

Modeling Flight Response Summary File

Data Cleaning And Exploration

Read Libraries

```
library(lme4) # fit regressions
library(rethinking) # Bayesian data analysis and plotting
library(popbio) # logistic regression plotting
library(binom) # binomial confidence intervals
```

Read Source Files

```
source_path = paste0(dir, "/Rsrc/")

script_names = c("center_flight_data.R", # 1 function: center_data()
                 "clean_flight_data.R", # 1 function: clean_flight_data()
                 "unique_flight_data.R", # 1 function: create_delta_data()
                 "compare_models.R", # 1 function: model_comparisonsAIC()
                 "AICprobabilities.R", # 1 function: AICprobs()
                 "get_warnings.R") # 1 function: withWarnings()

for (script in script_names) {
  path = paste0(source_path, script)
  source(path)
}
```

Read the Data

```
data_path = paste0(dir, "/Dispersal/Winter_2020/stats/data/all_flight_data-Winter2020.csv")

data = read_flight_data(data_path)
data_all = data[[1]]
data_tested = data[[2]] # subset of data already centered via read_flight_data

# keep bugs only tested once then re-center:
d <- create_delta_data(data_tested, remove_bugs_tested_once = FALSE)
dc <- center_data(d, is_not_unique_data = FALSE)
```

Data Definitions

- A **full dataset** is a dataset where each row has a unique ID and trial type. For example,

```
data_tested[c(1:2, 400:401), c("ID", "trial_type")]
```

```
##      ID trial_type
## 1   114         T1
```

```
## 2 318 T1
## 400 316 T2
## 401 416 T2
```

- A **unique dataset** is a dataset where each row has a unique ID because each trial has been grouped by ID. For example,

```
dc[c(1:2,295:296), c("ID", "trial_type")]
```

```
## # A tibble: 4 x 2
## # Groups:   ID [4]
##   ID   trial_type
##   <fct> <list>
## 1 1     <fct [2]>
## 2 2     <fct [2]>
## 3 400   <fct [2]>
## 4 401   <fct [2]>
```

Data Transformations

- **var_name_b** means that the data are binary (either 0s or 1s)
- **var_name_c** means that the data had been centered
- **var_name_s** means that the data had been standardized
- **avg_var_name** means that the data had been averaged across trial 1 (T1) and trial 2 (T2)
- **var_name_diff** means that the data are a difference between T1 and T2 (T2-T1)
- **var_name_per** means that the data a percent change between T1 and T2 (T2-T1)/T1 * 100
- **var_name_logsqrt** means that the data has been more normalized using a log-square-root transformation
- **var_name_logsqrt_i** means that the data has been more normalized using a log-square-root transformation but its sign is the inverse of the **var_name**.

Repeating Plot Parameters & Functions

```
# scale/magnifications
c1 = 1.3*2 # size of points
c2 = 1.2*2 # size of large text
c3 = 2 # size of smaller text
c4 = 2*2 # size of title

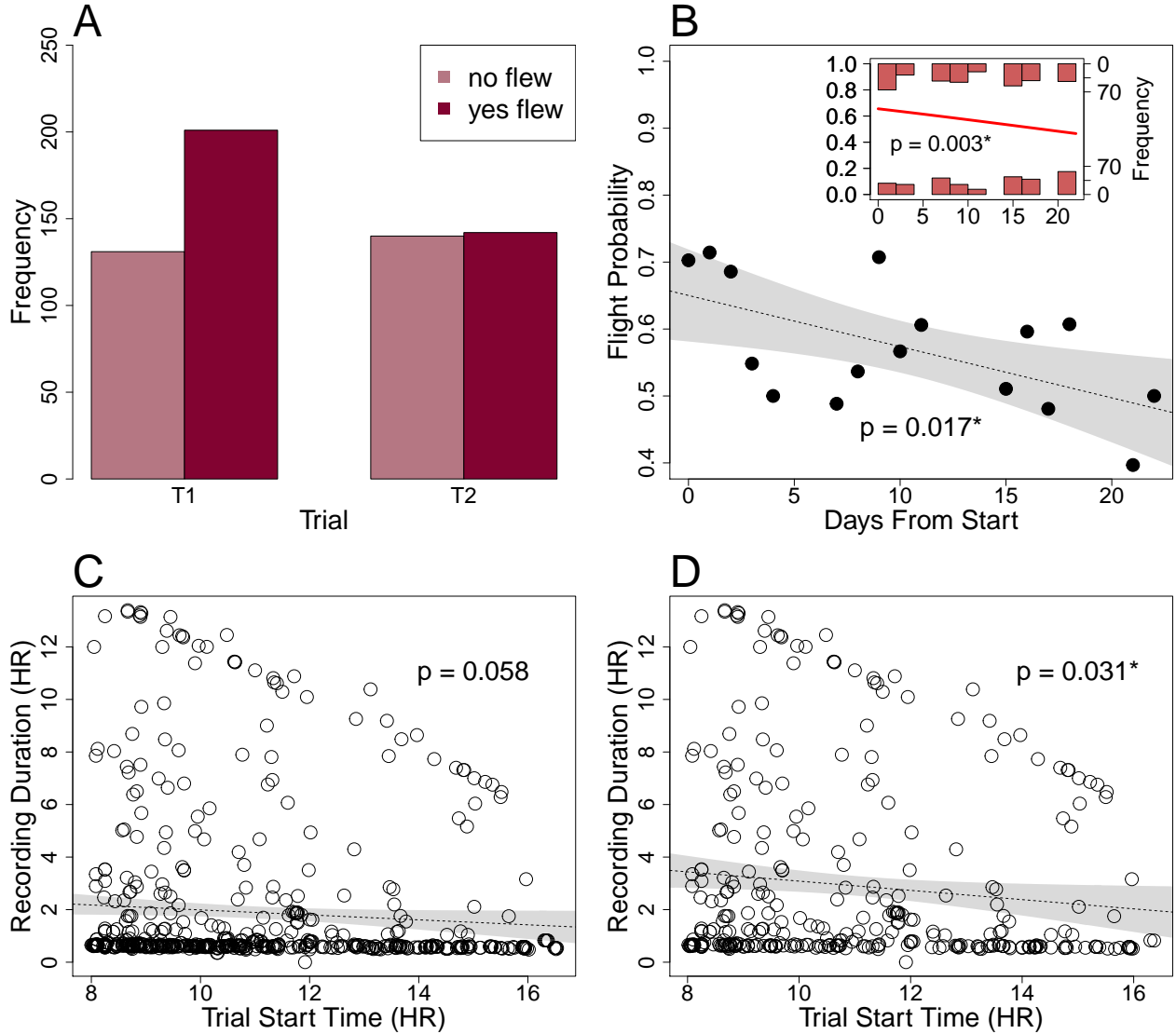
# compute 95% confidence interval
get_CI = function(x,y,m) {
  x.seq = seq(min(x) - sd(x), max(x) + sd(x), length.out=100)
  prd = data.frame(x=x.seq)
  err = predict(m, newdata = prd, se.fit = TRUE)
  prd$lci = err$fit - 1.96 * err$se.fit
  prd$fit = err$fit
  prd$uci = err$fit + 1.96 * err$se.fit
  mu_ci = t(matrix(c(prd$lci,prd$uci), ncol=2))
  return(list(mu_ci, prd))
}

# tailoring variables for plotting
d$mass_block=round(d$avg_mass/0.005)*0.005 # 0.005 g blocks
d$wing2body_block=round(d$wing2body, digits=2) # 0.01 blocks
d$days_block=round(d$avg_days, digits=0) # integer blocks
```

Across-Trial Flight Response

Experimental Effects

```
binary_counts = table(data_tested$flown_b, data_tested$trial_type)[,2:3] # flew yes or no per trial
dd = aggregate(flower_b ~ days_from_start, data=data_tested, FUN=mean)
dt = data_tested[,c("hr_start", "recording_duration")]
```



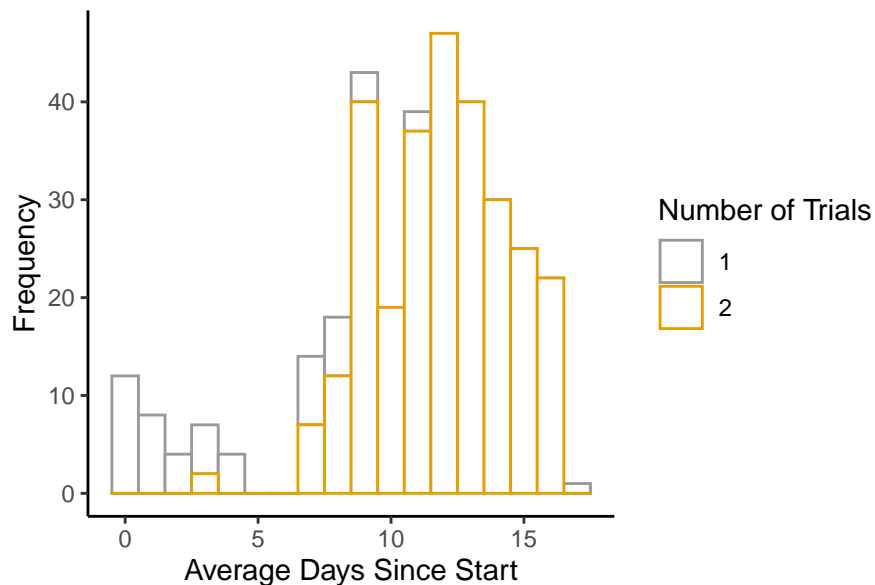
A & B. There was a negative effect of day a bug was tested (since the start of trials), but there was a significant effect only when the full dataset is considered (not the delta dataset, which is not shown here). **C & D.** There was a negative effect of the trial start time but only after removing bugs that didn't fly (D).

Binomial Modeling

We aimed to model the probability of a flight response with sex, host plant, and distance from the sympatric zone. Additionally, to understand how experimental factors affected flight response, we computed the average days since start and the average mass (log-square-root transformed). Finally, we used aggregated datasets for single-variate modeling and the unique dataset for multi-variate modeling.

Average Days Since Start Histogram

```
dc$num_trials <- as.factor(rowSums(dc[,c("num_flew", "num_notflew")]))
```



The advantage of this computed variable is that it controls for the fact that some bugs were tested once late, and some by chance had been tested twice early. This allows the multi-variate models, which control for ID, to converge, but average days does not show the same strong, significant effect as days from start:

```
days_model<-glm(cbind(num_flew,num_notflew)~avg_days_c, data=d, family=binomial)
summary(days_model)
```

```
##
## Call:
## glm(formula = cbind(num_flew, num_notflew) ~ avg_days_c, family = binomial,
##      data = d)
##
## Deviance Residuals:
##      Min       1Q   Median       3Q      Max
## -1.8429  -1.7825  -0.1593   1.5162   1.5795
##
## Coefficients:
##              Estimate Std. Error z value Pr(>|z|)
## (Intercept)  0.22942    0.08236   2.785  0.00535 **
## avg_days_c    0.01087    0.02354   0.462  0.64430
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##      Null deviance: 668.05  on 332  degrees of freedom
## Residual deviance: 667.84  on 331  degrees of freedom
## AIC: 759.17
##
## Number of Fisher Scoring iterations: 3
```

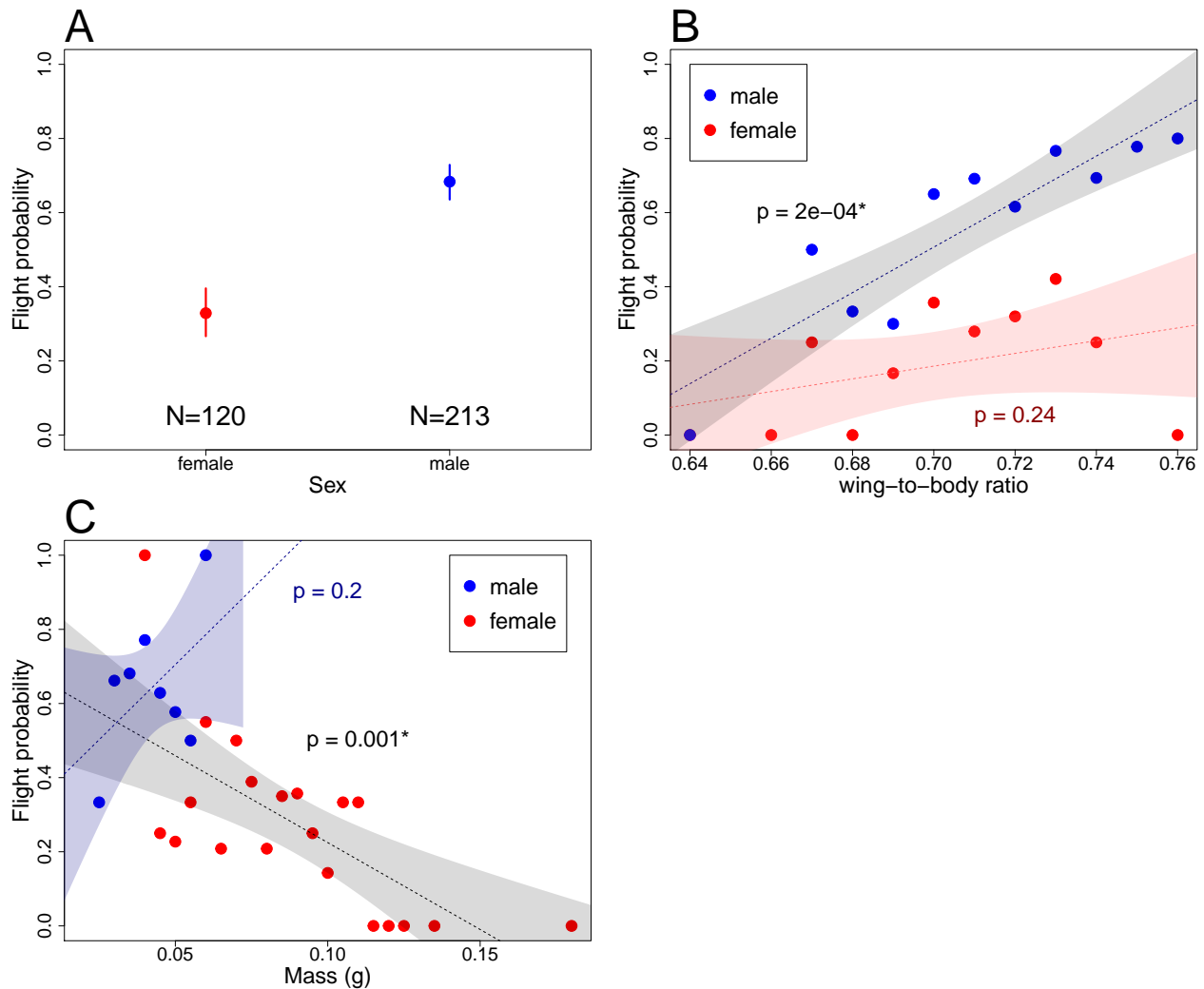
Single-Variate Effects

```
# aggregate data for plotting
dt=aggregate(flew_prob~sex, data=d, FUN=mean)
dt$trials=c(sum(d$num_flew[d$sex=="F"]+d$num_notflew[d$sex=="F"]),
            sum(d$num_flew[d$sex=="M"]+d$num_notflew[d$sex=="M"]))

ds=aggregate(flew_prob~sex*wing2body_block, data=d, FUN=mean)
ds$n=aggregate(flew_prob~sex*wing2body_block, data=d, FUN=length)$flew_prob

dm=aggregate(flew_prob~sex*mass_block, data=d, FUN=mean)
dm$n=aggregate(flew_prob~sex*mass_block, data=d, FUN=length)$flew_prob

# calculate binomial confidence interval
dt$successes = c(sum(d$num_flew[d$sex=="F"]),
                 sum(d$num_flew[d$sex=="M"]))
dt$CI = binom.confint(dt$successes, dt$trials, methods="exact")
```



Multi-Variate Modeling

```
data<-data.frame(R1 = dc$num_flew,
                 R2 = dc$num_notflew,
                 A = dc$host_c,
                 B = dc$sex_c,
                 C = dc$sym_dist,
                 D = dc$avg_mass_logsqrt,
                 E = dc$avg_days_c)

model_script = paste0(source_path,"generic models-binomial glm 2R ~ 4-FF + E.R")
errors = withWarnings(model_comparisonsAIC(model_script))
cat("Number of models that failed to converge: ", length(errors$warnings))

##           [,1]      [,2]      [,3]
## AICs    683.3784   683.9498   684.4483
## models  85         63         50
## probs   0.08875001 0.06669651 0.05198035
##
## m85  glm(formula = cbind(R1, R2) ~ A * D + B * D + C * D + E, family = binomial,
##        data = data)
## m63  glm(formula = cbind(R1, R2) ~ A * D + C * D + B + E, family = binomial,
##        data = data)
## m50  glm(formula = cbind(R1, R2) ~ A * D + B * D + E, family = binomial,
##        data = data)
## Number of models that failed to converge:  0
```

```
anova(m63, m85, test="Chisq") # Adding B*D does not improve fit
anova(m63, m36, test="Chisq") # Adding C*D does improve fit
```

```
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * D + C * D + B + E
## Model 2: cbind(R1, R2) ~ A * D + B * D + C * D + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         325      580.61
## 2         324      578.04  1    2.5713   0.1088
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * D + C * D + B + E
## Model 2: cbind(R1, R2) ~ A * D + B + C + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         325      580.61
## 2         326      585.11 -1   -4.4994  0.03391 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Best Fit

```
M1 <- glm(cbind(num_flew, num_notflew) ~ host_c * avg_mass_logsqrt
          + sym_dist_s * avg_mass_logsqrt + sex_c + avg_days_c, data=d, family=binomial)
summary(M1)
```

```
##
## Call:
## glm(formula = cbind(num_flew, num_notflew) ~ host_c * avg_mass_logsqr +
##       sym_dist_s * avg_mass_logsqr + sex_c + avg_days_c, family = binomial,
##       data = d)
##
## Deviance Residuals:
##      Min       1Q   Median       3Q      Max
## -2.54690  -1.08568  -0.03934   1.17713   2.41019
##
## Coefficients:
##              Estimate Std. Error z value Pr(>|z|)
## (Intercept)      0.03733    0.11152   0.335  0.73780
## host_c          -0.14192    0.13043  -1.088  0.27653
## avg_mass_logsqr -1.00309    0.88134  -1.138  0.25506
## sym_dist_s      -0.03962    0.12352  -0.321  0.74842
## sex_c           -0.46079    0.16797  -2.743  0.00608 **
## avg_days_c       0.01138    0.02596   0.438  0.66113
## host_c:avg_mass_logsqr  1.85579    0.59201   3.135  0.00172 **
## avg_mass_logsqr:sym_dist_s -1.36395    0.66260  -2.058  0.03954 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##      Null deviance: 668.05  on 332  degrees of freedom
## Residual deviance: 580.61  on 325  degrees of freedom
## AIC: 683.95
##
## Number of Fisher Scoring iterations: 4
```

By Sex

Females

```
data_fem <- dc[dc$sex=="F",]
data_fem <- center_data(data_fem, is_not_unique_data = FALSE)

data<-data.frame(R1 = data_fem$num_flew,
                 R2 = data_fem$num_notflew,
                 A = data_fem$host_c,
                 B = data_fem$sym_dist,
                 C = data_fem$avg_mass_logsqr,
                 D = data_fem$wing2body_logsqr_i,
                 E = data_fem$avg_days_c)

model_script = paste0(source_path,"generic models-binomial glm 2R ~ 4-FF + E.R")
errors = withWarnings(model_comparisonsAIC(model_script))
cat("Number of models that failed to converge: ", length(errors$warnings))

##      [,1]      [,2]      [,3]
## AICs 238.8713 239.0635 239.8444
## models 45      25      10
```

```
## probs 0.08178881 0.0742949 0.05027895
##
## m45 glm(formula = cbind(R1, R2) ~ A * C + A * D + E, family = binomial,
##       data = data)
## m25 glm(formula = cbind(R1, R2) ~ A * C + D + E, family = binomial,
##       data = data)
## m10 glm(formula = cbind(R1, R2) ~ C + D + E, family = binomial, data = data)
## Number of models that failed to converge: 0
```

```
anova(m25, m45, test='Chisq') #adding A*D does not improve fit
anova(m25, m13, test='Chisq') #adding A*C improves fit
anova(m25, m17, test="Chisq") #adding D improves fit
anova(m25, m45, test="Chisq") #adding D improves fit
```

```
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * C + D + E
## Model 2: cbind(R1, R2) ~ A * C + A * D + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         114      202.11
## 2         113      199.92  1    2.1922  0.1387
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * C + D + E
## Model 2: cbind(R1, R2) ~ A + C + D + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         114      202.11
## 2         115      206.87 -1    -4.764  0.02906 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * C + D + E
## Model 2: cbind(R1, R2) ~ A * C + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         114      202.11
## 2         115      206.35 -1    -4.243  0.03941 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * C + D + E
## Model 2: cbind(R1, R2) ~ A * C + A * D + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         114      202.11
## 2         113      199.92  1    2.1922  0.1387
```

Best Fit

```
M2 <- glm(cbind(num_flew, num_notflew) ~ host_c * avg_mass_logsqrt + wing2body_logsqrt_i +
          avg_days_c, data=data_fem, family=binomial)
summary(M2)
```



```
##
## Call:
## glm(formula = cbind(num_flew, num_notflew) ~ host_c * avg_mass_logsqr +
##      wing2body_logsqr + avg_days_c, family = binomial, data = data_fem)
##
## Deviance Residuals:
##      Min       1Q   Median       3Q      Max
## -2.1849  -1.1189  -0.7523   1.1182   2.7357
##
## Coefficients:
##              Estimate Std. Error z value Pr(>|z|)
## (Intercept)    -0.15913    0.34121  -0.466   0.6409
## host_c         -0.61037    0.33019  -1.849   0.0645 .
## avg_mass_logsqr -2.08700    1.45468  -1.435   0.1514
## wing2body_logsqr -5.37017    2.66359  -2.016   0.0438 *
## avg_days_c       0.11558    0.04757   2.430   0.0151 *
## host_c:avg_mass_logsqr 3.02237    1.39976   2.159   0.0308 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##      Null deviance: 223.66  on 119  degrees of freedom
## Residual deviance: 202.11  on 114  degrees of freedom
## AIC: 239.06
##
## Number of Fisher Scoring iterations: 4
```

Males

```
data_male <- dc[dc$sex=="M",]
data_male <- center_data(data_male, is_not_unique_data = FALSE)

data<-data.frame(R1 = data_male$num_flew,
                 R2 = data_male$num_notflew,
                 A = data_male$host_c,
                 B = data_male$sym_dist,
                 C = data_male$avg_mass_logsqr,
                 D = data_male$wing2body_logsqr_i,
                 E = data_male$avg_days_c)

model_script = paste0(source_path,"generic models-binomial glm 2R ~ 4-FF + E.R")
errors = withWarnings(model_comparisonsAIC(model_script))
cat("Number of models that failed to converge: ", length(errors$warnings))

##      [,1]      [,2]      [,3]
## AICs  427.3933  427.6501  428.1158
## models 105      50      83
## probs  0.08394083 0.07382556 0.05848926
##
## m105      glm(formula = cbind(R1, R2) ~ A * D + B * C + B * D + C * D +
##      E, family = binomial, data = data)
## m50      glm(formula = cbind(R1, R2) ~ A * D + B * D + E, family = binomial,
```

```
##      data = data)
## m83  glm(formula = cbind(R1, R2) ~ A * D + B * C + B * D + E, family = binomial,
##      data = data)
## Number of models that failed to converge: 0
```

```
anova(m83, m105, test="Chisq") # adding C*D marginally improves fit
anova(m83, m62, test="Chisq") # adding B*C marginally improves fit
anova(m50, m62, test="Chisq") # adding C does not improve fit
```

```
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * D + B * C + B * D + E
## Model 2: cbind(R1, R2) ~ A * D + B * C + B * D + C * D + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         204      347.73
## 2         203      345.01  1    2.7225  0.09894 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * D + B * C + B * D + E
## Model 2: cbind(R1, R2) ~ A * D + B * D + C + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         204      347.73
## 2         205      351.01 -1   -3.2794  0.07015 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## Analysis of Deviance Table
##
## Model 1: cbind(R1, R2) ~ A * D + B * D + E
## Model 2: cbind(R1, R2) ~ A * D + B * D + C + E
##   Resid. Df Resid. Dev Df Deviance Pr(>Chi)
## 1         206      351.27
## 2         205      351.01  1    0.25486  0.6137
```

Best Fit

```
M3<-glm(cbind(num_flew, num_notflew)~host_c*wing2body_logsqrt_i + sym_dist*wing2body_logsqrt_i
+ avg_days_c, family=binomial, data=data_male)
summary(M3)
```

```
##
## Call:
## glm(formula = cbind(num_flew, num_notflew) ~ host_c * wing2body_logsqrt_i +
##   sym_dist * wing2body_logsqrt_i + avg_days_c, family = binomial,
##   data = data_male)
##
## Deviance Residuals:
##      Min       1Q   Median       3Q      Max
## -2.6331  -0.7526   0.8309   1.1667   2.0725
##
## Coefficients:
##
##              Estimate Std. Error z value Pr(>|z|)
```

```
## (Intercept)                0.46485    0.22483    2.068    0.0387 *
## host_c                     -0.38215    0.18894   -2.023    0.0431 *
## wing2body_logsqr_i        -15.20820    5.22382   -2.911    0.0036 **
## sym_dist                   0.11229    0.13856    0.810    0.4177
## avg_days_c                 -0.03316    0.03421   -0.969    0.3323
## host_c:wing2body_logsqr_i  -9.45796    4.27415   -2.213    0.0269 *
## wing2body_logsqr_i:sym_dist 6.31212    3.02683    2.085    0.0370 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##    Null deviance: 372.15  on 212  degrees of freedom
## Residual deviance: 351.27  on 206  degrees of freedom
## AIC: 427.65
##
## Number of Fisher Scoring iterations: 4
```

Between-Trial Flight Response (T1 vs. T2)

Read Libraries

```
library(dplyr) # data manipulation
library(zoo) # data manipulation
library(nnet) # multinomial modeling
library(kableExtra) # table formatting
library(plot.matrix) # enables matrix/heatmap plotting
```

Read Source Files

```
script_names = c( "multinom_functions.R") # 4 relevant functions:
                                                # calculate_P2(), calculate_P3(),
                                                # get_significant_models(),
                                                # get_significant_modelsf(),

for (script in script_names) {
  path = paste0(source_path, script)
  source(path)
}
```

Read the Data

```
d = create_delta_data(data_tested, remove_bugs_tested_once=TRUE) # remove bugs tested only once
```

Encodings & Signs

We aimed to model the probability of different delta flight response cases with sex, host plant, percent changes in mass, and percent changes in egg-laying response as predictors. Since the outcomes (or response variables) were no longer binomial, we used multi-categorical logit models. Below are the categorical encodings and/or signs used. See the Appendix for additional explanations and examples of computing multi-categorical logit models.

Delta Flight Response Key	
Event	Encoding
flew in both trials	2
flew in T2 only	1
flew in neither trials	0
flew in T1 only	-1

Delta Percent Mass Key (%)	
Event	Sign
gained % mass from T1 to T2	+
no % mass change between trails	0
lost % mass from T1 to T2	-

Host Plant Key	
Host	Encoding
Golden Rain Tree (GRT)	1
Balloon Vine (BV)	-1

Sex Key	
Sex	Encoding
Female	1
Male	-1

Multinomial Modeling

Baseline

```
# remove any missing values for flight case or mass percent change between trials
df = d[with(d, !is.na(flight_case) & !is.na(mass_per)),]

# order the dataset by ascending mass percent change values
df = df[with(df, order(mass_per)),]

# relevel the flight case factors so as to set 0 as the first level.
df$flight_case = relevel(as.factor(df$flight_case), ref = "0")
```

Null Model

```
null = multinom(flight_case ~ 1, data = df)

## # weights:  8 (3 variable)
## initial  value 385.389832
```

```
## iter 10 value 319.269929
## final value 319.269680
## converged
```

Compare Models - predictors: % mass, sex, host

```
data = data.frame(R = df$flight_case,
  A = df$mass_per,
  B = df$sex_c,
  C = df$host_c)
model_script = paste0(source_path,"generic multinomial models- multinom 1RF + 3 FF.R")
model_comparisonsAIC(model_script)
```

```
##      [,1]      [,2]      [,3]      [,4]
## AICs 587.5607 591.9016 592.3168 592.4231
## models 4      7      13      12
## probs 0.7141852 0.0815063 0.06622882 0.06280119
##
## m4  multinom(formula = R ~ A + B, data = data, trace = FALSE)
## m7  multinom(formula = R ~ A + B + C, data = data, trace = FALSE)
## m13 multinom(formula = R ~ B * C + A, data = data, trace = FALSE)
## m12 multinom(formula = R ~ A * C + B, data = data, trace = FALSE)
```

```
anova(m4, m7, test="Chisq") # Adding C (host plant) does not improve fit
anova(m4, m8, test="Chisq") # Adding A*B does not improve fit
```

```
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev   Test      Df LR stat.    Pr(Chi)
## 1      A + B      825    569.5607
## 2 A + B + C      822    567.9016 1 vs 2       3 1.659076 0.6460701
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev   Test      Df LR stat.    Pr(Chi)
## 1 A + B      825    569.5607
## 2 A * B      822    569.4209 1 vs 2       3 0.1398496 0.9866598
```

Best Fit

```
M4 = multinom(flight_case ~ mass_per + sex_c, data = df)
model_table4 = calculate_P2(M4, "mass_per", "sex_c")
```

```
## # weights: 16 (9 variable)
## initial value 385.389832
## iter 10 value 286.869825
## iter 20 value 284.809036
## iter 30 value 284.797822
## final value 284.780360
## converged
##
## AIC: 587.5607
```

```
##      (Intercept) mass_per sex_c DF SEi SE1 SE2 zi z1 z2
## -1 -1.015 0.043 -0.692 9 0.239 0.010 0.203 -4.248 4.390 -3.408
## 1 -6.820 -0.009 -5.626 9 0.183 0.026 0.183 -37.245 -0.348 -30.721
## 2 0.124 0.019 -0.902 9 0.167 0.008 0.159 0.742 2.334 -5.684
##      waldi wald1 wald2 Pi > |z| P1 > |z| P2 > |z|
## -1 18.049 19.272 11.617 0.000 0.000 0.001
## 1 1387.197 0.121 943.764 0.000 0.728 0.000
## 2 0.551 5.447 32.310 0.458 0.020 0.000
```

Host plant was not a significant predictor, so we tested the wing-to-body ratio as a predictor next.

Compare Models - predictors: % mass, sex, wing2body (w2b)

```
df$wing2body_c = df$wing2body - mean(df$wing2body) # re-center the w2b predictor

data = data.frame(R = df$flight_case,
                  A = df$mass_per,
                  B = df$sex_c,
                  C = df$wing2body_c)
model_script = paste0(source_path, "generic multinomial models- multinom 1RF + 3 FF.R")
model_comparisonsAIC(model_script)
```

```
##      [,1]      [,2]      [,3]
## AICs 582.2678 585.1197 587.133
## models 7      12      13
## probs 0.6671688 0.1603139 0.05858546
##
## m7 multinom(formula = R ~ A + B + C, data = data, trace = FALSE)
## m12 multinom(formula = R ~ A * C + B, data = data, trace = FALSE)
## m13 multinom(formula = R ~ B * C + A, data = data, trace = FALSE)
```

```
anova(m7, m12, test="Chisq") # adding A*C does not improve fit
anova(m7, m13, test="Chisq") # Adding B*C does not improve fit
```

```
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev Test Df LR stat. Pr(Chi)
## 1 A + B + C      822 558.2678
## 2 A * C + B      819 555.1197 1 vs 2 3 3.148182 0.3693379
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev Test Df LR stat. Pr(Chi)
## 1 A + B + C      822 558.2678
## 2 B * C + A      819 557.1330 1 vs 2 3 1.134887 0.7686596
```

Best Fit

```
M5 = multinom(flight_case ~ mass_per + sex_c + wing2body_c, data = df)
model_table5 = calculate_P3(M5)
```

```
## # weights: 20 (12 variable)
## initial value 385.389832
## iter 10 value 286.740091
## iter 20 value 280.436850
## iter 30 value 279.437125
## iter 40 value 279.174660
## iter 50 value 279.134087
## final value 279.133921
## converged
##
## AIC: 582.2678
## (Intercept) mass % sex wing2body DF SEi SE1 SE2 SE3 zi
## -1 -0.935 0.041 -0.571 23.739 12 0.243 0.010 0.212 12.059 -3.854
## 1 -8.177 -0.005 -6.954 -6.595 12 0.187 0.025 0.187 18.786 -43.767
## 2 0.201 0.018 -0.760 28.094 12 0.172 0.008 0.166 9.718 1.173
## z1 z2 z3 waldi wald1 wald2 wald3 Pi>|z| P1>|z| P2>|z|
## -1 4.254 -2.698 1.969 14.850 18.096 7.278 3.875 0.000 0.000 0.007
## 1 -0.215 -37.102 -0.351 1915.510 0.046 1376.550 0.123 0.000 0.830 0.000
## 2 2.141 -4.590 2.891 1.375 4.585 21.071 8.357 0.241 0.032 0.000
## P3>|z|
## -1 0.049
## 1 0.726
## 2 0.004
```

Prediction Equations

```
get_prediction_eq = function(tb, table_rowA, table_rowB, var_lab1, var_lab2, var_lab3,
                             log_lab, title_lab) {
  I = (tb[table_rowA,1] - tb[table_rowB,1])
  M = (tb[table_rowA,2] - tb[table_rowB,2])
  S = (tb[table_rowA,3] - tb[table_rowB,3])
  W = (tb[table_rowA,4] - tb[table_rowB,4])
  EQ = paste0(log_lab, round(I, 2), " + ", round(M,2), var_lab1, " + ", round(S, 2),
              var_lab2, " + ", round(W, 2), var_lab3, title_lab)
  print(EQ)
  return(EQ)
}
```

```
EQ1 = get_prediction_eq(model_table5, 1, 2, " Mass %", " Sex", " Wing-to-Body",
                        "log(pi_-1 / pi_1) = ", " Flew in T1, not T2")
EQ2 = get_prediction_eq(model_table5, 3, 1, " Mass %", " Sex", " Wing-to-Body",
                        "log(pi_2 / pi_-1) = ", " Flew in both, not T1" )
EQ3 = get_prediction_eq(model_table5, 3, 2, " Mass %", " Sex", " Wing-to-Body",
                        "log(pi_2 / pi_1) = ", " Flew in both, not T2" )
```

```
## [1] "log(pi_-1 / pi_1) = 7.24 + 0.05 Mass % + 6.38 Sex + 30.33 Wing-to-Body Flew in T1, not T2"
## [1] "log(pi_2 / pi_-1) = 1.14 + -0.02 Mass % + -0.19 Sex + 4.36 Wing-to-Body Flew in both, not T1"
## [1] "log(pi_2 / pi_1) = 8.38 + 0.02 Mass % + 6.19 Sex + 34.69 Wing-to-Body Flew in both, not T2"
```

Visualize Significant Multinomial Functions

```
# define a run_multinom_model function based on the best fit model
run_multinom_model = function(d) {
```

```

m = multinom(flight_case ~ mass_per + sex_c + wing2body_c, trace=FALSE, data = d)
model_table = calculate_P3(m, print_table=FALSE)
return(model_table)
}

```

determine which multinomial model equations are significant with a plot

```
par(mfrow=c(2,2))
```

```
mass_per_ML = get_significant_models(19) # % mass
```

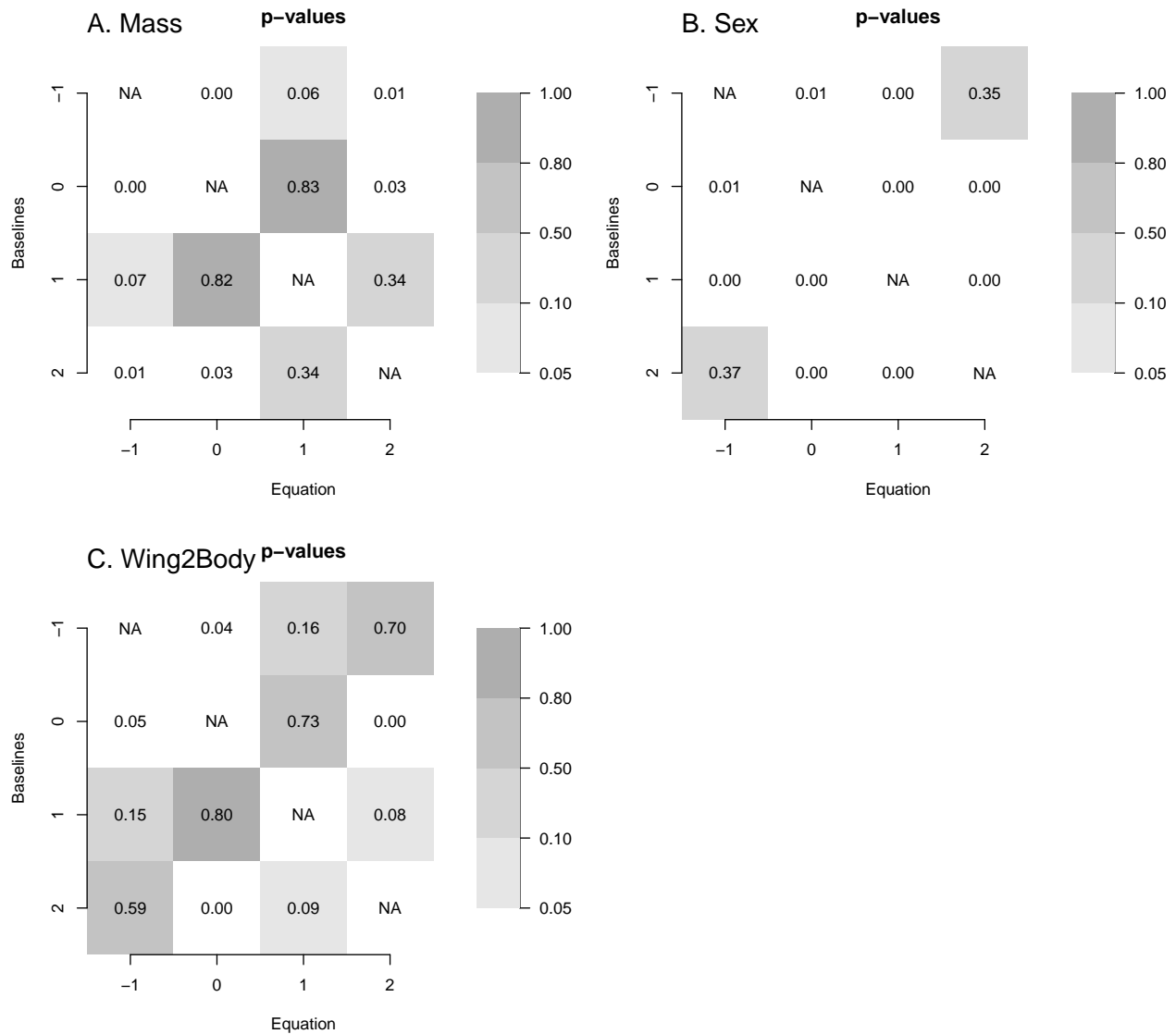
```
  mtext("A. Mass", side=3, adj=0, line=0.5, cex=1.3, font=1)
```

```
sex_ML = get_significant_models(20) # sex
```

```
  mtext("B. Sex", side=3, adj=0, line=0.5, cex=1.3, font=1)
```

```
w2b_ML = get_significant_models(21) # wing2body
```

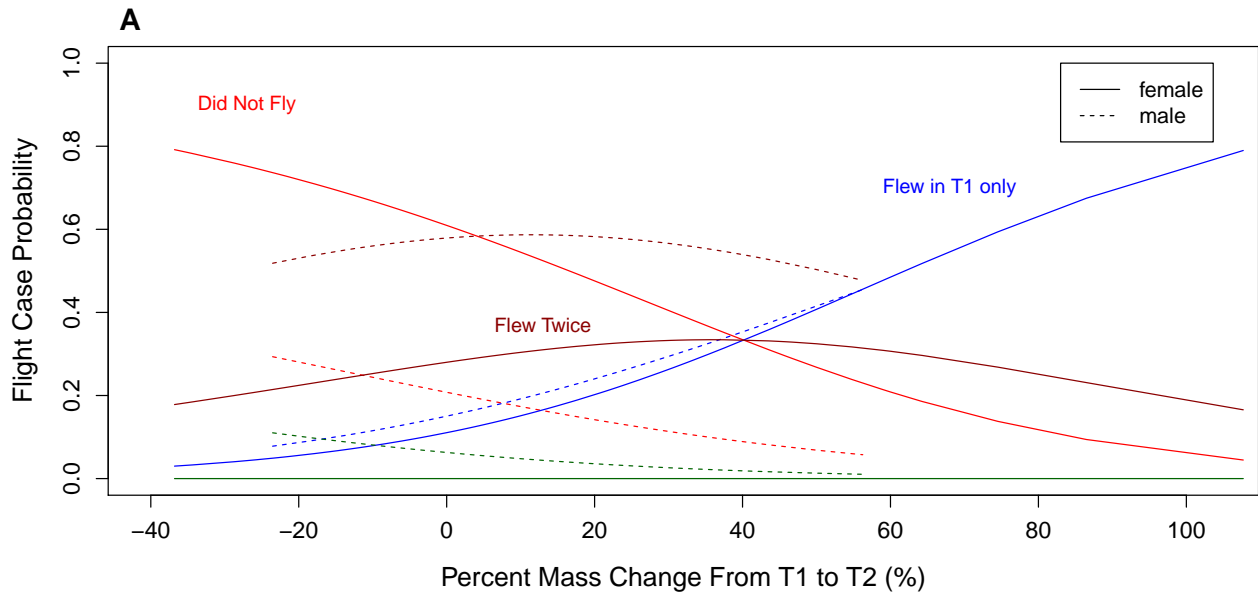
```
  mtext("C. Wing2Body", side=3, adj=0, line=0.5, cex=1.3, font=1)
```



Plot Predicted Probabilities

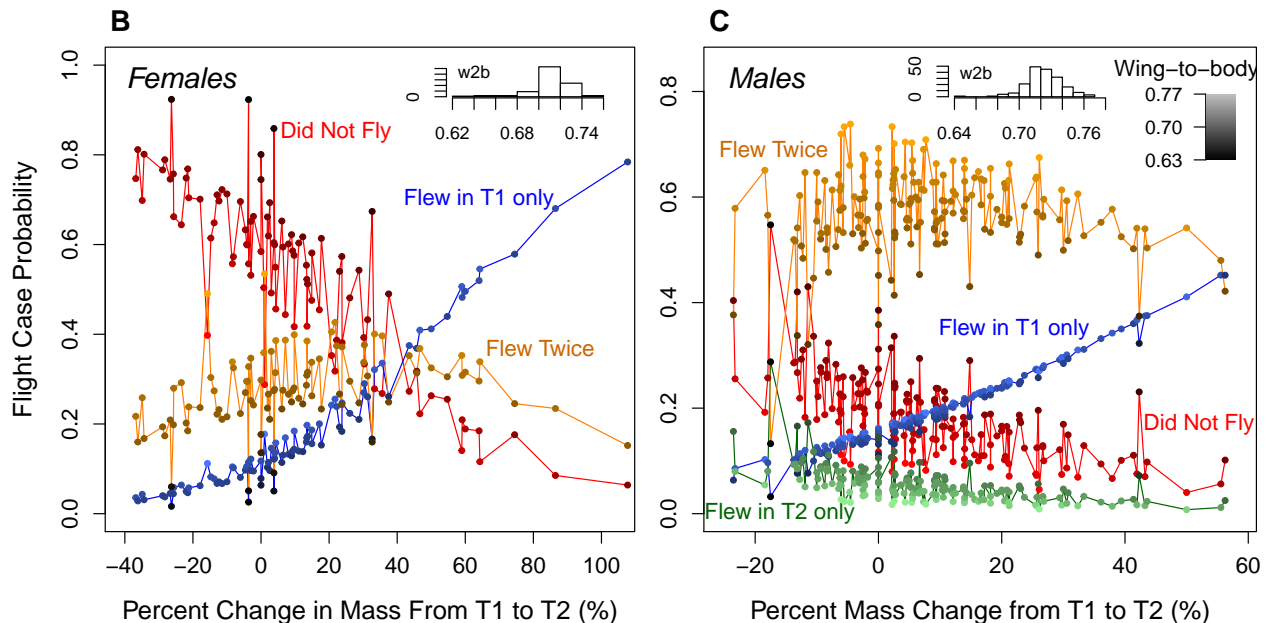
```
head(pp <- fitted(M4), 3) # compute fitted values of the best fit model without wing-to-body ratio
```

```
##           0           -1           1           2
## 1 0.7917303 0.03003973 4.362037e-06 0.1782256
## 2 0.7894639 0.03073036 4.325625e-06 0.1798015
## 3 0.7844677 0.03228066 4.247094e-06 0.1832474
```



```
head(pp <- fitted(M5), 3) # compute fitted values of the best fit model with wing-to-body ratio
```

```
##           0           -1           1           2
## 1 0.7470322 0.03581826 2.459149e-07 0.2171493
## 2 0.8116776 0.02845344 2.925412e-07 0.1598686
## 3 0.6983200 0.04316854 2.166785e-07 0.2585113
```



Multinomial Modeling (Females Only)

Egg Case

Delta Egg Response Key	
Event	Encoding
laid eggs in both trials	2
laid eggs in T2 only	1
laid eggs in neither trials	0
laid eggs in T1 only	-1

Baseline

```
# filter for females &
# remove any missing values for flight case, mass percent change, and egg case between trials
df = d[with(d,!is.na(flight_case) & !is.na(mass_per) & !is.na(egg_case) & sex=="F"),]

# order the dataset by ascending mass percent change values
df = df[with(df, order(mass_per)),]

# relevel the flight case factors so as to set 0 as the first level.
df$flight_case = relevel(as.factor(df$flight_case), ref = "0")

unique(df$flight_case) # no female bug only flew in T2, so can drop factor "1"
df$flight_case = droplevels(df$flight_case)

## [1] 2 0 -1
## Levels: 0 -1 1 2
```

Null model

```
null <- multinom(flight_case ~ 1, data = df)

## # weights: 6 (2 variable)
## initial value 102.170943
## final value 93.055466
## converged
```

Comparing Models - predictors: % mass, egg diff, host

```
data <- data.frame(R = df$flight_case,
  A = df$egg_case,
  B = df$mass_per,
  C = df$host_c)
model_script = paste0(source_path,"generic multinomial models- multinom 1RF + 3 FF.R")
model_comparisonsAIC(model_script)

##      [,1]      [,2]      [,3]      [,4]      [,5]      [,6]
## AICs 164.3817 165.6054 166.336 167.5638 167.9891 168.3593
## models 7      4      13      11      16      12
## probs 0.3761191 0.2039899 0.1415644 0.07661927 0.06194208 0.0514745
##
```

```
## m7 multinom(formula = R ~ A + B + C, data = data, trace = FALSE)
## m4 multinom(formula = R ~ A + B, data = data, trace = FALSE)
## m13 multinom(formula = R ~ B * C + A, data = data, trace = FALSE)
## m11 multinom(formula = R ~ A * B + C, data = data, trace = FALSE)
## m16 multinom(formula = R ~ B * C + A * B, data = data, trace = FALSE)
## m12 multinom(formula = R ~ A * C + B, data = data, trace = FALSE)
```

```
anova(m4, m7, test="Chisq") # Adding C does not improve fit
anova(m7, m13, test="Chisq") # Adding mass_per*host does not improve fit
```

```
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev   Test    Df LR stat.    Pr(Chi)
## 1      A + B      180    153.6054
## 2 A + B + C      178    148.3817 1 vs 2      2  5.223671 0.0733997
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev   Test    Df LR stat.    Pr(Chi)
## 1 A + B + C      178    148.3817
## 2 B * C + A      176    146.3360 1 vs 2      2  2.045698 0.3595691
```

Host plant was not a significant predictor for females as well, so we tested the wing-to-body ratio as a predictor next.

Comparing Models - predictors: % mass, egg diff, wing2body

```
##      [,1]      [,2]      [,3]      [,4]
## AICs 164.5293 164.9831 165.6054 167.7955
## models 7      13      4      12
## probs 0.3174096 0.2529723 0.1853291 0.06199495
##
## m7 multinom(formula = R ~ A + B + C, data = data, trace = FALSE)
## m13 multinom(formula = R ~ B * C + A, data = data, trace = FALSE)
## m4 multinom(formula = R ~ A + B, data = data, trace = FALSE)
## m12 multinom(formula = R ~ A * C + B, data = data, trace = FALSE)
```

```
anova(m4, m7, test="Chisq") # adding wing2body does not include fit
anova(m7, m13, test="Chisq") # Adding A*C does not improve fit
anova(m7, m12, test="Chisq") # Adding B*C does not improve fit
```

```
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev   Test    Df LR stat.    Pr(Chi)
## 1      A + B      180    153.6054
## 2 A + B + C      178    148.5293 1 vs 2      2  5.07612 0.07901956
## Likelihood ratio tests of Multinomial Models
##
```

```
## Response: R
##      Model Resid. df Resid. Dev   Test    Df LR stat.   Pr(Chi)
## 1 A + B + C      178   148.5293
## 2 B * C + A      176   144.9831 1 vs 2      2 3.546174 0.169808
## Likelihood ratio tests of Multinomial Models
##
## Response: R
##      Model Resid. df Resid. Dev   Test    Df LR stat.   Pr(Chi)
## 1 A + B + C      178   148.5293
## 2 A * C + B      176   147.7955 1 vs 2      2 0.7337197 0.6929067
```

Best Fit

```
M6 = multinom(flight_case ~ mass_per + egg_case, data = df) # same top model
model_table6 = calculate_P2(M6, "mass_per", "egg_case")

## # weights: 12 (6 variable)
## initial value 102.170943
## iter 10 value 76.802714
## final value 76.802689
## converged
##
## AIC: 165.6054
##      (Intercept) mass_per egg_case DF   SEi   SE1   SE2    zi    z1    z2 waldi
## -1      -0.950    0.041   -0.533  6 0.617 0.012 0.380 -1.539 3.389 -1.402 2.370
## 2         0.406    0.022   -1.098  6 0.424 0.011 0.297  0.957 2.038 -3.700 0.917
##      wald1  wald2 Pi > |z| P1 > |z| P2 > |z|
## -1 11.488  1.966  0.124  0.001  0.161
## 2  4.154 13.693  0.338  0.042  0.000
```

Prediction Equations

```
get_prediction_eq = function(tb, table_rowA, table_rowB, var_lab1, var_lab2,
                             log_lab, title_lab) {
  I = (tb[table_rowA,1] - tb[table_rowB,1])
  M = (tb[table_rowA,2] - tb[table_rowB,2])
  E = (tb[table_rowA,3] - tb[table_rowB,3])
  EQ = paste0(log_lab, round(I, 2), " + ", round(M,2), var_lab1, " + ", round(E, 2),
              var_lab2, title_lab)
  print(EQ)
  return(EQ)
}

EQ = get_prediction_eq(model_table6, 1, 2, " Mass %", " Egg Case",
                       "log(pi_-1 / pi_1) = ", " Flew in T1, not T2")

## [1] "log(pi_-1 / pi_1) = -1.36 + 0.02 Mass % + 0.56 Egg Case Flew in T1, not T2"
```

Visualize Significant Multinomial Functions

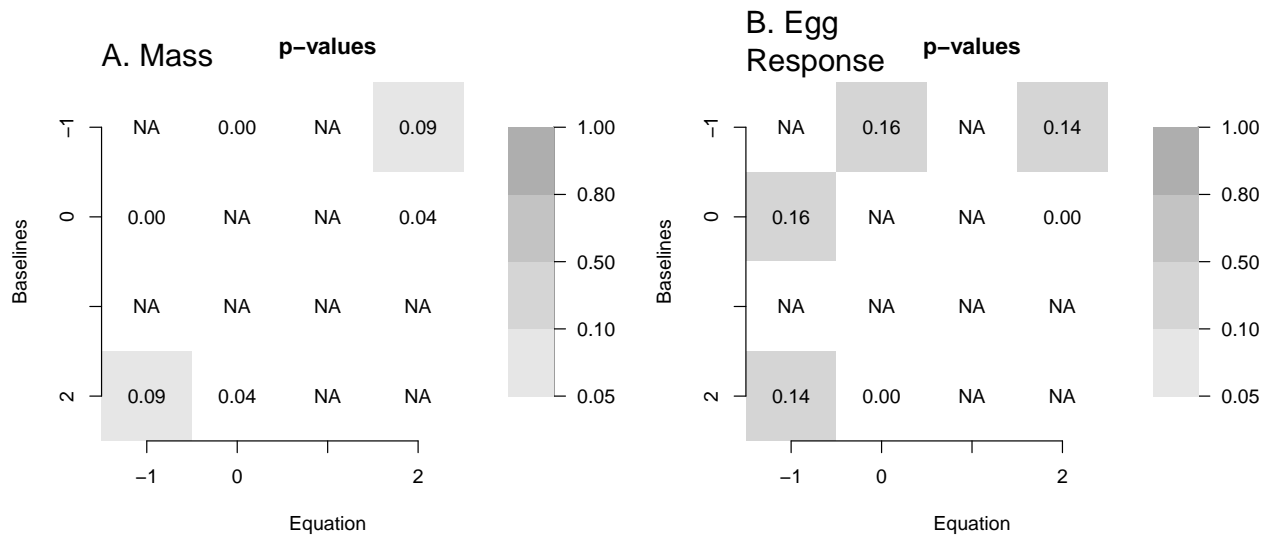
```
# define a run_multinom_model function based on the best fit model
run_multinom_model = function(d) {
  m <- multinom(flight_case ~ mass_per + egg_case, trace=FALSE, data = d)
```

```

model_table = calculate_P2(m, "mass_per", "egg_case", print_table=FALSE)
return(model_table)
}

# determine which multinomial model equations are significant with a plot
par(mfrow=c(1,2))
mass_per_ML = get_significant_models(15) # mass_per
mtext("A. Mass", side=3, adj=0, line=0.5, cex=1.6, font=1)
egg_case_ML = get_significant_models(16) # egg_case
mtext("B. Egg \nResponse", side=3, adj=0, line=0.3, cex=1.6, font=1)

```

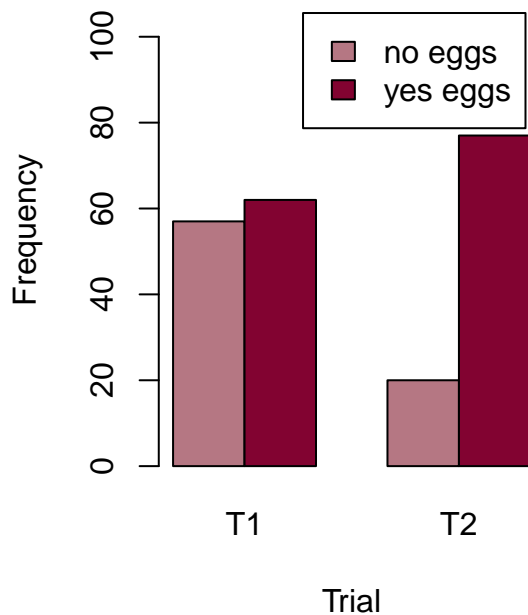


Barplot

```

data_fem = data_tested[data_tested$sex=="F",]
binary_counts <- table(data_fem$eggs_b, data_fem$trial_type)[,2:3]

```

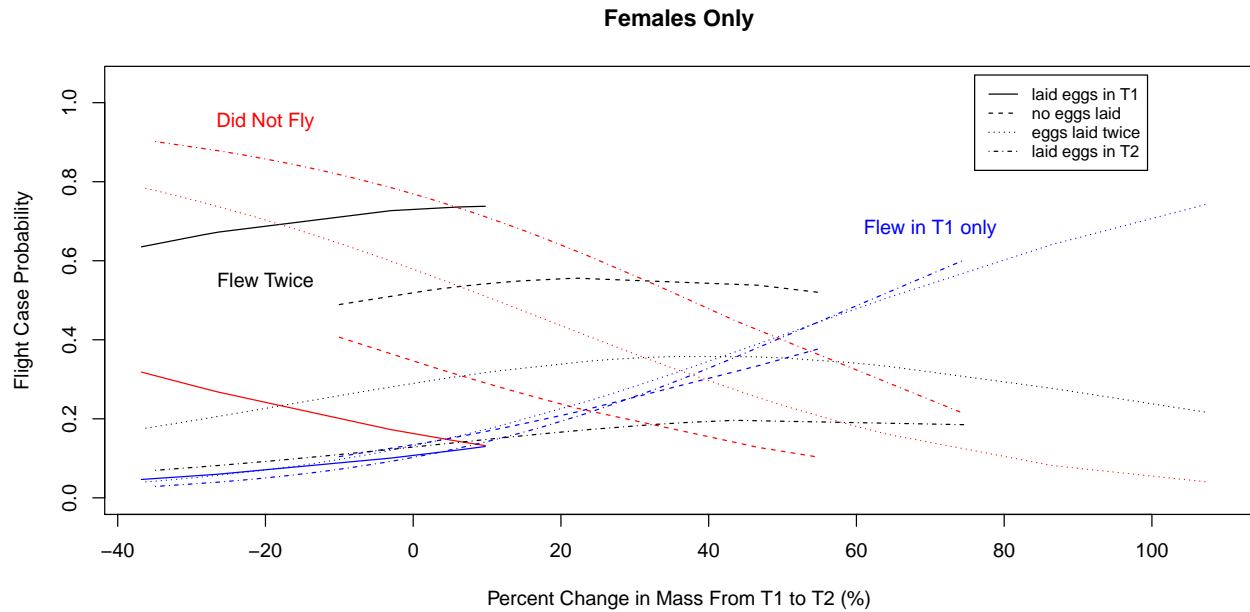


Notice that female bugs were laying more during the second trial (T2) than the first trial (T1).

Plot Predicted Probabilities

```
head(pp <- fitted(M6),3)
```

```
##           0           -1           2
## 1 0.3182776 0.04652361 0.63519881
## 2 0.7833277 0.04039434 0.17627792
## 3 0.9015654 0.02877502 0.06965959
```



Flight Response Predictions

Read Libraries

```
library(cvms) # cross-validating regressions
```

Read Source Files

```
script_names = c("clean_flight_data-Fall2.R", # 1 function: clean_flight_data.Fall()
                 "unique_flight_data-Fall.R", # 1 function: create_delta_data.Fall()
                 "prediction_accuracy.R", # 1 function: calculate_accuracy()
                 "confusion_matrix.R") # 1 function: get_confusion_matrix()

for (script in script_names) {
  path = paste0(source_path, script)
  source(path)
}
```

Read the Data

```
dataFall = clean_flight_data.Fall("data/full_data-Fall2019.csv")
```

```
# extract sets with an experimental design similar to the Winter tests
ongoing_data = dataFall[with(dataFall,!is.na(mass) & set_number > 71),]

# create delta data
d = create_delta_data.Fall(ongoing_data)
```

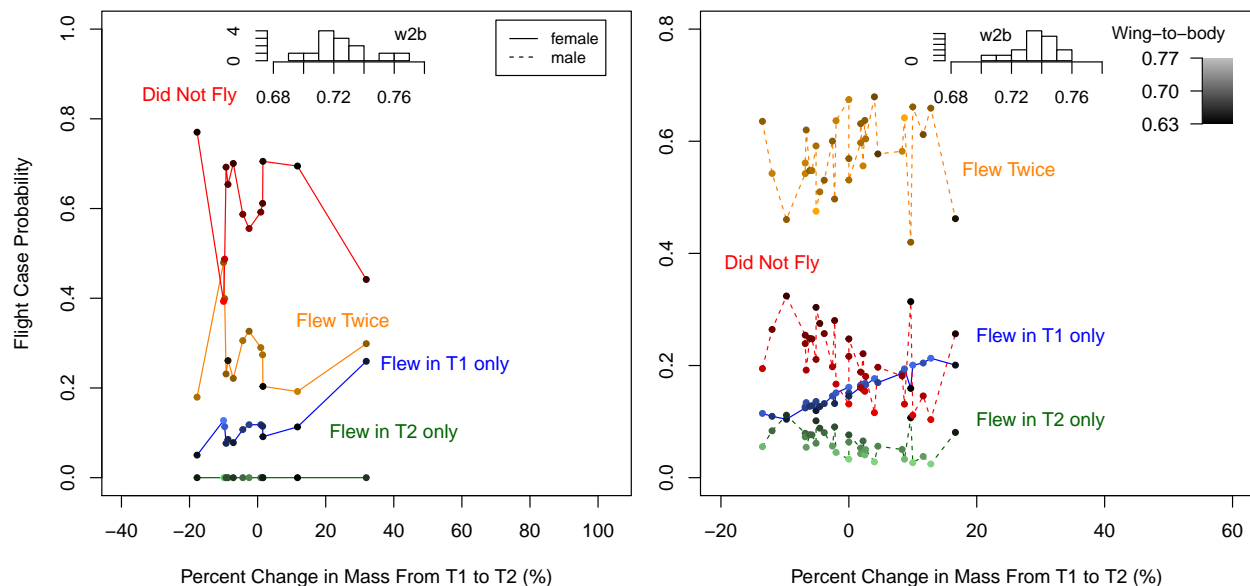
Compute predicted probabilities

```
d <- d[with(d, order(mass_per)),]

neither = c()
T1_rather_than_none = c()
T2_rather_than_none = c()
both_rather_than_none = c()

for (i in 1:nrow(d)) {
  m = d$mass_per[[i]]
  s = d$sex_c[[i]]
  w = d$wing2body_c[i]
  # extract effects from the best fit model
  top0 = exp(0) # equals 1
  top1 = exp(model_table5[1,1] + model_table5[1,2]*m + model_table5[1,3]*s + model_table5[1,4]*w)
  top2 = exp(model_table5[2,1] + model_table5[2,2]*m + model_table5[2,3]*s + model_table5[2,4]*w)
  top3 = exp(model_table5[3,1] + model_table5[3,2]*m + model_table5[3,3]*s + model_table5[3,4]*w)
  bottom = top0 + top1 + top2 + top3
  # calculate predicted probabilities
  neither = c(neither, top0/bottom)
  T1_rather_than_none = c(T1_rather_than_none, top1/bottom)
  T2_rather_than_none = c(T2_rather_than_none, top2/bottom)
  both_rather_than_none = c(both_rather_than_none, top3/bottom)
}
```

Plot predicted probabilities



Overall and Grouped Accuracies

```
probs = round(cbind(neither, T1_rather_than_none, T2_rather_than_none, both_rather_than_none),2)
summary_probs = cbind(as.character(d$flight_case), as.character(d$sex), probs)
colnames(summary_probs) = c("event", "sex", "none", "T1", "T2", "both")
dataframe = as.data.frame(summary_probs)
nrow(dataframe)

## [1] 45

# overall
acc = calculate_accuracy(dataframe,3,6)
paste("Overall prediction accuracy, ", round(acc,2))

# by sex
femdata = dataframe[dataframe$sex=="F",]
maledata = dataframe[dataframe$sex=="M",]

accF = calculate_accuracy(femdata,3,6)
paste("Female prediction accuracy, ", round(accF,2))
accM = calculate_accuracy(maledata,3,6)
paste("Male prediction accuracy, ", round(accM,2))

## [1] "Overall prediction accuracy, 0.6"
## [1] "Female prediction accuracy, 0.38"
## [1] "Male prediction accuracy, 0.69"
```

Confusion Matrix

```
acc_table = get_confusion_matrix(dataframe,3,6)
acc_table[,1:5]

## # A tibble: 1 x 5
##   `Overall Accuracy` `Balanced Accuracy` F1 Sensitivity Specificity
##   <dbl>             <dbl> <dbl>         <dbl>         <dbl>
## 1         0.6         0.538   NaN         0.293         0.784

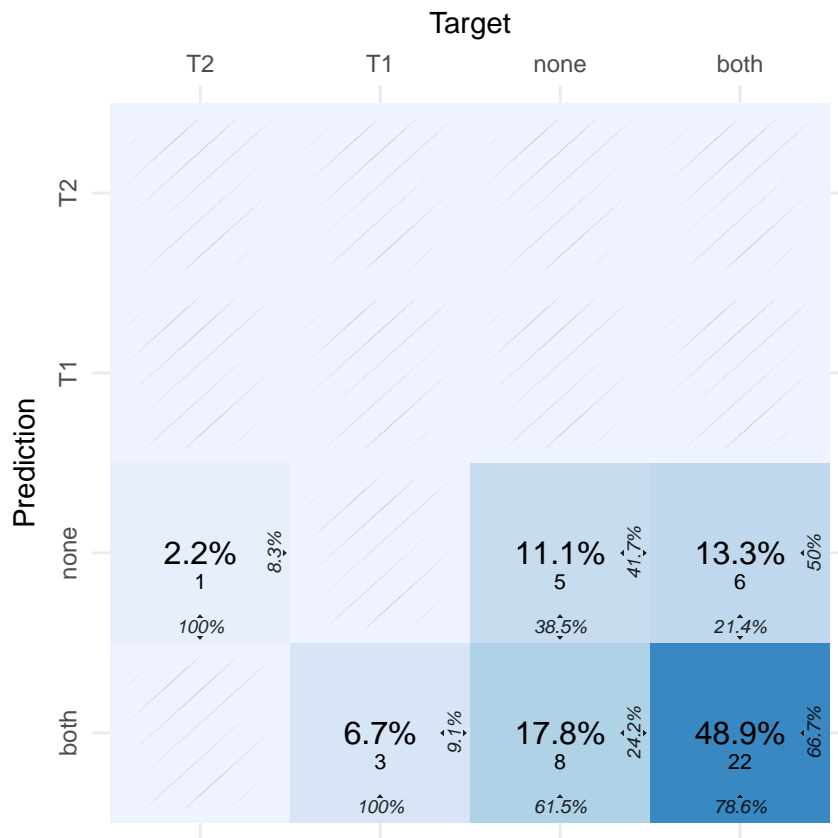
confusion_matrix <- acc_table$'Confusion Matrix'[[1]]
confusion_matrix

## # A tibble: 16 x 3
##   Prediction Target    N
##   <chr>         <chr> <int>
## 1 both         both    22
## 2 none         both     6
## 3 T1           both     0
## 4 T2           both     0
## 5 both         none     8
## 6 none         none     5
## 7 T1           none     0
## 8 T2           none     0
## 9 both         T1       3
## 10 none        T1       0
## 11 T1          T1       0
## 12 T2          T1       0
## 13 both        T2       0
```



```
## 14 none      T2      1
## 15 T1        T2      0
## 16 T2        T2      0
```

```
plot_confusion_matrix(confusion_matrix, add_sums=FALSE)
```



Females Only

```
dfem = d[d$sex=="F",]
```

```
dfem <- dfem[with(dfem, order(mass_per)),]
```

```
neither = c()
T1_rather_than_none = c()
both_rather_than_none = c()
for (i in 1:nrow(dfem)) {
  M = dfem$mass_per[[i]]
  EC = dfem$egg_diff[[i]]
  top0 = exp(0) # equals 1
  top1 = exp(model_table6[1,1] + model_table6[1,2]*M + model_table6[1,3]*EC)
  top2 = exp(model_table6[2,1] + model_table6[2,2]*M + model_table6[2,3]*EC)
  bottom = top0 + top1 + top2
  neither = c(neither, top0/bottom)
  T1_rather_than_none = c(T1_rather_than_none, top1/bottom)
  both_rather_than_none = c(both_rather_than_none, top2/bottom)
}
```

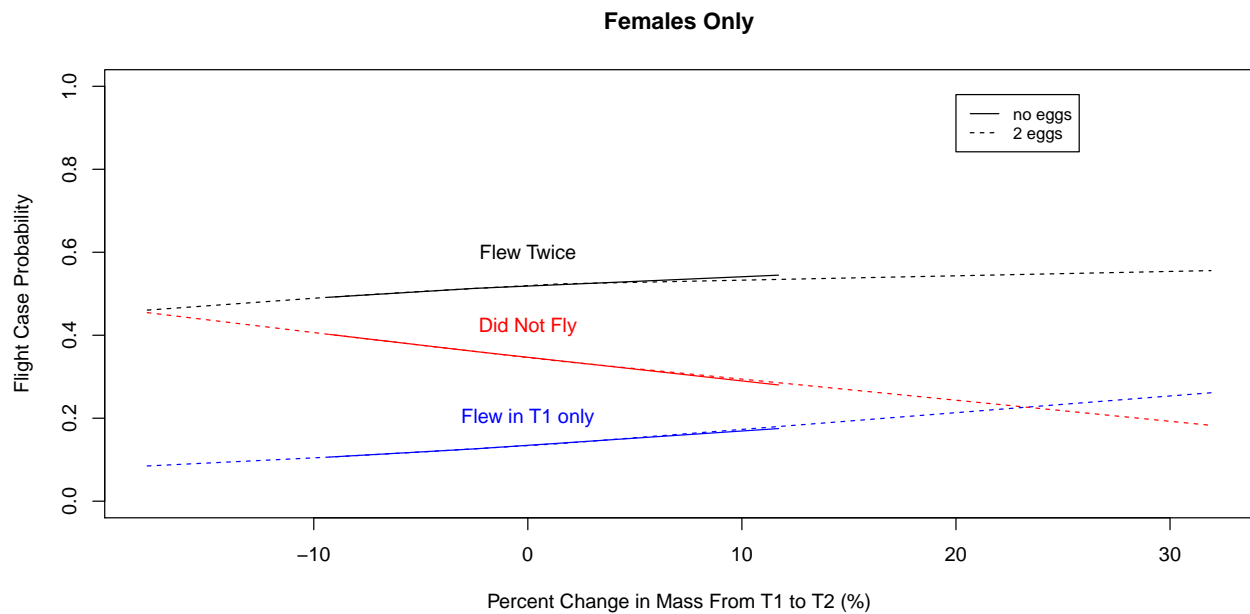
Compute predicted probabilities

```
probs = round(cbind(neither, T1_rather_than_none, both_rather_than_none),2)
summary_probs = cbind(as.character(dfem$flight_case), as.character(dfem$egg_diff), probs)
colnames(summary_probs) = c("event", "egg_diff", "none", "T1", "both")

egg2 = c(1,2,3,5,6,7,9,10,11,13)
noegg = c(4,8,12)

dataframe = as.data.frame(summary_probs)
dataframe$egg_cat = c(2,2,2,0,2,2,2,0,2,2,2,0,2)
```

Plot predicted probabilities



Overall and Grouped Accuracies

```
accF_eggs = calculate_accuracy(dataframe,3,5)
paste("Female prediction accuracy for mass diff and egg model, ", round(accF_eggs,2))
```

```
## [1] "Female prediction accuracy for mass diff and egg model, 0.46"
```

Confusion Matrix

```
acc_table = get_confusion_matrix(dataframe,3,5)
acc_table[,1:5]
```

```
## # A tibble: 1 x 5
##   `Overall Accuracy` `Balanced Accuracy` F1 Sensitivity Specificity
##   <dbl>             <dbl> <dbl>      <dbl>      <dbl>
## 1         0.462         0.5   NaN      0.333      0.667
```

```
confusion_matrix <- acc_table$'Confusion Matrix'[[1]]
confusion_matrix
```

```
## # A tibble: 9 x 3
##   Prediction Target    N
##   <chr>         <chr> <int>
## 1 both         both     6
## 2 none         both     0
## 3 T2           both     0
## 4 both         none     6
## 5 none         none     0
## 6 T2           none     0
## 7 both         T2       1
## 8 none         T2       0
## 9 T2           T2       0
```

```
plot_confusion_matrix(confusion_matrix, add_sums=FALSE)
```

