Supplementary material

Appendices 1-6

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.
Appendix 1. Variance estimation through posterior simulation

A simple and general method for computing the variance of non-linear functions of model parameters for a fitted generalized additive model (GAM) is outlined here (see also Marra et al. 2012 and Wood 2017). This is achieved by simulating a large number of replicate parameter sets from the posterior distribution of the GAM coefficients \( \hat{\beta} \). A prediction matrix, \( X_p \), maps the model parameters, \( \hat{\beta} \), to the linear predictor, \( \eta_p \), as

\[
\eta_p = X_p\hat{\beta}.
\]

A large number of replicate parameter value sets are drawn from the posterior distribution of \( \beta \) which is multivariate normal. The linear predictor is calculated for each of the replicate sets, and resulting quantiles are then used to compute CIs or the variance can be computed empirically.

A smoothing parameter uncertainty correction is incorporated in the posterior simulations as the covariance matrix which is computed as a first-order Taylor expansion (see pg 302 in Wood 2017). In \texttt{mgcv}, version 1.8-17, this correct covariance matrix is computed via \texttt{vcov(m, unconditional=TRUE)} provided \( m \) is estimated using REML. We found there to be minor computational costs in computing the unconditional covariance matrix and a wider correction factor in incorporating the smoothing parameter uncertainty (Appendix 1 Fig. 1).
Appendix 1 Fig. 1. Histograms of 1000 replicate parameter sets from the posterior distribution using a covariance matrix conditional (vcov(m, unconditional=FALSE); left panel) and unconditional (vcov(m, unconditional=TRUE); right panel) on the smoothing parameter.

R code for the above procedure follows. Although these data have been processed successfully on a computer system at the U.S. Geological Survey (USGS), no warranty expressed or implied is made regarding the display or utility of the data for other purposes, nor on all computer systems, nor shall the act of distribution constitute any such warranty. The USGS or the U.S. Government shall not be held liable for improper or incorrect use of the data described and/or
# Define grid over the study area for each year in the time series with grid size adjusted offset
pred.SpTm <- expand.grid(Year=unique(PointDataHI$Year),
    East=seq(from=255400, to=261200, by=200),
    North=seq(from=2189000, to=2200800, by=200),
    off.set=4) # 4, 1-ha plots per 200x200m grid

# Restrict predictions to within study area defined by polys.map
pred.SpTmInfer <- pred.SpTm[with(pred.SpTm, inSide(polys.map, East, North)), ]

# Predict density estimates to grid
pred.SpTmInfer[, "fit"] <- predict(dsmPredModel, pred.SpTmInfer,
    type="response")

# coerce the structure of Year in newdata to match to structure of the data used in fitted model
pred.SpTmInfer$Year <- as.integer(pred.SpTmInfer$Year)

# Propagate the detection probability uncertainty
dsm.SpTm.varprop <- dsm.var.prop(dsmPredModel, pred.data=pred.SpTmInfer,
    off.set = 1, seglen.varname = "Effort",
    type.pred = "response")

# Predict the propagated non-linear and detection probability uncertainty
ts.year <- unique(PointDataHI$Year) # years in time series
n.rep <- 999  # number of replicate draws

pred.SpTmInfer.b <- pred.SpTmInfer[,c(1:4)]  # added post run

# add extra column for additional parameters in the refitted model
pred.SpTmInfer.b["XX"] <- matrix(0, nrow(pred.SpTmInfer.b),
                                   length(dsm.SpTm$ddf$par))

pred.SpTmInfer.b$Year <- as.integer(pred.SpTmInfer.b$Year)

pred.SpTmInfer.b[, "fit"] <- predict(dsm.SpTm.varprop$model, pred.SpTmInfer.b,
                                       type="response")

# form the matrix X_p above
Lp.b <- predict(dsm.SpTm.varprop$model, newdata=pred.SpTmInfer.b,
                type="lpmatrix")

# create storage for the results
PredVar.b <- matrix(NA, nrow=30, ncol=n.rep)

# loop over the number of replicates
for (i in 1:n.rep){
  # generate new betas
  br.b.u <- rmvn(n=1, coef(dsm.SpTm.varprop$model),
                 vcov(dsm.SpTm.varprop$model, unconditional=TRUE))

  # calculate the predicted values
ex <- 40000*exp(Lp.b %*% matrix(br.b.u, ncol=1))

# calculate the estimates per year
for (j in 1:30)
{
    PredVar.b[j,i] <- sum(ex[pred.SpTmInfer$Year == ts.year[j],])/3061
}

# Extract quantiles and variances
PredVar.b.out <- apply(PredVar.b, 1, quantile, 
    probs = c(0.025, 0.5, 0.975)) # quantiles for each year

# print variance for each year
for (i in 1:nrow(PredVar.b)){
    print(var(as.vector(as.matrix(PredVar.b[i,]))))
}
Appendix 2. Point coverage and count distribution
Appendix 2 Fig. 2. Spatial position of each point per year.
Appendix 2 Fig. 3. Counts of Hawai‘i ‘ākepa per year.
Appendix 3. Diagnostics for the distance sampling model

Appendix 3 Fig. 4. Detection function plots for the model selected to estimate 'äkepa detection probability. Plots represent the detection probability (left panel) and probability density (right panel).
Appendix 3 Fig. 5. Quantile-quantile plot for the detection function model selected to estimate 'ākepa detection probability. The fitted cumulative distribution function (cdf) is plotted against the empirical cdf. The points seem to fall about the straight line, which provides evidence the function adequately fits the data.
Appendix 3 Table 1. Detection function models used to compute density estimates from point-transect distance sampling surveys on Hakalau Forest National Wildlife Refuge, Hawai‘i, between 1987 and 2017. Base models (Fun) include half-normal (HN) and hazard-rate (HR) key detection functions with cosine (Cos), hermite polynomial (Hp) and simple polynomial (Sp) adjustment terms (Adj). Covariates were incorporated with the highest AIC-ranked base model included cloud cover, rain, wind strength, gust strength, elevation (Elev), habitat type, minutes since survey start (MinSS), observer and year of survey (Yr). All covariates were treated as factor variables, except minutes since survey start was treated as a continuous variable. Also presented are the number of estimated parameters (Par), negative log-likelihood (-LogLike), AIC values, and change in AIC (ΔAIC). † Key model selected.

| Key | Covariate | Par | -LogLike | AIC      | ΔAIC |
|-----|-----------|-----|----------|----------|------|
| HR  | Yr        | 31  | 11106.00 | 22273.99 | 0    |
| HR  | Obs       | 13  | 11157.87 | 22341.74 | 67.75|
| HR  | Wind      | 5   | 11178.66 | 22367.31 | 93.32|
| HR  | Elev      | 3   | 11185.68 | 22377.35 | 103.36|
| HR  | Hab       | 3   | 11186.29 | 22378.58 | 104.59|
| HR  | None      | 2   | 11191.27 | 22386.53 | 112.54|
| HR  | Gust      | 5   | 11188.35 | 22386.69 | 112.70|
| HR  | MinSS     | 3   | 11191.22 | 22388.43 | 114.44|
| HR  | Rain      | 4   | 11190.86 | 22389.71 | 115.72|
| HR  | Cloud     | 12  | 11184.69 | 22393.39 | 119.40|
| HN  | None      | 1   | 11221.17 | 22444.33 | 170.34|
| HN  | Cos†      |     |          |          |      |
| HN  | Hpoly†    |     |          |          |      |
| HR  | Cos†      |     |          |          |      |
| HR  | Spoly†    |     |          |          |      |
Correlation and confounding effects were evaluated for combinations of covariates against year. Point coordinates, elevation, and habitat type covariates were confounded with year and their combinations were not evaluated in modelling a detection function. Observer participation varied from 1 to 26 times over the 31-year time series; thus, observer was confounded with year and the combined covariate model was not evaluated. Correlation was large between gust and wind with year and their combinations were excluded (Appendix 3 Table 2). Inference was made from the hazard-rate key detection function with year-only covariate.

Appendix 3 Table 2. Correlation between detection function covariates with year for the point-transect distance sampling surveys on Hakalau Forest National Wildlife Refuge, Hawai’i, between 1987 and 2017. Covariates included rain, wind strength, gust strength and minutes since survey start (MinSS). Spearman correlation was used for all covariates, except the continuous covariate minutes since survey start (MinSS), for which a Kendall rank correlation was used.

| Covariate | Correlation |
|-----------|-------------|
| MinSS     | 0.04        |
| Rain      | -0.08       |
| Wind      | -0.31       |
| Gust      | 0.50        |
Appendix 4. Refuge-wide and regional population densities

Appendix 4 Fig. 6. Comparison of uncertainty between CIs produced using posterior simulation and design-based methods. Points below the lines indicate uncertainty was improved with narrower intervals produced from the posterior simulation method.
Table 3. Density (Est), width of confidence interval (CIW) and change in uncertainty (ChgPrec) produced from design-based (DB), delta (DM) and variance propagated (VP) methods for the study area.

| Year | Est_DB | CIW_DB | Est_DM | CIW_DM | ChgPrec_DM | Est_VP | CIW_VP | ChgPrec_VP |
|------|--------|--------|--------|--------|------------|--------|--------|------------|
| 1987 | 0.959  | 0.937  | 0.871  | 0.453  | -0.517     | 0.541  | 0.464  | -0.505     |
| 1988 | 0.283  | 0.453  | 0.756  | 0.264  | -0.417     | 0.556  | 0.415  | -0.084     |
| 1989 | 0.696  | 0.807  | 0.673  | 0.286  | -0.645     | 0.572  | 0.376  | -0.534     |
| 1990 | 0.446  | 0.627  | 0.625  | 0.270  | -0.569     | 0.587  | 0.350  | -0.442     |
| 1991 | 0.396  | 0.769  | 0.611  | 0.250  | -0.675     | 0.607  | 0.329  | -0.572     |
| 1992 | 0.891  | 0.729  | 0.625  | 0.238  | -0.673     | 0.625  | 0.325  | -0.553     |
| 1993 | 0.622  | 0.455  | 0.662  | 0.198  | -0.565     | 0.646  | 0.318  | -0.301     |
| 1994 | 0.438  | 0.444  | 0.716  | 0.232  | -0.477     | 0.666  | 0.311  | -0.300     |
| 1995 | 0.509  | 0.769  | 0.781  | 0.252  | -0.673     | 0.688  | 0.306  | -0.602     |
| 1996 | 1.147  | 0.908  | 0.856  | 0.263  | -0.710     | 0.707  | 0.307  | -0.662     |
| 1997 | 1.061  | 0.676  | 0.931  | 0.324  | -0.520     | 0.721  | 0.317  | -0.531     |
| 1998 | 0.727  | 0.780  | 0.995  | 0.337  | -0.568     | 0.737  | 0.333  | -0.573     |
| 1999 | 0.770  | 0.780  | 1.025  | 0.316  | -0.456     | 0.753  | 0.339  | -0.417     |
| 2000 | 1.089  | 0.812  | 1.008  | 0.333  | -0.589     | 0.766  | 0.366  | -0.549     |
| 2001 | 0.874  | 0.638  | 0.948  | 0.303  | -0.524     | 0.780  | 0.388  | -0.391     |
| 2002 | 0.948  | 0.879  | 0.871  | 0.245  | -0.721     | 0.794  | 0.404  | -0.541     |
| 2003 | 0.534  | 0.572  | 0.811  | 0.270  | -0.529     | 0.810  | 0.417  | -0.271     |
| 2004 | 0.863  | 0.764  | 0.794  | 0.264  | -0.655     | 0.828  | 0.434  | -0.432     |
| 2005 | 0.305  | 0.291  | 0.836  | 0.320  | 0.098      | 0.844  | 0.451  | 0.549      |
| 2006 | 0.460  | 0.415  | 0.944  | 0.409  | -0.014     | 0.863  | 0.474  | 0.142      |
| 2007 | 1.072  | 0.697  | 1.109  | 0.407  | -0.416     | 0.877  | 0.490  | -0.297     |
| 2008 | 1.509  | 1.282  | 1.492  | 0.500  | -0.610     | 0.885  | 0.494  | -0.615     |
| 2009 | 1.200  | 0.830  | 1.457  | 0.665  | -0.199     | 0.889  | 0.491  | -0.408     |
| 2010 | 0.806  | 1.335  | 1.355  | 0.589  | -0.558     | 0.876  | 0.476  | -0.644     |
| 2011 | 1.123  | 0.707  | 1.171  | 0.461  | -0.348     | 0.870  | 0.483  | -0.317     |
| 2012 | 1.225  | 0.905  | 0.986  | 0.380  | -0.581     | 0.856  | 0.524  | -0.421     |
| 2013 | 0.613  | 0.978  | 0.851  | 0.322  | -0.670     | 0.845  | 0.600  | -0.387     |
| 2014 | 0.476  | 1.293  | 0.778  | 0.355  | -0.725     | 0.836  | 0.689  | -0.467     |
| 2015 | 0.710  | 1.019  | 0.757  | 0.328  | -0.678     | 0.831  | 0.843  | -0.172     |
| 2016 | 0.878  | 0.900  | 0.767  | 0.401  | -0.554     | 0.838  | 1.021  | 0.135      |
Appendix 4 Table 4. Density (Est), width of confidence interval (CIW) and change in uncertainty (ChgPrec) produced from design-based (DB), delta (DM) and variance propagated (VP) methods for the north stratum. Estimate not produced indicated with a —.

| Year | Est_DB | CIW_DB | Est_DM | CIW_DM | ChgPrec_DM | Est_VP | CIW_VP | ChgPrec_VP |
|------|--------|--------|--------|--------|------------|--------|--------|------------|
| 1987 | 0.131  | 1.087  | 0.047  | 0.056  | -0.948     | 0.060  | 0.083  | -0.924     |
| 1988 | 0.079  | 0.885  | 0.041  | 0.041  | -0.953     | 0.061  | 0.074  | -0.917     |
| 1989 | 0.059  | 0.368  | 0.036  | 0.034  | -0.908     | 0.062  | 0.068  | -0.816     |
| 1990 | 0.034  | 0.298  | 0.034  | 0.029  | -0.903     | 0.063  | 0.061  | -0.797     |
| 1991 | 0.014  | 0.148  | 0.033  | 0.026  | -0.824     | 0.064  | 0.056  | -0.623     |
| 1992 | 0.058  | 0.627  | 0.035  | 0.025  | -0.960     | 0.066  | 0.053  | -0.916     |
| 1993 | 0.086  | 0.452  | 0.037  | 0.025  | -0.944     | 0.069  | 0.051  | -0.887     |
| 1994 | 0      | —      | 0.042  | 0.028  | —          | 0.072  | 0.051  | —          |
| 1995 | 0.012  | 0.136  | 0.047  | 0.031  | -0.775     | 0.075  | 0.050  | -0.631     |
| 1996 | 0.060  | 0.233  | 0.054  | 0.033  | -0.858     | 0.079  | 0.051  | -0.781     |
| 1997 | 0.131  | 0.555  | 0.061  | 0.038  | -0.932     | 0.085  | 0.054  | -0.902     |
| 1998 | 0.179  | 1.664  | 0.069  | 0.042  | -0.975     | 0.090  | 0.058  | -0.965     |
| 1999 | 0.153  | 0.564  | 0.075  | 0.044  | -0.922     | 0.097  | 0.065  | -0.885     |
| 2000 | 0      | —      | 0.078  | 0.048  | —          | 0.103  | 0.073  | —          |
| 2001 | 0.204  | 0.680  | 0.078  | 0.048  | -0.930     | 0.111  | 0.076  | -0.888     |
| 2002 | 0.188  | 1.780  | 0.075  | 0.045  | -0.975     | 0.119  | 0.082  | -0.954     |
| 2003 | 0.070  | 0.775  | 0.074  | 0.045  | -0.942     | 0.128  | 0.087  | -0.888     |
| 2004 | 0.114  | 0.679  | 0.077  | 0.044  | -0.935     | 0.137  | 0.094  | -0.862     |
| 2005 | 0      | —      | 0.086  | 0.050  | —          | 0.148  | 0.101  | —          |
| 2006 | 0.139  | 0.331  | 0.103  | 0.063  | -0.811     | 0.159  | 0.110  | -0.668     |
| 2007 | 0.182  | 0.482  | 0.130  | 0.074  | -0.847     | 0.171  | 0.121  | -0.749     |
| 2008 | 0.543  | 1.363  | 0.164  | 0.099  | -0.928     | 0.186  | 0.131  | -0.904     |
| 2010 | 0.300  | 0.951  | 0.226  | 0.148  | -0.844     | 0.219  | 0.153  | -0.839     |
| 2011 | 0.136  | 5.236  | 0.236  | 0.147  | -0.972     | 0.240  | 0.168  | -0.968     |
| 2012 | 0.127  | 0.562  | 0.231  | 0.131  | -0.767     | 0.260  | 0.183  | -0.675     |
| 2013 | 0.484  | 1.151  | 0.221  | 0.121  | -0.895     | 0.285  | 0.207  | -0.820     |
| 2014 | 0.238  | 2.778  | 0.218  | 0.121  | -0.957     | 0.311  | 0.249  | -0.910     |
| 2015 | 0.224  | 6.238  | 0.228  | 0.145  | -0.977     | 0.341  | 0.319  | -0.949     |
| 2016 | 0.452  | 2.629  | 0.251  | 0.166  | -0.937     | 0.376  | 0.411  | -0.844     |
| 2017 | 0.476  | 1.181  | 0.288  | 0.221  | -0.813     | 0.420  | 0.539  | -0.544     |
Appendix 4 Table 5. Density (Est), width of confidence interval (CIW) and change in uncertainty (ChgPrec) produced from design-based (DB), delta (DM) and variance propagated (VP) methods for the south stratum.

| Year | Est_DB | CIW_DB | Est_DM | CIW_DM | ChgPrec_DM | Est_VP | CIW_VP | ChgPrec_VP |
|------|--------|--------|--------|--------|------------|--------|--------|------------|
| 1987 | 2.891  | 3.313  | 2.601  | 1.332  | -0.598     | 1.677  | 1.370  | -0.586     |
| 1988 | 0.757  | 1.475  | 2.267  | 0.781  | -0.470     | 1.723  | 1.246  | -0.155     |
| 1989 | 2.181  | 3.151  | 2.022  | 0.850  | -0.730     | 1.778  | 1.126  | -0.643     |
| 1990 | 1.408  | 2.504  | 1.878  | 0.801  | -0.680     | 1.833  | 1.077  | -0.570     |
| 1991 | 1.286  | 3.218  | 1.831  | 0.743  | -0.769     | 1.898  | 0.998  | -0.690     |
| 1992 | 2.832  | 2.697  | 1.868  | 0.711  | -0.736     | 1.955  | 0.977  | -0.638     |
| 1993 | 1.873  | 1.658  | 1.973  | 0.590  | -0.644     | 2.018  | 0.977  | -0.411     |
| 1994 | 1.459  | 1.781  | 2.130  | 0.690  | -0.613     | 2.067  | 0.980  | -0.450     |
| 1995 | 1.668  | 3.171  | 2.327  | 0.755  | -0.762     | 2.115  | 0.971  | -0.694     |
| 1996 | 3.680  | 3.574  | 2.550  | 0.807  | -0.774     | 2.156  | 0.963  | -0.730     |
| 1997 | 3.227  | 2.385  | 2.775  | 1.001  | -0.580     | 2.191  | 0.977  | -0.590     |
| 1998 | 2.005  | 2.157  | 2.955  | 1.038  | -0.519     | 2.225  | 1.018  | -0.528     |
| 1999 | 2.210  | 1.958  | 3.033  | 0.970  | -0.505     | 2.254  | 1.024  | -0.477     |
| 2000 | 3.629  | 3.116  | 2.968  | 1.008  | -0.677     | 2.281  | 1.069  | -0.657     |
| 2001 | 2.436  | 2.140  | 2.778  | 0.900  | -0.579     | 2.322  | 1.107  | -0.483     |
| 2002 | 2.719  | 2.591  | 2.544  | 0.708  | -0.727     | 2.355  | 1.137  | -0.561     |
| 2003 | 1.615  | 2.055  | 2.360  | 0.773  | -0.624     | 2.389  | 1.135  | -0.447     |
| 2004 | 2.608  | 2.841  | 2.302  | 0.754  | -0.735     | 2.440  | 1.169  | -0.589     |
| 2005 | 1.016  | 1.234  | 2.412  | 0.910  | -0.263     | 2.468  | 1.265  | 0.025      |
| 2006 | 1.210  | 1.537  | 2.707  | 1.155  | -0.249     | 2.501  | 1.391  | 0.095      |
| 2007 | 3.144  | 2.673  | 3.158  | 1.140  | -0.573     | 2.529  | 1.429  | -0.461     |
| 2008 | 3.759  | 4.628  | 3.653  | 1.415  | -0.694     | 2.532  | 1.504  | -0.675     |
| 2010 | 3.298  | 2.748  | 4.049  | 1.869  | -0.320     | 2.458  | 1.461  | -0.468     |
| 2011 | 2.367  | 4.532  | 3.717  | 1.638  | -0.639     | 2.375  | 1.441  | -0.682     |
| 2012 | 3.444  | 2.551  | 3.157  | 1.269  | -0.503     | 2.287  | 1.346  | -0.472     |
| 2013 | 2.953  | 2.813  | 2.600  | 1.025  | -0.635     | 2.206  | 1.339  | -0.524     |
| 2014 | 1.487  | 2.737  | 2.184  | 0.855  | -0.688     | 2.111  | 1.431  | -0.477     |
| 2015 | 1.063  | 1.164  | 1.932  | 0.922  | -0.208     | 2.002  | 1.676  | 0.440      |
| 2016 | 1.313  | 1.411  | 1.808  | 0.859  | -0.392     | 1.898  | 1.963  | 0.391      |
| 2017 | 1.814  | 3.026  | 1.754  | 1.019  | -0.663     | 1.832  | 2.298  | -0.241     |
Appendix 5. Diagnostics for the spatio-temporal GAM

We evaluated the fit of the Poisson, Tweedie, and negative binomial distributions to the data. We plotted the residuals versus fitted values, versus each covariate in the model, and versus the assumed distribution of the residuals. Inspection of residual diagnostic plots revealed that the Poisson distribution performed poorly. The poor model performance was particularly obvious in the quantile-quantile (QQ) plot where the observed values fell outside the QQ envelopes along the entire quantile plot. The negative binomial distribution diagnostic plots revealed it did a better job of handling residual errors than the Poisson distribution, which was particularly apparent in the QQ-plot where there was less deviation from the straight line (Appendix 5 Fig. 7, 8, 9, 10 and 11). The over-dispersion parameter for the negative binomial was 1.94. In-spection of the Tweedie distribution diagnostic plots revealed that the residual errors were approximately equal to those of the Poisson distribution, but that the Tweedie distribution did not perform as well as the negative binomial distribution. Again, this was particularly apparent in the QQ-plot. The Tweedie over-dispersion parameter, $p$, was 1.01 and the scale parameter, $\phi$, was 1.009 for the full model. Thus, the Tweedie distribution tended to a Poisson probability function (Shono 2008).

In addition to model selection using residual diagnostics, we computed Akaike’s information criterion (AIC). The negative binomial had the lowest AIC value (Appendix 5 Table 6). Given the diagnostics there was marginally more support that the deviance residuals of the negative binomial model showed acceptable behaviour and had the lowest AIC value, and was therefore chosen for the GAM (Appendix 5 Table 7). The EDF values are approximately zero for an
extremely flexible model fit to the residuals (Appendix 5 Table 8) indicating that there was little un-modelled residual auto-correlation.

Appendix 5 Table 6. Model selection statistics for the Poisson (pois), negative binomial (nb) and Tweedie (tw) distributions. Presented are the smoother degrees of freedom (df), Akaike’s information criterion (AIC), Δ AIC, REML and over-dispersion values. Estimate not produced indicated with a —.

| Model | df       | AIC     | Δ AIC | REML    | Over-dispersion |
|-------|----------|---------|-------|---------|-----------------|
| nb    | 50.22610 | 7664.627| 0     | 3877.6  | 1.94            |
| pois  | 74.50298 | 7871.632| 207.005| 3987.2  | —               |
| tw    | 65.11868 | 12689.527| 5024.900| 2496.1  | 1.01            |

Appendix 5 Table 7. Effective degrees of freedom (EDF), reference degrees of freedom (rf), χ² statistic (χ²) and p-value for each term in the fitted spatio-temporal model.

| Term            | EDF  | rf | χ²  | p-value |
|-----------------|------|----|-----|---------|
| s(east)         | 5.204| 9  | 38.99| <0.001  |
| s(north)        | 7.145| 9  | 176.29| <0.001  |
| s(year)         | 6.755| 9  | 105.69| <0.001  |
| ti(east, north) | 7.084| 16 | 73.98| <0.001  |
| ti(east, year)  | 0.0120| 16 | 0.01 | 0.19    |
| ti(north, year) | 7.653| 16 | 50.47| <0.001  |
| ti(east, north, year) | 8.737| 88 | 36.08| <0.001  |

Appendix 5 Table 8. Effective degrees of freedom (EDF) and reference degrees of freedom (rf) for each term in the model fitted to the residuals.

| Term            | EDF  | rf |
|-----------------|------|----|
| s(east)         | 0.0004| 9 |
| s(north)        | 0.0004| 9 |
| s(year)         | 0.0003| 9 |
| ti(east, north) | 0.0009| 16|
| ti(east, year)  | 0.0006| 16|
| ti(north, year) | 0.0005| 16|
| ti(east, north, year) | 0.0002| 88|
Appendix 5 Fig. 7. Diagnostic plots for spatio-temporal GAM fitted to the 'akepa count data. Residuals versus fitted values (top left panel), residuals versus easting (top right panel), residuals versus northing (middle left panel), residuals versus year (middle right panel), histogram of residuals (bottom left panel), and sorted residuals (bottom right panel). The plots show acceptable behaviour for the deviance residuals and error distribution.
Appendix 5 Fig. 8. Sorted deviance residuals (black line) for the spatio-temporal GAM against simulated theoretical quantiles (grey lines) fitted to the 'akepa count data. Most of the points seem to fall about the straight line, which provide evidence that the choice of negative binomial response is reasonable.
Appendix 5 Fig. 9. Violin plot of deviance residuals for the \textit{east} term of the spatio-temporal GAM fitted to the 'ākepa count data. A violin plot is a combination of a box plot and density plot that shows the distribution shape of the data. The red dot is the median and the black bar the mean. The interquartile range is indicated by the box and the whiskers the upper and lower adjacent values. Black dots indicate outliers. The density plot portion reveals the distribution of the data showing probability, relative amplitude, of observations. The distribution of the \textit{east} residuals were highly concentrated around the median with many outliers.
Appendix 5 Fig. 10. Violin plot of deviance residuals for the north term of the spatio-temporal GAM fitted to the 'ākepa count data. The distribution of the north residuals was mixed. In the southern portion of the study area the residuals were more evenly distributed than in the northern portion where the residuals were more concentrated around the median. Again, there are many outliers.
Appendix 5 Fig. 11. Violin plot of deviance residuals for the year term of the detection probability and spatio-temporal GAM fitted to the 'ākepa count data. There was a concentration of the residuals around the median in the year term and there were a large number of outliers. The medians of the residuals were consistently below the zero line indicating the predicted values tended to be too high.
Appendix 5 Fig. 12. Estimated model terms for the spatio-temporal GAM fitted to the 'ākepa count data. The distribution of the data is visualised in the rug plot along the x-axis for the 1D **Easting**, **Northing** and **Year** plots, while the EDFs are presented on the y-axis labels. The ribbon illustrates the error bounds. The locations of the points are plotted as black dots on the 2D contour plots and the EDF is provided in the plot panel title. Contours at plus and minus 1 SE of estimator variability relative to the mean are shown as blue lines. Estimates provided on the scale of the link function.
Appendix 5 Fig. 13. Estimated model terms for the 3-way smooths of the spatio-temporal GAM fitted to the ʻākepa count data. Maps shown for every three or four years between 1987 and 2017. Variability is minimal during the middle of the time series (middle row) and more variable early and late in the time series (bottom and top rows, respectively). The EDF is provided on the y-axis label and contours at plus and minus 1 SE of estimator variability relative to the mean are shown as black lines.
Appendix 5 Fig. 14. Predicted spatio-temporal maps of density (birds ha$^{-1}$) coefficient of variation.
Appendix 6. Modelling the covariate habitat with the smoother GAM

Appendix 6 Fig. 15. Location of points within each habitat type montane wet and montane mesic forest.
Appendix 6 Fig. 16. Diagnostic plots for spatio-temporal model that included categorical \textit{habitat} term fitted to the 'ikepa count data. Box plot of residuals versus habitat type (1 = wet and 2 = mesic; top left panel; the black bar is the mean while the interquartile range is indicated by the box, the whiskers are the upper and lower adjacent values and the black dots indicate outliers), residuals versus fitted values (top middle panel), residuals versus year (top right panel), residuals versus easting (centre left panel), residuals versus northing (centre middle panel), histogram of residuals (centre right panel), and sorted residuals (bottom panel). The plots show reasonable behaviour for the deviance residuals and error distribution.
Appendix 6 Table 9. Effective degrees of freedom (EDF), reference degrees of freedom (rf), $\chi^2$ statistic ($\chi^2$) and $p$-value for the habitat covariate and each smoother term in the fitted spatio-temporal model.

| Term                  | EDF | rf | $\chi^2$ | $p$-value |
|-----------------------|-----|-----|----------|-----------|
| habitat               | 4.814 |     |          | 0.028     |
| s(east)               | 5.056 | 9   | 33.43    | <0.001    |
| s(north)              | 7.101 | 9   | 183.48   | <0.001    |
| s(year)               | 6.680 | 9   | 102.31   | <0.001    |
| ti(east, north)       | 6.507 | 16  | 62.54    | <0.001    |
| ti(east, year)        | 1.716 | 16  | 3.45     | 0.003     |
| ti(north, year)       | 3.513 | 16  | 13.04    | <0.001    |
| ti(east, north, year) | 21.475 | 88  | 43.47    | <0.001    |
References

Marra, G., Miller, D. L., and Zanin, L. 2012. Modelling the spatiotemporal distribution of the incidence of resident foreign population. – *Stat. Neerl.*, 66:133–160.

Shono, H. 2008. Application of the Tweedie distribution to zero-catch data in CPUE analysis. – *Fish. Res.*, 93:154–162.

Wood, S. N. 2017. *Generalized additive models: An introduction with R*. – CRC press, Boca Raton, FL, USA.