

Scripps's Murrelet egg size model

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Introduction

This document includes code for likelihood ratio tests to test inclusion of random effects, model selection, and model diagnostics for a linear-mixed model of Scripps's Murrelet *Synthliboramphus scrippsi* egg size as a function of egg order and oceanographic indices at Santa Barbara Island, Channel Islands National Park, USA from 2009-2017.

```
knitr::opts_chunk$set(echo = TRUE)

## load libraries
library(here)
library(tidyverse)
library(janitor)
library(ggplot2)
library(lubridate)
library(viridis)
library(lme4)
library(RLRsim)
library(faraway)
library(sjPlot)
library(forecast)

## load egg size data and covariate data
egg <- read.csv(here("data", "SCMU_egg_data.csv"))
covars <- read.csv(here("data", "covariates", "covars.csv"))

## join covariate data with egg size data
SCMUdf <- left_join(egg, covars, by = "Year") %>% # join by year
  filter(TrueOrder == TRUE) %>% # select eggs with order known only
  filter(Size > 1210) %>% # remove the outliers
  dplyr::select(Year, Observer, Plot, Size, EggOrder, ANCHL, BEUTI, NPGO, ONI, PDO, SST)
```

Global Model

```
## create data frame specifying predictors to include
predictors <- as.data.frame(matrix(c(FALSE, TRUE), 2, 7)) # 7 potential predictors (includes EggOrder)

## add column names
cov_names <- colnames(predictors) <- colnames(SCMUdf[,5:11])
```

```

## create set of all possible combinations
full_set <- expand.grid(predictors)

## select models with correlated predictors
ii <- which(full_set$ANCHL + full_set$NPGO == 2 |
            full_set$ANCHL + full_set$ONI == 2 |
            full_set$ANCHL + full_set$PDO == 2 |
            full_set$BEUTI + full_set$ONI == 2 |
            full_set$BEUTI + full_set$PDO == 2 |
            full_set$NPGO + full_set$PDO == 2 |
            full_set$NPGO + full_set$SST == 2 |
            full_set$ONI + full_set$PDO == 2)

## create reduced set of models and convert to a matrix for easier indexing
use_set <- as.matrix(full_set[-ii,])

## number of models in set
(n_mods <- nrow(use_set))

## [1] 30

## find max number of predictors in a model
rowSums(use_set)

## 1 2 3 4 5 6 7 8 9 10 13 14 17 18 25 26 33 34 65 66 67 68 69 70 71 72
## 0 1 1 2 1 2 2 3 1 2 2 3 1 2 2 3 1 2 1 2 2 3 2 3 3 4
## 81 82 97 98
## 2 3 2 3

## covariates in global model
cov_names[use_set[26,]]

## [1] "EggOrder" "ANCHL" "BEUTI" "SST"

```

Likelihood Ratio Tests

We used likelihood ratio tests using the RLRsim package on the global model to test the support for inclusion of two random effects: 1. Plot: the monitoring plot from which the egg was obtained and measured ($n = 8$)
2. Observer: the person who measured the egg ($n = 27$)

```

## remove NAs in Observer field (e.g., unknown Observer)
SCMUdf2 <- SCMUdf[-c(which(is.na(SCMUdf$Observer)==TRUE))],]

## global model with both random effects
bm_both <- lmer(Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Observer) + (1 | Plot), data = SCMUdf2, REML = TRUE)

## run model with plot random effect only
bm_plot <- lmer(Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Plot), data = SCMUdf2, REML = FALSE)

## run model with observer random effect only
bm_obs <- lmer(Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Observer), data = SCMUdf2, REML = FALSE)

## boundary (singular) fit: see ?isSingular

## Exact RLRT test
# m is the reduced model containing only the RE to be tested (the random effect set to zero under the null)

```

```
# observer set to zero under the null hypothesis
exactRLRT(m = bm_obs, mA = bm_both, m0 = bm_plot, seed = 16)
```

```
## Using restricted likelihood evaluated at ML estimators.
```

```
## Refit with method="REML" for exact results.
```

```
##
```

```
## simulated finite sample distribution of RLRT.
```

```
##
```

```
## (p-value based on 10000 simulated values)
```

```
##
```

```
## data:
```

```
## RLRT = 0.52989, p-value = 0.1836
```

```
# plot set to zero under the null hypothesis
```

```
exactRLRT(m = bm_plot, mA = bm_both, m0 = bm_obs, seed = 16)
```

```
## Using restricted likelihood evaluated at ML estimators.
```

```
## Refit with method="REML" for exact results.
```

```
##
```

```
## simulated finite sample distribution of RLRT.
```

```
##
```

```
## (p-value based on 10000 simulated values)
```

```
##
```

```
## data:
```

```
## RLRT = 1.6371, p-value = 0.0598
```

Model Diagnostics

These diagnostics are done for the global model.

```
## run global model
```

```
global_mod <- lmer(Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Plot), data = SCMUdf, REML = TRUE)
```

Predicted Values

```
## extract predicted values and plot
```

```
preds <- predict(global_mod)
```

```
p1 <- ggplot() +
```

```
  geom_histogram(mapping = aes(preds), bins = 15) + # set bins
```

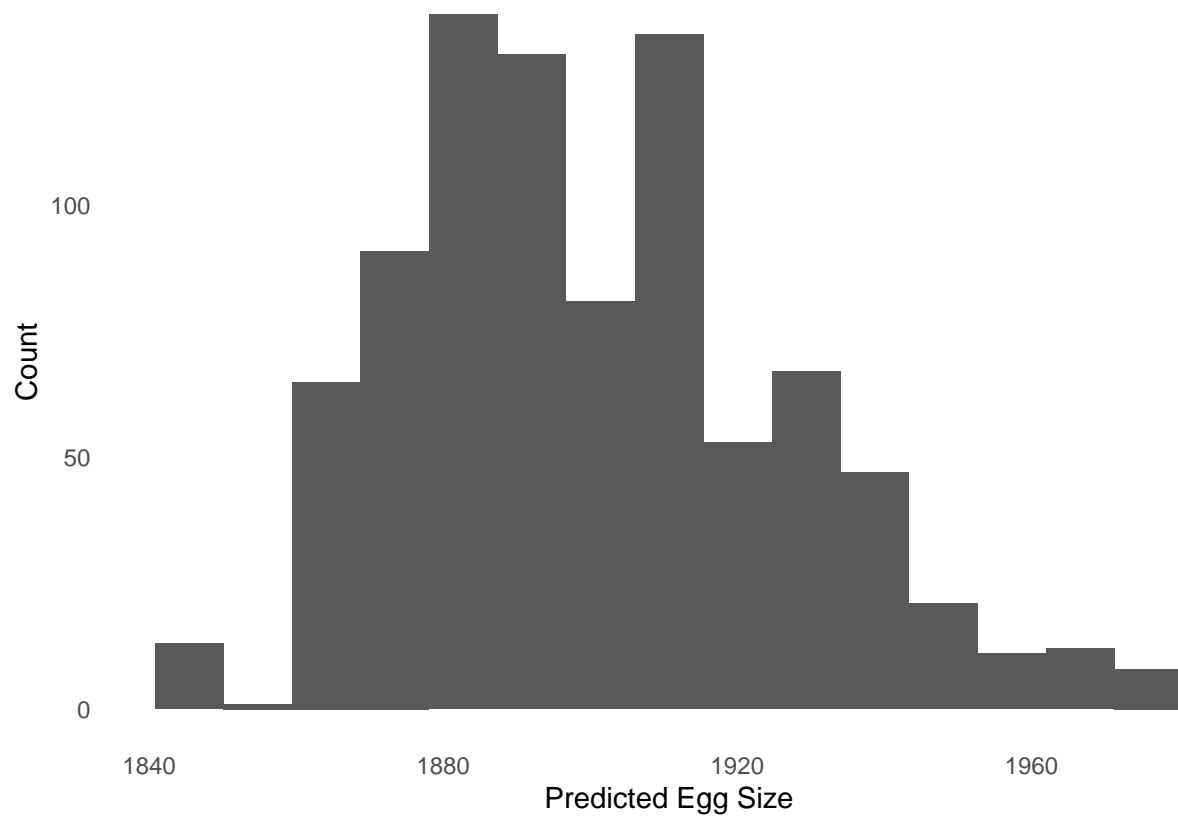
```
  theme_minimal() +
```

```
  xlab("Predicted Egg Size") + ylab("Count") +
```

```
  theme(panel.grid.major = element_blank(),
```

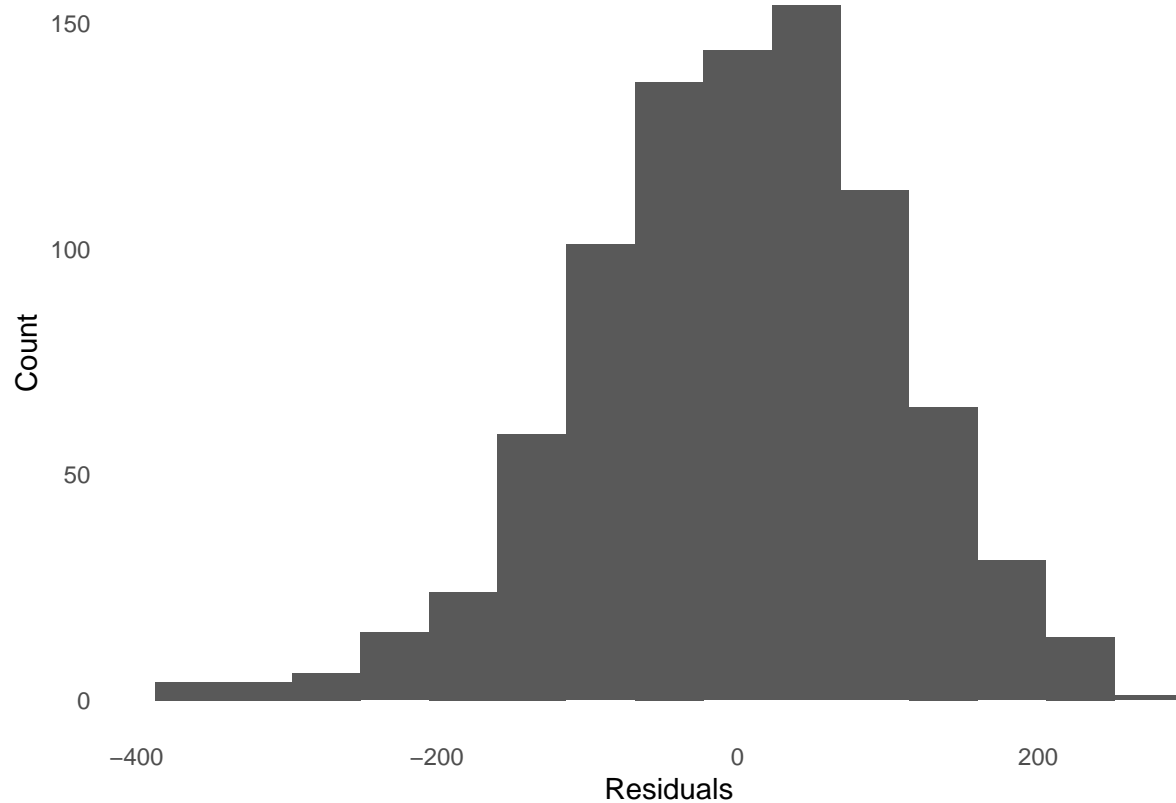
```
        panel.grid.minor = element_blank())
```

```
p1
```



Residuals

```
## extract residuals and plot
resids <- residuals(global_mod)
p2 <- ggplot() +
  geom_histogram(mapping = aes(resids), bins = 15) +
  theme_minimal() +
  xlab("Residuals") + ylab("Count") +
  theme(panel.grid.major = element_blank(),
        panel.grid.minor = element_blank())
p2
```



Model Coefficients

```
## extract coeffs and random effects
coef(global_mod) # this include fixed and random effects

## $Plot
##      (Intercept) EggOrderEgg2  ANCHL  BEUTI  SST
## APNC    1893.779    36.17656  4.813278 -14.30913  8.977387
## BH      1898.347    36.17656  4.813278 -14.30913  8.977387
## BT      1855.839    36.17656  4.813278 -14.30913  8.977387
## CC      1901.490    36.17656  4.813278 -14.30913  8.977387
## DO      1882.390    36.17656  4.813278 -14.30913  8.977387
## ESC     1883.689    36.17656  4.813278 -14.30913  8.977387
## LC      1881.975    36.17656  4.813278 -14.30913  8.977387
## WC      1875.124    36.17656  4.813278 -14.30913  8.977387
##
## attr(,"class")
## [1] "coef.mer"

ranef_pl <- ranef(global_mod)$Plot # plot random effect only

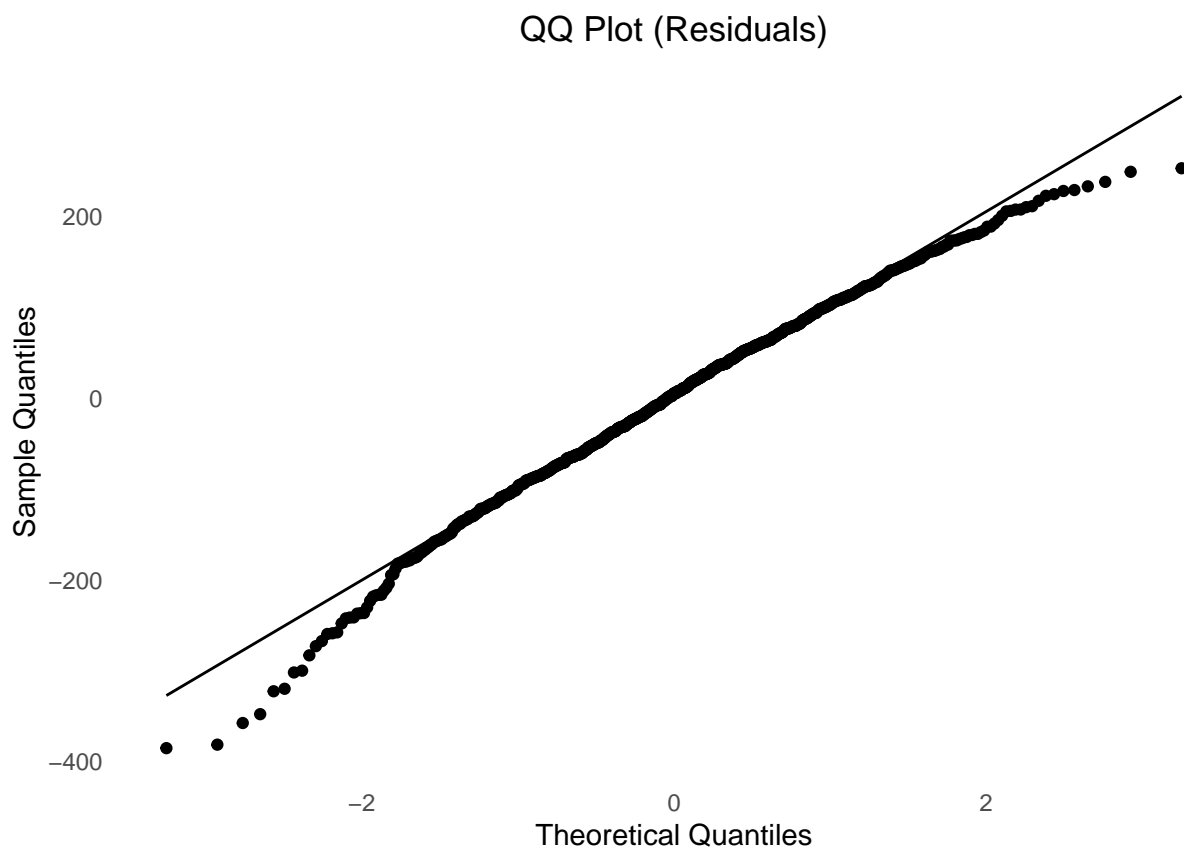
## look at data going into random effects
table(SCMUdf$Plot)

##
## APNC  BH  BT  CC  DO  ESC  LC  WC
```

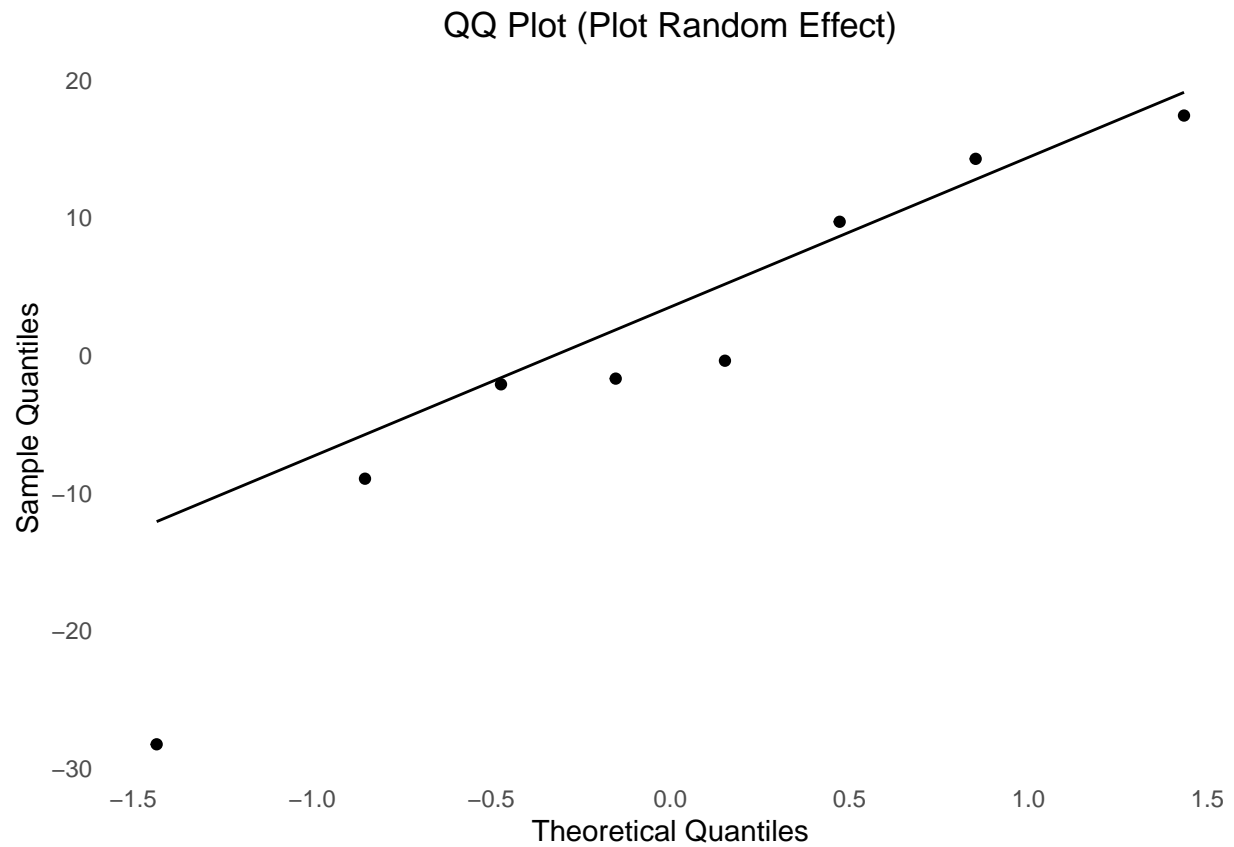
```
## 115 31 16 275 192 1 238 4
```

Q-Q Plots

```
qqresids <- as.data.frame(resids)
p3 <- ggplot(qqresids, aes(sample = resids)) +
  geom_qq() + geom_qq_line() +
  theme_minimal() +
  xlab("Theoretical Quantiles") + ylab("Sample Quantiles") +
  theme(panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        plot.title = element_text(hjust = 0.5)) +
  ggtitle("QQ Plot (Residuals)")
p3
```

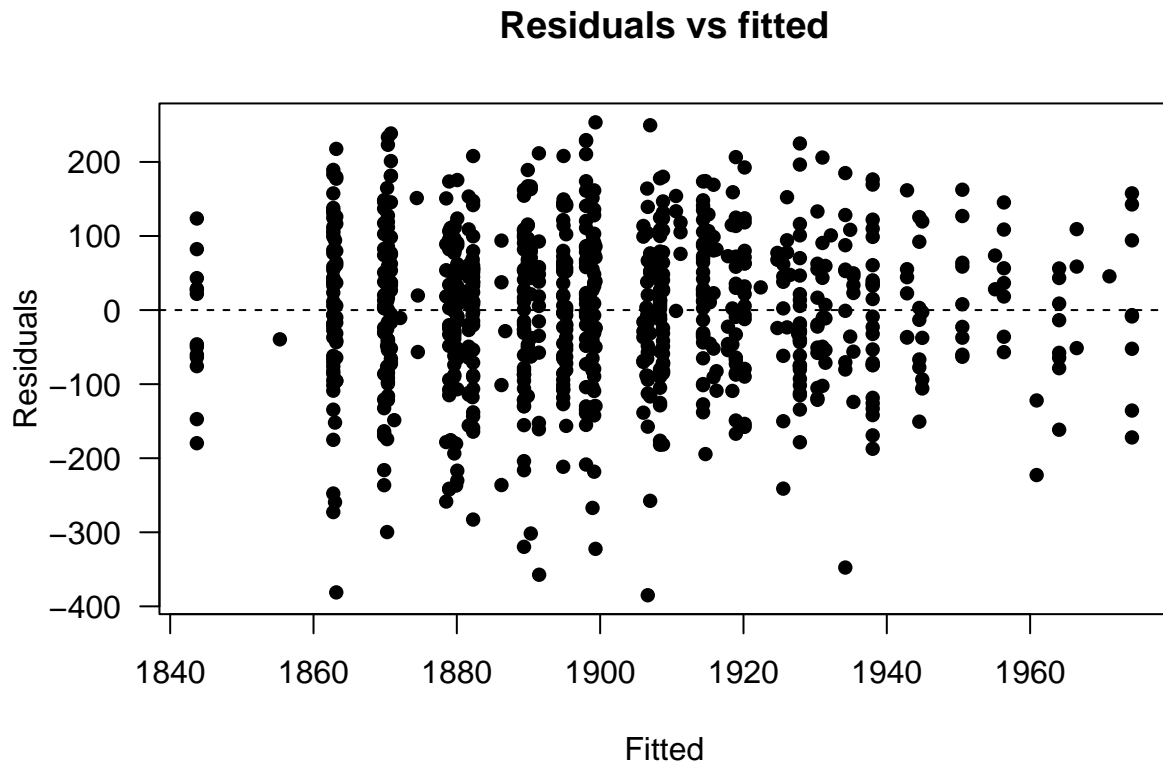


```
plotRE <- as.data.frame(unlist(ranef_pl))
p4 <- ggplot(plotRE, aes(sample = unlist(ranef_pl))) +
  geom_qq() + geom_qq_line() +
  theme_minimal() +
  xlab("Theoretical Quantiles") + ylab("Sample Quantiles") +
  theme(panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        plot.title = element_text(hjust = 0.5)) +
  ggtitle("QQ Plot (Plot Random Effect)")
p4
```



Fitted Values versus Residuals

```
## plot residuals versus fitted values
yh <- fitted(global_mod)
plot(yh, resid, las = 1, pch = 16,
      xlab = "Fitted", ylab = "Residuals",
      main = "Residuals vs fitted")
abline(h=0, lty = "dashed")
```



Levene's test

We can formally test the assumption of homogenous variance via the Levene's Test, which compares the absolute values of the residuals among groups.

```
## split residuals into 2 groups
```

```
g1 <- resid[yh <= median(yh)]
```

```
g2 <- resid[yh > median(yh)]
```

```
## Levene's test
```

```
var.test(g1, g2)
```

```
##
```

```
## F test to compare two variances
```

```
##
```

```
## data: g1 and g2
```

```
## F = 1.1289, num df = 437, denom df = 433, p-value = 0.2066
```

```
## alternative hypothesis: true ratio of variances is not equal to 1
```

```
## 95 percent confidence interval:
```

```
## 0.9352029 1.3626040
```

```
## sample estimates:
```

```
## ratio of variances
```

```
## 1.1289
```


Fit Candidate Models

```
## create empty matrix for storing results
mod_res <- matrix(NA, n_mods, 1)
colnames(mod_res) <- c("AIC")

## fit models and store AIC
for(i in 1:n_mods) {
  if(i == 1) {
    fmla <- "Size ~ 1 + (1 | Plot)"
  } else {
    fmla <- paste("Size ~ (1 | Plot) +", paste(cov_names[use_set[i,]], collapse = " + "))
  }
  mod_fit <- lmer(as.formula(fmla), data = SCMUdf, REML = TRUE)
  mod_res[i,"AIC"] <- AIC(mod_fit)
}

## create empty matrix for storing results
delta_res <- matrix(NA, n_mods, 1)
colnames(delta_res) <- c("deltaAIC")

## convert IC to deltaIC
delta_res[, "deltaAIC"] <- mod_res[, "AIC"] - min(mod_res[, "AIC"])
(delta_res <- round(delta_res, 2)) # round results
```

```
##      deltaAIC
## [1,]    58.26
## [2,]    37.82
## [3,]    40.37
## [4,]    19.37
## [5,]    42.07
## [6,]    21.23
## [7,]    32.89
## [8,]    11.79
## [9,]    31.76
## [10,]   10.78
## [11,]   21.25
## [12,]    0.00
## [13,]   37.23
## [14,]   15.70
## [15,]   22.94
## [16,]    1.37
## [17,]   29.14
## [18,]    7.92
## [19,]   44.95
## [20,]   24.26
## [21,]   35.55
## [22,]   14.56
## [23,]   29.63
## [24,]    8.54
## [25,]   25.68
## [26,]    4.54
## [27,]   31.55
## [28,]   10.07
```

```

## [29,]      25.99
## [30,]       4.78

## "best" models from our set
cov_names[use_set[12,]] # Egg order, BEUTI, NPGO

## [1] "EggOrder" "BEUTI"      "NPGO"

cov_names[use_set[16,]] # Egg order, NPGO, ONI

## [1] "EggOrder" "NPGO"        "ONI"

cov_names[use_set[26,]] # Egg order, ANCHL, BEUTI, SST (>2 AIC)

## [1] "EggOrder" "ANCHL"      "BEUTI"      "SST"

cov_names[use_set[30,]] # Egg order, PDO, SST (>2 AIC)

## [1] "EggOrder" "PDO"        "SST"

cov_names[use_set[18,]] # Egg order, PDO (>2 AIC)

## [1] "EggOrder" "PDO"

cov_names[use_set[24,]] # Egg order, BEUTI, SST (>2 AIC)

## [1] "EggOrder" "BEUTI"      "SST"

## run top models
topmod1 <- lmer(Size ~ EggOrder + BEUTI + NPGO + (1 | Plot), data = SCMUdf, REML = TRUE)
topmod2 <- lmer(Size ~ EggOrder + NPGO + ONI + (1 | Plot), data = SCMUdf, REML = TRUE)
topmod3 <- lmer(Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Plot), data = SCMUdf, REML = TRUE)
topmod4 <- lmer(Size ~ EggOrder + PDO + SST + (1 | Plot), data = SCMUdf, REML = TRUE)
topmod5 <- lmer(Size ~ EggOrder + PDO + (1 | Plot), data = SCMUdf, REML = TRUE)
topmod6 <- lmer(Size ~ EggOrder + BEUTI + SST + (1 | Plot), data = SCMUdf, REML = TRUE)

## Model selection table
AIC.tab <- matrix(NA, nrow = 6, ncol = 3) # 6 rows for 6 top models
AIC.tab[1,1] <- AIC(topmod1) # AIC for topmod1 in first row, first column
AIC.tab[2,1] <- AIC(topmod2) # AIC for topmod2 in second row, first column
AIC.tab[3,1] <- AIC(topmod3) # AIC for topmod3 in second row, first column
AIC.tab[4,1] <- AIC(topmod4) # AIC for topmod4 in second row, first column
AIC.tab[5,1] <- AIC(topmod5) # AIC for topmod5 in second row, first column
AIC.tab[6,1] <- AIC(topmod6) # AIC for topmod6 in second row, first column
AIC.tab[,2] <- AIC.tab[,1] - min(AIC.tab[,1]) # calculate delta AIC
AIC.tab[,3] <- exp(-0.5*AIC.tab[,2])/(sum(exp(-0.5*AIC.tab[,2]))) # calculate model weights
colnames(AIC.tab) <- c("AIC", "deltaAIC", "model_weights")
print(AIC.tab)

##           AIC deltaAIC model_weights
## [1,] 10558.27 0.000000   0.577498180
## [2,] 10559.64 1.372339   0.290770975
## [3,] 10562.81 4.539334   0.059682453
## [4,] 10563.05 4.778723   0.052949771
## [5,] 10566.19 7.915187   0.011035437
## [6,] 10566.81 8.542793   0.008063185

```

Top Models

Top Model 1

```
topmod1 <- lmer(Size ~ EggOrder + BEUTI + NPG0 + (1 | Plot), data = SCMUdf, REML = TRUE)
summary(topmod1)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: Size ~ EggOrder + BEUTI + NPG0 + (1 | Plot)
## Data: SCMUdf
##
## REML criterion at convergence: 10546.3
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.8401 -0.6528  0.0465  0.6904  2.4192
##
## Random effects:
## Groups Name Variance Std.Dev.
## Plot (Intercept) 161.8 12.72
## Residual 10701.0 103.45
## Number of obs: 872, groups: Plot, 8
##
## Fixed effects:
## Estimate Std. Error t value
## (Intercept) 1888.337 7.019 269.047
## EggOrderEgg2 36.179 8.713 4.152
## BEUTI -13.338 4.713 -2.830
## NPG0 -15.613 3.522 -4.433
##
## Correlation of Fixed Effects:
## (Intr) EggOE2 BEUTI
## EggOrdrEgg2 -0.258
## BEUTI 0.086 -0.004
## NPG0 -0.063 0.000 -0.230
```

```
confint(topmod1)
```

```
## Computing profile confidence intervals ...
```

```
##      2.5 %      97.5 %
## .sig01 0.00000 35.186121
## .sigma 98.63360 108.388816
## (Intercept) 1869.66658 1901.989483
## EggOrderEgg2 19.19568 53.351177
## BEUTI -22.91441 -4.318019
## NPG0 -22.67392 -8.856872
```

Top Model 2

```
topmod2 <- lmer(Size ~ EggOrder + NPG0 + ONI + (1 | Plot), data = SCMUdf, REML = TRUE)
summary(topmod2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: Size ~ EggOrder + NPG0 + ONI + (1 | Plot)
## Data: SCMUdf
##
```

```
## REML criterion at convergence: 10547.6
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.8019 -0.6556  0.0455  0.6769  2.5062
##
## Random effects:
##   Groups   Name      Variance Std.Dev.
##   Plot     (Intercept)  178.4    13.36
##   Residual                10715.2  103.51
## Number of obs: 872, groups: Plot, 8
##
## Fixed effects:
##              Estimate Std. Error t value
## (Intercept)  1888.353      7.238  260.899
## EggOrderEgg2   36.542      8.721   4.190
## NPG0          -13.431      3.847  -3.492
## ONI           12.399      4.855   2.554
##
## Correlation of Fixed Effects:
##              (Intr) EggOE2 NPG0
## EggOrdrEgg2 -0.252
## NPG0        -0.078  0.009
## ONI         -0.082  0.022  0.452
```

```
confint(topmod2)
```

```
## Computing profile confidence intervals ...
```

```
##              2.5 %      97.5 %
## .sig01         0.000000   37.370181
## .sigma        98.718950  108.487913
## (Intercept)  1868.448016 1902.242601
## EggOrderEgg2   19.565650   53.761071
## NPG0          -21.088561   -6.037404
## ONI           3.152548   22.321170
```

Top Model 3

```
topmod3 <- lmer(Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Plot), data = SCMUdf, REML = TRUE)
summary(topmod3)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: Size ~ EggOrder + ANCHL + BEUTI + SST + (1 | Plot)
##   Data: SCMUdf
##
## REML criterion at convergence: 10548.8
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.7095 -0.6318  0.0537  0.6870  2.4419
##
## Random effects:
##   Groups   Name      Variance Std.Dev.
##   Plot     (Intercept)  393.6    19.84
```

```
## Residual          10772.4 103.79
## Number of obs: 872, groups: Plot, 8
##
## Fixed effects:
##           Estimate Std. Error t value
## (Intercept) 1884.079      9.530 197.700
## EggOrderEgg2  36.177      8.744   4.137
## ANCHL         4.813      5.457   0.882
## BEUTI        -14.309      5.455  -2.623
## SST           8.977      4.213   2.131
##
## Correlation of Fixed Effects:
##           (Intr) EggOE2 ANCHL  BEUTI
## EggOrdrEgg2 -0.192
## ANCHL        0.094  0.007
## BEUTI        0.090 -0.001  0.532
## SST         -0.062 -0.002 -0.579 -0.273
confint(topmod3)

## Computing profile confidence intervals ...

##           2.5 %      97.5 %
## .sig01      0.0000000  47.030247
## .sigma      99.0003359 108.841747
## (Intercept) 1859.7243438 1901.850097
## EggOrderEgg2 19.1992218  53.500458
## ANCHL       -5.6373662  15.756027
## BEUTI       -25.5857618  -4.011488
## SST         0.7582154  17.270787
```

Top Model 4

```
topmod4 <- lmer(Size ~ EggOrder + PDO + SST + (1 | Plot), data = SCMUdf, REML = TRUE)
summary(topmod4)

## Linear mixed model fit by REML ['lmerMod']
## Formula: Size ~ EggOrder + PDO + SST + (1 | Plot)
## Data: SCMUdf
##
## REML criterion at convergence: 10551.1
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.7474 -0.6550  0.0462  0.6908  2.4459
##
## Random effects:
## Groups Name Variance Std.Dev.
## Plot (Intercept) 186.8 13.67
## Residual 10753.9 103.70
## Number of obs: 872, groups: Plot, 8
##
## Fixed effects:
##           Estimate Std. Error t value
## (Intercept) 1887.528      7.318 257.919
```

```
## EggOrderEgg2 36.222      8.735  4.147
## PD0          19.275      4.528  4.256
## SST           2.893      4.025  0.719
```

```
##
```

```
## Correlation of Fixed Effects:
```

```
##          (Intr) EggOE2 PD0
```

```
## EggOrdrEgg2 -0.248
```

```
## PD0          0.003  0.003
```

```
## SST          -0.020  0.001 -0.525
```

```
confint(topmod4)
```

```
## Computing profile confidence intervals ...
```

```
##          2.5 %      97.5 %
```

```
## .sig01      0.000000  38.14533
```

```
## .sigma     98.899099 108.68695
```

```
## (Intercept) 1867.226202 1901.54131
```

```
## EggOrderEgg2 19.206046  53.45492
```

```
## PD0         10.736526  28.75875
```

```
## SST         -5.125251  10.65872
```