warmXtrophic Project: Herbivory Analyses

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Main questions

Is herbivory different between warmed and ambient treatments? Hypothesis: Ambient plants will have higher herbivory

- only run analyses on plots with no insecticide
- include year as a treatment (is this difference seen each year)?

Is herbivory different between warmed/ambient for native vs exotic? same for growth habit

Load in and prepare data for analyses

```
# Clear all existing data
rm(list=ls())

#Load packages
library(tidyverse)
library(lmerTest)
library(olsrr)
library(predictmeans)
library(car)
library(fitdistrplus)
library(MASS)
library(pscl)
library(lmtest)
library(emmeans)

# Set working directory to Google Drive
# **** Update with the path to your Google drive on your computer
setwd("/Volumes/GoogleDrive/Shared drives/SpaCE_Lab_warmXtrophic/data/")

# Read in plant comp data & metadata
herb <- read.csv("L1/herbivory/final_herbivory_L1.csv")

# changing scale of years
herb$year1<-herb$year
herb$year[herb$year == 2015] <- 1
herb$year[herb$year == 2016] <- 2
herb$year[herb$year == 2017] <- 3
```

```
herb$year[herb$year == 2018] <- 4
herb$year[herb$year == 2019] <- 5
herb$year[herb$year == 2020] <- 6

# Remove NAs
herb <- herb[complete.cases(herb),]

# create dataframes for kbs and umbs only for plots with no insecticide
herb_kbs <- subset(herb, site == "kbs" & insecticide == "insects")
herb_umbs <- subset(herb, site == "umbs" & insecticide == "insects")

# only keep species that were recorded in both warmed and ambient plots
herb_kbs <- herb_kbs %>%
        group_by(species) %>%
        filter(all(c('warmed', 'ambient') %in% state))
herb_umbs <- herb_umbs %>%
        group_by(species) %>%
        filter(all(c('warmed', 'ambient') %in% state))

# checking to see if any species/state combos are all zeros
with(herb_kbs,table(species,state,p_eaten==0))
```

```
## , ,  = FALSE
##
##        state
## species ambient warmed
##    Cest      78     39
##    Eugr      33     65
##    Hisp      27     11
##    Hype       0      5
##    Phpr      13     21
##    Popr      19     14
##    Soca     192    173
##
## , ,  = TRUE
##
##        state
## species ambient warmed
##    Cest      64     42
##    Eugr      44    103
##    Hisp     165    117
##    Hype       8     11
##    Phpr      27     51
##    Popr     183    176
##    Soca     217    244
```

```
with(herb_umbs,table(species,state,p_eaten==0)) # looks good now, species were removed in herbivory_cle
```

```
## , ,  = FALSE
##
##        state
## species ambient warmed
##    Cape      10     14
##    Cest     142    175
```

```
##    Dasp      49     65
##    Hype       9      8
##    Poco       6     43
##    Popr       1     11
##    Posp      25     17
##    Ptaq      27     39
##    Ruac      80     98
##
## , ,  = TRUE
##
##        state
## species ambient warmed
##    Cape      70     10
##    Cest     182    153
##    Dasp     131     87
##    Hype      55     40
##    Poco       6     21
##    Popr     107     85
##    Posp      23     47
##    Ptaq      29     65
##    Ruac      64    102
```

```
# number of observation per species/state combo (to find rare species)
herb_kbs %>% count(state, species)
```

```
## # A tibble: 14 x 3
## # Groups:   species [7]
##    species state       n
##    <chr>   <chr>   <int>
##  1 Cest    ambient   142
##  2 Cest    warmed     81
##  3 Eugr    ambient    77
##  4 Eugr    warmed    168
##  5 Hisp    ambient   192
##  6 Hisp    warmed    128
##  7 Hype    ambient     8
##  8 Hype    warmed     16
##  9 Phpr    ambient    40
## 10 Phpr    warmed     72
## 11 Popr    ambient   202
## 12 Popr    warmed    190
## 13 Soca    ambient   409
## 14 Soca    warmed    417
```

```
herb_umbs %>% count(state, species)
```

```
## # A tibble: 18 x 3
## # Groups:   species [9]
##    species state       n
##    <chr>   <chr>   <int>
##  1 Cape    ambient    80
##  2 Cape    warmed     24
##  3 Cest    ambient   324
##  4 Cest    warmed    328
##  5 Dasp    ambient   180
```

```
##  6 Dasp    warmed    152
##  7 Hype    ambient    64
##  8 Hype    warmed     48
##  9 Poco    ambient    12
## 10 Poco    warmed     64
## 11 Popr    ambient   108
## 12 Popr    warmed     96
## 13 Posp    ambient    48
## 14 Posp    warmed     64
## 15 Ptaq    ambient    56
## 16 Ptaq    warmed    104
## 17 Ruac    ambient   144
## 18 Ruac    warmed    200
```

```
# removing rare species from KBS
herb_kbs <- herb_kbs[!grepl("Hype",herb_kbs$species),]
herb_kbs %>% count(state, species)
```

```
## # A tibble: 12 x 3
## # Groups:   species [6]
##    species state       n
##    <chr>   <chr>   <int>
##  1 Cest    ambient   142
##  2 Cest    warmed     81
##  3 Eugr    ambient    77
##  4 Eugr    warmed    168
##  5 Hisp    ambient   192
##  6 Hisp    warmed    128
##  7 Phpr    ambient    40
##  8 Phpr    warmed     72
##  9 Popr    ambient   202
## 10 Popr    warmed    190
## 11 Soca    ambient   409
## 12 Soca    warmed    417
```

```
# How much of the data is zeros?
100*sum(herb_kbs$p_eaten == 0)/nrow(herb_kbs) #68% - thats a lot! probably have to use a zero-inflated
```

```
## [1] 67.65817
```

```
# but I'll still check for normality & try some transformations below
100*sum(herb_umbs$p_eaten == 0)/nrow(herb_umbs) #61%
```

```
## [1] 60.92557
```

KBS

```
### determining distribution ###
# first, checking for normality
hist(herb_kbs$p_eaten)
qqnorm(herb_kbs$p_eaten)
shapiro.test(herb_kbs$p_eaten)
fit <- lm(p_eaten~state, data = herb_kbs)
qqPlot(fit)
hist(herb_kbs$p_eaten[herb_kbs$state == "ambient"])
```

```r
hist(herb_kbs$p_eaten[herb_kbs$state == "warmed"])
# not normal, attempting to transform data below
# log transform
herb_kbs$p_log <- log(herb_kbs$p_eaten+1)
hist(herb_kbs$p_log)
qqnorm(herb_kbs$p_log)
shapiro.test(herb_kbs$p_log) # NAs - data contains 0s
# mean centering p_eaten
herb_kbs$p_scaled <- herb_kbs$p_log - mean(herb_kbs$p_log)
hist(herb_kbs$p_scaled)
hist(herb_kbs$p_scaled[herb_kbs$state == "ambient"])
hist(herb_kbs$p_scaled[herb_kbs$state == "warmed"])
qqnorm(herb_kbs$p_scaled)
shapiro.test(herb_kbs$p_scaled)
# square root?
herb_kbs$p_sqrt <- sqrt(herb_kbs$p_eaten)
hist(herb_kbs$p_sqrt)
```

Transformations are a no-go

Going to try a zero-inflated model due to the excess number of zeros in the data

```r
# mean and var of non-zero counts
herb_kbs %>%
  dplyr::filter(p_eaten != "0") %>%
  dplyr::summarize(mean_eaten = mean(p_eaten, na.rm=T), var_eaten = var(p_eaten, na.rm=T))
```

```
## `summarise()` ungrouping output (override with `.groups` argument)
```

```
## # A tibble: 6 x 3
##   species mean_eaten var_eaten
##   <chr>        <dbl>     <dbl>
## 1 Cest          9.41     156.
## 2 Eugr          6.60      66.3
## 3 Hisp         10.9      210.
## 4 Phpr         14.3      445.
## 5 Popr         17.8      455.
## 6 Soca          9.31     120.
```

```r
# variance is also > mean, so can't be poisson
# I'll try zero-inflated negative binomial due to an excess of zeros

# zero-inflated negative binomial
# state as a fixed effect
m1 <- zeroinfl(p_eaten ~ state,
               dist = 'negbin',
               data = herb_kbs)
summary(m1)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state, data = herb_kbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
```

```
## -0.3791 -0.3791 -0.3650 -0.1706 13.5408
##
## Count model coefficients (negbin with log link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.8793     0.1236  15.208  < 2e-16 ***
## statewarmed  -0.2704     0.1225  -2.208   0.0273 *
## Log(theta)   -1.1840     0.1778  -6.657 2.79e-11 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  -0.2221     0.2274  -0.977    0.329
## statewarmed   0.1209     0.1466   0.825    0.410
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.3061
## Number of iterations in BFGS optimization: 14
## Log-likelihood: -3478 on 5 Df
```

```
# interaction between state and species
m2 <- zeroinfl(p_eaten ~ state * species,
                  dist = 'negbin',
                  data = herb_kbs)
summary(m2)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state * species, data = herb_kbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.5163 -0.4425 -0.2365 -0.1660 10.9305
##
## Count model coefficients (negbin with log link):
##                          Estimate Std. Error z value Pr(>|z|)
## (Intercept)               1.8886     0.1918   9.846  < 2e-16 ***
## statewarmed              -0.3420     0.3027  -1.130   0.2587
## speciesEugr              -0.2766     0.3206  -0.863   0.3883
## speciesHisp               0.1202     0.3461   0.347   0.7285
## speciesPhpr               0.4982     0.4671   1.067   0.2862
## speciesPopr               0.8255     0.4009   2.059   0.0395 *
## speciesSoca              -0.0439     0.2078  -0.211   0.8327
## statewarmed:speciesEugr  -0.1035     0.4474  -0.231   0.8171
## statewarmed:speciesHisp   0.1715     0.6310   0.272   0.7858
## statewarmed:speciesPhpr   0.1747     0.6280   0.278   0.7809
## statewarmed:speciesPopr  -0.1017     0.6284  -0.162   0.8714
## statewarmed:speciesSoca   0.1852     0.3433   0.539   0.5896
## Log(theta)               -1.0607     0.1645  -6.450 1.12e-10 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##                          Estimate Std. Error z value Pr(>|z|)
## (Intercept)              -1.73589    0.75678  -2.294   0.0218 *
## statewarmed               0.37047    0.83789   0.442   0.6584
## speciesEugr               0.89088    0.76741   1.161   0.2457
## speciesHisp               3.04215    0.73257   4.153 3.29e-05 ***
```

```
## speciesPhpr              1.87929    0.80374   2.338   0.0194 *
## speciesPopr              3.64937    0.75081   4.861 1.17e-06 ***
## speciesSoca              0.72910    0.63068   1.156   0.2477
## statewarmed:speciesEugr -0.36742    1.03034  -0.357   0.7214
## statewarmed:speciesHisp  0.18729    0.93647   0.200   0.8415
## statewarmed:speciesPhpr -0.22024    1.00326  -0.220   0.8262
## statewarmed:speciesPopr -0.16286    0.92547  -0.176   0.8603
## statewarmed:speciesSoca -0.05786    0.87903  -0.066   0.9475
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.3462
## Number of iterations in BFGS optimization: 33
## Log-likelihood: -3318 on 25 Df
```

```
# state and species as separate fixed effects
m3 <- zeroinfl(p_eaten ~ state + species,
                    dist = 'negbin',
                    data = herb_kbs)
summary(m3)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state + species, data = herb_kbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.5130 -0.4423 -0.2280 -0.1620 11.0764
##
## Count model coefficients (negbin with log link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  1.85217    0.16652  11.123  < 2e-16 ***
## statewarmed -0.23848    0.11937  -1.998   0.0457 *
## speciesEugr -0.37812    0.21503  -1.758   0.0787 .
## speciesHisp  0.17181    0.28973   0.593   0.5532
## speciesPhpr  0.57539    0.30652   1.877   0.0605 .
## speciesPopr  0.77610    0.30867   2.514   0.0119 *
## speciesSoca  0.02802    0.16609   0.169   0.8660
## Log(theta)  -1.06876    0.16412  -6.512 7.41e-11 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  -1.7171     0.6409  -2.679  0.00738 **
## statewarmed   0.2975     0.1799   1.653  0.09823 .
## speciesEugr   0.6616     0.5383   1.229  0.21905
## speciesHisp   3.1040     0.5945   5.221 1.78e-07 ***
## speciesPhpr   1.7594     0.5973   2.945  0.00323 **
## speciesPopr   3.5900     0.6027   5.956 2.58e-09 ***
## speciesSoca   0.7035     0.4821   1.459  0.14447
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.3434
## Number of iterations in BFGS optimization: 24
## Log-likelihood: -3318 on 15 Df
```

```r
# state, species and year as fixed effects
m4 <- zeroinfl(p_eaten ~ state + as.factor(year) + species,
               dist = 'negbin',
               data = herb_kbs)
summary(m4)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state + as.factor(year) + species, data = herb_kbs,
##     dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.7568 -0.4595 -0.2437 -0.1264 24.5632
##
## Count model coefficients (negbin with log link):
##                   Estimate Std. Error z value Pr(>|z|)
## (Intercept)        0.27490    0.14310   1.921   0.0547 .
## statewarmed       -0.22879    0.08973  -2.550   0.0108 *
## as.factor(year)2   1.00539    0.14799   6.794 1.09e-11 ***
## as.factor(year)3   2.11838    0.17565  12.060  < 2e-16 ***
## as.factor(year)4   2.25866    0.15781  14.313  < 2e-16 ***
## as.factor(year)5   2.18186    0.14707  14.835  < 2e-16 ***
## as.factor(year)6  -0.53881    0.23597  -2.283   0.0224 *
## speciesEugr        0.30066    0.17100   1.758   0.0787 .
## speciesHisp       -0.08568    0.21913  -0.391   0.6958
## speciesPhpr        0.96249    0.23019   4.181 2.90e-05 ***
## speciesPopr        1.45768    0.23949   6.087 1.15e-09 ***
## speciesSoca        0.27379    0.12256   2.234   0.0255 *
## Log(theta)        -0.16853    0.09807  -1.718   0.0857 .
##
## Zero-inflation model coefficients (binomial with logit link):
##                    Estimate Std. Error z value Pr(>|z|)
## (Intercept)       -16.0545  1638.7805  -0.010   0.9922
## statewarmed         0.1933     0.1357   1.425   0.1542
## as.factor(year)2   14.6235  1638.7804   0.009   0.9929
## as.factor(year)3   15.8370  1638.7803   0.010   0.9923
## as.factor(year)4   15.4532  1638.7804   0.009   0.9925
## as.factor(year)5   14.7907  1638.7804   0.009   0.9928
## as.factor(year)6   15.2518  1638.7805   0.009   0.9926
## speciesEugr         0.5715     0.3900   1.465   0.1429
## speciesHisp         2.8006     0.3579   7.825 5.09e-15 ***
## speciesPhpr         1.7573     0.4182   4.202 2.64e-05 ***
## speciesPopr         3.4030     0.3744   9.090  < 2e-16 ***
## speciesSoca         0.6532     0.3048   2.143   0.0321 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.8449
## Number of iterations in BFGS optimization: 50
## Log-likelihood: -3135 on 25 Df
```

```r
# interaction between state and year, + species
m5 <- zeroinfl(p_eaten ~ state * as.factor(year) + species,
```

```
               dist = 'negbin',
               data = herb_kbs)
```

```
## Warning in value[[3L]](cond): system is computationally singular: reciprocal
## condition number = 2.4206e-18FALSE
```

```
summary(m5) # all NAs
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state * as.factor(year) + species, data = herb_kbs,
##     dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.7640 -0.4562 -0.2444 -0.1169 16.8265
##
## Count model coefficients (negbin with log link):
##                                Estimate Std. Error z value Pr(>|z|)
## (Intercept)                    0.177604         NA      NA       NA
## statewarmed                   -0.046579         NA      NA       NA
## as.factor(year)2               1.268439         NA      NA       NA
## as.factor(year)3               2.367311         NA      NA       NA
## as.factor(year)4               2.347839         NA      NA       NA
## as.factor(year)5               2.186299         NA      NA       NA
## as.factor(year)6              -1.800419         NA      NA       NA
## speciesEugr                    0.195127         NA      NA       NA
## speciesHisp                   -0.047523         NA      NA       NA
## speciesPhpr                    0.995881         NA      NA       NA
## speciesPopr                    1.484288         NA      NA       NA
## speciesSoca                    0.313503         NA      NA       NA
## statewarmed:as.factor(year)2 -0.592013         NA      NA       NA
## statewarmed:as.factor(year)3 -0.481000         NA      NA       NA
## statewarmed:as.factor(year)4 -0.200522         NA      NA       NA
## statewarmed:as.factor(year)5 -0.008421         NA      NA       NA
## statewarmed:as.factor(year)6  1.868060         NA      NA       NA
## Log(theta)                    -0.096443         NA      NA       NA
##
## Zero-inflation model coefficients (binomial with logit link):
##                                Estimate Std. Error z value Pr(>|z|)
## (Intercept)                   -265.5385         NA      NA       NA
## statewarmed                    -79.1232         NA      NA       NA
## as.factor(year)2               264.1124         NA      NA       NA
## as.factor(year)3               265.9559         NA      NA       NA
## as.factor(year)4               264.7951         NA      NA       NA
## as.factor(year)5               264.1281         NA      NA       NA
## as.factor(year)6               248.3946         NA      NA       NA
## speciesEugr                      0.3595         NA      NA       NA
## speciesHisp                      2.8299         NA      NA       NA
## speciesPhpr                      1.8634         NA      NA       NA
## speciesPopr                      3.4062         NA      NA       NA
## speciesSoca                      0.6514         NA      NA       NA
## statewarmed:as.factor(year)2    79.3111         NA      NA       NA
## statewarmed:as.factor(year)3    77.9841         NA      NA       NA
```

```
## statewarmed:as.factor(year)4   79.7123         NA      NA       NA
## statewarmed:as.factor(year)5   79.7031         NA      NA       NA
## statewarmed:as.factor(year)6   96.2993         NA      NA       NA
##
## Theta = 0.9081
## Number of iterations in BFGS optimization: 66
## Log-likelihood: -3105 on 35 Df
```

```
# interaction between all 3
#m6 <- zeroinfl(p_eaten ~ state * as.factor(year) * species,
#               dist = 'negbin',
#               data = herb_kbs)
#summary(m6) # doesn't run

# is species the variable that predicts excess zeros?
m7 <- zeroinfl(p_eaten ~ state | species,
                  dist = 'negbin',
                  data = herb_kbs)
summary(m7)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state | species, data = herb_kbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.4944 -0.4441 -0.2159 -0.1798 14.1460
##
## Count model coefficients (negbin with log link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.8973     0.1226  15.471  < 2e-16 ***
## statewarmed  -0.3323     0.1140  -2.916  0.00355 **
## Log(theta)   -1.2025     0.1806  -6.658 2.78e-11 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  -1.9890     0.9480  -2.098 0.035901 *
## speciesEugr   1.2147     0.7575   1.604 0.108804
## speciesHisp   3.3783     0.8732   3.869 0.000109 ***
## speciesPhpr   1.9173     0.8445   2.270 0.023189 *
## speciesPopr   3.7865     0.8798   4.304 1.68e-05 ***
## speciesSoca   0.9037     0.6864   1.316 0.188015
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.3004
## Number of iterations in BFGS optimization: 20
## Log-likelihood: -3330 on 9 Df
```

```
# likelihood ratio test
lrtest(m1, m2, m3, m4, m7) # model four
```

```
## Likelihood ratio test
##
## Model 1: p_eaten ~ state
## Model 2: p_eaten ~ state * species
```

```
## Model 3: p_eaten ~ state + species
## Model 4: p_eaten ~ state + as.factor(year) + species
## Model 5: p_eaten ~ state | species
##   #Df  LogLik  Df    Chisq Pr(>Chisq)
## 1   5 -3478.4
## 2  25 -3317.6  20 321.6206     <2e-16 ***
## 3  15 -3318.4 -10   1.5764     0.9987
## 4  25 -3135.2  10 366.3154     <2e-16 ***
## 5   9 -3329.7 -16 388.9289     <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
# check dispersion
E <- resid(m4, type = "pearson")
N  <- nrow(herb_kbs)
p  <- length(coef(m4)) + 1 # '+1' is due to theta
sum(E^2) / (N - p) # pretty close to one
```

```
## [1] 1.302343
```

```
# pairwise comparisons
emmeans(m4, ~ state + year + species)
```

```
##  state   year species  emmean     SE  df asymp.LCL asymp.UCL
##  ambient    1 Cest     1.3164 0.1884 Inf    0.9472    1.6856
##  warmed     1 Cest     1.0472 0.1557 Inf    0.7420    1.3524
##  ambient    2 Cest     2.9035 0.3731 Inf    2.1722    3.6348
##  warmed     2 Cest     2.2184 0.3164 Inf    1.5983    2.8386
##  ambient    3 Cest     6.0676 1.1547 Inf    3.8043    8.3308
##  warmed     3 Cest     4.4077 0.8975 Inf    2.6487    6.1666
##  ambient    4 Cest     8.1379 1.2603 Inf    5.6679   10.6080
##  warmed     4 Cest     6.0193 1.0445 Inf    3.9721    8.0665
##  ambient    5 Cest     9.0964 1.3647 Inf    6.4216   11.7712
##  warmed     5 Cest     6.9115 1.0704 Inf    4.8135    9.0094
##  ambient    6 Cest     0.5304 0.1100 Inf    0.3147    0.7461
##  warmed     6 Cest     0.3958 0.0820 Inf    0.2350    0.5565
##  ambient    1 Eugr     1.7781 0.2968 Inf    1.1964    2.3598
##  warmed     1 Eugr     1.4145 0.2252 Inf    0.9731    1.8559
##  ambient    2 Eugr     3.4141 0.5006 Inf    2.4328    4.3953
##  warmed     2 Eugr     2.5539 0.3823 Inf    1.8046    3.3032
##  ambient    3 Eugr     6.0994 1.4558 Inf    3.2460    8.9527
##  warmed     3 Eugr     4.3118 1.0325 Inf    2.2882    6.3354
##  ambient    4 Eugr     8.6354 1.7680 Inf    5.1703   12.1006
##  warmed     4 Eugr     6.2166 1.3059 Inf    3.6571    8.7760
##  ambient    5 Eugr    10.5031 1.7037 Inf    7.1638   13.8424
##  warmed     5 Eugr     7.8004 1.2141 Inf    5.4209   10.1800
##  ambient    6 Eugr     0.5784 0.1050 Inf    0.3726    0.7843
##  warmed     6 Eugr     0.4204 0.0725 Inf    0.2783    0.5626
##  ambient    1 Hisp     1.2083 0.2732 Inf    0.6728    1.7438
##  warmed     1 Hisp     0.9612 0.2238 Inf    0.5226    1.3998
##  ambient    2 Hisp     0.6693 0.1600 Inf    0.3557    0.9829
##  warmed     2 Hisp     0.4550 0.1163 Inf    0.2271    0.6830
##  ambient    3 Hisp     0.7058 0.2249 Inf    0.2649    1.1467
##  warmed     3 Hisp     0.4686 0.1546 Inf    0.1655    0.7717
##  ambient    4 Hisp     1.1542 0.3137 Inf    0.5393    1.7691
##  warmed     4 Hisp     0.7703 0.2217 Inf    0.3358    1.2048
```

```
##  ambient    5 Hisp     1.8954 0.4566 Inf    1.0005    2.7903
##  warmed     5 Hisp     1.2827 0.3231 Inf    0.6494    1.9160
##  ambient    6 Hisp     0.0842 0.0275 Inf    0.0302    0.1381
##  warmed     6 Hisp     0.0564 0.0190 Inf    0.0191    0.0936
##  ambient    1 Phpr     3.4466 0.8260 Inf    1.8277    5.0655
##  warmed     1 Phpr     2.7417 0.6480 Inf    1.4716    4.0118
##  ambient    2 Phpr     3.9480 0.8915 Inf    2.2007    5.6953
##  warmed     2 Phpr     2.7945 0.6450 Inf    1.5303    4.0586
##  ambient    3 Phpr     5.0615 1.6185 Inf    1.8893    8.2337
##  warmed     3 Phpr     3.4250 1.0997 Inf    1.2697    5.5803
##  ambient    4 Phpr     7.8965 2.4273 Inf    3.1390   12.6540
##  warmed     4 Phpr     5.4050 1.6927 Inf    2.0873    8.7227
##  ambient    5 Phpr    11.5792 3.1964 Inf    5.3144   17.8439
##  warmed     5 Phpr     8.1342 2.2605 Inf    3.7037   12.5647
##  ambient    6 Phpr     0.5589 0.1820 Inf    0.2022    0.9157
##  warmed     6 Phpr     0.3853 0.1264 Inf    0.1375    0.6331
##  ambient    1 Popr     5.6552 1.3852 Inf    2.9403    8.3701
##  warmed     1 Popr     4.4987 1.0871 Inf    2.3681    6.6292
##  ambient    2 Popr     1.8882 0.5015 Inf    0.9053    2.8711
##  warmed     2 Popr     1.2652 0.3471 Inf    0.5850    1.9455
##  ambient    3 Popr     1.8680 0.6456 Inf    0.6027    3.1334
##  warmed     3 Popr     1.2335 0.4317 Inf    0.3874    2.0795
##  ambient    4 Popr     3.0976 0.9735 Inf    1.1895    5.0056
##  warmed     4 Popr     2.0517 0.6605 Inf    0.7571    3.3462
##  ambient    5 Popr     5.2800 1.5475 Inf    2.2469    8.3130
##  warmed     5 Popr     3.5273 1.0419 Inf    1.4853    5.5693
##  ambient    6 Popr     0.2280 0.0826 Inf    0.0661    0.3900
##  warmed     6 Popr     0.1514 0.0553 Inf    0.0431    0.2597
##  ambient    1 Soca     1.7310 0.2164 Inf    1.3069    2.1551
##  warmed     1 Soca     1.3770 0.1689 Inf    1.0459    1.7081
##  ambient    2 Soca     3.2414 0.3388 Inf    2.5775    3.9054
##  warmed     2 Soca     2.4163 0.2771 Inf    1.8732    2.9595
##  ambient    3 Soca     5.6547 0.9788 Inf    3.7362    7.5732
##  warmed     3 Soca     3.9826 0.7048 Inf    2.6012    5.3640
##  ambient    4 Soca     8.0681 1.1531 Inf    5.8080   10.3281
##  warmed     4 Soca     5.7853 0.8888 Inf    4.0432    7.5274
##  ambient    5 Soca     9.9422 1.2088 Inf    7.5731   12.3114
##  warmed     5 Soca     7.3569 0.8802 Inf    5.6317    9.0821
##  ambient    6 Soca     0.5426 0.0936 Inf    0.3592    0.7260
##  warmed     6 Soca     0.3929 0.0661 Inf    0.2633    0.5225
##
## Confidence level used: 0.95
```

UMBS

```
### determining distribution ###
# first, checking for normality
hist(herb_umbs$p_eaten)
qqnorm(herb_umbs$p_eaten)
shapiro.test(herb_umbs$p_eaten)
fit <- lm(p_eaten~state, data = herb_umbs)
qqPlot(fit)
hist(herb_umbs$p_eaten[herb_umbs$state == "ambient"])
```

```r
hist(herb_umbs$p_eaten[herb_umbs$state == "warmed"])
# not normal- attempting to transform data below
# log transform
herb_umbs$p_log <- log(herb_umbs$p_eaten)
hist(herb_umbs$p_log)
qqnorm(herb_umbs$p_log)
shapiro.test(herb_umbs$p_log)
```

Transformations are a no-go

Going to try a zero-inflated model due to the excess number of zeros in the data

```r
# mean and var of non-zero counts
herb_umbs %>%
        dplyr::filter(p_eaten != "0") %>%
        dplyr::summarize(mean_eaten = mean(p_eaten, na.rm=T), var_eaten = var(p_eaten, na.rm=T))
```

```
## `summarise()` ungrouping output (override with `.groups` argument)
```

```
## # A tibble: 9 x 3
##   species mean_eaten var_eaten
##   <chr>        <dbl>     <dbl>
## 1 Cape          5.62      96.2
## 2 Cest         16.9      562.
## 3 Dasp         16.4      578.
## 4 Hype         27.5      622.
## 5 Poco          5.65      40.3
## 6 Popr         20.6      445.
## 7 Posp         37.1      654.
## 8 Ptaq          8.27      52.3
## 9 Ruac         22.3      606.
```

```r
# variance is also > mean, so can't be poisson
# I'll try zero-inflated negative binomial due to an excess of zeros

# zero-inflated negative binomial
# is state the variable that predicts the excess zeros?
# this is probably the right one since the 0's in the data are real counts
m8 <- zeroinfl(p_eaten ~ state | state,
                  dist = 'negbin',
                  data = herb_umbs)
summary(m8)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state | state, data = herb_umbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.4225 -0.4225 -0.3644 -0.1282  5.4643
##
## Count model coefficients (negbin with log link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   2.5920     0.1030  25.172   <2e-16 ***
## statewarmed  -0.1678     0.1132  -1.482    0.138
```

```
## Log(theta)   -1.1336     0.1290  -8.785   <2e-16 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  0.03949    0.14194   0.278    0.781
## statewarmed -0.59583    0.14157  -4.209 2.57e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.3219
## Number of iterations in BFGS optimization: 11
## Log-likelihood: -4445 on 5 Df
```

```
# interaction between state and species
m9 <- zeroinfl(p_eaten ~ state * species,
               dist = 'negbin',
               data = herb_umbs)
summary(m9) # NaNs produced due to complete separation
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state * species, data = herb_umbs, dist = "negbin")
##
## Pearson residuals:
##      Min       1Q   Median       3Q      Max
## -0.63999 -0.45715 -0.32756 -0.06206 14.20504
##
## Count model coefficients (negbin with log link):
##                          Estimate Std. Error z value Pr(>|z|)
## (Intercept)               1.48758    0.45240   3.288 0.001008 **
## statewarmed              -0.42205    0.59197  -0.713 0.475873
## speciesCest               0.93346    0.46615   2.002 0.045232 *
## speciesDasp               1.37004    0.49467   2.770 0.005612 **
## speciesHype               0.89607    0.65414   1.370 0.170737
## speciesPoco              -1.08210    0.66564  -1.626 0.104026
## speciesPopr               0.49242    1.49058   0.330 0.741134
## speciesPosp               2.04144    0.53461   3.819 0.000134 ***
## speciesPtaq               0.30931    0.52707   0.587 0.557305
## speciesRuac               1.58636    0.47824   3.317 0.000910 ***
## statewarmed:speciesCest   0.70489    0.61345   1.149 0.250538
## statewarmed:speciesDasp  -0.18879    0.65047  -0.290 0.771640
## statewarmed:speciesHype   1.64353    0.91317   1.800 0.071891 .
## statewarmed:speciesPoco   1.41451    0.79183   1.786 0.074038 .
## statewarmed:speciesPopr   1.30468    1.59833   0.816 0.414344
## statewarmed:speciesPosp   0.23621    0.74430   0.317 0.750971
## statewarmed:speciesPtaq   0.34232    0.69071   0.496 0.620172
## statewarmed:speciesRuac   0.08087    0.62988   0.128 0.897847
## Log(theta)               -0.78588    0.09440  -8.325  < 2e-16 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##                            Estimate Std. Error z value Pr(>|z|)
## (Intercept)                 1.45516    0.38675   3.762 0.000168 ***
## statewarmed                -5.16862    8.61324  -0.600 0.548454
## speciesCest                -1.72690    0.41246  -4.187 2.83e-05 ***
## speciesDasp                -0.77032    0.42619  -1.807 0.070695 .
```

```
## speciesHype                0.04109    0.54406   0.076 0.939804
## speciesPoco              -17.90640 6343.14046  -0.003 0.997748
## speciesPopr                2.89156    1.10409   2.619 0.008820 **
## speciesPosp               -1.88150    0.52231  -3.602 0.000315 ***
## speciesPtaq               -2.24103    0.61045  -3.671 0.000242 ***
## speciesRuac               -2.16253    0.44852  -4.822 1.42e-06 ***
## statewarmed:speciesCest    4.74200    8.61254   0.551 0.581913
## statewarmed:speciesDasp    4.21435    8.61079   0.489 0.624540
## statewarmed:speciesHype    5.10589    8.63353   0.591 0.554251
## statewarmed:speciesPoco    5.49332 6523.00212   0.001 0.999328
## statewarmed:speciesPopr    2.62882    8.68223   0.303 0.762057
## statewarmed:speciesPosp    6.38132    8.63127   0.739 0.459709
## statewarmed:speciesPtaq    5.78537    8.63894   0.670 0.503058
## statewarmed:speciesRuac    5.42289    8.61974   0.629 0.529267
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.4557
## Number of iterations in BFGS optimization: 67
## Log-likelihood: -4259 on 37 Df
```

```
# state and species as separate fixed effects
m10 <- zeroinfl(p_eaten ~ state + species,
                dist = 'negbin',
                data = herb_umbs)
summary(m10) # NaNs produced due to complete separation
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state + species, data = herb_umbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.6206 -0.4564 -0.3392 -0.1233 12.7533
##
## Count model coefficients (negbin with log link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  1.27936    0.30754   4.160 3.18e-05 ***
## statewarmed -0.02801    0.10706  -0.262 0.793622
## speciesCest  1.30581    0.30874   4.229 2.34e-05 ***
## speciesDasp  1.26957    0.32796   3.871 0.000108 ***
## speciesHype  1.85424    0.46366   3.999 6.36e-05 ***
## speciesPoco  0.03985    0.35454   0.112 0.910497
## speciesPopr  1.54323    0.51765   2.981 0.002871 **
## speciesPosp  2.16189    0.37543   5.759 8.49e-09 ***
## speciesPtaq  0.44828    0.34711   1.291 0.196542
## speciesRuac  1.60773    0.31775   5.060 4.20e-07 ***
## Log(theta)  -0.84553    0.09832  -8.600  < 2e-16 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##              Estimate Std. Error z value Pr(>|z|)
## (Intercept)    0.6326     0.3132   2.020  0.04340 *
## statewarmed   -0.3529     0.1314  -2.686  0.00723 **
## speciesCest   -0.9841     0.3242  -3.036  0.00240 **
## speciesDasp   -0.2477     0.3346  -0.740  0.45904
```

```
## speciesHype    1.0087     0.4127   2.444  0.01453 *
## speciesPoco  -15.7204  1244.4038  -0.013  0.98992
## speciesPopr    2.0744     0.4333   4.788 1.69e-06 ***
## speciesPosp   -0.2279     0.3789  -0.601  0.54762
## speciesPtaq   -0.8805     0.4048  -2.175  0.02961 *
## speciesRuac   -1.0566     0.3416  -3.093  0.00198 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.4293
## Number of iterations in BFGS optimization: 42
## Log-likelihood: -4292 on 21 Df
```

```
# state, species and year as fixed effects
m11 <- zeroinfl(p_eaten ~ state + as.factor(year) + species,
                dist = 'negbin',
                data = herb_umbs)
summary(m11)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state + as.factor(year) + species, data = herb_umbs,
##     dist = "negbin")
##
## Pearson residuals:
##      Min       1Q   Median       3Q      Max
## -0.70260 -0.49987 -0.32878 -0.01447 11.66668
##
## Count model coefficients (negbin with log link):
##                   Estimate Std. Error z value Pr(>|z|)
## (Intercept)      -0.40972    0.35052  -1.169 0.242448
## statewarmed       0.26343    0.09307   2.830 0.004650 **
## as.factor(year)2  1.17523    0.24755   4.748 2.06e-06 ***
## as.factor(year)3  3.06518    0.24034  12.754  < 2e-16 ***
## as.factor(year)4  2.28318    0.24552   9.299  < 2e-16 ***
## as.factor(year)5  2.99940    0.24663  12.161  < 2e-16 ***
## as.factor(year)6  3.28438    0.23403  14.034  < 2e-16 ***
## speciesCest       0.15545    0.28274   0.550 0.582459
## speciesDasp       0.41035    0.29147   1.408 0.159171
## speciesHype       0.38761    0.40744   0.951 0.341443
## speciesPoco       0.43451    0.31758   1.368 0.171253
## speciesPopr       0.29092    0.44567   0.653 0.513902
## speciesPosp       0.80799    0.34166   2.365 0.018035 *
## speciesPtaq      -0.01442    0.30768  -0.047 0.962609
## speciesRuac       0.49122    0.28612   1.717 0.086013 .
## Log(theta)       -0.33330    0.08651  -3.853 0.000117 ***
##
## Zero-inflation model coefficients (binomial with logit link):
##                   Estimate Std. Error z value Pr(>|z|)
## (Intercept)       -14.9891  1547.7504  -0.010  0.99227
## statewarmed        -0.2966     0.1191  -2.490  0.01277 *
## as.factor(year)2   15.2197  1547.7504   0.010  0.99215
## as.factor(year)3   16.0462  1547.7503   0.010  0.99173
## as.factor(year)4   16.7231  1547.7503   0.011  0.99138
## as.factor(year)5   16.1363  1547.7503   0.010  0.99168
```

```
## as.factor(year)6   16.5355  1547.7503   0.011  0.99148
## speciesCest        -1.4338     0.3093  -4.635 3.57e-06 ***
## speciesDasp        -0.4142     0.2989  -1.386  0.16583
## speciesHype         0.6283     0.3917   1.604  0.10871
## speciesPoco        -1.8193     0.7522  -2.419  0.01558 *
## speciesPopr         1.3788     0.4077   3.382  0.00072 ***
## speciesPosp        -0.4734     0.3713  -1.275  0.20228
## speciesPtaq        -1.0125     0.3584  -2.825  0.00473 **
## speciesRuac        -1.4319     0.3053  -4.690 2.73e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.7166
## Number of iterations in BFGS optimization: 53
## Log-likelihood: -4154 on 31 Df
```

```
# interaction between state and year, + species
m12 <- zeroinfl(p_eaten ~ state * as.factor(year) + species,
                dist = 'negbin',
                data = herb_umbs)
summary(m12)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state * as.factor(year) + species, data = herb_umbs,
##     dist = "negbin")
##
## Pearson residuals:
##      Min       1Q   Median       3Q      Max
## -0.72576 -0.52877 -0.31795 -0.01539  8.73467
##
## Count model coefficients (negbin with log link):
##                               Estimate Std. Error z value Pr(>|z|)
## (Intercept)                  -0.36103    0.39230  -0.920  0.35742
## statewarmed                   0.10443    0.39889   0.262  0.79347
## as.factor(year)2              0.45343    0.32625   1.390  0.16459
## as.factor(year)3              3.29141    0.31455  10.464  < 2e-16 ***
## as.factor(year)4              2.50139    0.35161   7.114 1.13e-12 ***
## as.factor(year)5              2.90004    0.35200   8.239  < 2e-16 ***
## as.factor(year)6              3.34587    0.31622  10.581  < 2e-16 ***
## speciesCest                   0.18514    0.27390   0.676  0.49908
## speciesDasp                   0.29383    0.28266   1.040  0.29856
## speciesHype                   0.33117    0.38870   0.852  0.39422
## speciesPoco                   0.15000    0.31071   0.483  0.62927
## speciesPopr                   0.26790    0.43154   0.621  0.53473
## speciesPosp                   0.72716    0.32927   2.208  0.02722 *
## speciesPtaq                   0.08019    0.30118   0.266  0.79003
## speciesRuac                   0.38982    0.27715   1.407  0.15957
## statewarmed:as.factor(year)2  1.25735    0.44020   2.856  0.00429 **
## statewarmed:as.factor(year)3 -0.34532    0.42850  -0.806  0.42031
## statewarmed:as.factor(year)4 -0.19427    0.46241  -0.420  0.67439
## statewarmed:as.factor(year)5  0.30431    0.46214   0.658  0.51023
## statewarmed:as.factor(year)6 -0.09283    0.45074  -0.206  0.83683
## Log(theta)                   -0.22542    0.08001  -2.817  0.00484 **
##
```

```
## Zero-inflation model coefficients (binomial with logit link):
##                                Estimate Std. Error z value Pr(>|z|)
## (Intercept)                   -13.5754  1663.7577  -0.008 0.993490
## statewarmed                    -7.1172 24249.6222   0.000 0.999766
## as.factor(year)2               12.8481  1663.7577   0.008 0.993839
## as.factor(year)3               14.0933  1663.7577   0.008 0.993241
## as.factor(year)4               15.5256  1663.7577   0.009 0.992555
## as.factor(year)5               15.0466  1663.7577   0.009 0.992784
## as.factor(year)6               14.6051  1663.7577   0.009 0.992996
## speciesCest                    -1.0852     0.3157  -3.437 0.000588 ***
## speciesDasp                    -0.1597     0.3164  -0.505 0.613736
## speciesHype                     0.9346     0.4129   2.264 0.023602 *
## speciesPoco                    -1.8735     0.6952  -2.695 0.007043 **
## speciesPopr                     1.7314     0.4273   4.052 5.08e-05 ***
## speciesPosp                    -0.2770     0.3778  -0.733 0.463405
## speciesPtaq                    -0.6467     0.3558  -1.817 0.069159 .
## speciesRuac                    -1.1845     0.3147  -3.763 0.000168 ***
## statewarmed:as.factor(year)2    8.0099 24249.6222   0.000 0.999736
## statewarmed:as.factor(year)3    7.4529 24249.6222   0.000 0.999755
## statewarmed:as.factor(year)4    6.0620 24249.6222   0.000 0.999801
## statewarmed:as.factor(year)5    5.7609 24249.6222   0.000 0.999810
## statewarmed:as.factor(year)6    7.2913 24249.6222   0.000 0.999760
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.7982
## Number of iterations in BFGS optimization: 60
## Log-likelihood: -4112 on 41 Df
```

```
# interaction between all 3
#m13 <- zeroinfl(p_eaten ~ state * as.factor(year) * species,
#                dist = 'negbin',
#                data = herb_umbs)
#summary(m13) # doesn't run

# is species the variable that predicts excess zeros?
m14 <- zeroinfl(p_eaten ~ state | species,
                  dist = 'negbin',
                  data = herb_umbs)
summary(m14)
```

```
##
## Call:
## zeroinfl(formula = p_eaten ~ state | species, data = herb_umbs, dist = "negbin")
##
## Pearson residuals:
##     Min      1Q  Median      3Q     Max
## -0.5363 -0.4486 -0.3395 -0.1438  8.5309
##
## Count model coefficients (negbin with log link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  2.54693    0.10402  24.485   <2e-16 ***
## statewarmed -0.08452    0.10855  -0.779    0.436
## Log(theta)  -1.13074    0.12915  -8.755   <2e-16 ***
##
```

```
## Zero-inflation model coefficients (binomial with logit link):
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   0.7018     0.2818   2.490  0.01276 *
## speciesCest  -1.5535     0.3183  -4.880 1.06e-06 ***
## speciesDasp  -0.6806     0.3083  -2.208  0.02728 *
## speciesHype   0.5712     0.3920   1.457  0.14507
## speciesPoco  -3.3355     1.5153  -2.201  0.02772 *
## speciesPopr   1.6771     0.4074   4.117 3.84e-05 ***
## speciesPosp  -0.8702     0.3800  -2.290  0.02201 *
## speciesPtaq  -1.0920     0.3602  -3.032  0.00243 **
## speciesRuac  -1.7864     0.3670  -4.868 1.13e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Theta = 0.3228
## Number of iterations in BFGS optimization: 22
## Log-likelihood: -4338 on 12 Df
```

```
# likelihood ratio test
lrtest(m8, m9, m10, m11, m12, m14) # model 11 or 12
```

```
## Likelihood ratio test
##
## Model 1: p_eaten ~ state | state
## Model 2: p_eaten ~ state * species
## Model 3: p_eaten ~ state + species
## Model 4: p_eaten ~ state + as.factor(year) + species
## Model 5: p_eaten ~ state * as.factor(year) + species
## Model 6: p_eaten ~ state | species
##   #Df  LogLik  Df   Chisq Pr(>Chisq)
## 1   5 -4445.5
## 2  37 -4259.0  32 372.910  < 2.2e-16 ***
## 3  21 -4292.4 -16  66.756  3.665e-08 ***
## 4  31 -4153.7  10 277.526  < 2.2e-16 ***
## 5  41 -4112.4  10  82.589  1.558e-13 ***
## 6  12 -4338.1 -29 451.560  < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
# check dispersion
E2 <- resid(m11, type = "pearson")
N2  <- nrow(herb_umbs)
p2  <- length(coef(m11)) + 1 # '+1' is due to theta
sum(E2^2) / (N2 - p2) # pretty close to one
```

```
## [1] 1.033222
```

```
E3 <- resid(m12, type = "pearson")
p3  <- length(coef(m12)) + 1
sum(E3^2) / (N2 - p3) # pretty close to one
```

```
## [1] 0.9622932
```

```
#pairwise comparisons
emmeans(m11, ~ state + year + species)
```

```
##  state   year species emmean    SE  df asymp.LCL asymp.UCL
```

```
##  ambient    1 Cape     0.664 0.233 Inf    0.2078     1.120
##  warmed     1 Cape     0.864 0.307 Inf    0.2628     1.465
##  ambient    2 Cape     0.952 0.283 Inf    0.3973     1.506
##  warmed     2 Cape     1.445 0.417 Inf    0.6288     2.262
##  ambient    3 Cape     3.670 1.236 Inf    1.2473     6.093
##  warmed     3 Cape     5.900 1.997 Inf    1.9853     9.815
##  ambient    4 Cape     0.977 0.344 Inf    0.3039     1.650
##  warmed     4 Cape     1.626 0.565 Inf    0.5195     2.733
##  ambient    5 Cape     3.212 1.079 Inf    1.0961     5.327
##  warmed     5 Cape     5.191 1.714 Inf    1.8304     8.551
##  ambient    6 Cape     3.112 1.138 Inf    0.8806     5.343
##  warmed     6 Cape     5.136 1.885 Inf    1.4421     8.831
##  ambient    1 Cest     0.775 0.163 Inf    0.4552     1.096
##  warmed     1 Cest     1.009 0.213 Inf    0.5917     1.427
##  ambient    2 Cest     1.932 0.263 Inf    1.4167     2.447
##  warmed     2 Cest     2.672 0.311 Inf    2.0620     3.283
##  ambient    3 Cest     9.860 1.299 Inf    7.3152    12.405
##  warmed     3 Cest    14.328 1.947 Inf   10.5120    18.145
##  ambient    4 Cest     3.236 0.513 Inf    2.2318     4.241
##  warmed     4 Cest     4.940 0.696 Inf    3.5761     6.304
##  ambient    5 Cest     8.891 1.439 Inf    6.0706    11.712
##  warmed     5 Cest    13.002 1.867 Inf    9.3427    16.661
##  ambient    6 Cest     9.768 1.342 Inf    7.1370    12.399
##  warmed     6 Cest    14.705 2.017 Inf   10.7518    18.658
##  ambient    1 Dasp     1.001 0.256 Inf    0.4990     1.502
##  warmed     1 Dasp     1.302 0.336 Inf    0.6427     1.962
##  ambient    2 Dasp     1.769 0.275 Inf    1.2294     2.308
##  warmed     2 Dasp     2.606 0.366 Inf    1.8892     3.322
##  ambient    3 Dasp     7.393 1.230 Inf    4.9822     9.803
##  warmed     3 Dasp    11.566 1.948 Inf    7.7487    15.384
##  ambient    4 Dasp     2.069 0.446 Inf    1.1955     2.943
##  warmed     4 Dasp     3.377 0.680 Inf    2.0444     4.710
##  ambient    5 Dasp     6.519 1.379 Inf    3.8172     9.221
##  warmed     5 Dasp    10.263 2.028 Inf    6.2875    14.239
##  ambient    6 Dasp     6.511 1.503 Inf    3.5643     9.457
##  warmed     6 Dasp    10.514 2.393 Inf    5.8234    15.204
##  ambient    1 Hype     0.978 0.364 Inf    0.2651     1.691
##  warmed     1 Hype     1.273 0.474 Inf    0.3438     2.202
##  ambient    2 Hype     0.943 0.343 Inf    0.2710     1.614
##  warmed     2 Hype     1.497 0.524 Inf    0.4700     2.523
##  ambient    3 Hype     3.280 1.244 Inf    0.8412     5.718
##  warmed     3 Hype     5.448 2.048 Inf    1.4340     9.461
##  ambient    4 Hype     0.826 0.338 Inf    0.1629     1.489
##  warmed     4 Hype     1.404 0.560 Inf    0.3076     2.501
##  ambient    5 Hype     2.845 1.057 Inf    0.7731     4.916
##  warmed     5 Hype     4.743 1.698 Inf    1.4139     8.072
##  ambient    6 Hype     2.665 1.066 Inf    0.5751     4.754
##  warmed     6 Hype     4.506 1.783 Inf    1.0113     8.001
##  ambient    1 Poco     1.025 0.312 Inf    0.4139     1.636
##  warmed     1 Poco     1.334 0.403 Inf    0.5442     2.124
##  ambient    2 Poco     2.757 0.518 Inf    1.7424     3.772
##  warmed     2 Poco     3.751 0.616 Inf    2.5449     4.958
##  ambient    3 Poco    14.985 3.934 Inf    7.2748    22.695
##  warmed     3 Poco    21.235 5.105 Inf   11.2293    31.241
```

```
##  ambient    4 Poco     5.241 1.852 Inf    1.6107     8.872
##  warmed     4 Poco     7.777 2.374 Inf    3.1242    12.429
##  ambient    5 Poco    13.622 3.970 Inf    5.8416    21.403
##  warmed     5 Poco    19.412 4.988 Inf    9.6352    29.188
##  ambient    6 Poco    15.537 5.141 Inf    5.4605    25.614
##  warmed     6 Poco    22.742 6.708 Inf    9.5950    35.890
##  ambient    1 Popr     0.888 0.371 Inf    0.1601     1.616
##  warmed     1 Popr     1.156 0.479 Inf    0.2165     2.095
##  ambient    2 Popr     0.479 0.221 Inf    0.0461     0.913
##  warmed     2 Popr     0.794 0.354 Inf    0.0991     1.488
##  ambient    3 Popr     1.532 0.709 Inf    0.1430     2.921
##  warmed     3 Popr     2.610 1.196 Inf    0.2652     4.954
##  ambient    4 Popr     0.371 0.170 Inf    0.0376     0.704
##  warmed     4 Popr     0.640 0.287 Inf    0.0782     1.202
##  ambient    5 Popr     1.320 0.581 Inf    0.1821     2.458
##  warmed     5 Popr     2.254 0.965 Inf    0.3616     4.145
##  ambient    6 Popr     1.207 0.580 Inf    0.0709     2.343
##  warmed     6 Popr     2.077 0.988 Inf    0.1412     4.012
##  ambient    1 Posp     1.489 0.451 Inf    0.6044     2.374
##  warmed     1 Posp     1.938 0.594 Inf    0.7729     3.103
##  ambient    2 Posp     2.703 0.691 Inf    1.3481     4.058
##  warmed     2 Posp     3.965 0.955 Inf    2.0933     5.837
##  ambient    3 Posp    11.433 2.550 Inf    6.4349    16.431
##  warmed     3 Posp    17.814 3.921 Inf   10.1281    25.500
##  ambient    4 Posp     3.226 1.004 Inf    1.2584     5.194
##  warmed     4 Posp     5.248 1.538 Inf    2.2346     8.262
##  ambient    5 Posp    10.094 3.026 Inf    4.1641    16.024
##  warmed     5 Posp    15.827 4.457 Inf    7.0917    24.563
##  ambient    6 Posp    10.130 3.148 Inf    3.9602    16.301
##  warmed     6 Posp    16.301 4.910 Inf    6.6784    25.924
##  ambient    1 Ptaq     0.654 0.178 Inf    0.3054     1.003
##  warmed     1 Ptaq     0.852 0.238 Inf    0.3845     1.319
##  ambient    2 Ptaq     1.454 0.257 Inf    0.9510     1.957
##  warmed     2 Ptaq     2.058 0.346 Inf    1.3798     2.736
##  ambient    3 Ptaq     6.858 1.350 Inf    4.2110     9.504
##  warmed     3 Ptaq    10.272 2.064 Inf    6.2263    14.318
##  ambient    4 Ptaq     2.099 0.454 Inf    1.2091     2.989
##  warmed     4 Ptaq     3.302 0.659 Inf    2.0108     4.593
##  ambient    5 Ptaq     6.126 1.440 Inf    3.3037     8.948
##  warmed     5 Ptaq     9.237 2.046 Inf    5.2271    13.247
##  ambient    6 Ptaq     6.456 1.579 Inf    3.3603     9.551
##  warmed     6 Ptaq    10.023 2.404 Inf    5.3104    14.735
##  ambient    1 Ruac     1.085 0.262 Inf    0.5707     1.599
##  warmed     1 Ruac     1.412 0.348 Inf    0.7292     2.095
##  ambient    2 Ruac     2.701 0.396 Inf    1.9260     3.477
##  warmed     2 Ruac     3.737 0.498 Inf    2.7606     4.714
##  ambient    3 Ruac    13.784 1.803 Inf   10.2503    17.318
##  warmed     3 Ruac    20.033 2.768 Inf   14.6081    25.458
##  ambient    4 Ruac     4.523 0.774 Inf    3.0059     6.040
##  warmed     4 Ruac     6.905 1.083 Inf    4.7825     9.027
##  ambient    5 Ruac    12.429 2.002 Inf    8.5056    16.352
##  warmed     5 Ruac    18.178 2.678 Inf   12.9296    23.426
##  ambient    6 Ruac    13.652 2.389 Inf    8.9700    18.334
##  warmed     6 Ruac    20.555 3.636 Inf   13.4285    27.681
```

```
##
## Confidence level used: 0.95
```