Trends in Mammalian Predator Control Trapping Events Intended to Protect Ground-Nesting, Endangered Birds at Haleakalā National Park, Hawai'i: 2000–14

Trends in Mammalian Predator Control Trapping Events Intended to Protect Ground-Nesting, Endangered Birds at Haleakalā National Park, Hawai'i: 2000–14

By Emily C. Kelsey, Josh Adams, Max F. Czapanskiy, Jonathan J. Felis, Julie L. Yee, Raina L. Kaholoaa, and Cathleen Natividad Bailey

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

Acknowledgments

iv

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
Area		
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
Volume		
milliliter (mL)	0.03381402	ounce, fluid (fl. oz)
milliliter (mL)	0.002113	pint (pt)
milliliter (mL)	0.001057	quart (qt)
milliliter (mL)	0.0002642	gallon (gal)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 × °C) + 32.$$

Datum

Elevation, as used in this report, refers to distance above mean sea level.

Abbreviations

AIC	Akaike's information criterion
DEM	digital elevation model
EVT	Existing Vegetation Type
EWM	HALE Endangered Wildlife Management
GPS	Global Positioning System
GIS	geographic information system
HALE	Haleakalā National Park
USGS	U.S. Geological Survey

Trends in Mammalian Predator Control Trapping Events Intended to Protect Ground-Nesting, Endangered Birds at Haleakalā National Park, Hawai'i: 2000–14

By Emily C. Kelsey, Josh Adams, Max F. Czapanskiy, Jonathan J. Felis, Julie L. Yee, Raina L. Kaholoaa, and Cathleen Natividad Bailey

Abstract

Predation and habitat degradation by non-native species are principal terrestrial threats to the federally endangered Hawaiian Petrel ('ua'u, *Pterodroma sandwichensis*) and Hawaiian Goose (nēnē, *Branta sandvicensis*) within Haleakalā National Park (HALE), Maui, Hawai'i (fig. 1). Since 1981, HALE has maintained a network of live traps to control invasive mammalian predators and protect these endangered birds. To evaluate trapping efficiency in HALE, we evaluated four types of trap outcomes for the years 2000–14: Bait Lost (62 percent), No Event (23 percent), Trap Triggered (10 percent), and Predator Event (Rat Caught, Cat Caught, or Mongoose Caught; 4 percent). We used a multinomial logistic regression model to explore trends in the probabilities of broad outcomes (No Event, Other Event [Bait Lost or Trap Triggered], or Predator Event [Rat Caught, Cat Caught, or Mongoose Caught]). Temporal variations in the probabilities of No Event, Other Event, or Predator Event were best explained by 'ua'u season (off-season, pre-laying, incubation, or nestling), month, year, and seasonal rainfall with greater probabilities of Predator Event during the 'ua'u nestling period (July–October). The probability of Predator Event or Other Event decreased with increased rainfall. Spatial analysis showed that percent vegetative cover and vegetation type best explained variations in the probabilities of trapping outcomes with the probability of Predator Event being greatest in developed and tree covered areas. The proportion of trapping events that resulted in Rat Caught was at least 20 times greater than the proportions of events resulting in Cat or Mongoose Caught throughout the 15-year management period. Temporal analysis showed that season, year, and maximum temperature best explained variations in probabilities of Predator Event; the probability of Rat Caught was greatest during the 'ua'u pre-laying and incubation periods (February–June), was greater during periods of warmer maximum temperatures, and overall, increased over the 15-year management period. The probability of Mongoose Caught was greatest during the 'ua'u offseason (November–January), decreased through time (2000–14), and decreased with increasing weekly maximum temperatures. Trends in Cat Caught were hard to detect because of small sample sizes, though slight trends indicated cat captures were most frequent during the 'ua'u off season and less frequent through time (2000–14). The probability of a Cat Caught event was also negatively correlated with weekly temperatures. Spatial analysis showed elevation best explained variations in probabilities of capture for rats, cats, and mongoose. Overall, predator catches were fewer at higher elevations, and of predators caught at higher elevations, the clear majority were rats. Our results are being used by HALE Endangered Wildlife Management staff to evaluate existing methods for predator control and efficacy of existing trap-based control strategies intended to protect 'ua'u and nēnē.

Introduction

Predation and habitat degradation by non-native species are principal terrestrial threats to endangered Hawaiian Petrel ('ua'u, *Pterodroma sandwichensis*) and Hawaiian Goose (nēnē, *Branta sandvicensis*) within Haleakalā National Park (HALE; Natividad Hodges and Nagata, 2001; U.S. Fish and Wildlife Service, 2009). High-priority recovery actions include predator control, habitat restoration, and population monitoring. The invasive mammal species found in the park that prey on nesting birds and eggs include feral cat (*Felis catus*), Indian mongoose (*Herpestes javanicus)*, black rat (*Rattus rattus*), Norway rat (*Rattus norvegicus*), Polynesian rat (*Rattus exulans*), and house mouse (*Mus musculus*), with cats, mongoose, and black rats being the most commonly observed predators (Kaholoaa and others, 2019). We evaluated seasonal, annual, and environmental factors that might influence outcomes of small mammal trapping efforts (probability of predator capture, bait loss, a trap being triggered, and no event). These analyses are intended to help the HALE Endangered Wildlife Management (EWM) staff evaluate existing methods for predator control and inform future predator control efforts. More information about the predators can be found in the HALE Predator Control Plan (Kaholoaa and others, 2019).

The history and previous analyses of time-series data on predator control at HALE were summarized and presented in Natividad Hodges and Nagata (2001). Trapping of predators within the park to help reduce their impact on native species first occurred from 1979 to 1981 (Simmons, 1985). Targeted, annual trapping efforts were initiated by the National Park Service at HALE in 1981, primarily by the EWM program, and have continued, targeting the same predator species and using the same methods, to the present. Here, we present analyses of trap events from HALE that were made available for the period January 2000 through December 2014.

Our goals were to (1) evaluate monthly, seasonal, and annual trends in the probability rates of small mammal capture (Predator Event: Rat Caught, Cat Caught, Mongoose Caught) and non-predator trapping outcomes (Trap Triggered, Bait Lost, No Event); (2) evaluate trapping outcomes in relationship to weather (temperature and precipitation) and lunar periodicity; and (3) evaluate spatial patterns in trapping outcomes in relationship to landscape features (vegetation class, vegetation cover, elevation, slope), proximity to infrastructure (buildings, trails, roads, fences), and 'ua'u nest-site density.

Methods

To understand trends throughout time and space, data were classified by event type: No Event, Bait Lost (trap was still open, but no bait was present), Trap Triggered (trap was closed, but no predator was caught with bait either present or missing), Rat Caught, Cat Caught, and Mongoose Caught. Event-type classifications were hierarchical and included three Predator Events: Rat Caught, Cat Caught, and Mongoose Caught; three Other Events: Bird Caught, Trap Triggered, and Bait Lost; and the singular No Event type (table 1). Instances of Bait Lost and Trap Triggered could be due to a predator being present but not getting caught, but they could also be due to other factors, such as weather and time, that change the trap conditions. Owing to uncertainty associated with these factors, Bait Lost and Trap Triggered events were considered separately from Predator Events.

Table 1. Classifications of event types occurring at traps in Haleakalā National Park, 2000–14.

[Bait Lost describes traps found open but no longer baited. Trap Triggered describes traps found triggered (closed and empty, includes traps from which a predator might have escaped). The 32 Mouse Caught and 1 Other Caught events were not included in analysis]

Trap event	Event type classification
Cat Caught	Predator Event
Rat Caught	Predator Event
Mongoose Caught	Predator Event
Bird Caught	Other Event
Trap Triggered	Other Event
Bait Lost	Other Event
No Event	No Event

Trapping and Data Collection

Predator trapping used cage traps (Havahart® and Tomahawk® brands, 7 inches (in.) × 7 in. or 10 in. × 12 in.) designed for small mammals and baited with ~120 milliliters (mL) of some combination of dog and (or) cat food or commercially available bait, such as Sullivan's Last Lunch, Caven's Minnesota Valley, or Mark June's Widowmaker (Haleakalā National Park, unpub. data, 2019). Although incidental captures of ʻuaʻu and nēnē are rare, HALE used cage traps to minimize risk for accidental injury to these two endangered species if captured (Natividad Hodges and Nagata, 2001). Traps were deployed along traplines located mostly along park boundaries, roads, trails, fences, near buildings, and to a lesser degree, within existing ʻuaʻu colony areas (~22 percent of trapping effort occurred within ʻuaʻu

colony areas; Natividad Hodges and Nagata, 2001; fig. 1). On average, during the 15-year management period there were 1,500 traps deployed at any given time throughout the 62 square kilometers (km²) predator control area in HALE. Traps were checked weekly, and contents and trap status were recorded. Back-country traps (within HALE crater; fig. 1) were sometimes checked less frequently or closed for periods of time owing to inclement weather or lack of available EWM staff. All traps, including front-country traps (along northwest side of crater, fig. 1) were checked less frequently during off-season owing to inclement weather (December and January). Captured mongoose and cats were euthanized. After recording trap status, traps were rebaited, reset, and redeployed. A more detailed description of front-country and back country sites, methods used, and the reasoning behind those methods can be found in the HALE EWM Predator Control Management Plan (Kaholoaa and others, 2019).
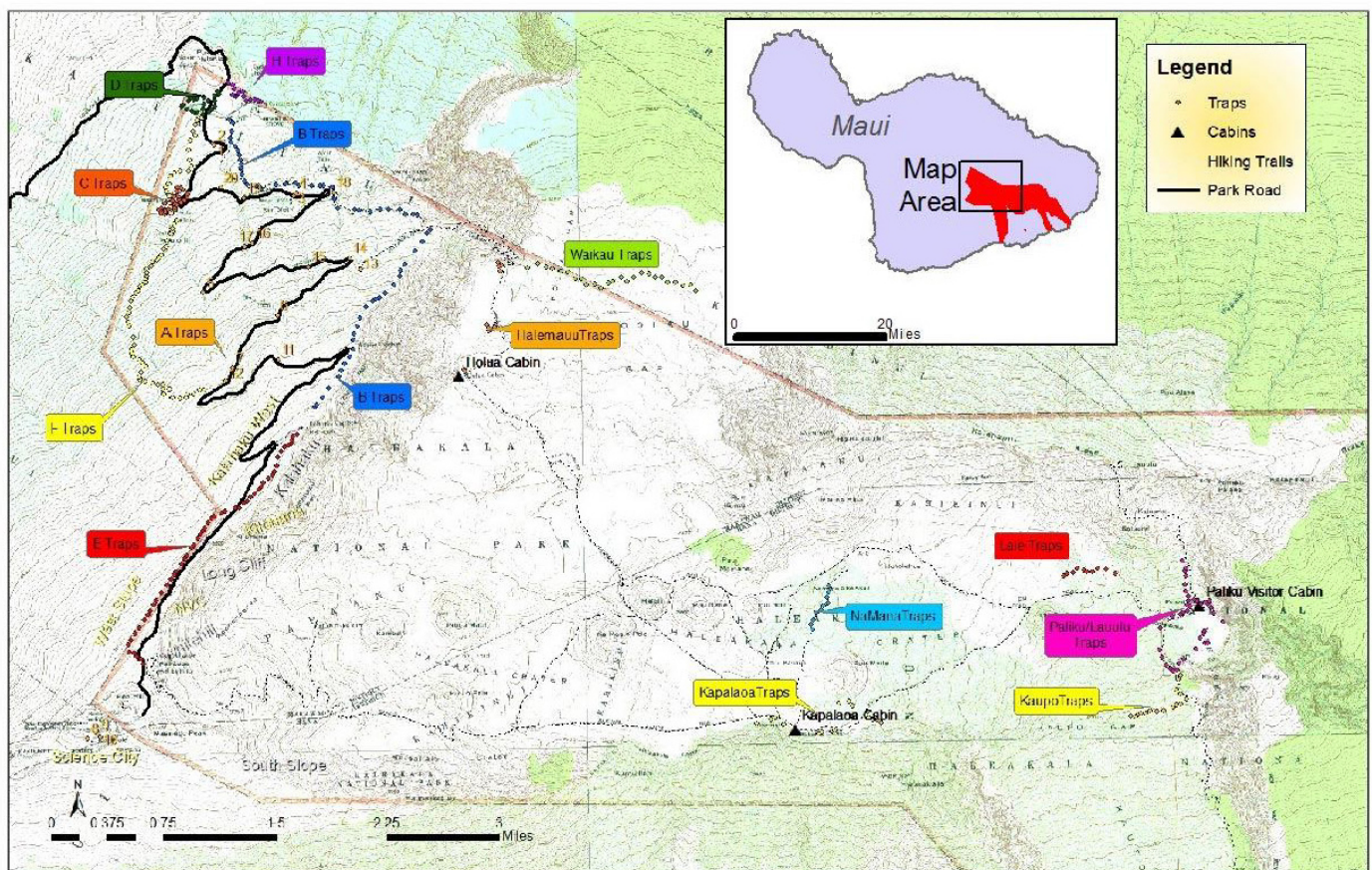
Figure 1. Haleakalā National Park, Maui, Hawaiʻi, property and current trap lines, 2000–14 (map provided by the National Park Service, Haleakalā National Park, Endangered Wildlife Management program). Inset map shows Maui, with Haleakalā National Park in red. "Front Country" traplines (A–H) are located in the northwest section of the park near the access road. "Back Country" traplines (Waikau, Halemauu, Kapalaoa, NaMana, Kaupō, Lāʻie and Palikū) are located in the eastern portion of the park, within the crater and only accessible by trail.

Data Clean-Up and Preparation for Analyses

Live (cage) trapping and data collection methods are defined in standard operating procedures (Haleakalā National Park, unpub. data, 2019). Specifically, data were recorded in the field using data notebooks and then transcribed to paper data sheets in the office before being entered into a database (HALE Predator Control Database; Microsoft Access). Data from 2000 to 2014 consisted of 304,617 original trap records. Before analyses, the HALE Predator Control Database was compiled, reviewed for quality assurance and control, and cleaned up to ensure entry consistency. The database consisted of recorded weekly checks for each trap along multiple traplines (fig. 1). We identified 3,100 duplicate data entries (for example, more than one weekly entry recorded for a unique trap). We rectified inconsistencies in duplicate entries by reviewing original hand-transcribed datasheets to determine which of the inconsistent duplicate records were correct. We standardized inconsistent data entries with consistent coding. For example, the bait type "Canned cat + canned dog with other" was recorded in many ways, such as "CD & DRY DOG," "CD&DRY DOG," "CD + Dry dog," "CD + mac'n'cheese," "CD +," "CD/D," "CD/DO+chicken," or "CD/DRY DOG," but is all listed as "Canned cat + canned dog with other" in the final database.

We excluded records from analysis when they failed to meet data integrity standards. Trap number was missing for 25 records, and for one record, the item caught was listed as "other"; together, these 26 records were excluded before analyses. For 32 records, mice (*Mus musculus*) were reported captured; although impossible to confirm, these were considered by EWM staff to be misidentified juvenile rats (*Rattus* spp.). Owing to the ambiguity in mouse identification, these records also were excluded from analyses. Mice are known to exist in HALE, but most are probably too small to be effectively caught in the types of traps used. Although all mongoose and cats were euthanized and removed from traps, on 6,111 occasions, captured rats were left in the trap until the following week's checks. Because these traps with rats were effectively removed from the trapping effort (the traps were closed and not available to catch another predator), trap records corresponding with the week following the initial rat capture event were excluded from analysis. For statistical analyses, we assume that the remaining data records represent an unbiased sample for the probability of trap outcomes within the park. We recognize that removing records from the dataset when incomplete or removing traps from the trapping effort (when traps with rats were left unset for a week) could potentially lead to bias. For example, leaving rats in traps for longer than a week could lead to underrepresentation of rats if these exclusions tended to occur in locations and conditions with greater rat activity. However, the trap exclusions are a byproduct of the management program design and were not intended to cause bias.

After removing incomplete and misleading records, the data were filtered in preparation for two types of analyses: temporal and spatial. For the temporal analysis, the data were filtered into weekly trapping outcome records (catch-per-unit-effort = trap events per weekly trap check) and did not include data from traps that were left unchecked for more than 13 days (n = 25,822; 8.4 percent of original records). We flagged these records and did not include them in our temporal analysis because they were not a weekly trapping outcome. For the filtered spatial analysis, we removed 6,408 records (2.1 percent) with missing trap locations (no Global Positioning System [GPS] coordinates were associated with the trap event) before spatial analysis. Thus, of 304,617 original records, we retained 259,061 (85.0 percent) for temporal analysis and 258,260 (84.7 percent) for spatial analysis. The final version of the data, along with identification of all entries used for analysis, was published (Bailey and others, 2019).

Temporal Trends

We evaluated monthly, seasonal, and annual temporal patterns in trapline checks (trap check-per-unit-effort and probability of various trap outcomes) for all traplines (fig. 1). For temporal analysis, we quantified effort according to weekly trap checks per trapline (trap check trapline^{-1} week^{-1}). We classified four 'ua'u seasons according to the Haleakalā 'ua'u breeding phenology (Simons, 1985): off-season (November–January), pre-laying (February–April), incubation (May–June), and nestling (July–October).

Weather and Lunar Trends

We evaluated the potential effects of abiotic factors (weather and lunar state) on temporal event probabilities. The five abiotic/weather variables included total precipitation during the week previous, total precipitation during the previous 90 days, weekly average (n = 7 days) minimum temperature, weekly average (n = 7 days) maximum temperature, and weekly average lunar index (eq. 1). Weather data (total precipitation, minimum temperature, and maximum temperature) for each trap location were determined using the nearest weather station (six of the HaleNet stations described by Longman and others, 2015). The average weekly lunar index was calculated as the average number of hours the moon was above the horizon during night in each 24-hour cycle multiplied by the percent of the lunar disk that was illuminated during each night (eq. 1). Moon elevation and disk illumination were estimated using the *oce* R package (Kelly, 2017).

$$\text{Lunar Index ("moon")} = \frac{\sum(\textit{nightly moonlight hours} \times \% \textit{ disk illuminated})}{7} \quad (1)$$

All abiotic variables were summarized per trapline-week except total precipitation, which was also summed for the previous 90 days to account for seasonal changes in cumulative precipitation that could influence mammalian abundance prior to the trapline-week. If weather data were not available, we excluded these records from modeling analyses. For statistical analyses, we assume that the remaining data records represent an unbiased sample for the probability of trap outcomes within the park.

Spatial Data Annotation and Analysis

Trapline transects were not evenly spaced throughout HALE (fig. 2). We used geographic information system (GIS; ArcMap 10.3.1, ArcGIS 2015, Environmental Systems Research Institute, Redlands, California) to annotate trap event data with spatial habitat variables based on GPS trap locations recorded by EWM staff. All environmental parameter extraction and annotation was performed using ArcMap 10.3.1. We conducted spatial analyses using the original projected coordinate system in which trap locations were recorded (Universal Transverse Mercator, Zone 4 North, North American Datum 1983). Each trap event was associated according to its trap location with the following 12 habitat

variables (all values were extracted from data provided by HALE, unless otherwise indicated):

- Number of ʻuaʻu burrows within a 10-meter (m) radius of the trap
- Number of ʻuaʻu burrows within a 50-m radius of the trap
- Number of ʻuaʻu burrows within a 100-m radius of the trap
- Elevation (m Above Sea Level [ASL]; Landfire 2010 digital elevation model [DEM])
- Slope: median slope within 50-m radius of the trap (degrees; Landfire 2010 DEM)
- Percent cover of vegetation within 50-m radius of the trap (derived from Landfire 2010 Existing Vegetation Type)
- Majority vegetation cover type within a 50-m radius of the trap (derived from Landfire 2010 Existing Vegetation Cover)
- Distance to nearest shelter or human structure (m)
- Distance to nearest road (m)
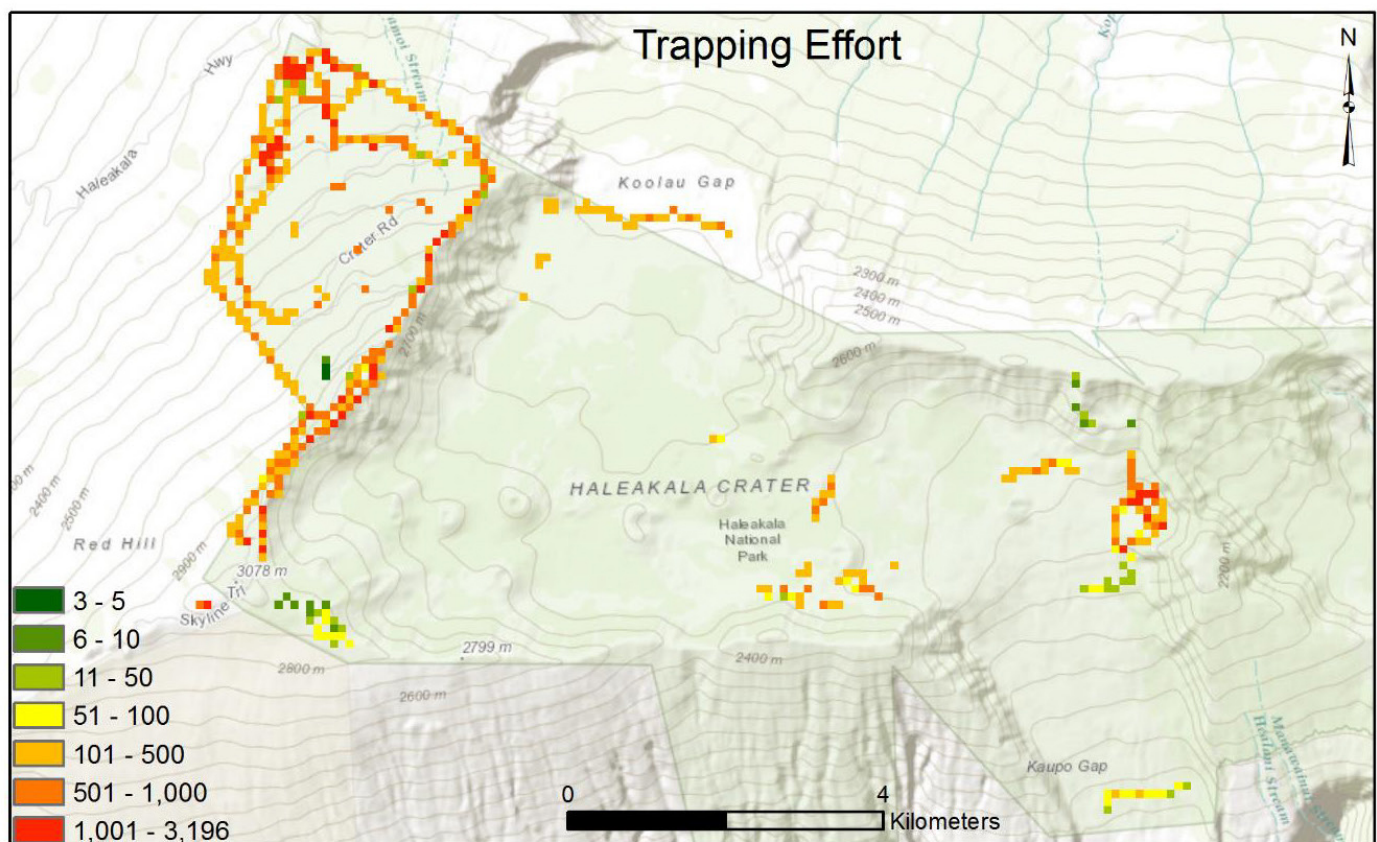- Distance to nearest trail (m)
- Distance to nearest fence (m)

Figure 2.   Trapping effort in Haleakalā National Park, Maui, Hawaiʻi, during 2000–14. Colors and values in cells indicate the number of traps per week per 100 square meters (m²). Given spatial layout of the traps, some cells represent multiple traps for the 15-year period, whereas others represent one trap used for a shorter interval.

We counted the number of known 'ua'u burrows (Haleakalā National Park, unpub. data, 2019) within three search radii (10, 50, and 100 m) of each trap location using *Zonal Statistics 2* (Spatial Analyst Supplemental Tools toolbox, ArcGIS 2017). For distance to road, trail, fence, and shelter, we used the *Near Tool* (Proximity Toolset, ArcGIS 2017) to find the distance between each trap location and feature classes of interest. All elevation and vegetation metrics were extracted or derived from Landfire raster products (Landfire, 2010). We identified the elevation at each trap location using the Landfire digital elevation model (DEM) and the *Extract Values to Points* toolbox in ArcGIS. For slope (derived from Landfire DEM), we identified the median slope within a 50-m buffer for each trap location using *Zonal Statistics 2*. We interpolated the Landfire Existing Vegetation Type (EVT) and Existing Vegetation Cover raster from 30-m cells to 1 m using the Resample tool in ArcGIS with the Nearest Neighbor algorithm, reclassified EVT values into two classes (Vegetated and Non-vegetated; table 2), and calculated percent vegetated cover (PctVeg) by dividing the sum of 1-m vegetated cells within a 50-m buffer of trap locations by the total number of 1-m cells in each 50-m buffer. We reclassified existing vegetation cover values into five classes (Barren, Developed, Herb Cover, Shrub Cover, Tree Cover; table 2) and calculated Majority Vegetation Cover Type (vegMajCover) as the majority cell value in 50-m buffers.

The spatial frequency of trapping events was also analyzed visually by intersecting events per trap-week on a 100 square meter (m²) grid and representing frequency of trap events by a color scale.

Statistical Trends

We developed a hierarchical model-ranking scheme to compare models with different combinations of variables and to evaluate specific trap-event probabilities associated with our suite of variables. For all data collected on the standard weekly check schedule (<14 days between checks), we fit models based on different temporal variables (month, 'ua'u season, year). Next, we proceeded by adding weather and lunar variables to the best temporal models and compared the resulting models to evaluate model improvement. For all data with a known GPS locations, we added spatial variables (geographic and vegetation) and compared those resulting models. Models were ranked according to their Akaike's information criterion (AIC) value (candidate models listed in tables 3–8). The best supporting model was the model with the lowest AIC value, that is, the highest AIC rank. In cases where the difference in AIC value between the top-ranked model and the second ranked model was less than two, both models were selected for best explaining trap event probabilities (Burnham and Anderson, 2003). Model results are presented in the appendix. Ranges around means reported indicate standard deviation.

Table 2.   Existing Vegetation Cover values in Haleakalā National Park identified by Landfire (2010) and reclassified to Majority Vegetation Cover Type (vegMajCover) used for analysis of vegetation types in relation to predator catches.

[≥, greater than or equal to; <, less than; <=, less than or equal to; %, percent]

Existing vegetation cover	vegMajCover
Barren	Barren
Developed - Low Intensity	Developed
Developed - Medium Intensity	Developed
Developed - Open Space	Developed
Herb Cover ≥ 50 and < 60%	Herb Cover
Herb Cover ≥ 60 and < 70%	Herb Cover
Herb Cover ≥ 70 and < 80%	Herb Cover
Herb Cover ≥ 80 and < 90%	Herb Cover
Herb Cover ≥ 90 and <= 100%	Herb Cover
Shrub Cover ≥ 10 and < 20%	Shrub Cover
Shrub Cover ≥ 20 and < 30%	Shrub Cover
Shrub Cover ≥ 30 and < 40%	Shrub Cover
Shrub Cover ≥ 40 and < 50%	Shrub Cover
Shrub Cover ≥ 50 and < 60%	Shrub Cover
Shrub Cover ≥ 60 and < 70%	Shrub Cover
Shrub Cover ≥ 70 and < 80%	Shrub Cover
Shrub Cover ≥ 80 and < 90%	Shrub Cover
Tree Cover ≥ 40 and < 50%	Tree Cover
Tree Cover ≥ 50 and < 60%	Tree Cover
Tree Cover ≥ 60 and < 70%	Tree Cover
Tree Cover ≥ 70 and < 80%	Tree Cover

We fit multinomial logistic regression models to the multilevel outcomes of the trap event data (*mlogit* in R; Train and Croissant, 2012; Croissant, 2013). Multinomial logistic regression models are computationally intensive and prone to processing errors when fit to large datasets with relatively infrequent occurrences (small percentages) of one or more categorical outcomes of events (Croissant, 2013)—both are attributes of this dataset. Thus, we constructed a tiered set of models to evaluate trends and relationships in the HALE dataset by partitioning the analyses into two parts:

• Part 1. We analyzed the effects of selected variables by previously defined broad groupings of trap event types (Predator, Other, or No Event).

• Part 2. For the subset of events comprising Predator Events, we analyzed the effects of selected variables on the probabilities of specific Predator Events (Rat Caught, Cat Caught, or Mongoose Caught). Species-specific Predator Events occurred at low frequencies (Rat Caught: 3.7 percent, Cat Caught: <0.1 percent, and Mongoose Caught: <0.1 percent) among the full dataset, which caused computing errors during preliminary analyses.

The analysis of broad event types (Part 1) included all 259,021 records, which exceeded the computational capacity of the multinomial logistic regression model. Thus, to compute model outcomes for broad event types, we randomly subsampled 2.5 percent of the full dataset without replacement and ranked candidate models by evaluating mean AIC weights (relative likelihood [probability] of the model; Burnham and Anderson, 2003) from 1,000 random resampling iterations (thus, over 1,000 iterations, we sampled >6,000,000 records from the 259,021 dataset). We used the best model, based on mean AIC weight, to estimate the associated probabilities for the three broad event types using a larger, randomly selected subset of the data (25 percent, n = 64,755) with a single sample run. For Part 2, the model was run on all Predator Event data (n = 10,246 records).

Selected temporal variables for broad events (Part 1) and predator events (Part 2) were year, month, and 'ua'u season. We evaluated support for a linear temporal trend (for example, rates of a particular trapping outcome increasing over time) by including year as a continuous variable. We also included a categorical year variable as a random effect to represent and account for interannual variation (different years having higher or lower rates than a perfect linear pattern would predict). The random year effect, when added with a continuous year effect, encapsulates unexplained annual variation while allowing the model to reveal linear trends in the time series. Month and 'ua'u season were treated as categorical variables to represent monthly and seasonal patterns. The trapline variable was included as a random effect to represent spatial variations across different traplines (fig. 1). Thus, we used the best temporal models to generate estimated probabilities of event occurrences along specific traplines during specific trap weeks. We report event probabilities associated with the best temporal models selected.

We followed a similar model-ranking approach to evaluate weather and lunar variables. We added weather and lunar parameters to the variables identified in the top-ranked temporal models (see above) and analyzed trends in broad event types and specific predator event types (Part 1 and Part 2). Because of missing weather data, the dataset analyzed for weather and lunar parameters was smaller (n = 19,654). Five weather and lunar variables included sum of rainfall during the trap week (Rain1w; the week preceding the trap check), sum of rainfall during the 3 months preceding (Rain3m), average minimum temperature during the trap week (Tmin), average maximum temperature during the trap week (Tmax), and average lunar index (moon) during the trap week (eq. 1). We report event probabilities associated with the best models selected.

Lastly, we followed a model-ranking approach to evaluate potential effects among five spatial variables on trap event probabilities (table 2). We performed the analysis in two parts: effects of parameters on Part 1, broad event type (Predator Event, Other Event, No Event), and Part 2, specific Predator Event type (Rat Caught, Cat Caught, or Mongoose Caught). We calculated AIC values and weights and identified the best supporting model as the model with the lowest AIC value and the highest AIC rank. There were no cases where the change in AIC value between the top-ranked model and the second-ranked model was less than two, so only the top-ranked model was used for estimating event probabilities (Burnham and Anderson, 2003). The spatial model included 'ua'u season as a predictor and trapline and year (categorical) as random effects. We report event probabilities associated with the best models selected. The probabilities estimated for the various event types in spatial analyses are different than the probabilities estimated in the temporal and climatic/lunar analyses. Because the spatial parameters were summarized and generated according to *the specific trap location*, the probability that an event occurred reflects the probability associated with that specific location (probability of event trap^{-1} week^{-1}) rather than the trapline (probability of event trapline^{-1} week^{-1}) used to evaluate temporal trends among event probabilities in the temporal analysis.

Results

Summary of Trap Events

The most frequent trap event in HALE from 2000 through 2014 was Bait Lost (62 percent of events), followed by No Event (23 percent of events), and Trap Triggered (10 percent of events; fig. 3). Capture of mammalian predators combined (rats, mongoose, and cats) accounted for 4 percent of the total recorded trap events (fig. 3). The most frequently used bait type was a combination of canned cat and dog food (43 percent), followed by dry dog food mixed with used cooking oil (42 percent). The frequency of bait type varied among predator event types (table 2). Adjusting for the overall frequency of event types, the most frequent bait present in Cat Caught events was a combination of cat and dog food (table 3). Cat food was most frequent in Mongoose Caught events, dog food was most frequent in Rat Caught events, other baits (for example, human food leftovers) were most frequent in Trap Triggered events, lures were most commonly associated with Bait Lost, and commercial bait was most frequent in No Event (table 3).
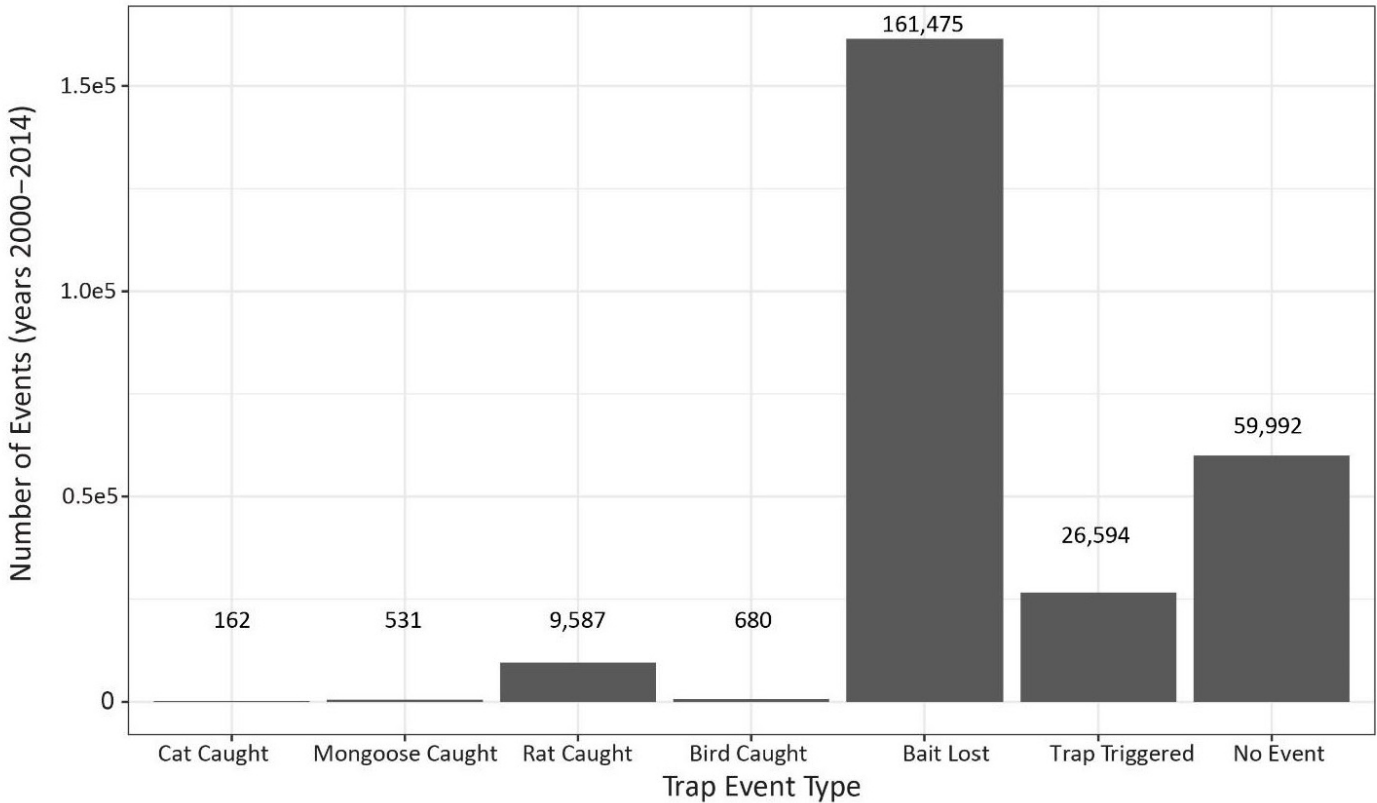
Figure 3. Total counts of trap event types for all traps in Haleakalā National Park, Maui, Hawai'i, 2000–14. The total number of events (259,021) represents all events counted during trap-sets checked after ≤13 days (see Methods: Data clean-up and preparation).

Table 3. Count and percentage of bait type used in association with each trap event type at Haleakalā National Park, 2000–14.

[Highlighted cells indicate the bait type that was most frequently used in a given event type, adjusted for the frequency of events. Traps were baited with ~120 milliliters of dog and (or) cat food, or commercially available bait, such as Sullivan's Last Lunch, Caven's Minnesota Valley, or Mark June's Widowmaker. %, percent]

Predator event	Commercial bait (%)	Lure (%)	Cat food (%)	Cat and dog food (%)	Dog food (%)	Other (%)
Cat Caught	0 (0.00)	0 (0.00)	4 (2.19)	104 (57.14)	53 (29.12)	21 (11.54)
Mongoose Caught	0 (0.00)	0 (0.00)	51 (7.37)	337 (48.70)	189 (27.31)	115 (16.61)
Rat Caught	1 (0.01)	5 (0.05)	92 (0.96)	3,304 (34.57)	4,754 (49.74)	1,402 (14.66)
Bird Caught	0 (0.00)	0 (0.00)	13 (1.79)	293 (40.36)	354 (48.76)	66 (9.09)
Bait Lost	22 (0.01)	103 (0.06)	2,479 (1.53)	73,199 (45.04)	71,637 (44.07)	15,106 (9.29)
Trap Triggered	2 (0.01)	7 (0.03)	387 (1.44)	8,874 (33.09)	11,624 (43.35)	5,921 (22.08)
No Event	10 (0.01)	20 (0.03)	842 (1.40)	26,038 (43.20)	20,744 (34.42)	12,618 (20.94)
Percent of Total	**0.01**	**0.05**	**1.48**	**43.00**	**41.93**	**13.52**

Temporal Trends

Based on the top-ranked model explaining temporal trends in broad trap event types (Part 1), the probability of No Event was greatest during March (0.193 ± 0.002) and least during October (0.110 ± 0.001; Model 1; appendix table 1–1). The occurrence of No Event had a cyclical pattern with the months around March (relatively greater probabilities) and the months around October (relatively lesser probabilities; fig. 4). The probability of Other Event was greatest during November (0.836 ± 0.018) and least during June (0.721 ± 0.022; fig. 4). The probability of a Predator Event was infrequent and monthly patterns were not apparent.

Model 2 (appendix table 1–1) indicated that the probability of No Event was greatest during the 'ua'u incubation period (0.20 ± 0.01; May–June) and least during the off-season (0.14 ± 0.01; November–January). The probability of Other Event was greatest during the off-season (0.81 ± 0.02) and least during the 'ua'u incubation period (0.74 ± 0.03; fig. 5). The probability of a Predator Event was greatest during the 'ua'u nestling season (0.07 ± 0.02; July–October) and least during the off-season (0.05 ± 0.02; fig. 5).

From 2000 to 2014, slight trends (slopes were all near zero) in annual probabilities of broad event types occurred. The probabilities of Other Events decreased, No Event increased, and Predator Events increased through the 15-year period (fig. 6).

The top-ranked model explaining temporal trends in predator events (Part 2) included categorical season. The probability of Rat Caught along a trapline was greatest during the 'ua'u incubation period (0.966 ± 0.004; May–June) and least during the off-season (0.913 ± 0.010; November–January; fig. 7; Model 14; appendix table 1–2). The probability of Cat Caught along a trapline was greatest during the off-season (0.026 ± 0.005) and least during the 'ua'u pre-laying period (0.011 ± 0.002; February–June; fig. 7). The probability of Mongoose Caught along a trapline was greatest during the off-season (0.061 ± 0.005) and least during the 'ua'u incubation period (0.021 ± 0.001; May–June; fig. 7). Model 14 explained trends in annual predator captures with the probability of Rat Caught increasing, the probability of Cat Caught decreasing, and the probability of Mongoose Caught decreasing across the 15-year period (fig. 8).
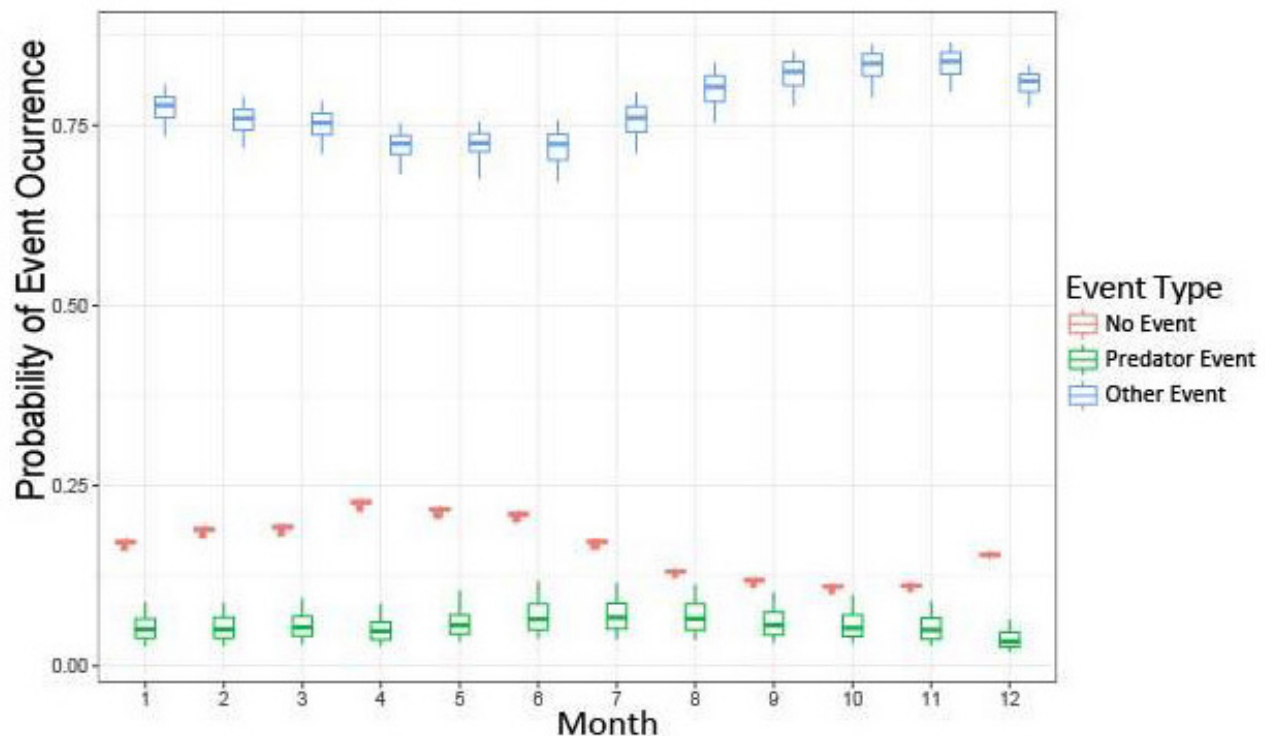
Figure 4. Probability of broad trap event types (No Event [no change in set trap], Predator Event [Cat, Rat, or Mongoose Caught], or Other Event [Bird Caught, Bait Lost, Trap Triggered]) among months for all traps (2000–14). Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 1). The horizontal bar indicates the median probability, and the lower and upper hinges correspond to the first and third quartiles (25th and 75th percentiles).
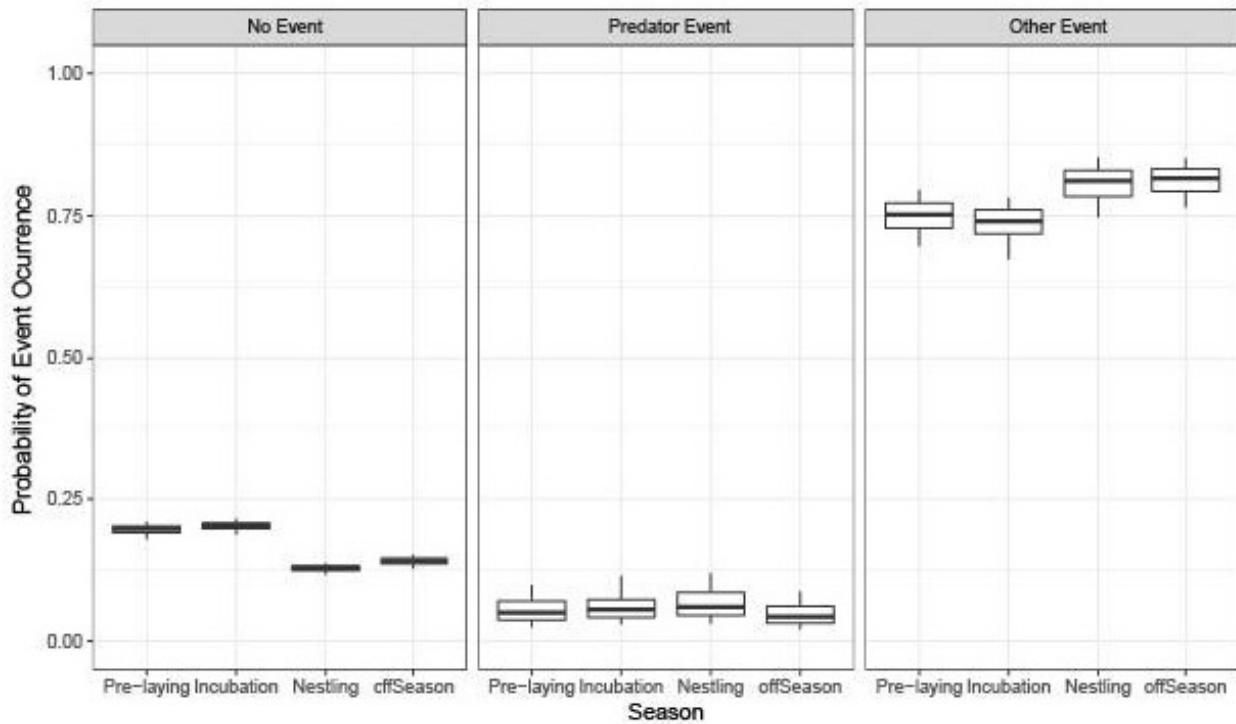
Figure 5. Probability of broad trap event types (No Event [no change in set trap], Predator Event [Cat, Rat, or Mongoose Caught], or Other Event [Bird Caught, Bait Lost, Trap Triggered]) among ʻuaʻu seasons for all traps (2000–14). Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 2). The horizontal bar indicates the median probability, and the lower and upper hinges correspond to the first and third quartiles (25th and 75th percentiles).
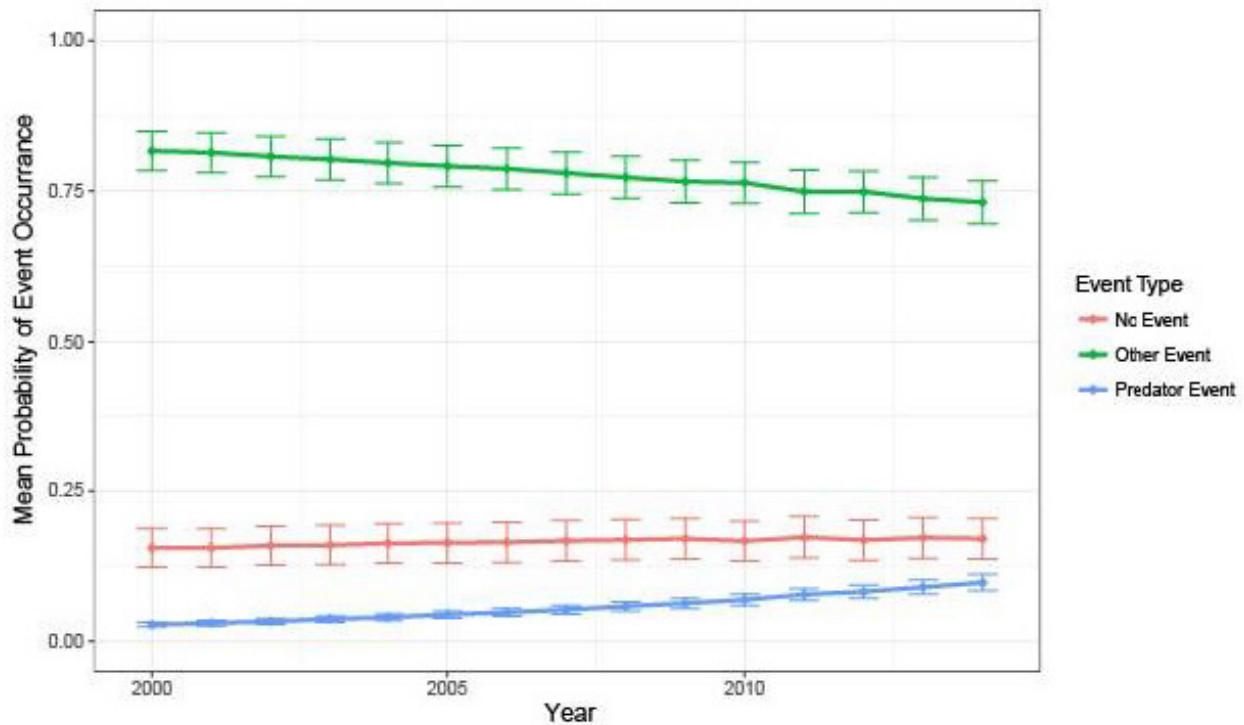
Figure 6. Trends in mean annual probability (± standard deviation) of broad events types (Predator Event, Other Event, No Event) during 2000–14. Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 1).
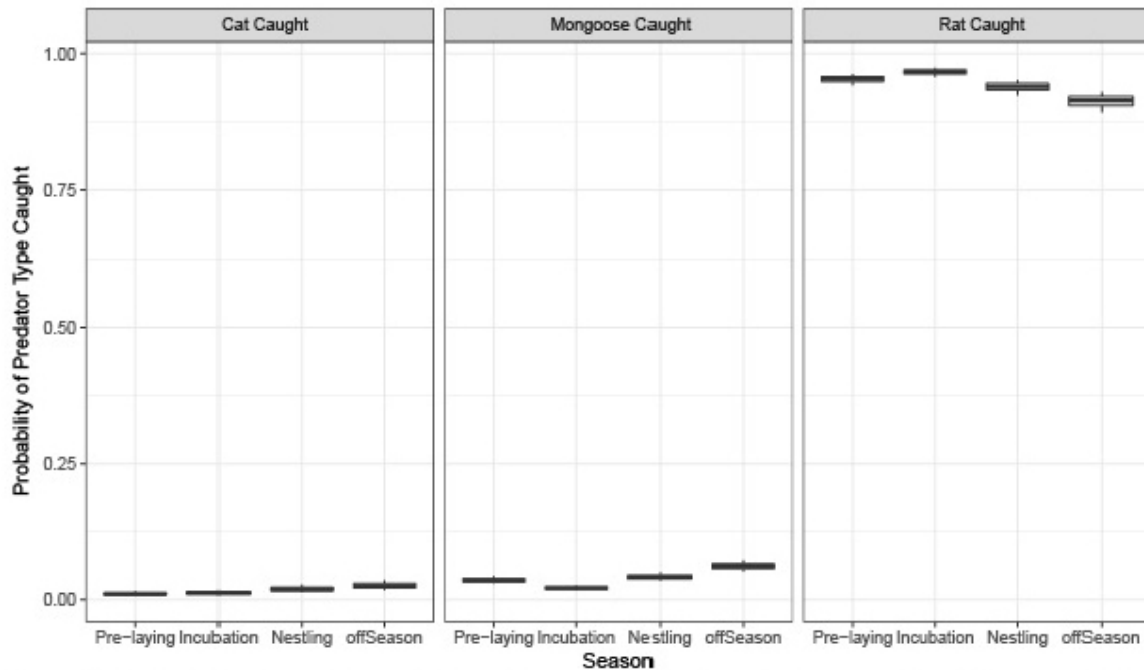
Figure 7. Probability of specific predator catch event (Rat, Cat, or Mongoose Caught) among 'ua'u seasons. Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 14). The horizontal bar indicates the median probability, and the lower and upper hinges correspond to the first and third quartiles (25th and 75th percentiles).
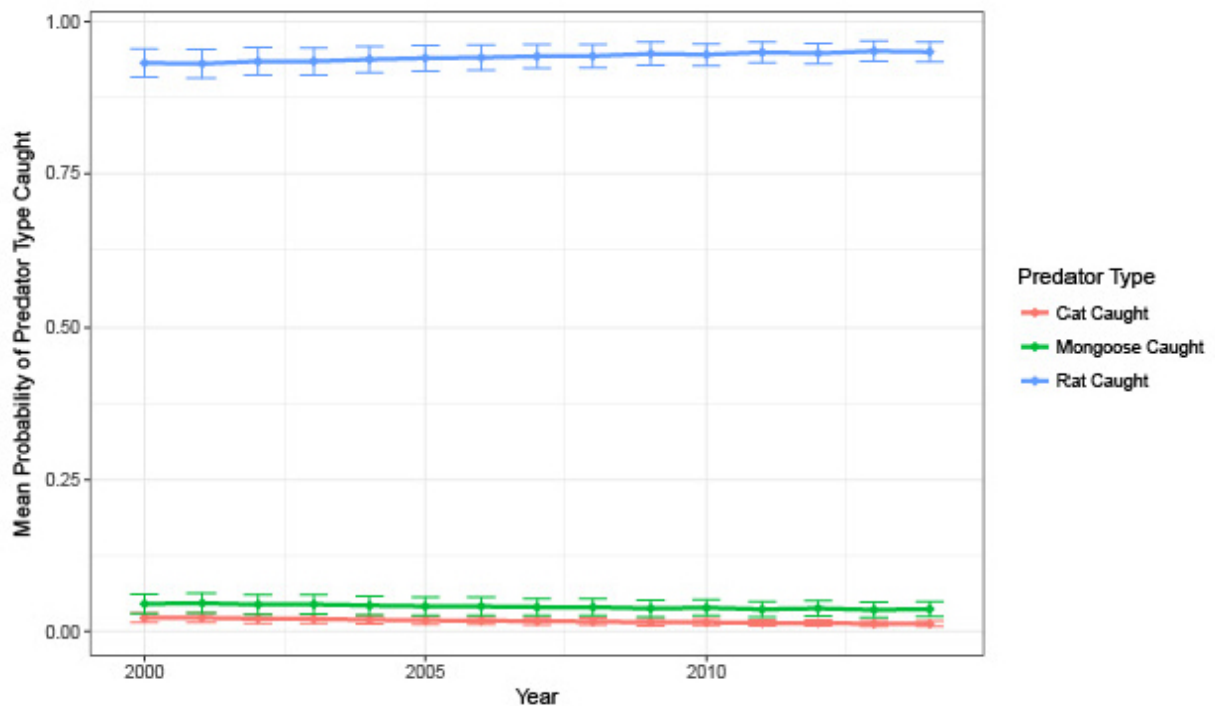
Figure 8. Trends in annual probabilities of predator events from 2000–14. Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 14).

To further understand temporal patterns in trap events, we graphed the proportions of different trap event types for broad event types and specific predator events during each month (fig. 9). The proportion of Other Events (Bird Caught, Bait Lost, Trap Triggered) was at least eight times greater than a predator event (Rat Caught, Cat Caught, or Mongoose Caught) and at least four times greater than No Event (fig. 9A). The proportion of Rat Caught was at least 20 times greater than the proportions of Cat Caught or Mongoose Caught (fig. 9B).

Weather and Lunar Trends

Based on top-ranked model of weather and lunar trends in broad trap event types (Part 1), the probability of Other Event (Bait Lost, Trap Triggered, Bird Caught) decreased with increased seasonal rainfall (cumulative rainfall during the three months preceding; Model 27; appendix table 1–3). The trend in probability of No Event was the opposite of Other Event and increased with increasing seasonal rainfall (fig. 10). There was no indication of any trend in probability of Predator Events associated with cumulative rainfall during the preceding 3 months (fig. 10).

The top-ranked model of weather and lunar trends in Predator Events (Part 2) indicated decreasing probability of Mongoose Caught with increasing temperature during the week trap period and greatest probability of Mongoose Caught during the nestling and off-seasons (fig. 11; Model 37; appendix table 1–4). The opposite was indicated for rats; probability of Rat Caught increased with temperature and was greatest during incubation and pre-laying periods. There were no strong trends apparent in predicted probabilities of Cat Caught associated with seasonal temperature (fig. 11).

Spatial Trends

Trends can also be seen in the spatial frequency (catch-per-unit-effort) of the different event types (figs. 12–17). No Event records were clustered at the northern-most aggregations of traps near the park entrance, at higher elevations along the western to southwestern crater rim (E trapline [fig. 1]), and at Palikū (fig. 12). In contrast, Bait Lost was greater along the front-country fence lines, Kapalaoa, Kaupō, and Lāʻie (fig. 1), and lesser along the northernmost boundary traps (D and H traplines [fig. 1]), crater rim (E trapline), and throughout most of the Palikū trapline (fig. 13). Similar to No Event, records of Trap Triggered were clustered near the northern park entrance and were uncommon along front-country fence lines, there was no distinctive spatial patterns for Trap Triggered events in the backcountry (fig. 14). A more detailed description of the sites and traplines can be found in the HALE EWM Predator Control Management Plan (Kaholoaa and others, 2019).

Cat catch-per-unit-effort (events trapline^{-1} week^{-1}) was least among the three targeted predators (<2 percent of total events within a given grid cell). Although few cats were caught overall, catches were distributed throughout HALE and with no clear spatial patterns in capture frequency (fig. 15). Mongoose catch-per-unit-effort (<9 percent of total events within a given grid cell) was greatest at lower elevations near the park entrance, at Halemauu, Kaupō, and Palikū traplines (fig. 1); mongooses were infrequently captured along the crater rim (E trapline; fig. 16). Rat catch-per-unit-effort (<33 percent of total events within a given grid cell) was greatest at lower elevations in the north (B, C, D, and H traplines), at Kaupō, and Palikū traplines (figs. 1 and 17).

Based on top-ranked multinomial logistic regression models of the spatial analysis of broad event types (Part 1), predicted probabilities associated with major vegetation type and percent cover of vegetation reflected subtle trends for each event type (for example, Predator Events were least probable in barren areas and greatest where traps were associated with developed land and tree cover; fig. 18). To better understand patterns in probabilities of event occurrence in different vegetation types, we graphed the raw frequency of event occurrence (for all seven event type classifications, including No Event) associated with each majority vegetation cover type (fig. 19). We determined differences in the proportion of different trap event types in areas with different majority vegetation cover types when compared with proportions for All Events (fig. 19). When compared with All Events, rats and cats were caught disproportionately more among traps set in shrub cover and less in barren and developed areas. Rats were caught more frequently than other predators in developed areas. When compared with All Events, mongoose were caught most frequently in vegetative cover (herb, shrub, and tree) and disproportionately less frequently in barren and developed areas. The relative proportions for Bait Lost and Trap Triggered were most similar to proportions for Cat Caught and Rat Caught. The occurrence of No Event and Bird Caught were disproportionately more frequent in barren areas and less in herb, shrub, or tree cover (fig. 19).

Based on the top-ranked model of the spatial trends of predator events (Part 2), predator captures were least likely at high elevations (for example, the crater rim, figs. 15–17). However, of predators caught at higher elevations, the probability that it was a rat increased with elevation (fig. 20). Conversely, the probability that a capture was a mongoose decreased with increasing elevation (fig. 20). There was no apparent trend in capture of cats in traps at HALE associated with elevation (fig. 20).
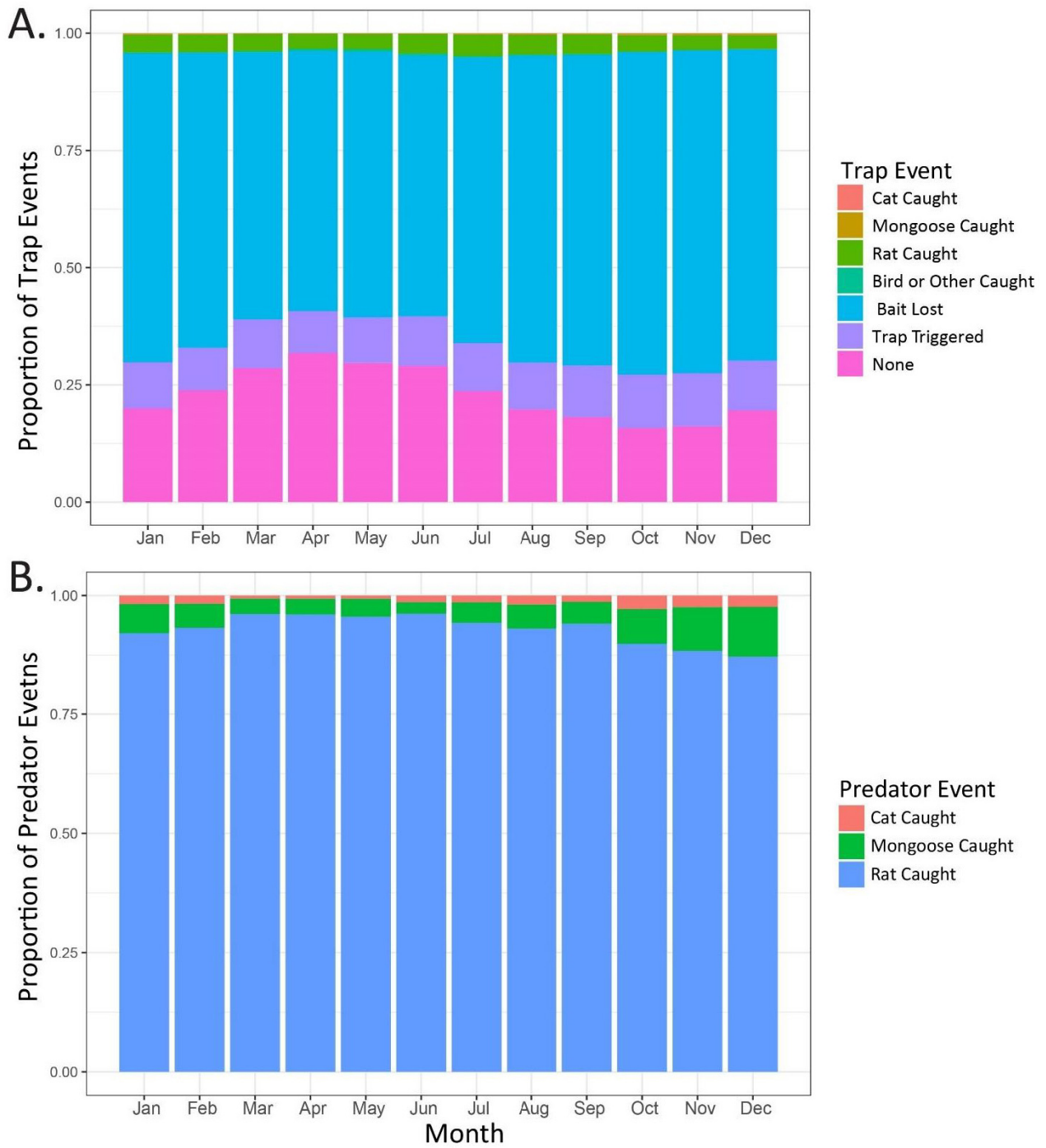
Figure 9.   Relative proportions of different trap event types in each month. *A*, All event types (the proportion of Predator Events [Cat, Mongoose, and Rat Caught] are small proportions and hard to see, thus graphed separately in B); and *B*, Predator Events.
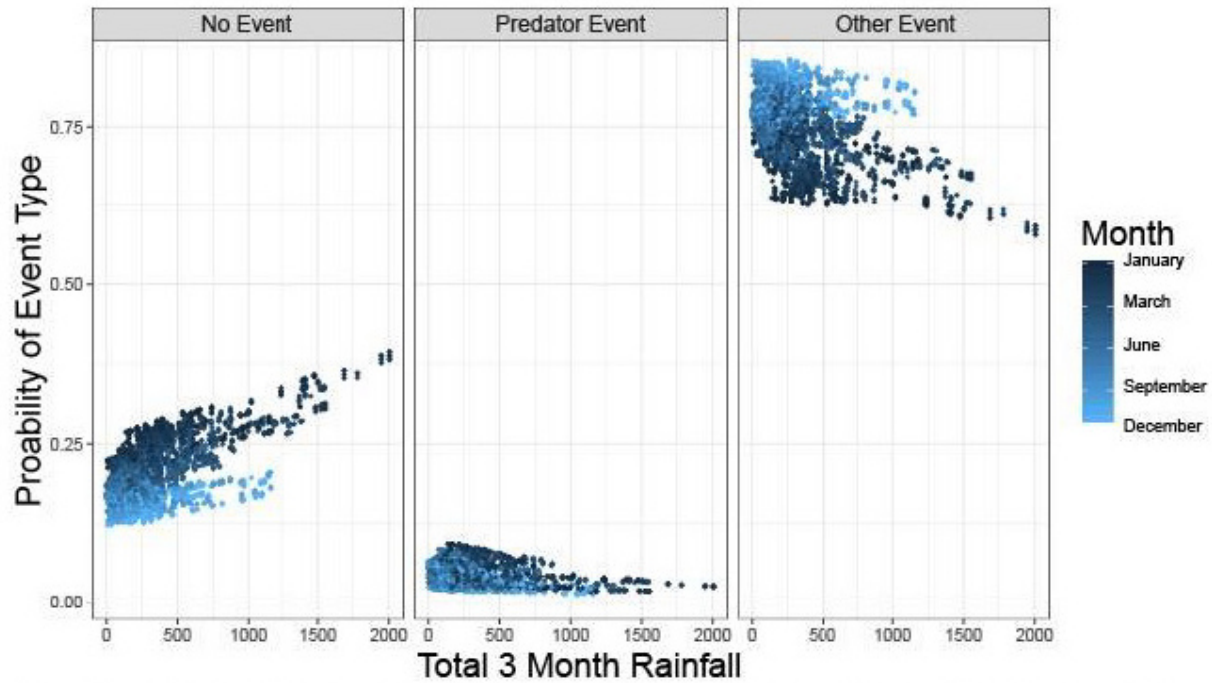
Figure 10.   Probability of broad trap event types in relationship to total rainfall (in millimeters) during the previous 3 months. ‘Ua‘u seasonal probabilities are depicted by color. Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 27).
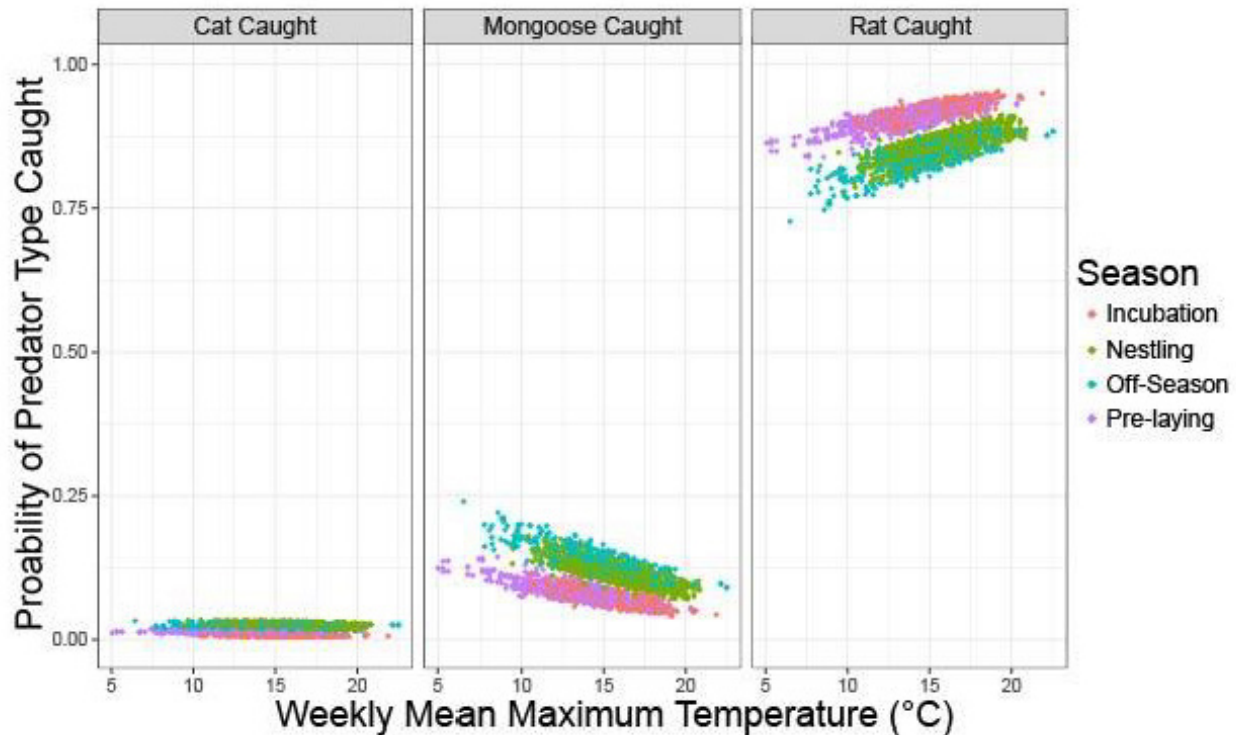
Figure 11.   Probability of specific predator trap event types in relation to weekly mean maximum temperature (°C). ‘Ua‘u seasonal probabilities are depicted by color. Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 37).
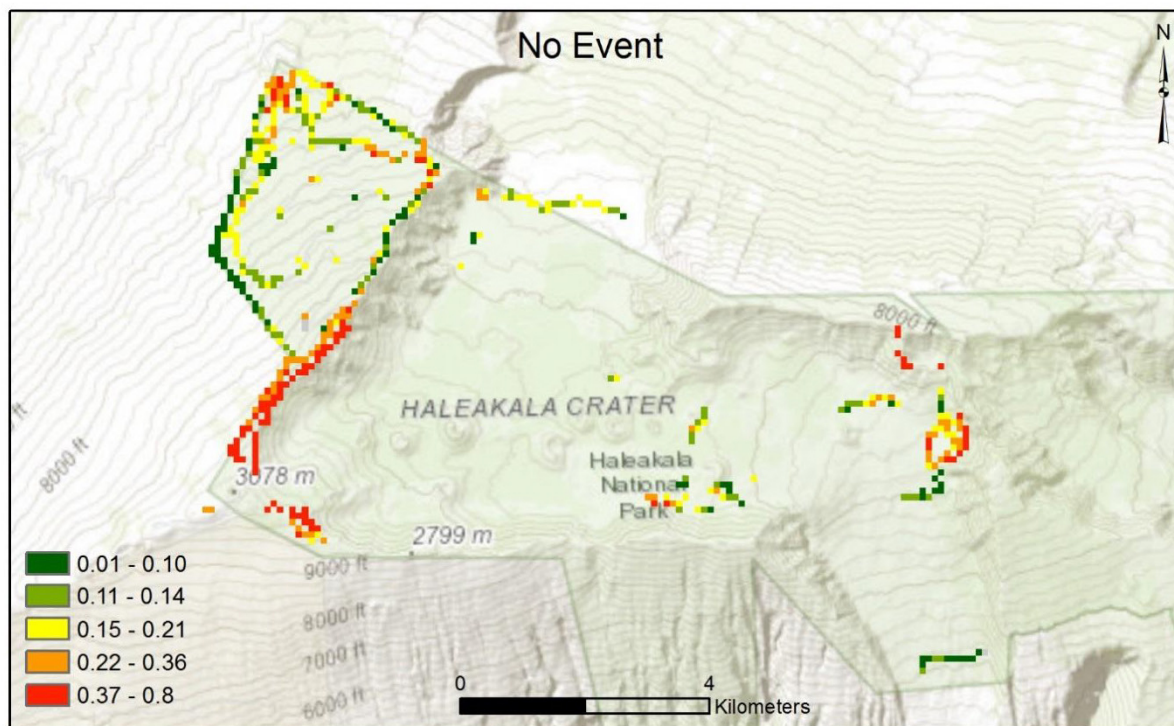
Figure 12.   Spatial distribution of No Event in Haleakalā National Park, Maui, Hawai'i, during 2000–14. Colors and values indicate the number of events per trap-week per 100 square meters (m²).
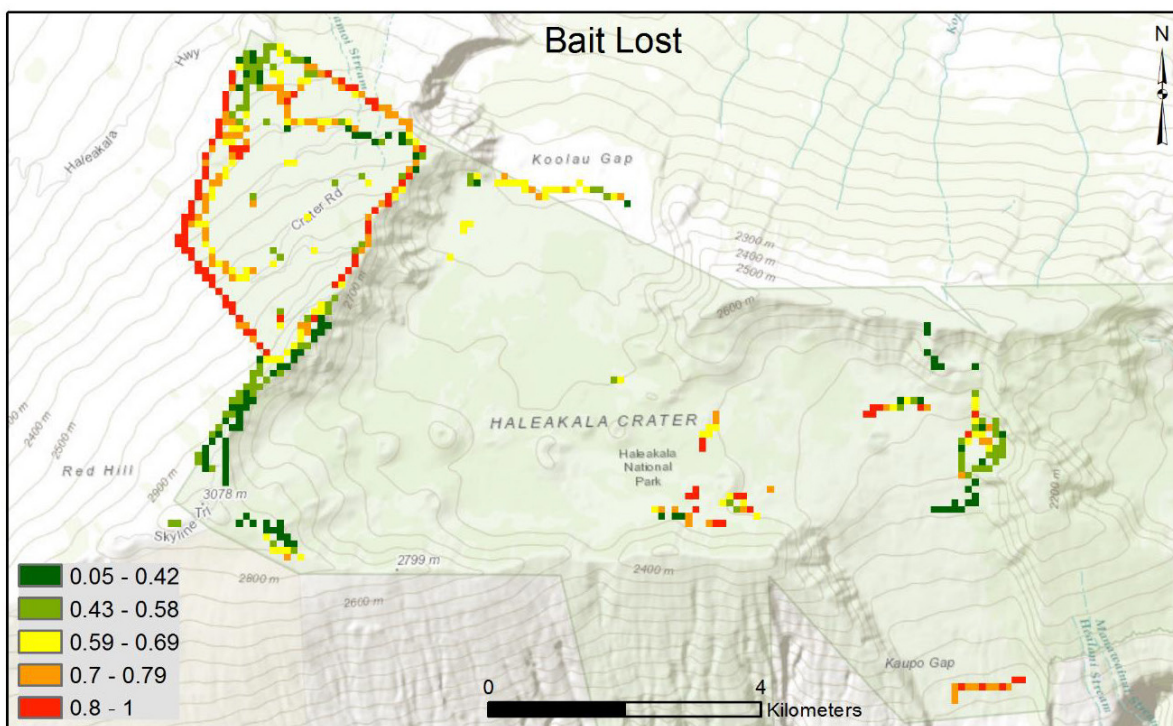
Figure 13.   Spatial distribution of Bait Lost associated with traps in Haleakalā National Park, Maui, Hawai'i, during 2000–14. Colors and values indicate number of events per trap-week per 100 square meters (m²).
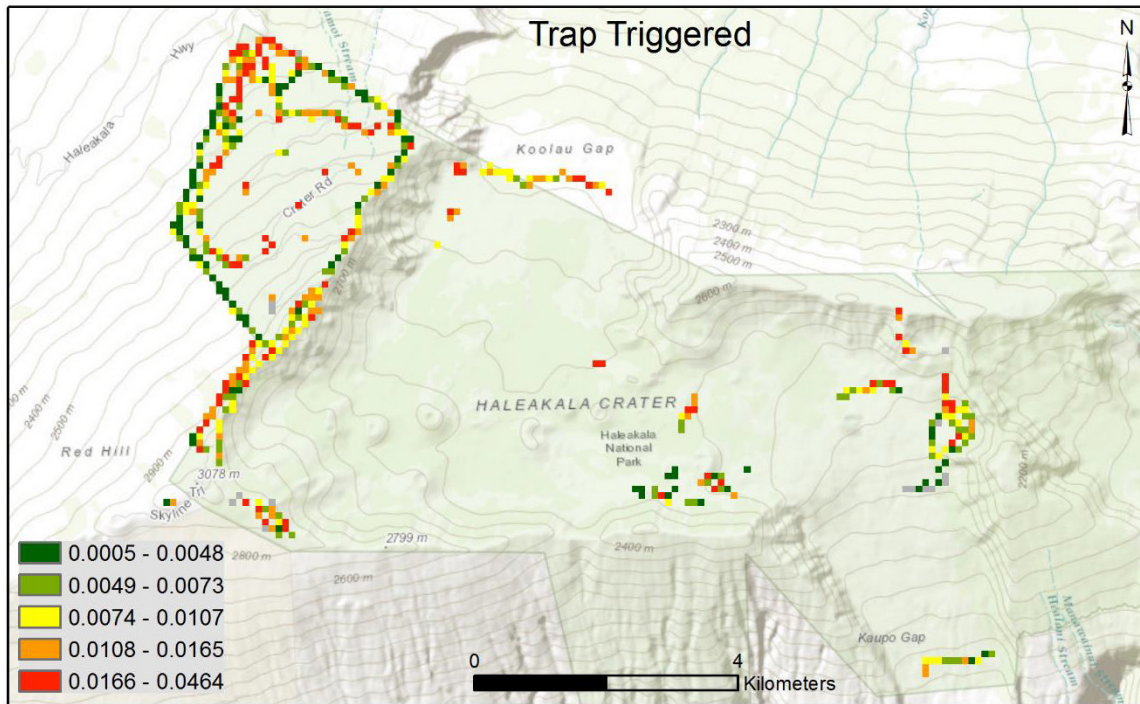
Figure 14.   Spatial distribution of Trap Triggered events associated with traps in Haleakalā National Park, Maui, Hawai'i, during 2000–14. Colors and values indicate the number of events per trap-week per 100 square meters (m²).
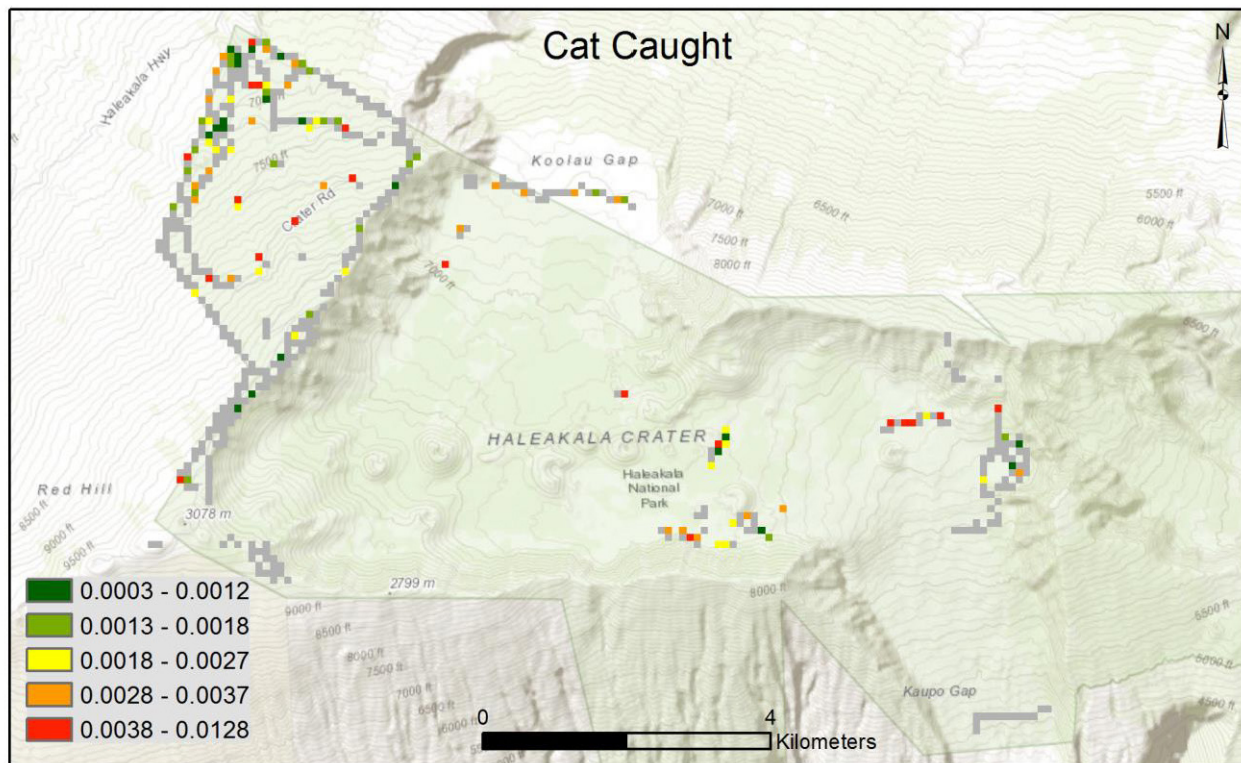
Figure 15.   Spatial distribution of Cat Caught associated with traps in Haleakalā National Park, Maui, Hawai'i, during 2000–14. Colors and values indicate number of events per trap-week per 100 square meters (m²).
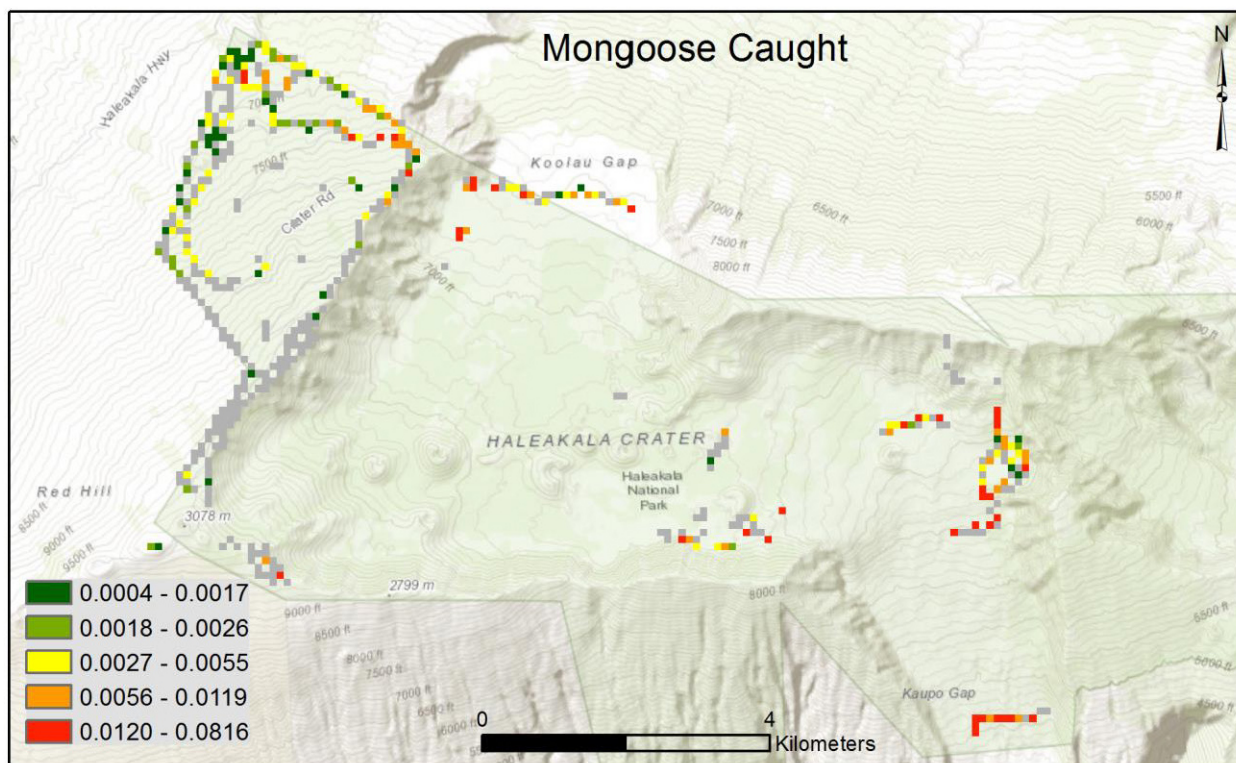
Figure 16. Spatial distribution of Mongoose Caught associated with traps in Haleakalā National Park, Maui, Hawai'i, during 2000–14. Colors and values indicate number of events per trap-week per 100 square meters (m^2).
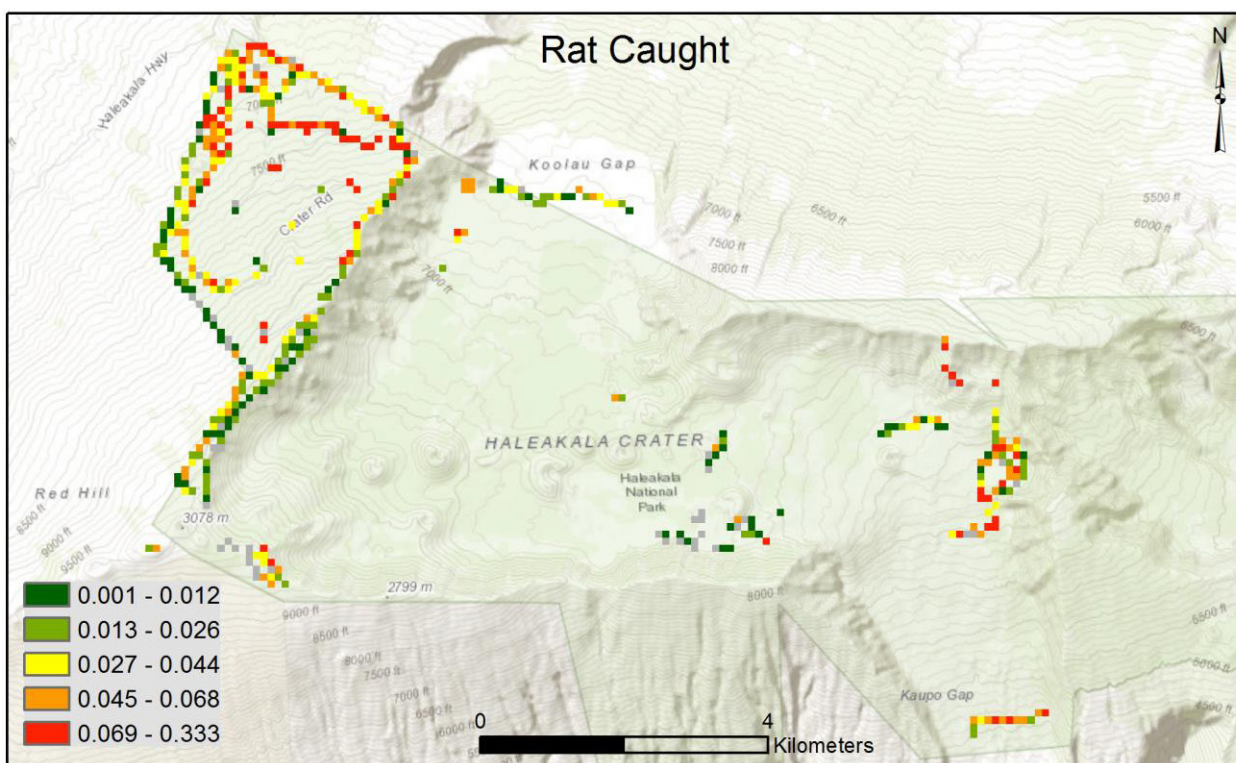
Figure 17. Spatial distribution of Rat Caught associated with traps in Haleakalā National Park, Maui, Hawai'i, during 2000–14. Colors and values indicate the number of events per trap-week per 100 square meters (m^2).
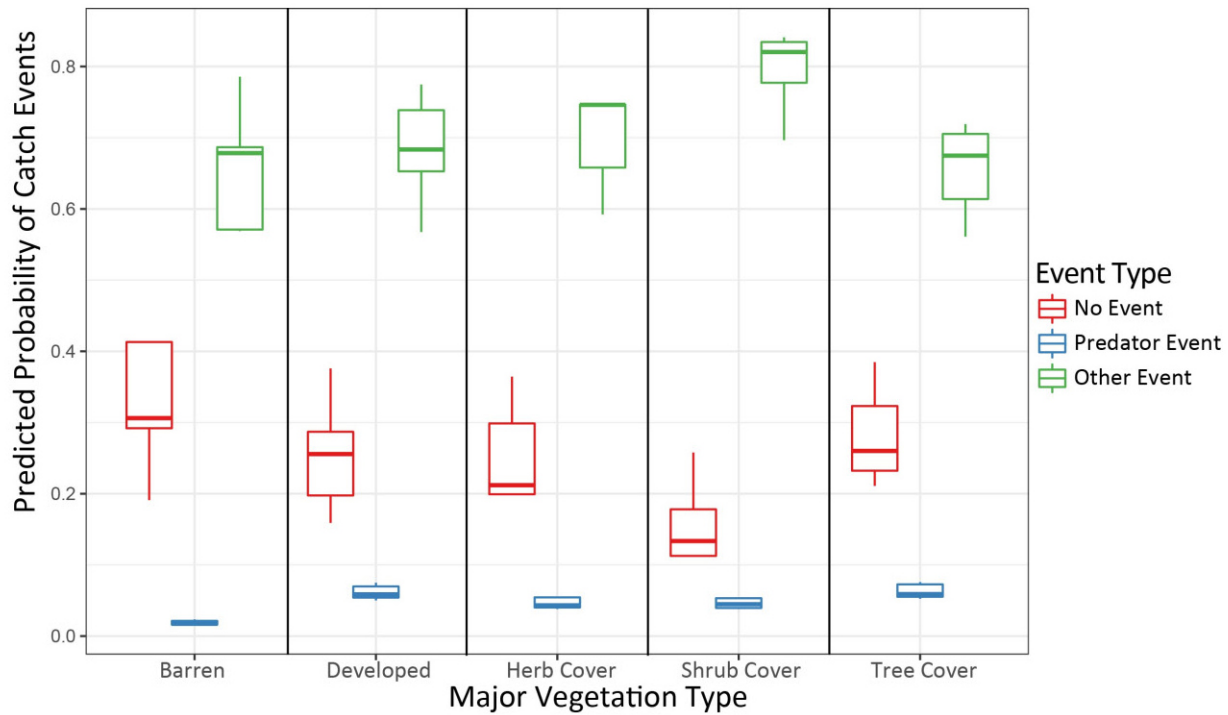
Figure 18.   Probability of broad trap event types associated with majority vegetation cover types. Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 57). The horizontal bar indicates the median probability, and the lower and upper hinges correspond to the first and third quartiles (25th and 75th percentiles).
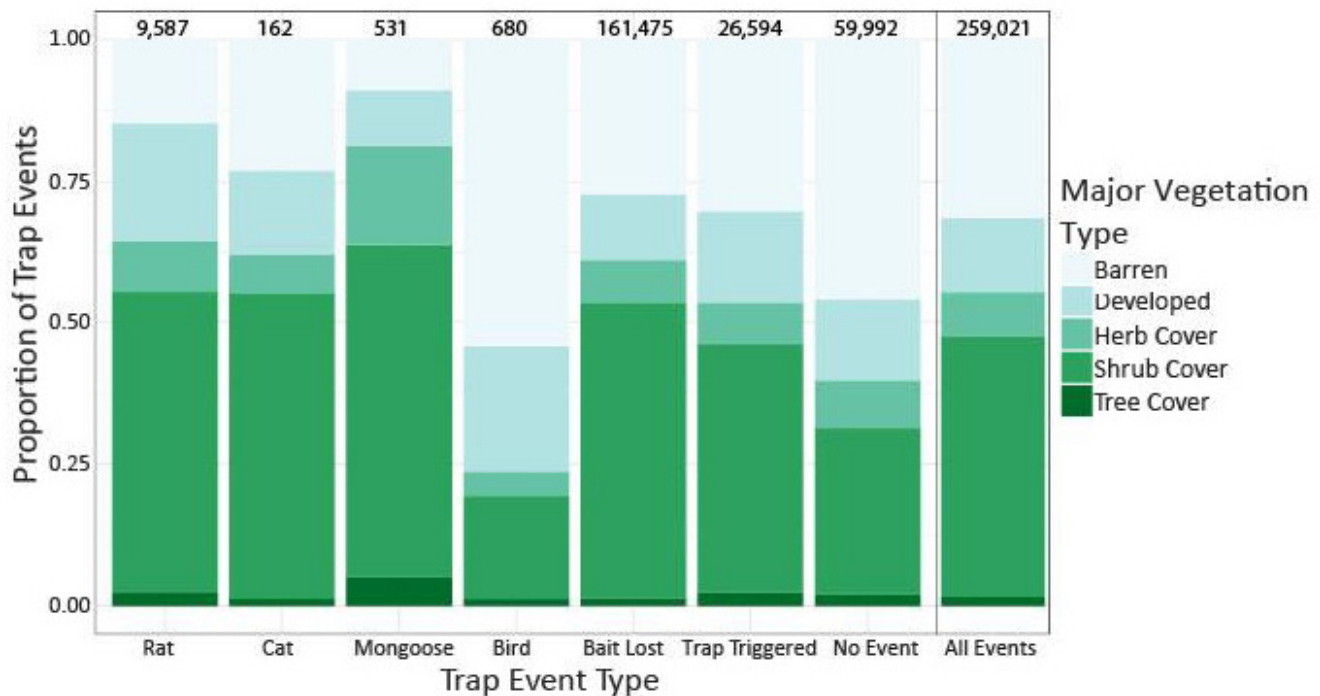
Figure 19.   Proportion of trap event types associated with majority vegetation cover types. Each column shows proportion of vegetation cover type where a specific trap event type occurred; numbers above columns indicate sample size. Rightmost column shows proportion of majority vegetation cover types around all traps combined.
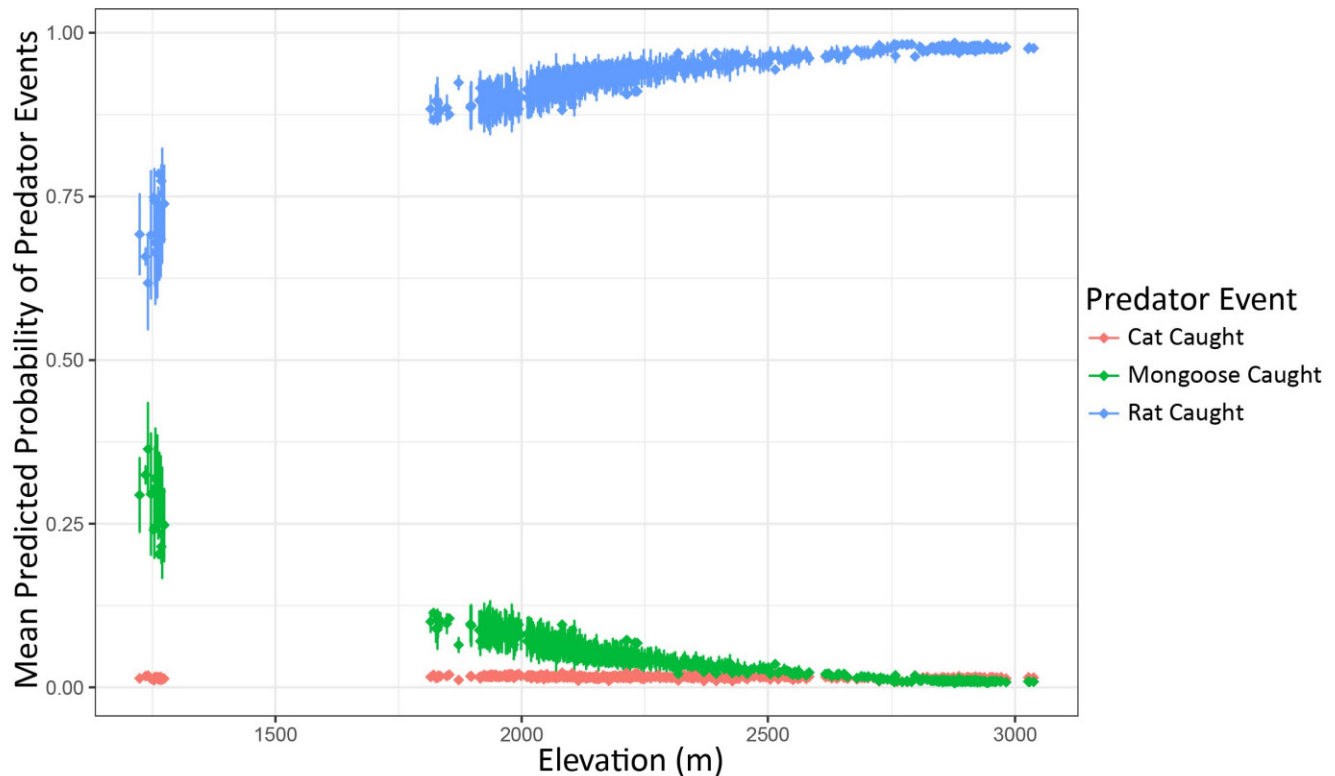
Figure 20. Probability of specific predator trap event types associated with elevation (in meters). Probabilities are relative to each other and generated from the top-ranked multinomial logistic regression model (Model 57). The points indicate the mean probabilities, and the vertical bars indicate the standard deviation of the mean probabilities.

Discussion

The goal of these analyses were twofold: (1) to evaluate temporal (monthly, seasonal, and annual) trends in the probability rates of small mammal capture (Predator Event: Rat Caught, Cat Caught, Mongoose Caught) and non-predator trapping outcomes (Trap Triggered, Bait Lost, No Event) and the relationship between these temporal trends and weather (temperature and precipitation) and lunar periodicity, and (2) to evaluate spatial patterns in trapping outcomes in relationship to landscape features (vegetation class, vegetation cover, elevation, slope), proximity to infrastructure (buildings, trails, roads, fences), and 'ua'u nest site density.

Temporal Trends

For temporal variables, we expected catch events to vary throughout the months and according to seasons defined by 'ua'u phenology because we suspect predator populations fluctuate throughout the year. Although we have no access to data directly related to 'ua'u breeding success or abundance, we hypothesized sustained trapping efforts to remove predators from the landscape should result in no increases

in probabilities of Predator Events between 2000 and 2014. We also anticipated variable correlations between weather variables and trap events.

Models 1 and 2 indicated associations between broad event types (Part 1) and time of year ('ua'u season or month), but the differences were not pronounced. Opposing trends between occurrences of Other Event and No Event throughout the 15-year management period (greater Other Event occurrences with lesser No Event occurrences and vice-versa; figs. 4, 5, 9A) make it difficult to determine periods of low overall trap efficiency. Furthermore, because rats were not always identified to species, it was hard to determine if smaller rodent species (small rats and house mice) were too small to be contained by traps and may have contributed to Bait Lost and Trap Triggered events. If temporal patterns were more clear, efforts could be made to increase trap efficiency and potentially reduce overall effort. It is important to note that trends in each broad event type were driven by the most abundant event in that grouping (Bait Lost in Other Event and Rat Caught in Predator Event; fig. 3). Thus, further insight into causes of high rates of Bait Lost may help managers decrease the rate of bait loss in traps and adjust trapping effort accordingly.

Without knowledge quantifying changes in predator densities within the park, it is hard to interpret the slight annual increase in predator catches through time (fig. 6). If predator density has remained constant through the 15-year period, the decrease in No Event and Other Event occurrences through time could indicate an increase in predator catches (resulting from an increase in trap efficiency) between 2000 and 2014. In 2007, HALE began to send long-term staff to intensive, hands-on trappers training, which may have increased trapping efficiency. More efficient foothold traps were used on cats starting in 2007 (Haleakalā National Park, unpub. data, 2019). These traps were not used consistently and, therefore, were not incorporated into this analysis. It would be valuable to know if changes in existing and modified trapping methods influenced predator density.

Part 2 results indicate slight trends in seasonal and monthly predator catch events (the probabilities and overall proportions of catches being either mongoose or cat were greatest during the ʻuaʻu off-season; figs. 7 and 9B, respectively). Although the probability of all predator events was slightly greater during the ʻuaʻu nestling season (fig. 5), trends were not pronounced, with no peaks among individual species (fig. 7). Abundance of each species within HALE is not known; therefore, it is unclear if frequencies of capture events are proportional to overall abundance. Furthermore, because rats weren't consistently identified to species, it is especially hard to decipher the trends in Rat Caught because different species or age-class (for example, mice and juvenile rats, respectively) may respond to trapping effort differently during different seasons. These results can inform more focused trapping in the future. For example, enhanced and targeted predator control might be achieved by increasing deployments of rat-specific or rat- and mongoose-specific baits and lethal traps (for example, DOC 250 traps) during the ʻuaʻu pre-laying and incubation seasons when the probability of rat capture is greatest. Model results also indicate slight cyclic annual patterns for all three predator event types (fig. 4). Although we also found evidence for interannual trends in specific predator catch events (fig. 8), these trends were slight and indicate no appreciable change in capture probabilities through time.

Weather and Lunar Trends

Overall, we knew that there were high rates of Bait Lost from traps in HALE, and one hypothesis was that bait washed out of open bait containers during rain events. In addition, we suspected that predators would be less active on dark nights when visibility was low; therefore, we would see a relationship between lunar state and trap events (table 2).

When we added weather and lunar variables to our temporal, broad event type (Part 1) models, we found that temperature, moon index, and weekly rainfall did not contribute meaningfully to patterns seen in trap events (appendix table 1–3). Seasonal (3 month) rainfall did, however, increase model rank (Model 27; appendix table 1–3). Other Events (primarily Bait Lost) decreased with increased seasonal cumulative rainfall, and the probability of No Event increased with increasing seasonal rainfall (fig. 10). These results (fewer trap events and more non-target trap events) indicated that trap efficiency decreased with increased seasonal rainfall and can inform seasonal adjustments in trapping effort. It has been hypothesized that the high rates of Bait Lost from traps (fig. 3) resulted from bait washing out of open bait containers during rain events; however, including weekly average rainfall did not improve model ranking. Therefore, it is unlikely that Bait Lost was due to heavy rain and likely resulted from other factors (such as insect or small rodent scavenging). Camera traps along traplines, and specifically in areas with high bait loss (fig. 13), could help determine factors associated with bait loss.

When we added weather and lunar variables to our temporal predator event type analysis (Part 2), we found support for weekly average maximum temperature effects on trapline predator events. Increased temperatures were associated with greater probabilities of rat catches and lesser probabilities of mongoose catches. Cat catches were rare, and we were not able to determine how temperature affected cat catches (fig. 11). Predator-specific trapping could be adjusted for seasonal temperature fluctuations (for example, increased rat trapping during warmer seasons and increased mongoose trapping during cooler seasons). Moon index and total 3-month rainfall did not contribute to models explaining patterns in trapline predator events. Weekly total rainfall and average minimum temperature did not improve model ranking when compared with a more simple, temporal model (appendix table 1–4).

Spatial Trends

We did not expect to find a correlation between slope and trap events and expected to find an inverse relationship between trap events and elevation because predators are thought to be less frequent at higher elevations. We anticipated that trap events would be more frequent closer to human structures (fences, roads, trails, and buildings) because these structures could attract predators.

Trap placement was non-uniform throughout HALE (fig. 3), and this hampered detection of spatial trends in trap events associated with landscape features. However, the contrasting frequency of No Event and Bait Lost (figs. 12 and 13) indicated that, when an event occurred, it was most likely Bait Lost. As mentioned above, implementing studies to understand the cause of bait loss from cage traps (such as camera traps in areas of high bait loss [fig. 13]) could help refine targeted predator trapping or minimize bait loss in the future. Also, the distribution of Trap Triggered events did not reveal strong spatial patterns, but there appeared to be fewer Trap Triggered events along the fence traplines (B and F; fig. 14). Supplemental camera monitoring studies could also be used to help understand instances of traps being triggered.

Percent cover of vegetation and majority vegetation cover type within a 50-m radius around the trap contributed to the best model explaining broad event types (Part 2; appendix table 1–5). We found no support to help explain broad event type occurrence among models when we included elevation, slope, and 'ua'u burrow density within 10, 50, and 100 m. No Event and Bird Caught were more likely to occur in barren areas, indicating that trapping effort in barren habitats could possibly be decreased in favor of additional trapping in more vegetated habitats, provided that this strategy decreased the abundance or likelihood of a predators occurring near nesting 'ua'u. Predator and Other Events were more likely in shrub cover areas, indicating that increased trapping in these areas likely would increase predator catches (figs. 18 and 19). Figure 19 also indicated that the proportions associated with habitat cover for Bait Lost was most similar to proportions for Cat Caught and Rat Caught, indicating that Bait Lost events might be caused in part by these predators. Rat Caught was the most common event in developed areas, indicating increased rat-specific trapping in these areas may be beneficial.

Although elevation was not included as a predictor in the top-ranked broad event type model (appendix table 1–5), elevation was included in the top-ranked specific predator event model (appendix table 1–6). Predator catches overall were less at higher elevations, indicating that higher elevation trapping is less effective than low elevation trapping. However, the greatest relative probability of capture at higher elevations (>2,000 m), where most 'ua'u nest, was predicted to be rats (fig. 20). Therefore, trapping at higher elevations could be made more effective by targeting rats more specifically. Mongoose were rarely caught at higher elevations. Targeted trapping for this species could be focused in lower elevation areas, with trapping also continuing at higher elevations to protect the 'ua'u nesting there. Few cat captures throughout HALE made it difficult to evaluate how elevation might be considered when specifically targeting cats. Researching other factors related to cat captures (such as trap type, bait and lure

options, and trap location attributes) might increase probability of capture in the future.

Summary of Trap Events and Conclusions

Limitations in management program design are accounted for in our analysis and resulting conclusions. Owing to duplicated or missing data, we retained 85.0 percent of the original data for temporal analysis and 84.7 percent for spatial analysis. Because missing data resulted from the management program design and were not intended to cause bias, we assume that the remaining data records represent an unbiased sample for the probability of trap outcomes within the park.

It is difficult to determine the cause of the high rate of Bait Lost throughout the 15-year management period (2000–14; fig. 3); bait loss indicates potentially compromised trapping efficacy. Bait Lost from cage traps also could contribute additional food resources for some predators and non-native pests. Non-native pests (house mouse *Mus musculus*, Argentine ants *Linepithema humile,* and Western Yellow-jackets *Vespula pensylvanica*) have been observed on bait in some traps and could be contributing to bait loss (Haleakalā National Park, unpub. data, 2019). Observation of trap events (such as cameras deployed in association with traps that have frequent bait loss events; fig. 12) could help EWM staff understand the cause(s) of bait loss and decrease bait loss events in the future.

The frequency of bait types used for each trap event and the variation in bait type frequencies between different trap event types are outlined in table 3. Some interesting patterns in the frequency of baits associated with different trap type events were that No Event and Bait Lost were the most frequent trap events associated with both commercial baits and lures, indicating that if expensive commercial baits lures were not effective in attracting predators *to* the trap, it did not attract them *into* the trap (table 3). However, the small sample size of commercial baits and lures could inadequately represent the effectiveness of these methods. Trap Triggered was the most frequent trap event associated with other baits (such as combinations of leftover human foods), indicating these baits may have been more attractive to small predators (such as small rats and mice) that do not get caught in the cage traps used. Again, cameras associated with traps would help to understand the relationship of Bait Lost and Trap Triggered with different bait types. The results in table 3 indicate that cat food, dog food, and a combination of the two are most frequently associated with predator catches, and thus could be considered the most effect bait types. Containing these baits within cage traps so that they are not accessible to scavengers might improve bait retention and increase capture probabilities.

Rats, cats, and mongoose cause devastating impacts to biodiversity and seabird populations worldwide (Jones and others, 2008; Towns and others, 2011). More than half of the world's 8 most-endangered petrels are threatened by rats and cats (Le Corre, 2008). At a global scale, *R. rattus*, was determined to have the greatest impact on seabird populations (Doherty and others, 2016). Effective control, exclusion, and eradication of introduced predators has clear-cut advantages for the recovery of impacted seabirds. For example, in Hawai'i, control of *R. rattus* and mongoose using a variety of traps and poison bait increased breeding success for Red-tailed Tropicbird (*Phaethon rubricauda*) nesting on O'ahu (Vanderwerf and Young, 2014). Exclusion of cats, rats, and mongoose from a colony of Wedge-tailed Shearwaters (*Puffinus pacificus*) at Ka'ena Point, O'ahu, resulted in a 384 percent increase in chick production and a 45 percent increase in pairs attempting to nest (Vanderwerf and Young, 2014). Pascal and others (2008) recorded a doubling in average breeding success among Cory's Shearwater (*Calonectris diomedea*) subcolonies when *R. rattus* were controlled or eradicated. These examples highlight the importance for enhancing efforts to effectively control rats at HALE and also highlight the importance for continued or enhanced monitoring of burrow occupancy and reproductive success among 'ua'u and nēnē.

Our results show that the probability of capturing mongoose is greater during colder temperatures, during 'ua'u off-season (November–January), and in shrub- and tree-covered areas at lower elevations (figs. 7, 9, 11, 16). Owing to the small sample size of cat captures, it was hard to detect patterns, but the probability of cat captures also increased during 'ua'u off-season (November–January) and in shrub-covered areas at lower elevations (figs. 7, 9, 11, 15). Based on these results, efficiency in mongoose and cat trapping could increase by targeting captures November through January (when temperatures are lower and 'ua'u are not present) in vegetated areas at lower elevations. For cat captures specifically, efficiency could be increased by using footholds or other inconspicuous trap types (Goodale and others, 2014). A comparison of less conspicuous foothold traps with standard cage traps showed that cats at HALE were caught at a significantly higher rate with foothold traps (p <0.01; Goodale and others, 2014). Lethal trapping methods could also increase efficiency of cat, mongoose, and rat captures; however, any efforts to supplement current efforts with lethal trapping would need to be implemented in a way that minimizes the risk of injury to protected 'ua'u and nēnē. Probabilities of rat capture are greatest during warmer temperatures, during 'ua'u pre-laying and incubation periods (February–June), and at lower elevations in herb, shrub, and tree-covered areas (figs. 7, 9, 11, 17). Although all predators were caught less frequently at higher elevations, when a predator was caught at higher elevation it was almost always a rat (fig. 20). All rats identified to species at HALE have been *R. rattus*. Therefore, if predator control efforts are to continue at higher elevations, using specific baits and (or) traps targeting *R. rattus* could increase efficiency. Because of the possibility that other rat species may also be present in HALE (Polynesian [*R. exulans*] and Norway Rats [*R. norvegicus*]; each of which responds to trapping efforts differently and could have variable spatial and temporal distributions), it is important for HALE staff to continue rat species identification with trapping efforts. An assessment of the presence of house mice would also potentially shed light on occurrence and future trends in bait loss.

The probability of Other Event was greatest during 'ua'u off-season, specifically during November, and decreased with increased seasonal rainfall (figs. 4, 5, 9, 10). Bait Lost events accounted for 86 percent of Other Event occurrences (fig. 3). Therefore, understanding more about the occurrence of bait loss events could help keep traps "live" (available to predators) and potentially increase trapping efficiency. Bait Lost was common at all elevations, especially along fence lines and ridgelines and in shrub-covered areas (fig. 13). The high percentage of bait loss events and the wide distribution of these events indicate a need for varied trapping strategies to prevent bait loss, such as more durable bait, placing bait in solid containers with small holes, using scents and lures, and increasing the use of other traps (for example, foothold traps; Goodale and others, 2014) especially by pairing live traps with specific rodent traps, which could increase captures and decrease instances of Bait Lost.

In conclusion, our analyses showed temporal and spatial trends existed in trap events within HALE during 2000–14. These trends can help inform predator management by guiding trapping efforts in times and locations that are most effective for trapping predators. Furthermore, our results reveal gaps where additional studies could be implemented to help understand occurrences of non-targeted trap events and improve trap efficacy. A better understanding of non-target trap events and implementation of targeted lethal traps for mice, rats, cats, and mongoose would further increase predator-trapping success and benefit 'ua'u. In addition, a more complete understanding of the effects of predator control efforts at HALE could be achieved with quantitative information about seasonal and spatial patterns in predator abundances and by including measures of 'ua'u breeding success and site occupancy.

References Cited

Bailey, C.N., Kaholoaa, R.L.,Kelsey, E.C., Adams, J., Czapanskiy, M.F., and Felis, J.J., 2019, Trap records used to analyze trends in mammalian predator control trapping events intended to protect ground-nesting, endangered birds at Haleakalā National Park, Hawaiʻi (2000–14): U.S. Geological Survey data release, https://doi.org/10.5066/P98RJ12I.

Burnham, K.P., and Anderson, D.R., 2003, Model selection and multimodel inference—A practical information-theoretic approach (2d ed.): New York, N.Y., Springer-Verlag Inc., 488 p.

Croissant, Y., 2013, mlogit—Multinomial logit model, R package version 0.2-4: Comprehensive R Archive Network, https://CRAN.R-project.org/package=mlogit.

Doherty, T.S., Glen, A.S., Nimmo, D.G., Ritchie, E.G., and Dickman, C.R., 2016, Invasive predators and global biodiversity loss: Proceedings of the National Academy of Sciences of the United States of America, v. 113, no. 40, p. 11261–11265, https://doi.org/10.1073/pnas.1602480113.

Goodale, K., Bailey, C.N., Kaholoaʻa, R., Tamayose, J., and Orwi, S., 2014, Capture rates using a variety of traps, baits and lures, Haleakalā National Park, Makawao, HI, USA: Honolulu, Hawaiʻi, Hawaiʻi Conservation Conference, Poster Presentation.

Jones, H.P., Tershy, B.R., Zavaleta, E.S., Croll, D.A., Keitt, B.S., Finkelstein, M.E., and Howald, G.R., 2008, Severity of the effects of invasive rats on seabirds—A global review: Conservation Biology, v. 22, no. 1, p. 16–26, https://doi.org/10.1111/j.1523-1739.2007.00859.x.

Kaholoaa, R.L., Bailey, C.N., Kekiwi, E.K., Purdy, K.K., Judge, S.W., Tamayose, J.A., and Schwarz, C.J., 2019, Predator control management plan Haleakalā National Park: Natural Resource Report NPS/HALE/NRR—2019/2005, National Park Service, Fort Collins, Colo., 78 p., https://irma.nps.gov/DataStore/Reference/Profile/2266574.

Kelly, D., 2017, Package 'oce'—Analysis of oceanographic data: R package version 0.9-21: Comprehensive R Archive Network, 721 p., https://cran.r-project.org/web/packages/oce/oce.pdf.

Landfire, 2010, Existing vegetation type layer, Existing vegetation cover layer, elevation layer, slope layer, LANDFIRE 1.2.0: U.S. Geological Survey web page, accessed October 24, 2016, at https://landfire.cr.usgs.gov/viewer/.

Le Corre, M., 2008, Cats, rats and seabirds: Nature, v. 451, p. 134–135, https://doi.org/10.1038/451134a.

Longman, R.J., Giambelluca, T.W., Nullet, M.A., and Loope, L.L., 2015, Climatology of Haleakalā: Honolulu (HI): Pacific Cooperative Studies Unit, University of Hawaiʻi at Manoa, Technical Report 193, 126 p., http://hdl.handle.net/10125/36675.

Natividad Hodges, C.S., and Nagata, R.J., Sr., 2001, Effects of predator control on the survival and breeding success of the endangered Hawaiian Dark-Rumped Petrel: Studies in Avian Biology, v. 22, p. 308–318, https://sora.unm.edu/node/139630.

Pascal, M., Lorvelec, O., Bretagnolle, V., and Culioli, J.-M., 2008, Improving the breeding success of a colonial seabird—A cost-benefit comparison of the eradication and control of its rat predator: Endangered Species Research, v. 4, p. 267–276, https://doi.org/10.3354/esr00080.

Simons, T.R., 1985, Biology and behavior of the endangered Hawaiian Dark-Rumped Petrel: The Condor, v. 87, no. 2, p. 229–245, https://doi.org/10.2307/1366887.

Towns, D.R., Byrd, G.V., Jones, H.P., Rauzon, M.J., Russell, J.C., and Wilcoz, C., 2011, Impacts of introduced predators on seabirds, chap. 3 in Mulder, C.P.H., Anderson, W.B., Towns, D.R., and Bellingham, P.J., eds., Seabird Islands—Ecology, invasion, and restoration: Oxford Scholarship Online, https://doi.org/10.1093/acprof:osobl/9780199735693.003.0003.

Train, K., and Croissant, Y., 2012, Kenneth Train's exercises using the mlogit package for R: R, no. 25, 30 p., https://pdfs.semanticscholar.org/923a/8251e742a1f11a7892555e18406766639d58.pdf.

U.S. Fish and Wildlife Service, 2009, Endangered and threatened wildlife and plants; Initiation of 5-year reviews of 103 species in Hawaii: Federal Register, v. 74, no. 49, p. 11130–11133, https://www.govinfo.gov/content/pkg/FR-2009-03-16/pdf/E9-5523.pdf.

Vanderwerf, E.A., and Young, L.C., 2014, Breeding biology of red-tailed tropicbirds Phaethon rubricauda and response to predator control on Oʻahu, Hawaiʻi: Marine Ornithology, v. 42, no. 1, p. 73–76, https://sora.unm.edu/node/136421.

Appendix 1

Temporal Trends

Resampled model ranking of the 13 model variations evaluating temporal trends in broad event types (model subset 1) indicated the best models (combined Akaike's information criterion [AIC] weight = 0.99) were Model 1 with year (continuous) and month as predictors (AIC weight = 0.52) and Model 2 with both year (continuous) and 'ua'u season as predictors (AIC weight = 0.47). Both top models included trapline and year (categorical) as random effects (appendix table 1–1). For specific predator capture events (Rat, Cat, or Mongoose Caught; Part 2), the best-fit model (Model 14) explaining temporal trends in probability of multinomial capture events per trapline effort used year (continuous variable) and 'ua'u season as predictors with trapline as a random effect (AIC weight = 0.89; appendix table 1–2).

Weather and Lunar Trends

We added several weather/lunar variables to the top-ranked, broad event type model (Model 1). We found improved model ranking with total precipitation during the 3 months preceding as a model coefficient (Model 27; mean AIC weight of 1,000 resample runs = 10,000; appendix table 1–3). Including moon index, weekly average minimum temperature, and weekly average maximum temperature also increased model rank, but the AIC weight of these models was much less than Model 27, indicating that their relative improvement to model quality was low. Weekly rainfall did not improve model fit.

When we added weather and lunar variables (temperature, rainfall, and lunar cycle) to the top-ranked

predator-specific event model (Model 14) to evaluate trends in specific predator events (Rat Caught, Cat Caught, or Mongoose Caught), we found support for improved model rank when average maximum temperature was added to the model (Model 37; appendix table 1–4). Moon index and total 3-month rainfall also added to model fit but the AIC weight of these models was much less than Model 37, indicating that their relative improvement to model quality was low. Average minimum temperature and weekly cumulative rainfall did not improve model rank.

Spatial Trends

Similar to temporal and weather variables, we assessed patterns in spatial variables for broad event types and predator-specific events using multinomial logistic regression models. Model ranking for multinomial logistic regressions of broad event types (Predator Event, Other Event, No Event) indicated the best spatial model included 'ua'u season, percent cover of vegetation, and majority vegetation cover type as coefficients with trapline and year (categorical) as random effects (AIC weight = 1.00; Model 47; appendix table 1–5). Slope, elevation, and burrow density also improved model rank but had an AIC weight of less than one and therefore were not thought to be significant coefficient.

Model ranking for spatial multinomial logistic regression of predator-specific trap events (cat, rat, mongoose) indicated the best spatial model included 'ua'u season and elevation as predictors with trapline and year (categorical) as random effects (Model 56; AIC weight = 1.00; appendix table 1–6). Inclusion of remaining predictors (median slope, percent cover of vegetation, majority vegetation cover type, and burrow density) also improved model rank but had an AIC weight of less than one and therefore were not thought to be significant predictors.

Table 1–1. Models describe effects of temporal variables on broad event type (Predator Event, Other Event, No Event).

[Average (mean) multinomial logistic regression model statistics from 1,000 random resamples (2.5% of the dataset). AIC = Akaike's information criterion, df = degrees of freedom, YearCo = year as a continuous variable, YearCa = year as a categorical variable, * = models selected to best describe trends in event type frequency]

Model	Variables	Random effect(s)	AIC	Δ AIC	AIC Weight	df
1*	Month + YearCo	Trapline + YearCa	6,321.02	0.00	0.52	28
2*	'ua'u Season + YearCo	Trapline + YearCa	6,322.60	1.58	0.47	12
3	Month + YearCo	Trapline	6,401.21	80.19	0.01	28
4	'ua'u Season + YearCo	Trapline	6,403.31	82.29	<0.01	12
5	'ua'u Season + YearCo	YearCa	6,509.46	188.44	<0.01	12
6	Month + YearCo	YearCa	6,510.74	189.72	<0.01	28
7	'ua'u Season + Trapline + YearCo		6,581.30	260.29	<0.01	44
8	Month + Trapline + YearCo		6,581.56	260.55	<0.01	60
9	'ua'u Season + YearCo		6,789.77	468.76	<0.01	10

Table 1–2. Multinomial logistic regression models of effects of temporal variables on specific Predator Event Type (Rat Caught, Cat Caught, and Mongoose Caught).

[AIC = Akaike's information criterion, df = degrees of freedom, YearCo = year as a continuous variable, YearCa = year as a categorical variable, * = model selected to best describe trends in predator event frequency]

Model	Coefficients	Random effect(s)	AIC	Δ AIC	AIC Weight	df
14*	'ua'u Season + YearCo	Trapline	5,109.06	0.00	0.89	12
15	Month + YearCo	Trapline	5,113.19	4.13	0.11	28
16	'ua'u Season + YearCo	Trapline + YearCa	5,194.16	85.10	0.00	12
17	Month + YearCo	Trapline + YearCa	5,200.74	91.69	0.00	28
18	'ua'u Season + YearCo	YearCa	5,312.10	203.05	0.00	12
19	Month + YearCo	YearCa	5,317.51	208.45	0.00	28
20	'ua'u Season + YearCo + Trapline		5,800.76	691.70	0.00	46
21	Month + YearCo + Trapline		5,818.63	709.57	0.00	62
22	'ua'u Season + YearCo		5,861.35	752.29	0.00	10
23	Month + YearCo		5,881.06	772.01	0.00	26
24	'ua'u Season		5,865.06	756.01	0.00	8
25	Month		5,883.47	774.41	0.00	24
26	YearCo		5,882.03	772.98	0.00	4

Table 1–3.   Average (mean) multinomial logistic regression model rankings of effects of temporal and weather/lunar variables on Event Type data (Predator Event, Other Event, No Event).

[Averages from 1,000 random resamples (5% the dataset) of was run to determine the best model; the complete dataset was used to estimate probabilities associated with selected coefficients based on the top-ranked model. Abbreviations: AIC = Akaike's information criterion, df = degrees of freedom, YearCo = year as continuous variable, YearCa = year as categorical variable, Rain3m = 3 month total rainfall, Rain1w = total week rainfall, Tmin = average weekly minimum temperature (°C), Tmax = average weekly maximum temperature, moon = (total moonlight hours per trap week) × (average moon illumination in trap week). * = model that best explains temporal and climatic patterns in event type]

Model	Coefficients	Random effects	Mean AIC	Δ AIC	Mean AIC Weight	df
27*	Month + YearCo + Rain3m	Trapline + YearCa	9,704.20	0.00	0.40	10
28	Month + YearCo + moon + Rain3m	Trapline + YearCa	9,706.49	2.29	0.14	12
29	Month + YearCo + Tmin	Trapline + YearCa	9,707.66	3.45	0.17	10
30	Month + YearCo + Tmax	Trapline + YearCa	9,709.78	5.57	0.06	10
31	Month + YearCo + moon + Tmin	Trapline + YearCa	9,709.90	5.69	0.06	12
32	Month + YearCo	Trapline + YearCa	9,710.79	6.58	0.05	8
33	Month + YearCo + Rain1w	Trapline + YearCa	9,711.86	7.66	0.06	10
34	Month + YearCo + moon + Tmax	Trapline + YearCa	9,712.01	7.80	0.02	12
35	Month + YearCo + moon	Trapline + YearCa	9,713.04	8.84	0.02	10
36	Month + YearCo + moon + Rain1w	Trapline + YearCa	9,714.14	9.93	0.02	12

Table 1–4.   Multinomial logistic regression models of effects of temporal and weather/lunar variables on specific Predator Events (Rat Caught, Cat Caught, and Mongoose Caught).

[AIC = Akaike's information criterion, df = degrees of freedom, YearCa = year as categorical variable, Rain3m = 3 month total rainfall, Rain1w = total week rainfall, Tmin = average weekly minimum temperature (°C), Tmax = average weekly maximum temperature, moon = (total moonlight hours per trap week) × (average moon illumination in trap week). * = models that best explains temporal and climatic patterns in event type (ΔAIC ≤ 2)]

Model	Coefficients	Random effects	AIC	Δ AIC	AIC Weight	df
37*	'ua'u Season + YearCo + Tmax	Trapline + YearCa	3,338.51	0.00	0.71	14
38	'ua'u Season + YearCo + moon + Tmax	Trapline + YearCa	3,340.70	2.19	0.24	16
39	'ua'u Season + YearCo + Rain3m	Trapline + YearCa	3,346.07	7.56	0.02	14
40	'ua'u Season + YearCo	Trapline + YearCa	3,346.54	8.03	0.01	12
41	'ua'u Season + YearCo + moon + Rain3m	Trapline + YearCa	3,348.02	9.51	0.01	16
42	'ua'u Season + YearCo + moon	Trapline + YearCa	3,348.61	10.10	0.00	14
43	'ua'u Season + YearCo + Rain1w	Trapline + YearCa	3,349.34	10.84	0.00	14
44	'ua'u Season + YearCo + Tmin	Trapline + YearCa	3,350.20	11.69	0.00	14
45	'ua'u Season + YearCo + moon + Rain1w	Trapline + YearCa	3,351.45	12.94	0.00	16
46	'ua'u Season + YearCo + moon + Tmin	Trapline + YearCa	3,352.38	13.87	0.00	16

Table 1–5.   Multinomial logistic regression models of effects of spatial variables on broad Event Types (Predator Event, Other Event, or No Event).

[AIC = Akaike's information criterion, df = degrees of freedom, 'ua'u Season = 'ua'u phenology, YearCa = year as categorical variable, Trapline = specific HALE trapline name, Burrrows10/50/100 = number of 'ua'u burrows within 10/50/100 m, MedSlope = median slope within 50 meters (m) of trap, Elevation = elevation at location of trap, PctVeg = % cover of vegetation (any type) within 50 m, vegMajCover = majority vegetation cover type within 50 m. * = model selected as best]

Model	Coefficients	Random effects	AIC	Δ AIC	AIC Weight	df
47*	'ua'u Season + PctVeg + vegMajCover	Trapline + YearCa	345,020.15	0.00	1.00	20
48	'ua'u Season + Burrows100	Trapline + YearCa	345,062.06	41.92	0.00	12
49	'ua'u Season + vegMajCover	Trapline + YearCa	345,664.08	643.94	0.00	18
50	'ua'u Season + Burrows50	Trapline + YearCa	346,086.01	1,065.86	0.00	12
51	'ua'u Season + PctVeg	Trapline + YearCa	347,695.12	2,674.97	0.00	12
52	'ua'u Season + Elevation	Trapline + YearCa	349,863.90	4,843.75	0.00	12
53	'ua'u Season + MedSlope	Trapline + YearCa	350,769.89	5,749.74	0.00	12
54	'ua'u Season + Burrows10	Trapline + YearCa	353,239.69	8,219.55	0.00	12
55	'ua'u Season	Trapline + YearCa	356,747.32	11,727.17	0.00	10

Table 1–6.   Multinomial logistic regression models of effects of spatial variables on specific Predator Event data (Rat Caught, Cat Caught, and Mongoose Caught).

[AIC = Akaike's information criterion, df = degrees of freedom, 'ua'u Season = 'ua'u phenology, YearCa = year as categorical variable, Trapline = specific HALE trapline name, Burrrows10/50/100 = number of 'ua'u burrows within 10/50/100 m, MedSlope = median slope within 50 meters (m) of trap, Elevation = elevation at location of trap, PctVeg = % cover of vegetation (any type) within 50 m, vegMajCover = majority vegetation cover type within 50 m. * = model selected as best]

Model	Coefficients	Random effects	AIC	Δ AIC	AIC Weight	df
56*	'ua'u Season + Elevation	Trapline + YearCa	5,590.77	0.00	1.00	12
57	'ua'u Season + PctVeg + vegMajCover	Trapline + YearCa	5,656.34	65.57	0.00	20
58	'ua'u Season + vegMajCover	Trapline + YearCa	5,663.15	72.38	0.00	18
59	'ua'u Season + PctVeg	Trapline + YearCa	5,683.19	92.42	0.00	12
60	'ua'u Season + Burrows100	Trapline + YearCa	5,716.90	126.13	0.00	12
61	'ua'u Season + Burrows50	Trapline + YearCa	5,724.09	133.32	0.00	12
62	'ua'u Season + MedSlope	Trapline + YearCa	5,729.48	138.71	0.00	12
63	'ua'u Season + Burrows10	Trapline + YearCa	5,741.43	150.66	0.00	12
64	'ua'u Season	Trapline + YearCa	5,749.23	158.46	0.00	10