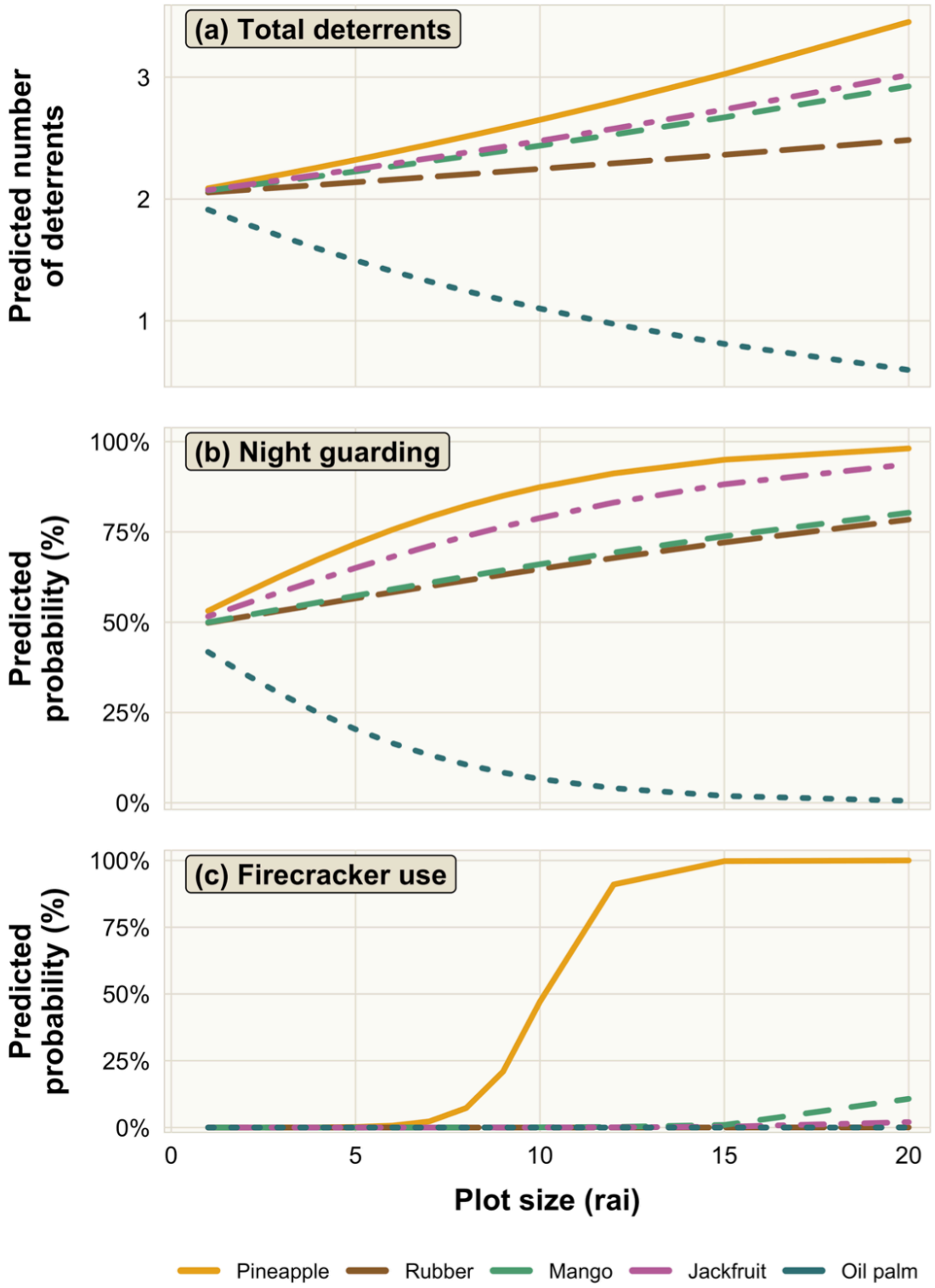


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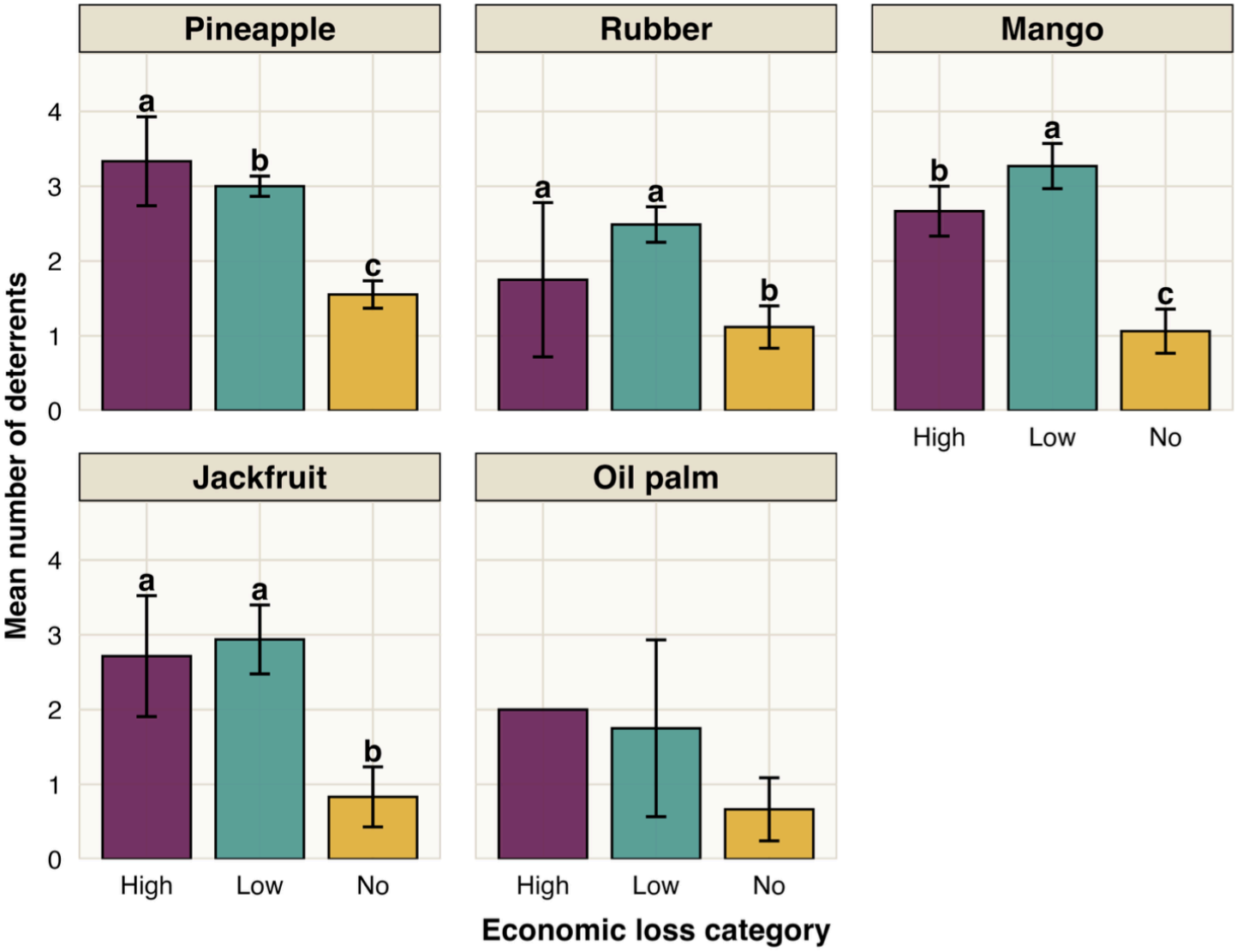


Figure 4

Model-estimated mean number of deterrents (± SE) across economic loss categories for each crop species. Bars depict predicted means from crop-specific models and error bars indicate standard errors. Different letters indicate statistically significant groupings and directionality among loss categories within each crop (Tukey-adjusted post hoc comparisons at $\alpha = 0.05$). Shared letters indicate no significant difference. Post hoc comparisons could not be conducted for oil palm because of insufficient sample sizes, so no significance letters are shown for this crop species

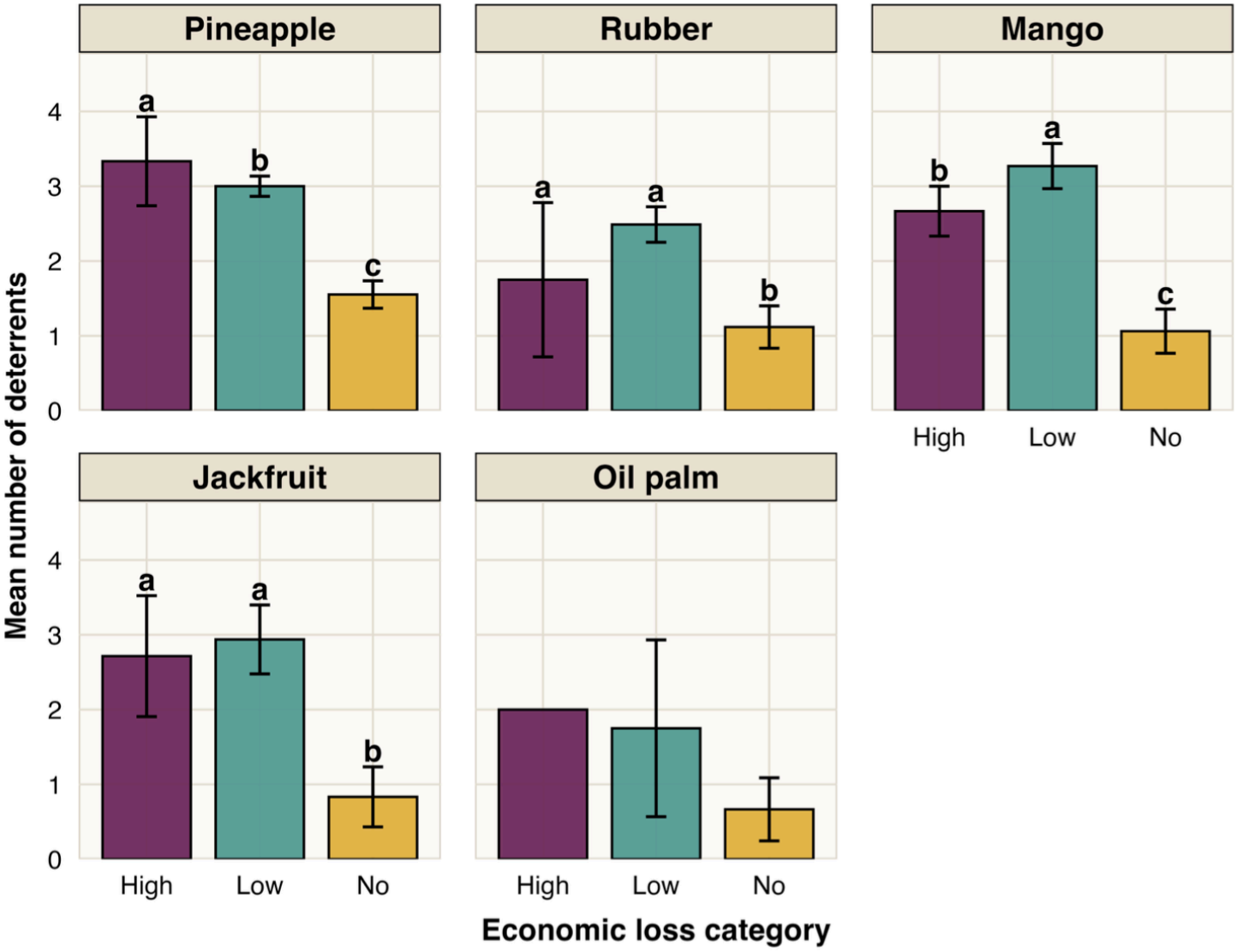


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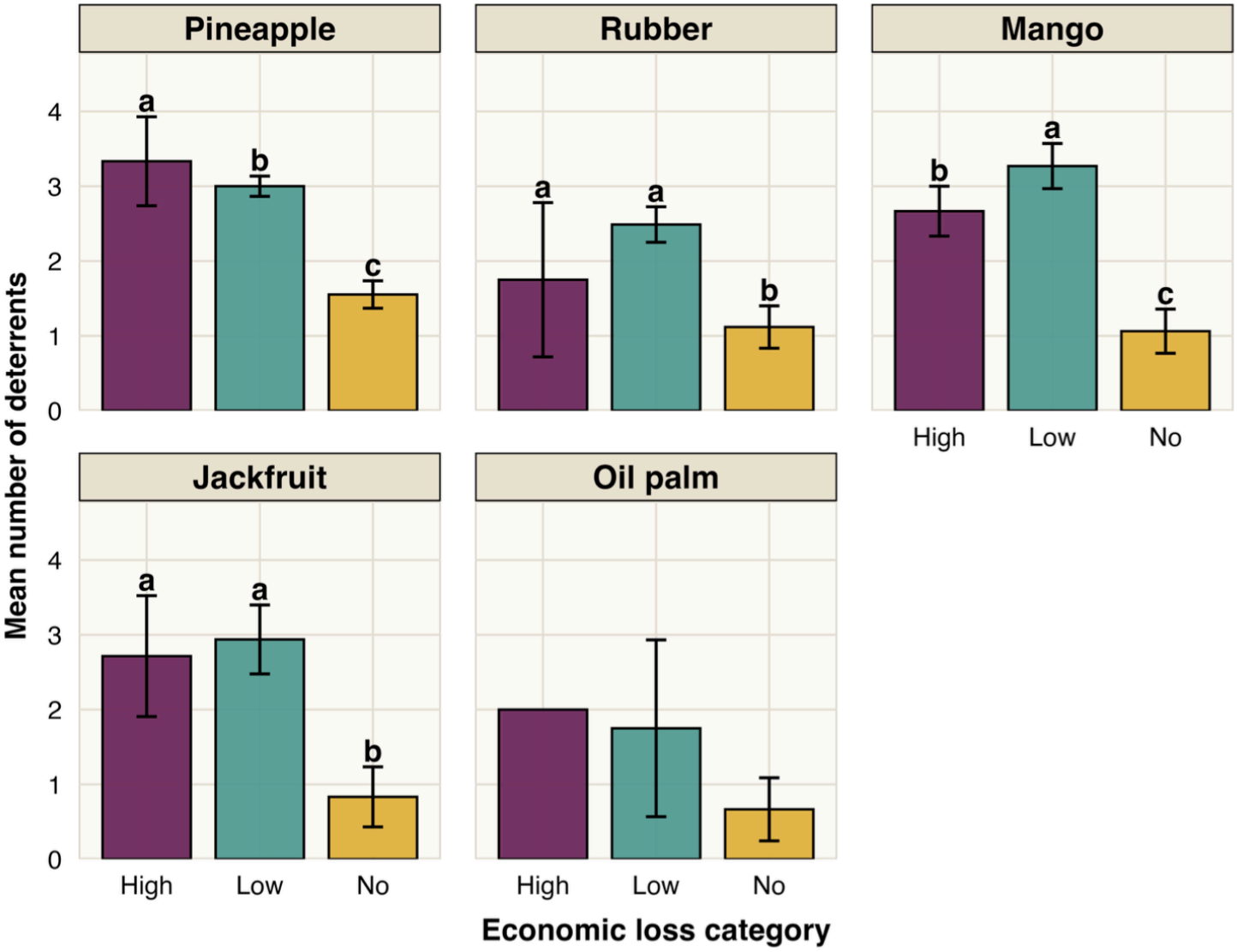


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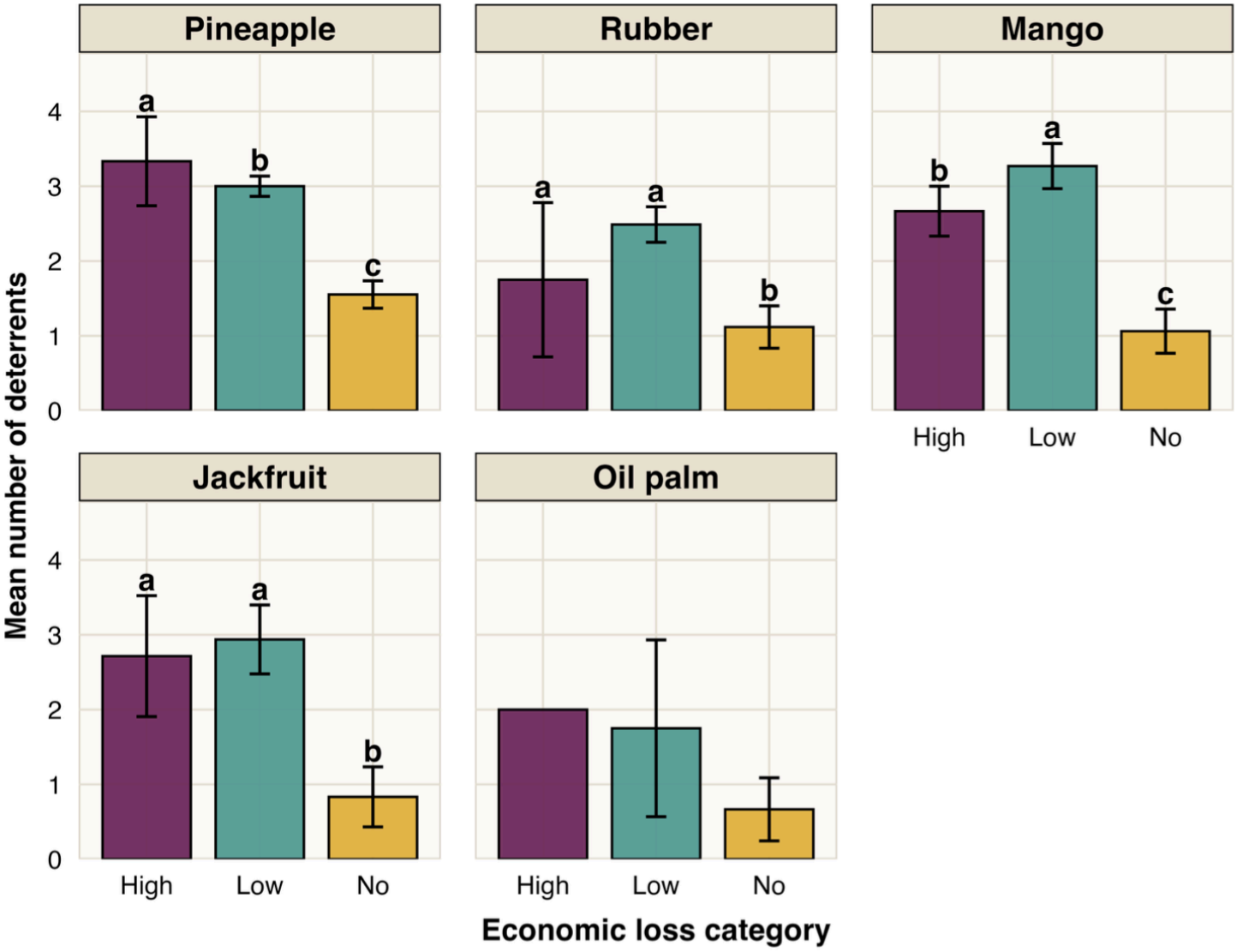


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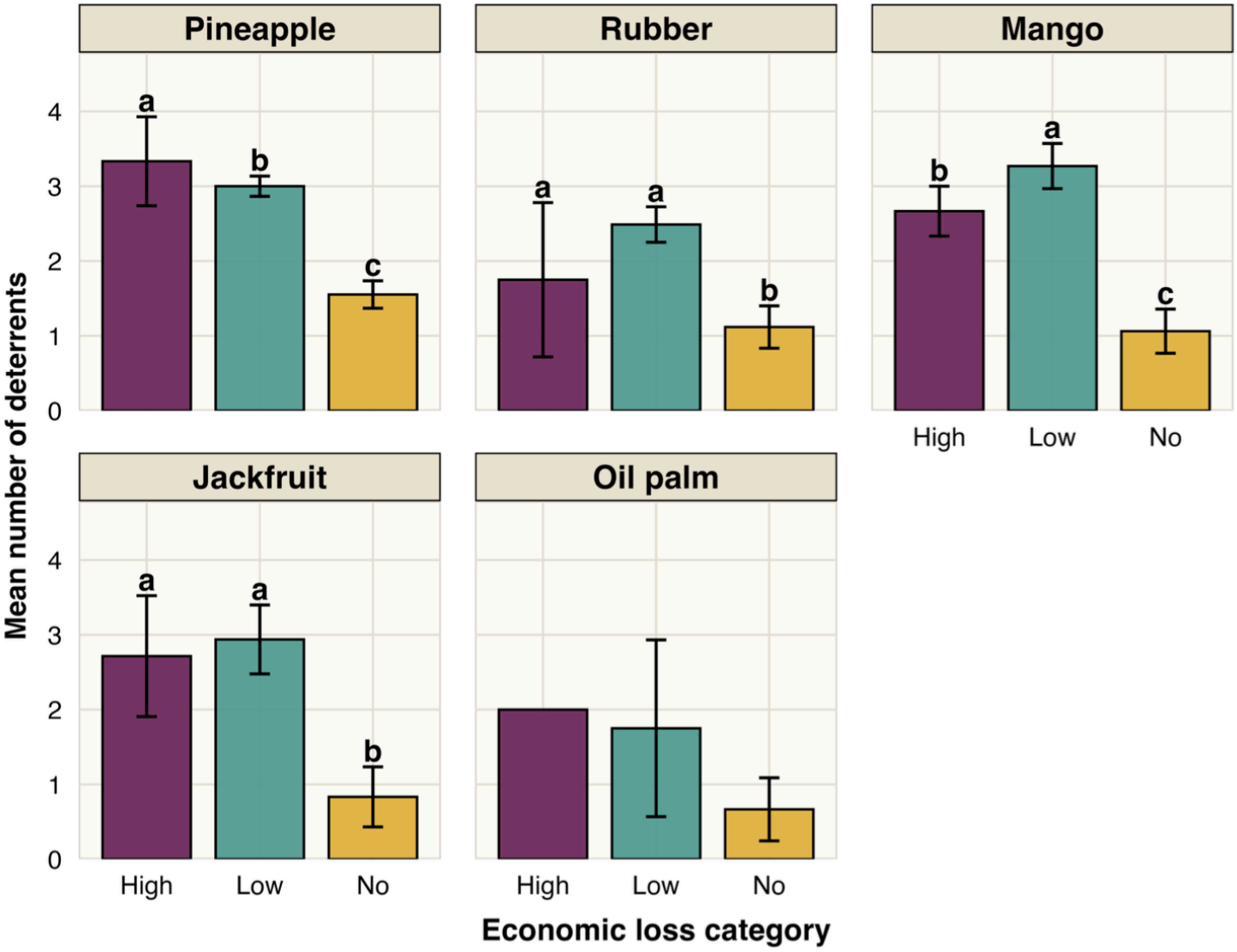


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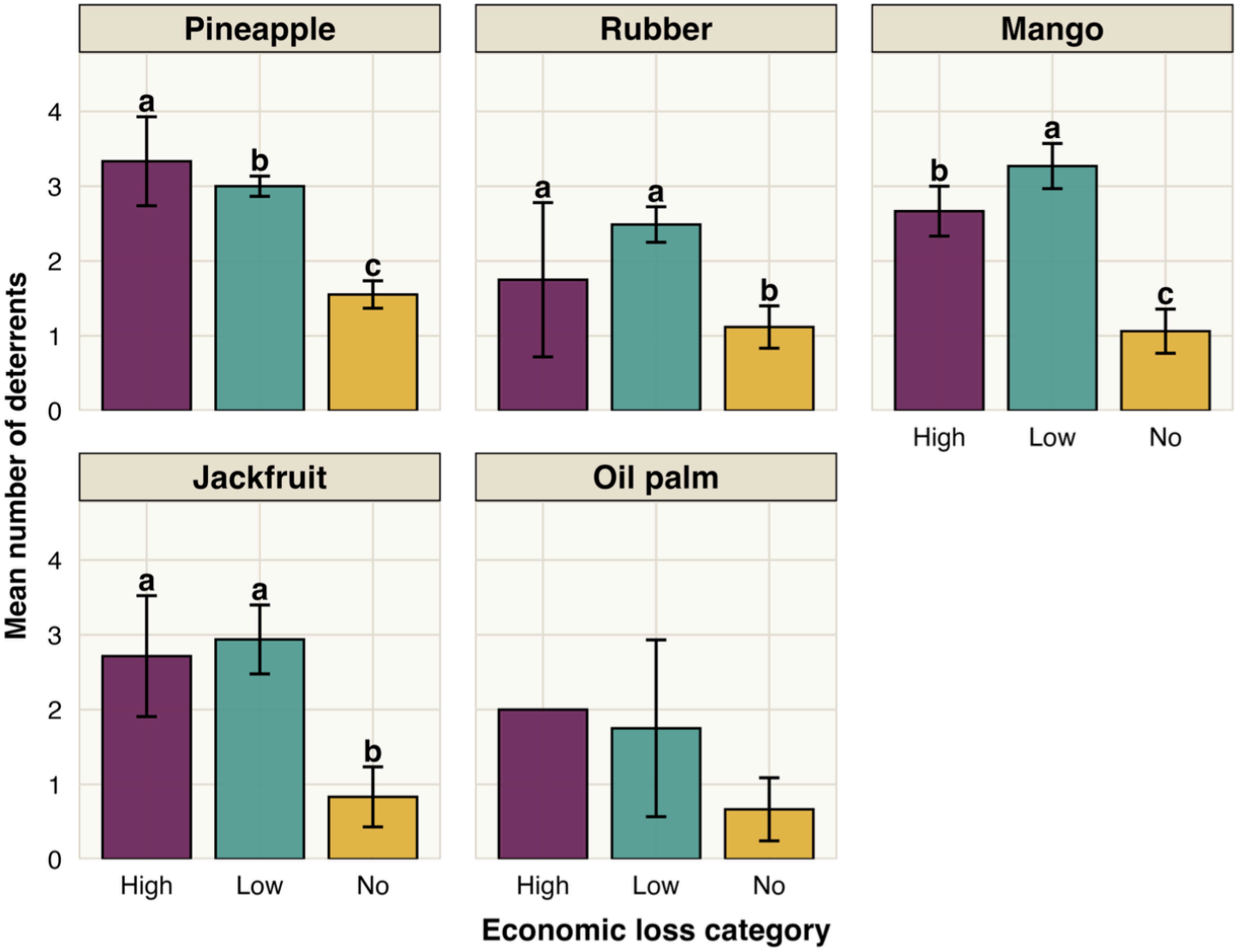


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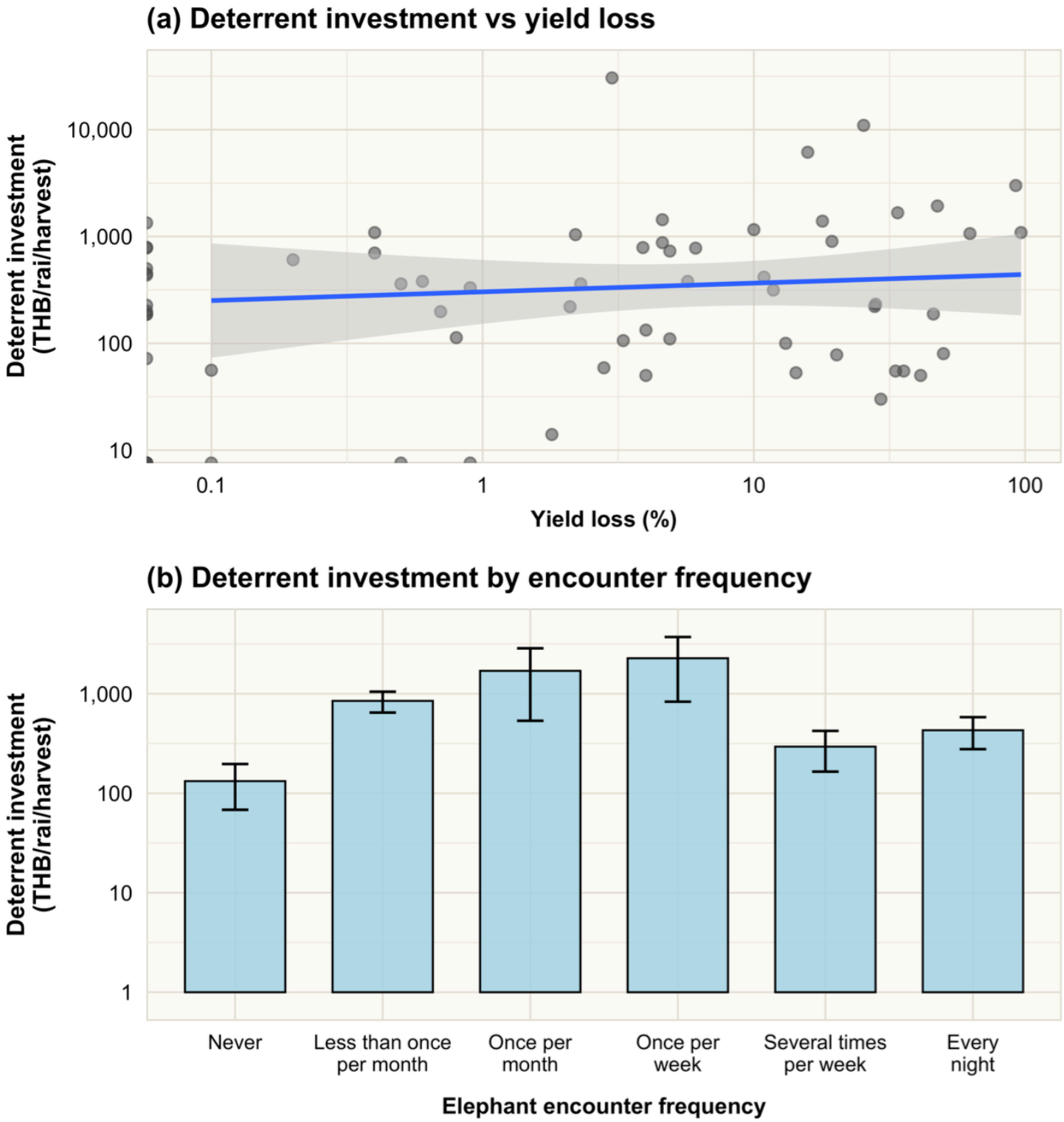


Figure 5

Farmers' financial investment in deterrents (THB/rai/harvest) in relation to elephant exposure and impact. (a) Relationship between deterrent investment and proportion of total crop yield lost to elephant-caused crop damage. Points show individual farmer reports and the trend line is fitted with a 95% confidence interval. (b) Deterrent investment across different elephant encounter frequencies. Bars show model-estimated means with standard errors

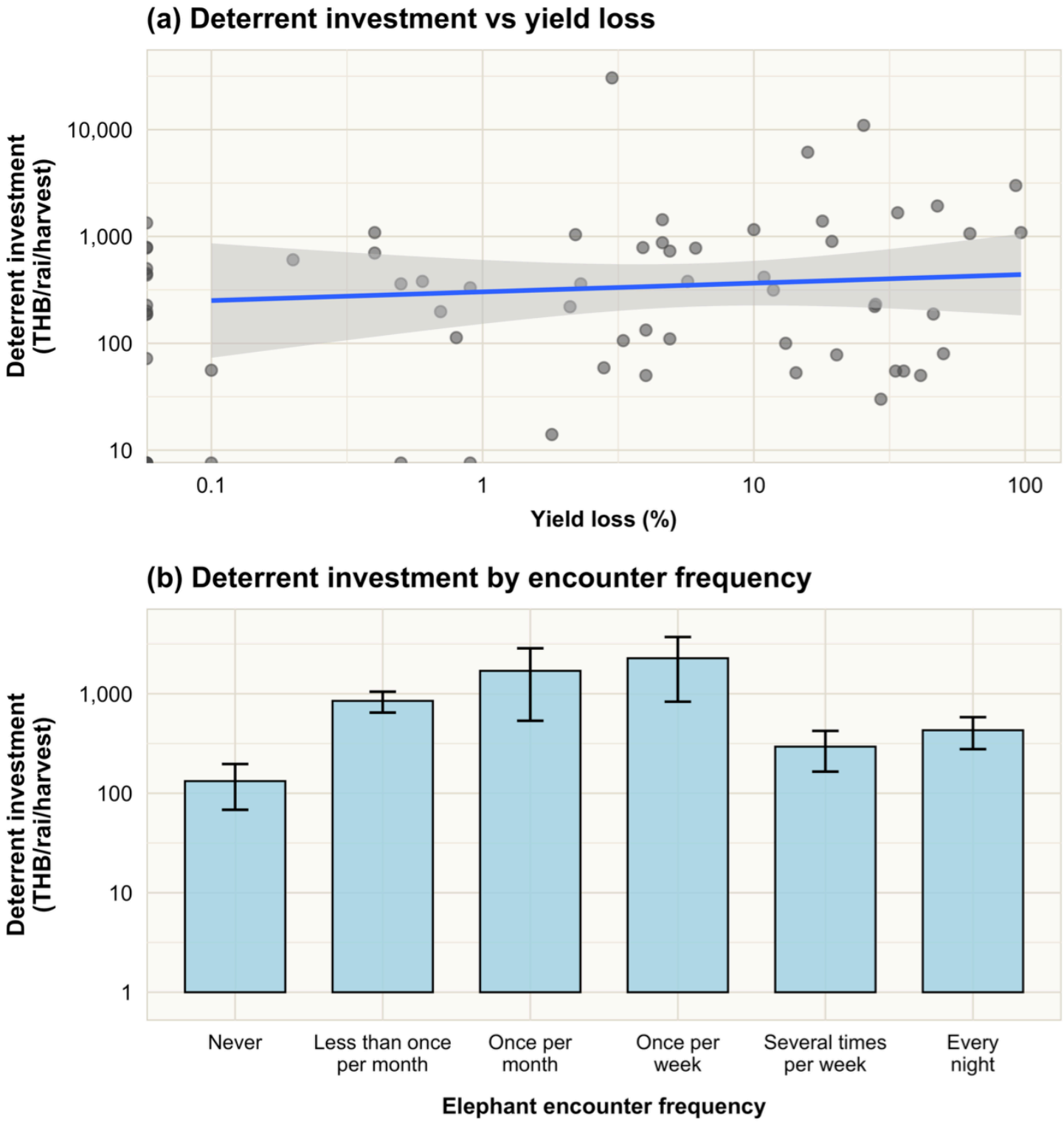


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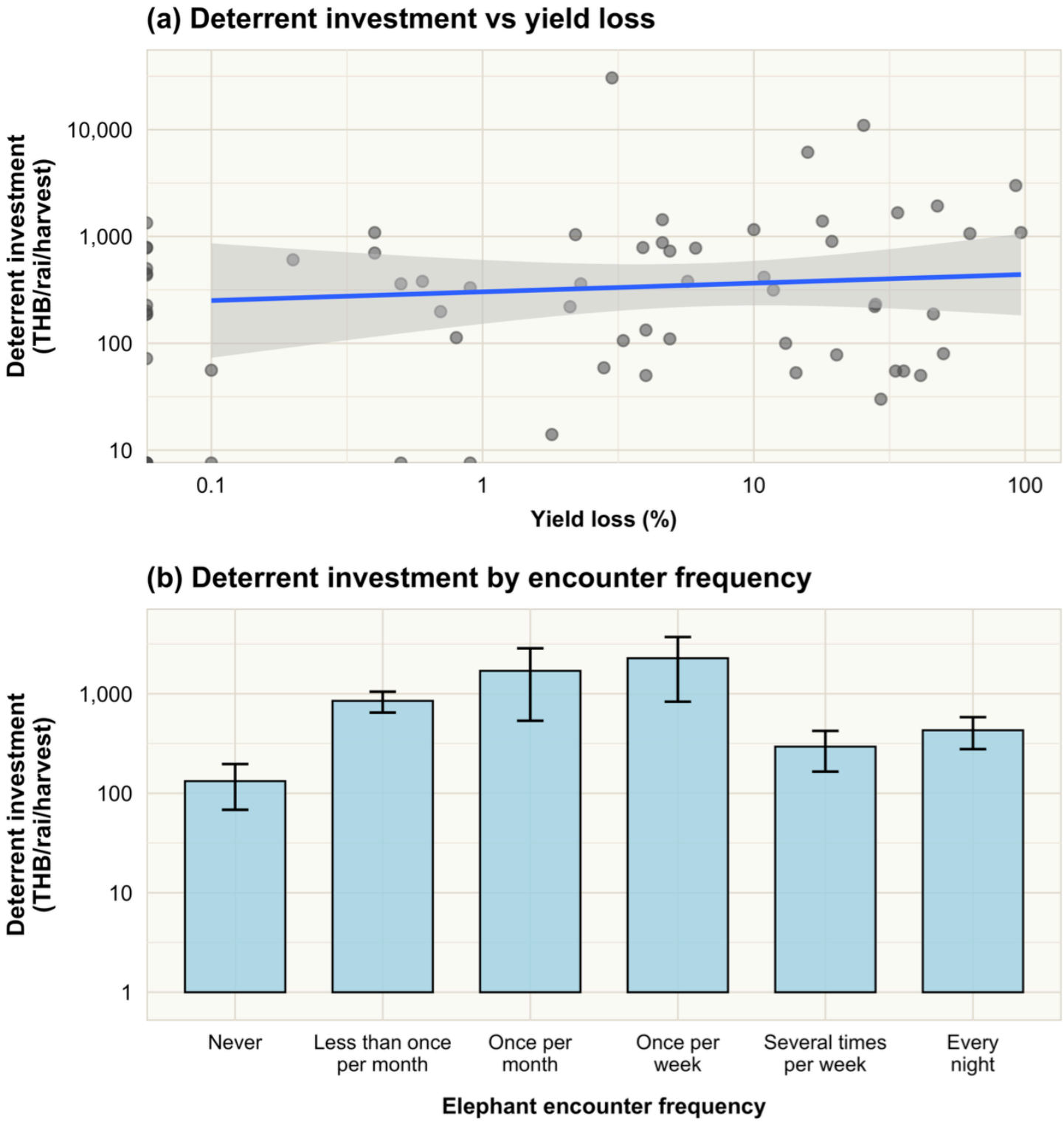


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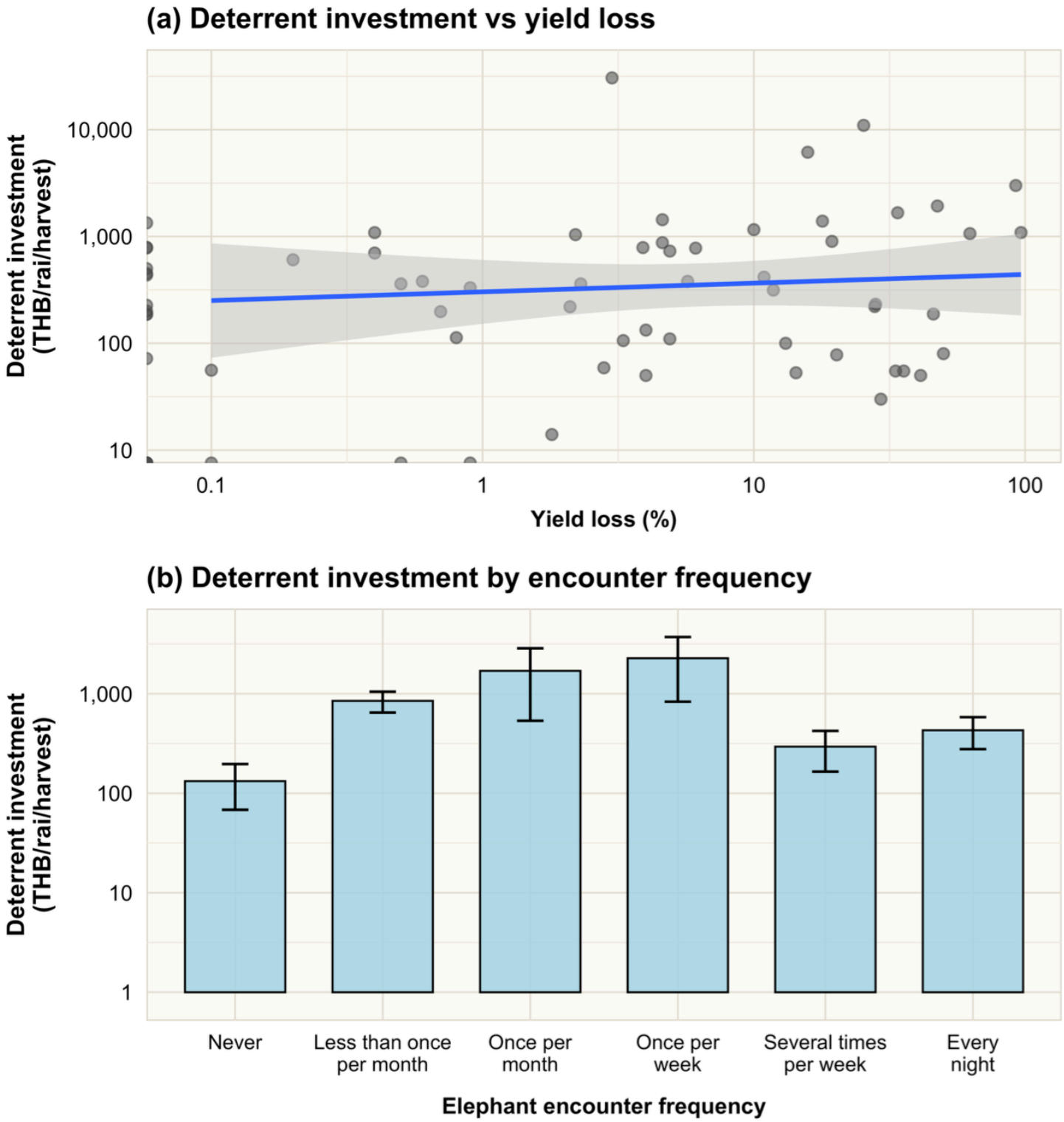


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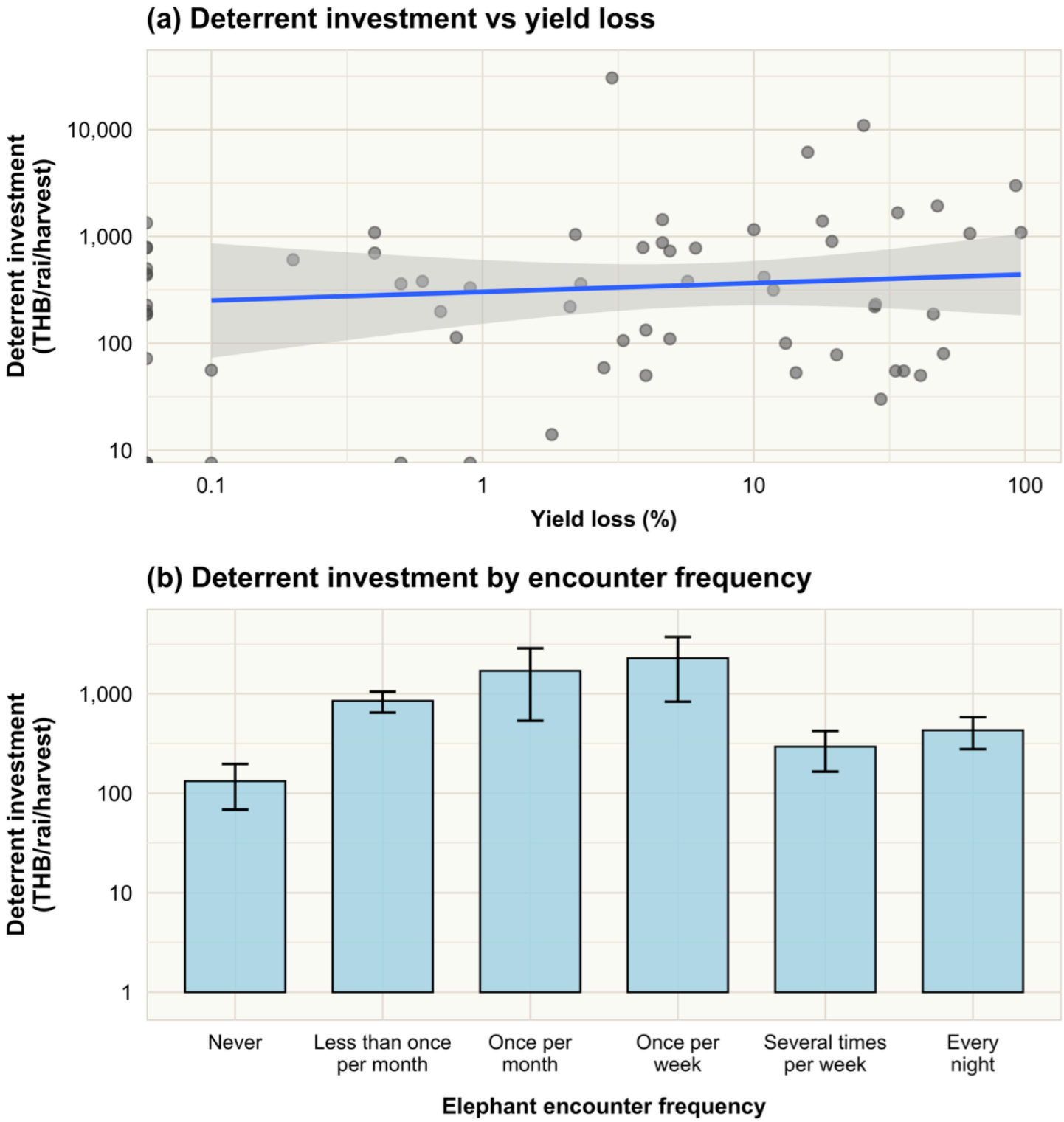


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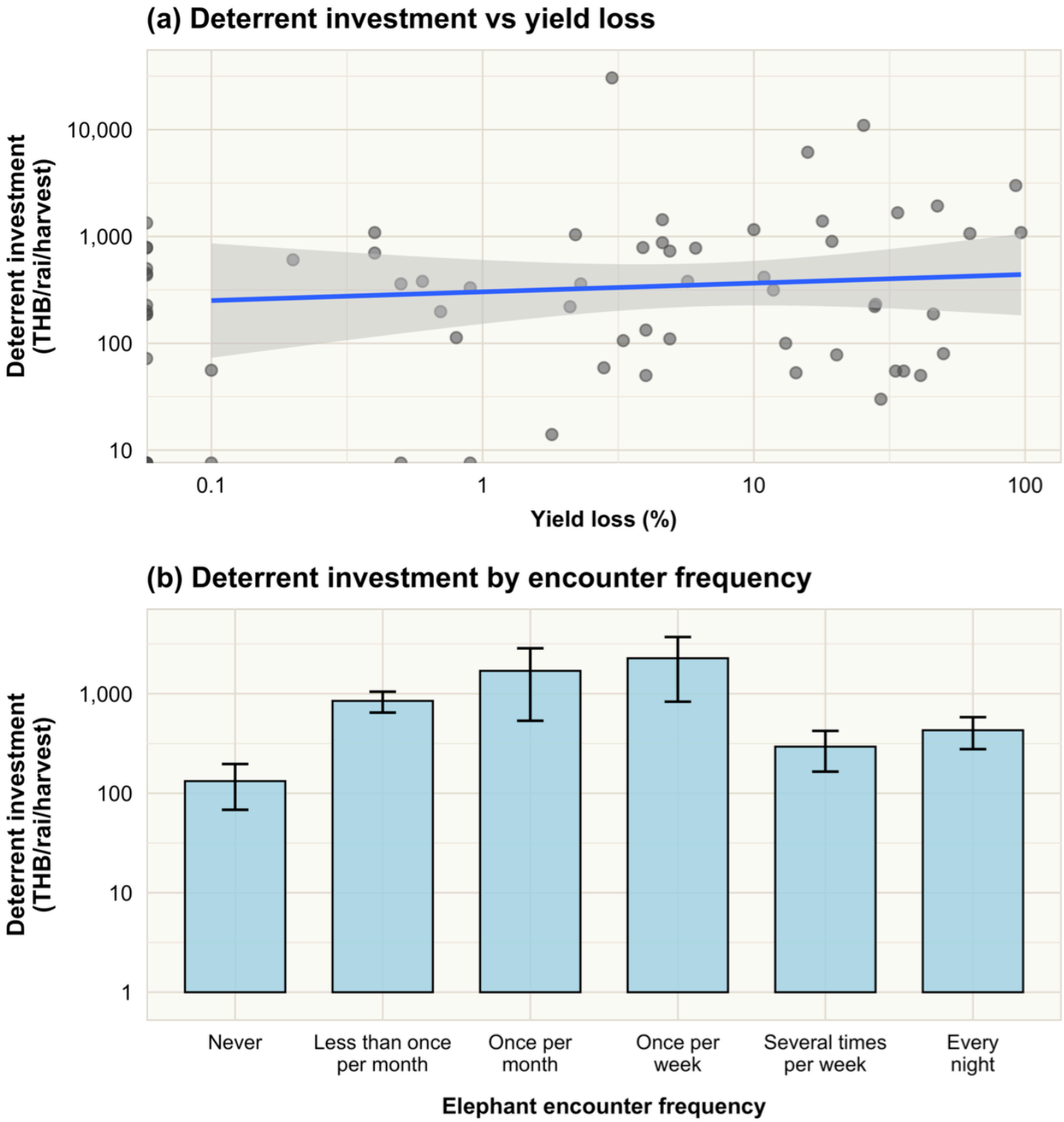


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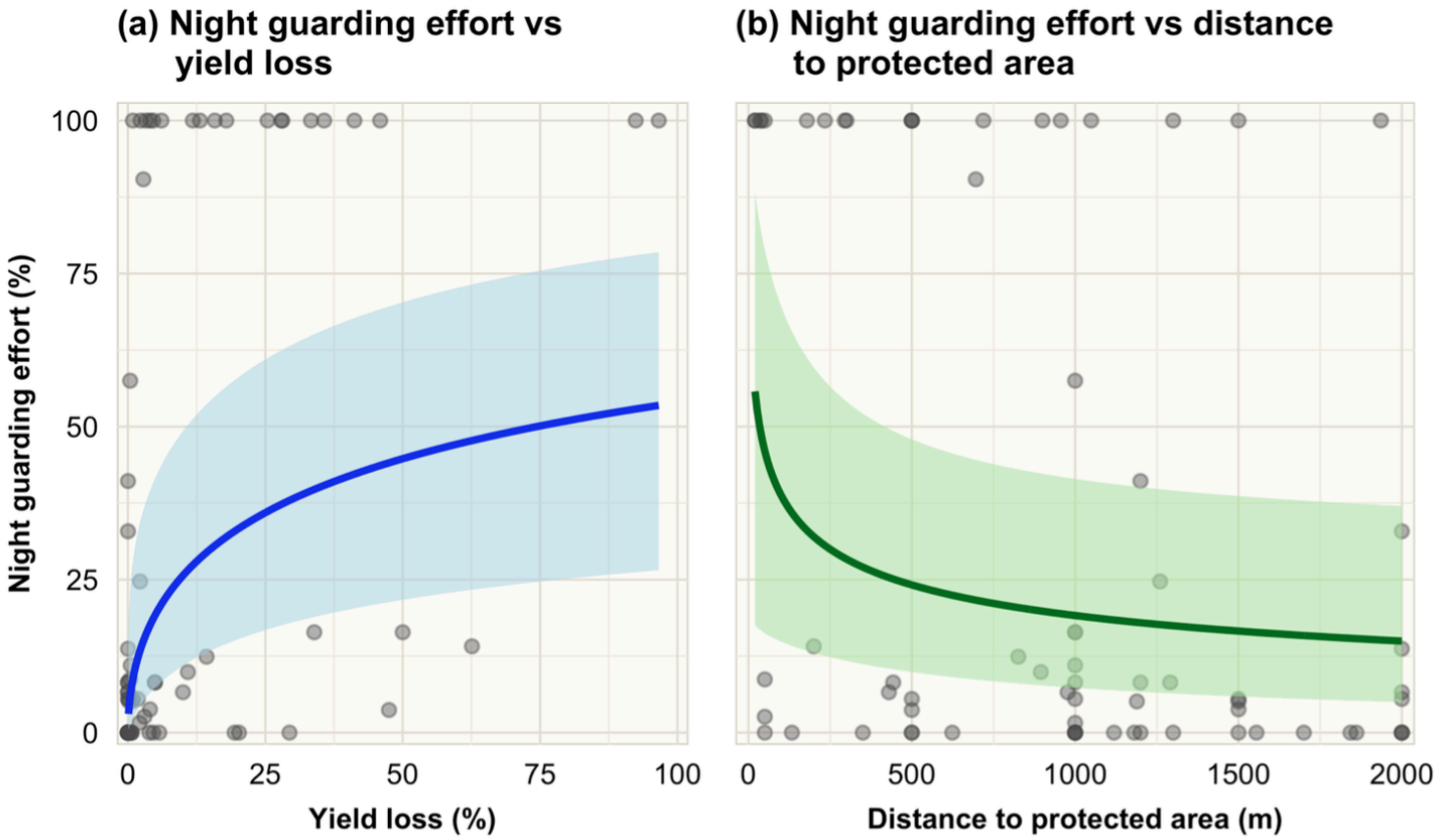


Figure 6

Relationships between night guarding effort (the proportion of nights the farmer engaged in night guarding throughout their most recent harvest) and elephant exposure and impact variables. (a) Night guarding effort in relation to elephant-caused yield loss (%). (b) Night guarding effort in relation to the farm's distance to the protected area (m). Points represent individual farmers' guarding effort, lines show model predictions and shaded bands indicate 95% confidence intervals

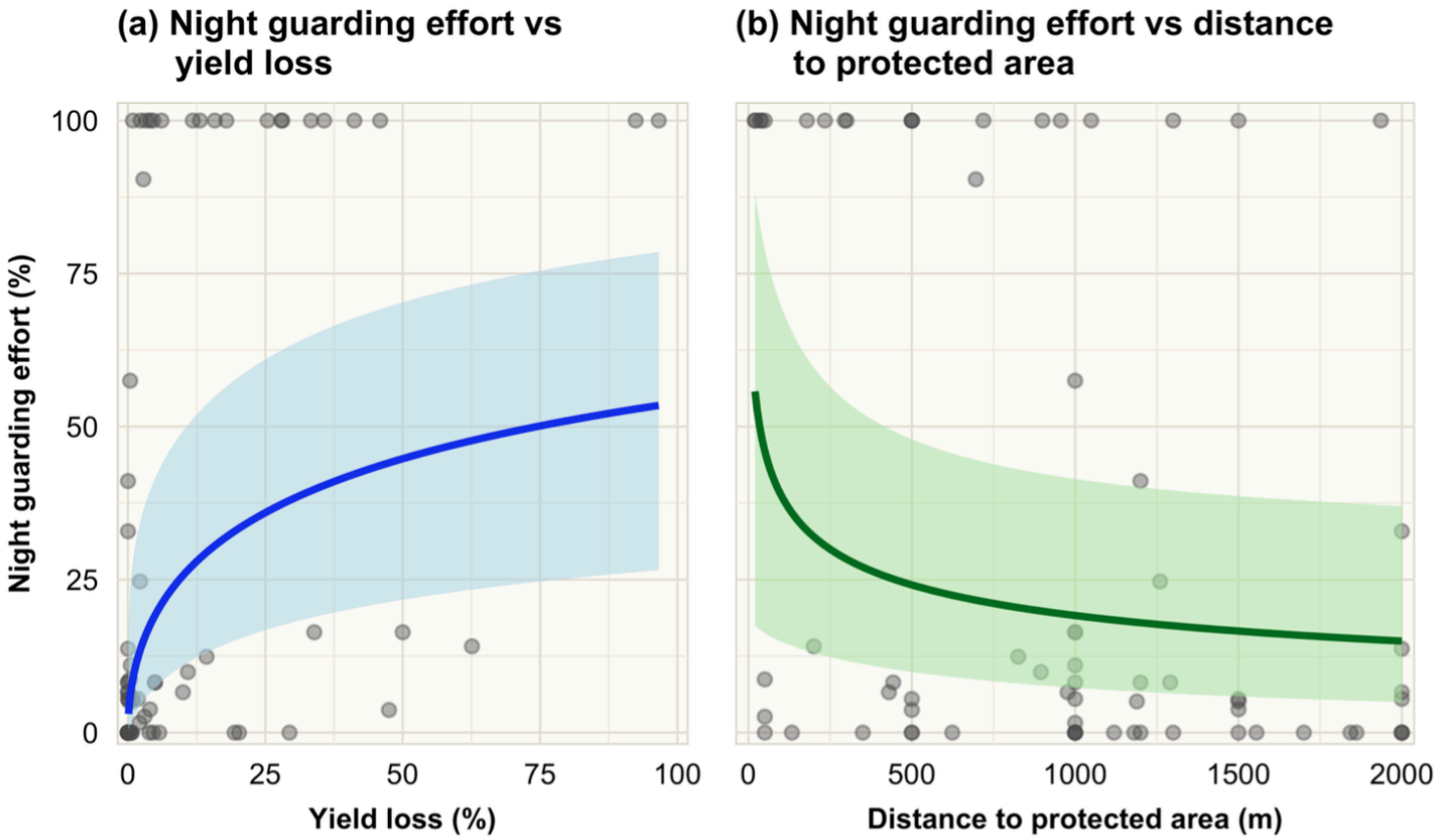


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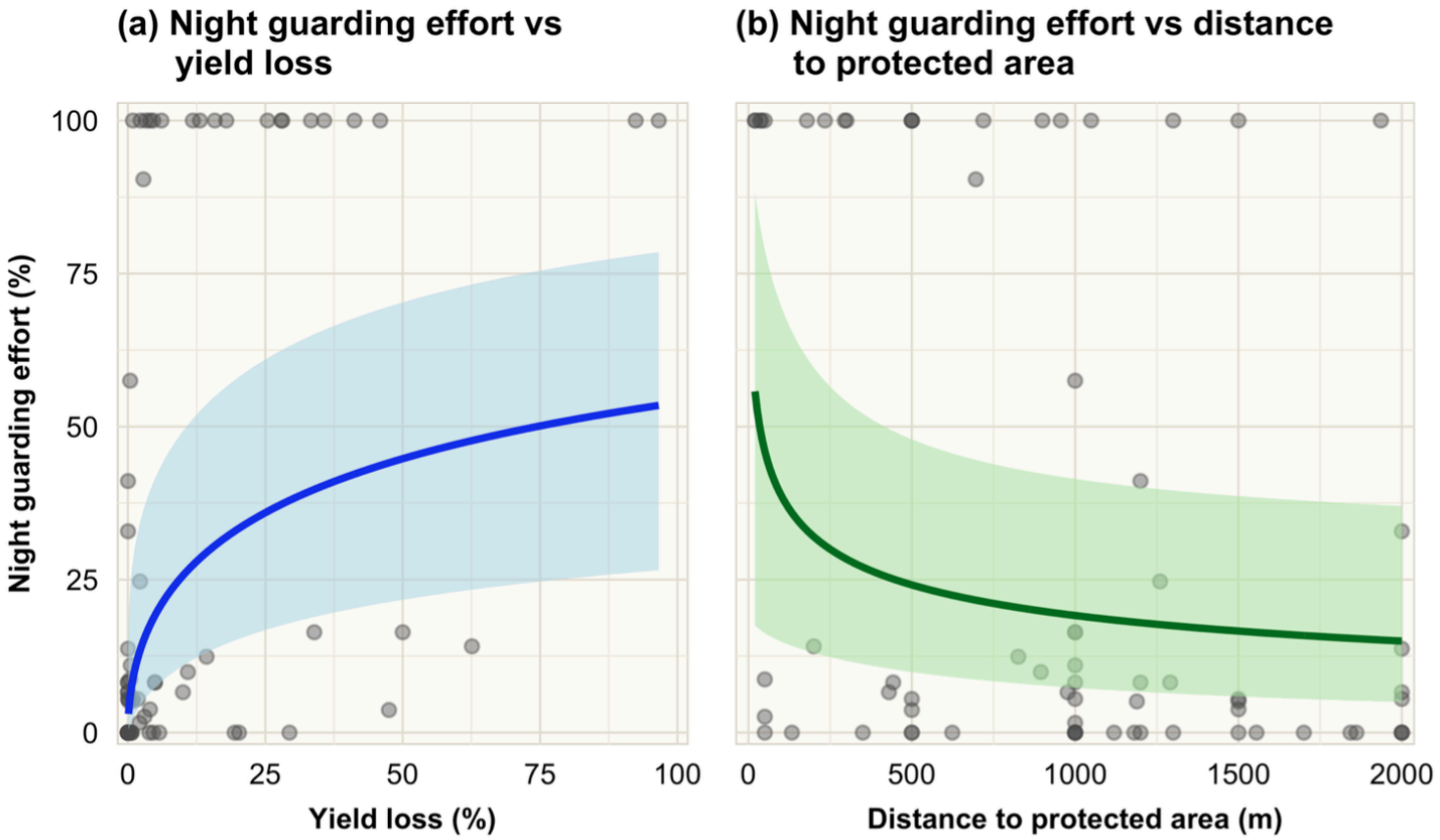


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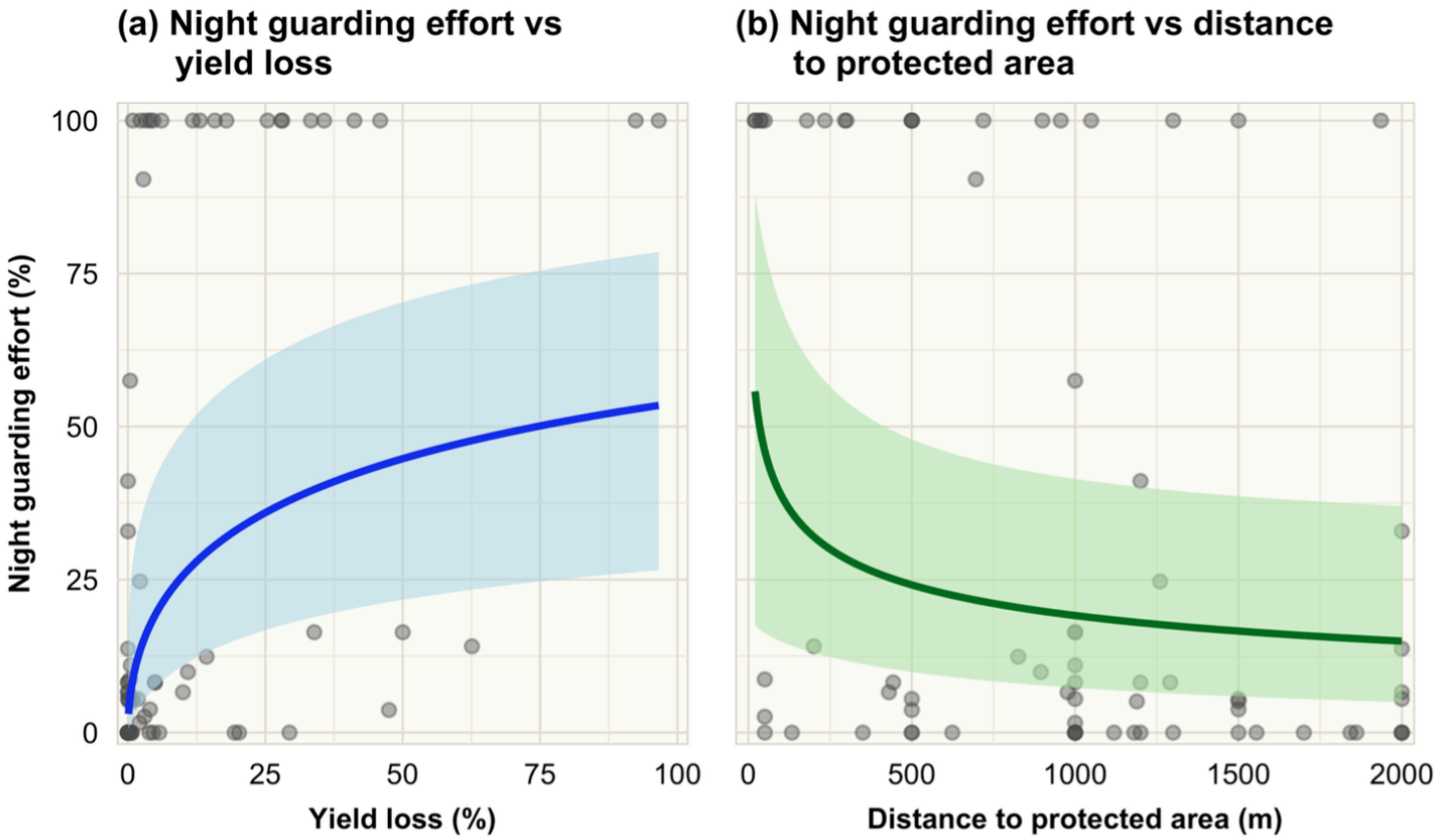


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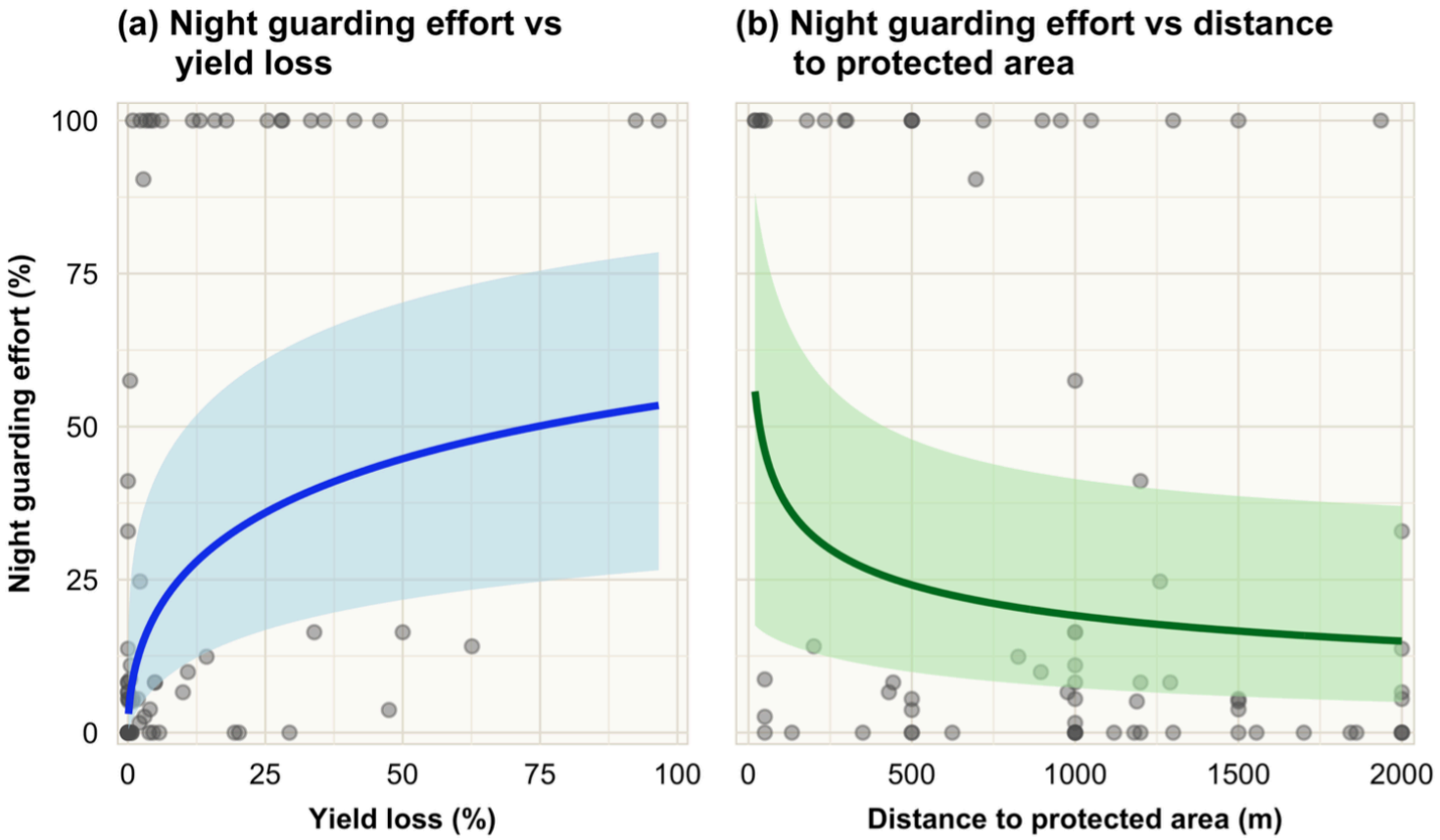


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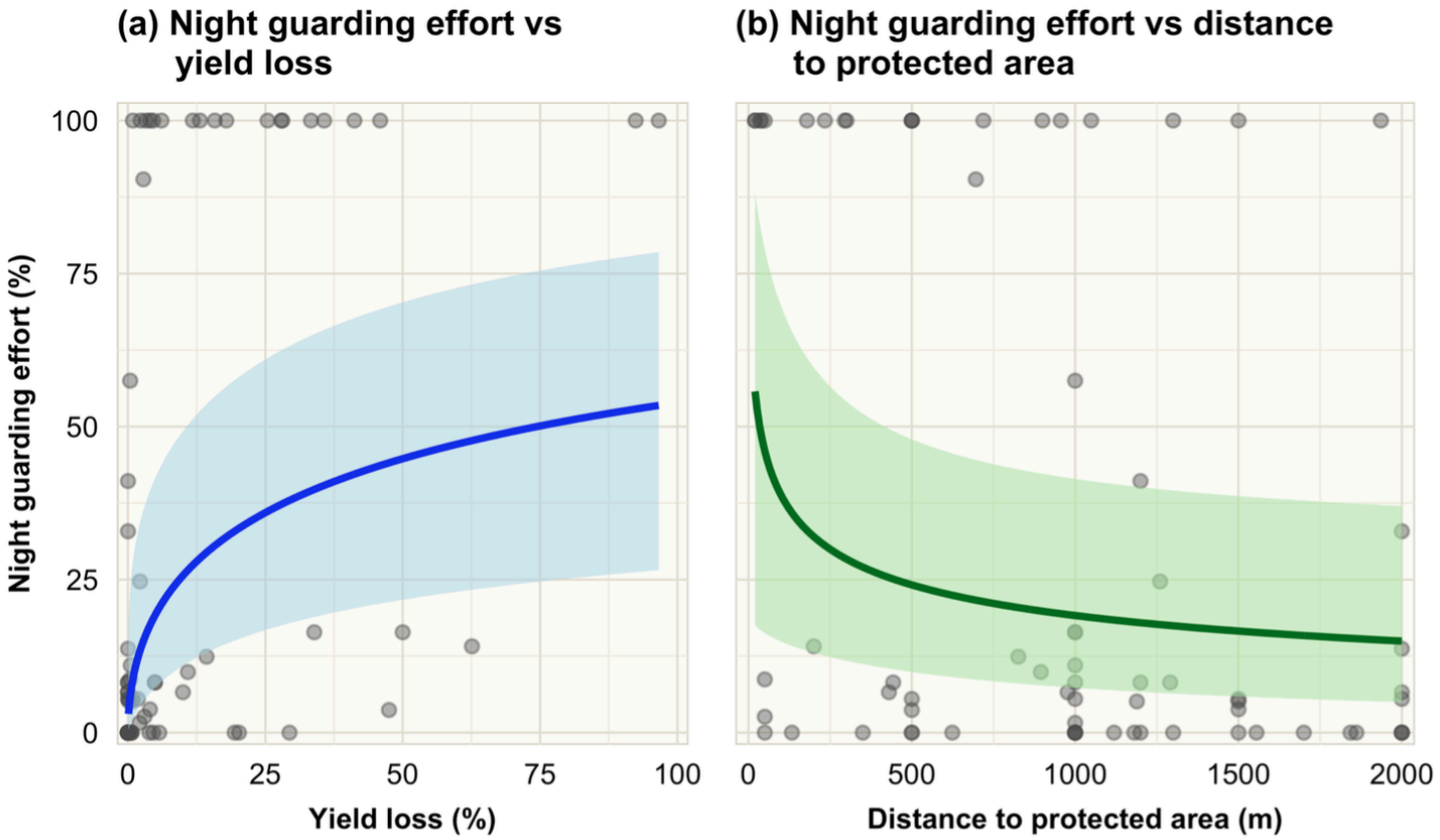


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Supplementary Files

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