Osmia Apple Orchard Nesting Structure Survival Rate

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1. Introduction

1.1 Background

Like many species around the world, pollinators are heavily affected by habitat loss, often driven by agricultural intensification, among other factors like pesticide use, disease and climate change (Potts et al. 2010). Natural habitats provide floral and nesting resources to pollinators which are both essential to survival and growth (Roulston and Goodell 2011). Ironically, while, most pollinator population declines are often attributed to agriculture, pollinators have been shown to not only enhance crop production but also, to be uniquely essential to the production of certain crops like macadamia, cantaloupe and watermelon (Klein et al. 2006). Several studies have used artificial nesting structures, also known as trap nests or bee hotels (Geslin et al. 2020), to not only study wild bees but also, to promote their conservation in urban and agricultural settings (MacIvor and Packer 2015; N. K. Boyle and Pitts-Singer 2017). Understanding how bees respond to their environment, and in particular, to changes in resource availability like with floral and nesting resources, can allow us to better predict their abundance and by extension their survival. Most importantly, this can aid in developping better conservation strategies in both natural and agricultural environments.

1.2 Study System

While nesting structures are widely used in the study of bees, no study has yet examined whether the provision of nesting structures actually increases local bee populations in comparison to control populations, establishing that bees are nest site limited (Westerfelt, Weslien, and Widenfalk 2018; Roulston and Goodell 2011). In order to conduct such a study, I must first test that nesting structures installed in anthropogenic habitat are not a population sink, attracting nesting female bees to a potentially unfit environment for larval survival, which could theoretically harm, rather than protect, local wild bee populations.

In Hungarian apple orchards, it has been found that when comparing nesting structures installed in paired apple orchard and natural habitat sites, higher colonization rates and counts of bee and wasp live offspring were observed in semi-natural habitat (Bihaly et al. 2020). This is possibly due to a higher prevalence of floral resources in semi-natural habitat when compared to orchard floral resources (Bihaly et al. 2020).

In fruit orchards, a wide variety of pollinators such as butterflies, wasps and of course, bees, both domestic and wild, can be found. *Osmia* spp. is a common wild bee genus in fruit orchards that distinguishes itself from other bees, like honey bees, by its ability to fly at cooler temperatures (Isaacs et al. 2017; Natalie K. Boyle and Pitts-Singer 2019) and deposit higher pollen loads on a wide-range of flowers (Földesi et al. 2015). To test whether similar observations can be made in orchards within the greater Ottawa area, nesting structure survival rates of *Osmia* spp. ("mason bees") offspring in orchard and natural habitats will be compared with one another.

Figure 1: Osmia Entering Nesting Structure

1.3 Hypothesis

The installation of nesting structures in apple orchards, are potential population sinks rather than populations sources, conceivably due to lesser floral resource availability over the entire growing season. As a result, nesting structures in natural habitat will have a greater ratio of survival of *Osmia spp.* offspring when compared to apple orchard habitat.

1.4 Prediction

If nesting structures placed in natural environments have a significantly greater *Osmia spp.* survival ratio than orchard environments, then it is likely that nesting structures placed in orchard environments are an *Osmia spp.* population sink.

2. Methods

2.1 Data Collection

This study was conducted from May to August 2017 in 7 apple orchards and 8 natural habitats (6 on National Capital Commission (NCC) grounds and 2 on City of Ottawa grounds) around the Ottawa-area for a total of 15 sites. Overall, 75 nesting blocks were installed in both natural and orchard habitats with 5 blocks per site. Each block had 10 nests or holes.

Throughout these 4 months, various insects, mostly wasps and bees, inhabited the holes, and some nested within them, laying their eggs. The eggs developed first as larvae, then as pupae. In September, the blocks were collected and stored in a laboratory environment where the insects over-wintered (hibernated). Before their expected scheduled emergence, the nests were inspected and *Osmia* spp. cell survival count was estimated using visual markers such as nest material and cell size.

2.2 Data Set

The "Osmia Survival.xlsx" data set contains the data that will be used for subsequent statistical analyses. It includes information such as the original number of cells observed in the straw (*No.cells*), the initial perceived number of surviving cells (*No.surv.cells*) as well as a validated revised number of surviving *Osmia* spp. cells (*No.surv.osmia*). The number of *Osmia* spp. cell deaths was calculated as the difference between the number of cells and the revised number of surviving *Osmia* spp. cells (*No.death*).

It is important to note that the number of surviving cells does not account for bees that died over winter due to unfavorable storage conditions. Therefore, we are only accounting for deaths of bees that have clearly died as larvae either through parasitization or other un-diagnosed causes. Deaths at the larval stage can only be attributed to causes occurring during the growing season or associated with either orchard or natural conditions. By the developmental stage of adult eclosion, nests were already transferred to a laboratory environment. Any deaths occurring at the adult stage are therefore ignored.

2.2 Statistical Methods

To explore frequentist and bayesian statistics, as an exercise, I will be running the same model using these two different approaches. Due to differences in code structure, the response for the frequentist approach will be written as ratio (*No.surv.osmia/No.cells*) while the bayesian approach will be written as a combined column (*cbind(No.surv.osmia, No.death)*). The random effects of each approach will be the same (block ID nested within site ID).

Because the response that is measured is the proportion of surviving Osmia offspring, the data will is not normally distributed but binomially distributed. This was verified using both a histogram (***Figure__***) of the distribution of the frequency of *Osmia* spp. survival ratios and a q-q plot (***Figure__***). Thus, all models will be run using a binomial distribution.

```
## [1] 28 62
```

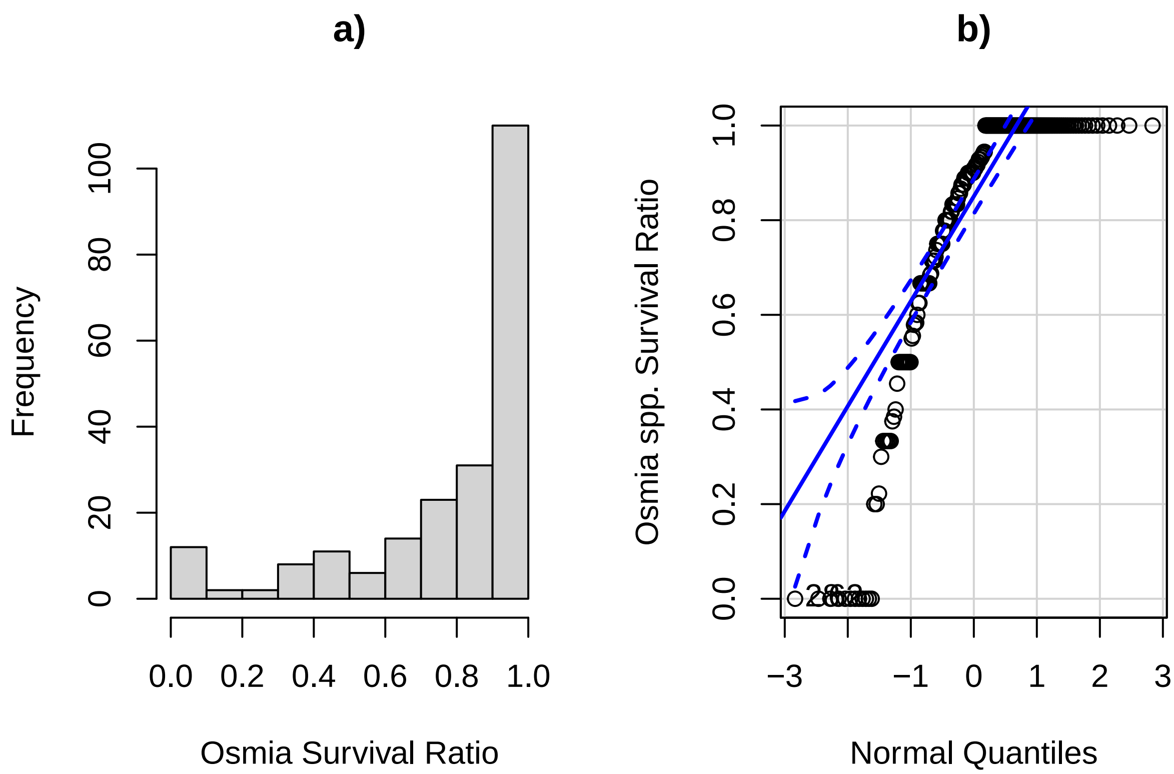

Figure 2: Normality Tests of *Osmia* spp. survival ratio a) Histogram and b) Q-Q Plot

2.2.1 Frequentist Approach

Knowing that the data was hierarchical with random effects of block nested within site, I wanted to test the significance of these terms. To do this, I ran a simple generalized linear model (GLM).

```
##
## Call:
## glm(formula = No.surv.osmia/No.cells ~ s.type, family = binomial(link = "logit"),
##     data = Osmia, weights = No.cells)
##
## Deviance Residuals:
##     Min       1Q   Median       3Q      Max
## -5.6454  -0.6845   0.6313   1.4834   2.6942
##
## Coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.5839     0.0918   17.25   <2e-16 ***
## s.typeo      -0.0851     0.1290   -0.66    0.509
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##     Null deviance: 576.71  on 218  degrees of freedom
## Residual deviance: 576.28  on 217  degrees of freedom
## AIC: 820.78
##
## Number of Fisher Scoring iterations: 4
```

Out of curiosity, I also wanted to test the results that I would get if I ignored the hierarchical structure of the data and simply fit site as a random effect in a generalized linear mixed model (GLMM).

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: No.surv.osmia/No.cells ~ s.type + (1 | s.ID)
##    Data: Osmia
##
##      AIC      BIC   logLik deviance df.resid
##    198.0    208.2    -96.0    192.0      216
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.4651 -0.4188  0.1935  0.4577  0.4577
##
## Random effects:
##  Groups Name        Variance Std.Dev.
##  s.ID   (Intercept) 0        0
## Number of obs: 219, groups:  s.ID, 15
##
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.5629     0.2345   6.666 2.64e-11 ***
## s.typeo       0.2416     0.3802   0.635    0.525
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##         (Intr)
## s.typeo -0.617
## optimizer (Nelder_Mead) convergence code: 0 (OK)
## boundary (singular) fit: see ?isSingular
```

Afterwards, I accounted for the hierarchical structure of the data and ran a more adequate GLMM using block nested within site as a random effect.

```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: No.surv.osmia/No.cells ~ s.type + (1 | s.ID/Block_ID)
##    Data: Osmia
```

```
## Weights: No.cells
##
##      AIC      BIC   logLik deviance df.resid
##    765.5    779.0   -378.7    757.5      215
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.6866 -0.6447  0.4800  0.9038  1.8469
##
## Random effects:
##  Groups        Name        Variance Std.Dev.
##  Block_ID:s.ID (Intercept) 0.70518  0.8397
##  s.ID          (Intercept) 0.06338  0.2518
## Number of obs: 219, groups:  Block_ID:s.ID, 57; s.ID, 15
##
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  1.77702    0.22137   8.027 9.97e-16 ***
## s.typeo      0.04725    0.31990   0.148    0.883
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##         (Intr)
## s.typeo -0.666
```

2.2.1.1 Frequentist Key Assumptions The main assumption of a GLMM, is that the chosen probability distribution and associated link function is appropriate for the data. As previously stated, due to the use of proportional data, the distribution used was binomial and the link function was the logarithm of the odds (logit). Another assumption is that the random effects are normally distributed. Finally, it is assumed that there is no over-dispersion or under-dispersion. This refers to the constancy of the variance and was verified by comparing the ratio of the residual deviance to the degrees of freedom using the *overdisp.glmm* function. A final implicit assumptions of GLMMs as with all model types is to match the model with the data and its structure and to properly identify the fixed versus the random effects.

To evaluate model fit, a likelihood ratio test using the *drop1* function was conducted. The GLMM and GLM versions of the model output (one with the random effect term of block nested within site and one without) were compared via a likelihood ratio test and also by simply comparing their Aikake Information Criteria (AIC) from their model outputs (*Table_*). The normality of the random effects was assessed visually using a q-q plot (*Figure_*). While this is not an explicit assumption of GLMM, the normality of the residuals were evaluated visually using a residuals versus fitted values plot (*Figure_*).

2.2.2 Bayesian Approach

Two Monte Carlo Markov Chains (MCMC) were run following the same model structure described previously (random effects of block nested within site and the binomial probability distribution). The first chain consisted of a test run and was sequenced using the default settings of the *MCMCglmm* package (sample size of 1,000, number of iterations of 13,000, burnin of 3,000, thin of 10). The second chain (with R model output below) was run with a larger sample size and number of iterations as well as adjusted priors (sample size of 4,000, number of iterations of 2,020,000, burnin of 20,000, thin of 500, V=1, nu=1).

```
##
##                        MCMC iteration = 0
```

```
##
##  Acceptance ratio for liability set 1 = 0.000630
##
##                      MCMC iteration = 1000
##
##  Acceptance ratio for liability set 1 = 0.426242
##
##                      MCMC iteration = 2000
##
##  Acceptance ratio for liability set 1 = 0.425689
##
##                      MCMC iteration = 3000
##
##  Acceptance ratio for liability set 1 = 0.425187
##
##                      MCMC iteration = 4000
##
##  Acceptance ratio for liability set 1 = 0.372333
##
##                      MCMC iteration = 5000
##
##  Acceptance ratio for liability set 1 = 0.374589
##
##                      MCMC iteration = 6000
##
##  Acceptance ratio for liability set 1 = 0.378589
##
##                      MCMC iteration = 7000
##
##  Acceptance ratio for liability set 1 = 0.375082
##
##                      MCMC iteration = 8000
##
##  Acceptance ratio for liability set 1 = 0.374447
##
##                      MCMC iteration = 9000
##
##  Acceptance ratio for liability set 1 = 0.367744
##
##                      MCMC iteration = 10000
##
##  Acceptance ratio for liability set 1 = 0.373534
##
##                      MCMC iteration = 11000
##
##  Acceptance ratio for liability set 1 = 0.364521
##
##                      MCMC iteration = 12000
##
##  Acceptance ratio for liability set 1 = 0.364050
##
##                      MCMC iteration = 13000
##
##  Acceptance ratio for liability set 1 = 0.367740
```

```
##
##  Iterations = 3001:12991
##  Thinning interval  = 10
##  Sample size  = 1000
##
##  DIC: 1305.524
##
##  G-structure:  ~s.ID
##
##      post.mean  l-95% CI u-95% CI eff.samp
## s.ID   0.04751 9.591e-17   0.3224    58.36
##
##               ~Block_ID:s.ID
##
##               post.mean  l-95% CI u-95% CI eff.samp
## Block_ID:s.ID     0.156 2.856e-12   0.8865    8.981
##
##  R-structure:  ~units
##
##       post.mean l-95% CI u-95% CI eff.samp
## units     2.335    1.333     3.29    291.5
##
##  Location effects: cbind(No.surv.osmia, No.death) ~ s.type
##
##             post.mean l-95% CI u-95% CI eff.samp  pMCMC
## (Intercept)   2.02339  1.53113  2.44148    419.2 <0.001 ***
## s.typeo       0.05709 -0.57927  0.64097    726.7  0.874
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
##  Iterations = 20001:2019501
##  Thinning interval  = 500
##  Sample size  = 4000
##
##  DIC: 1301.327
##
##  G-structure:  ~s.ID
##
##      post.mean  l-95% CI u-95% CI eff.samp
## s.ID    0.2718 5.478e-09   0.8931     4000
##
##               ~Block_ID:s.ID
##
##               post.mean  l-95% CI u-95% CI eff.samp
## Block_ID:s.ID    0.6005 1.428e-05    1.445     4000
##
##  R-structure:  ~units
##
##       post.mean l-95% CI u-95% CI eff.samp
## units     2.079    1.183    3.101     4251
##
##  Location effects: cbind(No.surv.osmia, No.death) ~ s.type
##
```

```
##              post.mean l-95% CI u-95% CI eff.samp  pMCMC
## (Intercept)    2.0502   1.3993   2.6360     4000 <3e-04 ***
## s.typeo        0.1131  -0.7232   1.0732     4000  0.819
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

2.2.2.1 Bayesian Key Assumptions Posterior trace and density plots were used to visually diagnose the variance and autocorrelation of each iterative value in the chains. The *autocorr.diag* functions were used to assess the autocorrelation of the chain in further detail. The *raftery.diag* function was used to diagnostically determine the optimal sample size for the final chain (sample size of 4,000).

3. Results

3.1 General Results

At the end of August 2017, 71 out of the initial 75 installed nests were occupied, with 37 occupied blocks in natural habitats and 34 occupied blocks in orchard habitats by various species of bees and wasps.

3.2 Statistical Results

3.2.1 Frequentist Results

Following the GLMM, in ***Figure 2***, we see that orchard sites do not have a significant effect on *Osmia* spp. survival (p = 0.883) and that as a result, there is no difference among survival ratios in orchard sites when compared to natural sites. This applies not only to the GLMM ouput in ***Figure 2a*** but also the means of the raw data in ***Figure 2b***.

```
##     Straw no. Container s.ID s.type Block Hole Date started Date collected Size
## 1         1.0         1   MB      n     2    8   2017-05-18     2017-05-18    s
## 2         2.0         1   CH      n     1    9   2017-05-09     2017-05-22    m
## 3         3.0         1   CH      n     4    6   2017-05-09     2017-05-22    l
## 4         4.0         1   CH      n     5    5   2017-05-09     2017-05-22    l
## 5         5.0         1   CH      n     5    9   2017-05-22     2017-05-22    m
## 6         6.0         1   CH      n     5   10   2017-05-22     2017-05-22    m
## 7         7.0         1   DF      o     4    3   2017-05-22     2017-05-22    s
## 8         8.0         1   DF      o     4    4   2017-05-15     2017-05-22    s
## 9         9.0         1   SS      n     5    2   2017-05-23     2017-05-23    m
## 10       10.0         1   BP      n     1    9   2017-05-24     2017-05-24    m
## 11       11.0         1   CO      n     1    6   2017-05-11     2017-05-24    l
## 12       12.0         1   CO      n     1    7   2017-05-16     2017-05-24    s
## 13       13.0         1   CO      n     2    5   2017-05-16     2017-05-24    l
## 14       14.0         1   CO      n     4    9   2017-05-16     2017-05-24    m
## 15       15.0         1   VW      o     2    4   2017-05-19     2017-05-26    s
## 16       16.0         1   VW      o     3    8   2017-05-19     2017-05-26    s
## 17       18.0         1   DF      o     5    4   2017-05-22     2017-05-30    s
## 18       19.0         1   DF      o     3   10   2017-05-15     2017-05-30    m
## 19       20.0         1   SB      n     1    3   2017-05-23     2017-05-30    s
## 20       21.0         1   SS      n     3    3   2017-05-23     2017-05-30    s
## 21       22.0         1   SS      n     3    7   2017-05-23     2017-05-30    s
## 22       23.0         1   SS      n     5    1   2017-05-23     2017-05-30    m
```

```
## 23        24.0          1  BP     n     1    7  2017-05-30     2017-05-30     s
## 24        25.0          1  BP     n     1   10  2017-05-24     2017-05-30     m
## 25        28.0          1  VW     o     3    4  2017-05-26     2017-05-30     s
## 26        29.0          1  CA     o     3    7  2017-05-25     2017-05-30     s
## 27        30.0          1  AL     n     4    7  2017-05-24     2017-05-30     s
## 28        31.0          1  CO     n     1    8  2017-05-30     2017-05-30     s
## 29        32.0          1  CO     n     3    1  2017-06-01     2017-05-30     m
## 30        33.0          1  CO     n     3    3  2017-05-16     2017-05-30     s
## 31        34.0          1  MB     n     2   10  2017-05-18     2017-05-30     m
## 32        35.0          1  DF     o     3    8  2017-05-22     2017-06-05     s
## 33        36.0          1  CP     o     1    8  2017-05-26     2017-06-09     s
## 34        37.0          1  CP     o     3    8  2017-05-26     2017-06-09     s
## 35        38.0          1  CP     o     3    9  2017-05-26     2017-06-09     s
## 36        39.0          1  CP     o     4    4  2017-05-26     2017-06-09     s
## 37        40.0          1  CP     o     4    8  2017-05-26     2017-06-09     s
## 38        41.0          1  VW     o     5    3  2017-05-26     2017-06-09     s
## 39        42.0          1  VW     o     2    7  2017-05-26     2017-06-09     s
## 40        43.0          1  SS     n     1    1  2017-06-13     2017-06-13     m
## 41        44.0          1  SS     n     1    4  2017-05-30     2017-06-13     s
## 42        45.0          1  SS     n     1    7  2017-06-13     2017-06-13     s
## 43        46.0          1  SS     n     1    8  2017-05-30     2017-06-13     s
## 44        47.0          1  SS     n     2    3  2017-06-13     2017-06-13     s
## 45        47.1          1  SS     n     2    6  2017-06-13     2017-06-13     s
## 46        48.0          1  SS     n     3    2  2017-06-13     2017-06-13     m
## 47        49.0          1  SS     n     3    3  2017-06-13     2017-06-13     s
## 48        50.0          1  SS     n     3    4  2017-05-30     2017-06-13     s
## 49        51.0          1  SS     n     3    7  2017-06-13     2017-06-13     s
## 50        52.0          1  SS     n     3    8  2017-05-30     2017-06-13     s
## 51        53.0          1  SS     n     3    9  2017-05-30     2017-06-13     m
## 52        54.0          1  SS     n     3   10  2017-06-13     2017-06-13     m
## 53        55.0          1  SS     n     4    2  2017-06-13     2017-06-13     m
## 54        56.0          1  SS     n     3    9  2017-06-13     2017-06-13     m
## 55        57.0          1  SS     n     4    6  2017-05-23     2017-06-13     l
## 56        58.0          1  SS     n     4    7  2017-06-13     2017-06-13     s
## 57        59.0          1  SS     n     5    1  2017-06-13     2017-06-13     m
## 58        60.0          1  SS     n     5    2  2017-06-13     2017-06-13     m
## 59        61.0          1  CO     n     1   10  2017-05-16     2017-06-13     m
## 60        62.0          1  CO     n     2    4  2017-06-13     2017-06-13     s
## 61        63.0          1  CO     n     3    3  2017-06-13     2017-06-13     s
## 62        64.0          1  CO     n     3    8  2017-06-01     2017-06-13     s
## 63        65.0          1  CO     n     4    8  2017-06-01     2017-06-13     s
## 64        66.0          1  AL     n     4    3  2017-06-01     2017-06-13     s
## 65        67.0          1  AL     n     4    7  2017-06-13     2017-06-13     s
## 66        67.1          1  AL     n     4    8  2017-06-13     2017-06-13     s
## 67        68.0          1  AL     n     3    3  2017-06-01     2017-06-13     s
## 68        69.0          1  AL     n     3    7  2017-06-13     2017-06-13     s
## 69        70.0          1  AL     n     1    3  2017-06-13     2017-06-13     s
## 70        71.0          1  AL     n     1    7  2017-05-24     2017-06-13     s
## 71        72.0          1  AL     n     1    8  2017-06-01     2017-06-13     s
## 72        73.0          1  MF     n     1   10  2017-06-14     2017-06-14     m
## 73        74.0          1  MF     n     3    3  2017-05-24     2017-06-14     s
## 74        75.0          1  MF     n     3    7  2017-06-14     2017-06-14     s
## 75        76.0          1  BP     n     1    1  2017-06-14     2017-06-14     m
## 76        77.0          1  BP     n     1    2  2017-06-14     2017-06-14     m
```

```
## 77      78.0        1  BP     n    1    4  2017-06-14    2017-06-14    s
## 78      79.0        1  BP     n    1    6  2017-05-24    2017-06-14    l
## 79      80.0        1  BP     n    1   10  2017-06-14    2017-06-14    m
## 80      81.0        1  BP     n    2    8  2017-05-30    2017-06-14    s
## 81      87.0        1  BP     n    4    7  2017-05-24    2017-06-14    s
## 82      91.0        1  MB     n    1    8  2017-06-14    2017-06-14    s
## 83      92.0        1  MB     n    1    7  2017-05-18    2017-06-14    s
## 84      93.0        1  MB     n    2    4  2017-06-14    2017-06-14    s
## 85      94.0        1  MB     n    2    8  2017-06-14    2017-06-14    s
## 86      97.0        1  MB     n    5    7  2017-06-14    2017-06-14    s
## 87      98.0        2  CA     o    1   10  2017-05-25    2017-06-15    m
## 88     100.0        2  CA     o    3    4  2017-05-25    2017-06-15    s
## 89     101.0        2  CA     o    5    4  2017-05-19    2017-06-15    s
## 90     103.0        2  CH     n    1    2  2017-06-15    2017-06-15    m
## 91     104.0        2  CH     n    1    3  2017-06-15    2017-06-15    s
## 92     105.0        2  CH     n    1    6  2017-05-09    2017-06-15    l
## 93     106.0        2  CH     n    1   10  2017-05-09    2017-06-15    m
## 94     116.0        2  CH     n    4   10  2017-05-22    2017-06-15    m
## 95     122.0        2  HM     o    1    9  2017-05-22    2017-06-21    s
## 96     125.0        2  HM     o    2    7  2017-05-30    2017-06-21    s
## 97     129.0        2  DF     o    2    3  2017-06-21    2017-06-21    s
## 98     130.0        2  DF     o    2    7  2017-06-21    2017-06-21    s
## 99     132.0        2  DF     o    3    2  2017-06-21    2017-06-21    m
## 100    133.0        2  DF     o    3    6  2017-06-05    2017-06-21    l
## 101    135.1        2  DF     o    4    3  2017-06-21    2017-06-21    s
## 102    136.0        2  DF     o    4    7  2017-05-22    2017-06-21    s
## 103    148.0        2  SB     n    5    4  2017-06-05    2017-06-21    s
## 104    149.0        2  SB     n    5    7  2017-06-21    2017-06-21    s
## 105    150.0        2  SB     n    5    9  2017-06-21    2017-06-21    m
## 106    151.0        2  SB     n    4    4  2017-06-21    2017-06-21    s
## 107    152.0        2  SB     n    4    3  2017-06-21    2017-06-21    s
## 108    153.0        2  SB     n    3    4  2017-06-21    2017-06-21    s
## 109    154.0        2  SB     n    3    7  2017-06-21    2017-06-21    s
## 110    155.0        2  SB     n    3    8  2017-06-21    2017-06-21    s
## 111    156.0        2  SB     n    3   10  2017-06-21    2017-06-21    m
## 112    157.0        2  SB     n    1    3  2017-06-05    2017-06-21    s
## 113    158.0        2  SB     n    1    4  2017-06-21    2017-06-21    s
## 114    159.0        2  SB     n    1    7  2017-05-23    2017-06-21    s
## 115    161.0        2  FF     o    3    8  2017-06-21    2017-06-22    s
## 116    162.0        2  FF     o    4    8  2017-05-11    2017-06-22    s
## 117    163.0        2  FF     o    5    7  2017-06-02    2017-06-22    s
## 118    168.0        2  OR     o    4    8  2017-05-15    2017-06-22    s
## 119    172.0        2  CP     o    2    7  2017-05-26    2017-06-22    s
## 120    173.0        2  CP     o    3    3  2017-05-26    2017-06-22    s
## 121    174.0        2  CP     o    3    7  2017-05-26    2017-06-22    s
## 122    175.0        2  CP     o    4    3  2017-05-26    2017-06-22    s
## 123    176.0        2  CP     o    4    7  2017-05-26    2017-06-22    s
## 124    177.0        2  CP     o    4    9  2017-05-26    2017-06-22    m
## 125    178.0        2  CP     o    4   10  2017-06-22    2017-06-22    s
## 126    180.0        2  VW     o    1    7  2017-05-26    2017-06-22    s
## 127    181.0        2  VW     o    1    8  2017-06-09    2017-06-22    s
## 128    182.0        2  VW     o    2    3  2017-05-26    2017-06-22    s
## 129    183.0        2  VW     o    2    4  2017-06-09    2017-06-22    s
## 130    184.0        2  VW     o    3    3  2017-05-31    2017-06-22    s
```

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## 131     185.0        2  VW    o   4   3  2017-05-26   2017-06-22   s
## 132     186.0        2  VW    o   4   7  2017-05-19   2017-06-22   s
## 133     187.0        2  VW    o   4   8  2017-05-19   2017-06-22   s
## 134     188.0        2  VW    o   5   8  2017-06-09   2017-06-22   s
## 135     190.0        2  CA    o   1   7  2017-06-15   2017-06-26   s
## 136     192.0        2  CA    o   2   8  2017-06-15   2017-06-26   s
## 137     193.0        2  CA    o   3   3  2017-06-15   2017-06-26   s
## 138     194.0        2  CA    o   4   4  2017-06-15   2017-06-26   s
## 139     195.0        2  CA    o   5   7  2017-06-15   2017-06-26   s
## 140     196.0        2  CO    n   3   1  2017-06-26   2017-06-26   m
## 141     198.0        2  CO    n   3   3  2017-06-26   2017-07-25   s
## 142     199.0        2  CO    n   3   4  2017-05-16   2017-06-26   s
## 143     201.0        2  CO    n   4   3  2017-06-13   2017-06-26   s
## 144     202.0        2  CO    n   4   4  2017-06-13   2017-06-26   s
## 145     203.0        2  CO    n   4   6  2017-05-11   2017-06-26   l
## 146     204.0        2  CO    n   4  10  2017-06-13   2017-06-26   m
## 147     205.0        2  MB    n   1   8  2017-06-26   2017-06-26   s
## 148     213.0        2  MB    n   5   4  2017-06-14   2017-06-26   s
## 149     214.0        2  MB    n   5   7  2017-06-26   2017-06-26   s
## 150     217.0        3  CH    n   1   9  2017-06-15   2017-06-27   m
## 151     232.0        3  SS    n   2   3  2017-06-27   2017-06-27   s
## 152     236.0        3  SS    n   3   5  2017-06-13   2017-06-27   l
## 153     243.0        3  SS    n   4   3  2017-06-27   2017-06-27   s
## 154     244.0        3  SS    n   4   4  2017-06-27   2017-06-27   s
## 155     247.0        3  SS    n   4   8  2017-06-13   2017-06-27   s
## 156     252.0        3  SS    n   5   4  2017-06-27   2017-06-27   s
## 157     256.0        3  MF    n   1   4  2017-06-14   2017-06-28   s
## 158     257.0        3  MF    n   3   4  2017-06-14   2017-06-28   s
## 159     261.0        3  BP    n   1   3  2017-06-14   2017-06-28   s
## 160     263.0        3  BP    n   2   3  2017-06-28   2017-06-28   s
## 161     264.0        3  BP    n   2   7  2017-06-14   2017-06-28   s
## 162     266.0        3  BP    n   4   2  2017-06-14   2017-06-28   m
## 163     271.0        3  AL    n   3   3  2017-06-28   2017-06-28   s
## 164     272.0        3  AL    n   3   8  2017-06-13   2017-06-28   s
## 165     279.0        3  CP    o   1   8  2017-06-21   2017-07-07   s
## 166     280.0        3  CP    o   3   8  2017-06-21   2017-07-07   s
## 167     281.0        3  CP    o   4   4  2017-06-21   2017-07-07   s
## 168     282.0        3  CP    o   5   3  2017-05-26   2017-07-07   s
## 169     283.0        3  VW    o   5   4  2017-06-21   2017-07-07   s
## 170     284.0        3  VW    o   5   7  2017-05-26   2017-07-07   s
## 171     285.0        3  VW    o   4   4  2017-06-21   2017-07-07   s
## 172     286.0        3  VW    o   3   4  2017-06-21   2017-07-07   s
## 173     287.0        3  VW    o   3   7  2017-05-19   2017-07-07   s
## 174     288.0        3  VW    o   3   8  2017-06-21   2017-07-07   s
## 175     289.0        3  VW    o   3   9  2017-06-21   2017-07-07   m
## 176     290.0        3  VW    o   2   7  2017-07-07   2017-07-07   s
## 177     291.0        3  VW    o   1   3  2017-06-21   2017-07-07   s
## 178     292.0        3  VW    o   1   4  2017-05-26   2017-07-07   s
## 179     298.0        3  CO    n   3   7  2017-06-26   2017-07-10   s
## 180     308.0        3  SS    n   3   7  2017-07-12   2017-07-12   s
## 181     308.1        3  SS    n   3  10  2017-07-12   2017-07-12   m
## 182     327.0        4  SB    n   2   4  2017-07-14   2017-07-14   s
## 183     330.0        4  SB    n   5   3  2017-06-21   2017-07-14   s
## 184     333.0        4  SB    n   5  10  2017-06-21   2017-07-14   m
```

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## 185     334.0           4   SB      n     4    3   2017-06-21     2017-07-14    s
## 186     335.0           4   SB      n     4    4   2017-07-14     2017-07-14    s
## 187     336.0           4   SB      n     3    1   2017-06-21     2017-07-14    m
## 188     339.0           4   SB      n     3    4   2017-07-14     2017-07-14    s
## 189     343.0           3   DF      o     3    1   2017-06-21     2017-07-14    m
## 190     350.0           4   CA      o     3    8   2017-05-19     2017-07-15    s
## 191     356.0           4   FF      o     1    3   2017-07-06     2017-07-18    s
## 192     358.0           4   FF      o     3    3   2017-06-21     2017-07-18    s
## 193     362.0           4   FF      o     4    4   2017-06-21     2017-07-18    s
## 194     363.0           4   FF      o     4    7   2017-06-21     2017-07-18    s
## 195     365.0           4   MB      n     1    4   2017-06-26     2017-07-18    s
## 196     376.0           4   MB      n     5    7   2017-07-18     2017-07-18    s
## 197     380.0           4   BP      n     5    4   2017-06-28     2017-07-18    s
## 198     398.0           4   HM      o     2    4   2017-06-21     2017-07-19    s
## 199     423.0           4   VW      o     5    2   2017-07-20     2017-07-20    m
## 200     428.0           4   VW      o     4    8   2017-07-20     2017-07-20    s
## 201     438.0           4   CP      o     1    4   2017-07-07     2017-07-20    s
## 202     439.0           4   CP      o     1    7   2017-07-07     2017-07-20    s
## 203     440.0           4   CP      o     1   10   2017-06-21     2017-07-20    m
## 204     442.0           4   CP      o     4    7   2017-07-07     2017-07-20    s
## 205     443.0           4   CP      o     4    8   2017-06-21     2017-07-20    s
## 206     446.1           5   CO      n     3    3   2017-07-25     2017-07-25    s
## 207     468.0           5   DF      o     4    8   2017-07-14     2017-07-26    s
## 208     500.0           5   HM      o     5    8   2017-07-19     2017-08-01    s
## 209     507.0           5   HM      o     1    3   2017-06-21     2017-08-01    s
## 210     508.0           5   CP      o     1    8   2017-07-20     2017-08-01    s
## 211     526.0           5   CA      o     3    7   2017-07-15     2017-08-08    s
## 212     527.0           5   CA      o     3    8   2017-08-08     2017-08-08    s
## 213     529.0           5   CA      o     2    3   2017-07-15     2017-08-08    s
## 214     559.0           6   VW      o     4    3   2017-07-07     2017-08-09    s
## 215     569.0           6   CP      o     1    1   2017-07-20     2017-08-09    m
## 216     589.1           6   BP      n     4    7   2017-06-28     2017-08-14    s
## 217     637.0           6   HM      o     5    4   2017-08-01     2017-08-16    s
## 218     639.0           6   HM      o     1    7   2017-08-01     2017-08-16    s
## 219     642.0           6   HM      o     4    3   2017-08-16     2017-08-16    s
##     No.cells No.surv.cells No.surv.osmia  Species      Seal material surv.ratio
## 1          6             6             6 lignaria    dust, clay, mud  1.0000000
## 2         10             9             9 lignaria    dust, clay, mud  0.9000000
## 3          8             7             7 lignaria          clay, mud  0.8750000
## 4         10            10            10 lignaria                mud  1.0000000
## 5          6             6             6 lignaria                mud  1.0000000
## 6          7             7             7 lignaria                mud  1.0000000
## 7          3             3             2   pumila chewed leaf, green  0.6666667
## 8          6             5             5   pumila chewed leaf, green  0.8333333
## 9          9             9             9 lignaria                mud  1.0000000
## 10         7             5             5 lignaria                mud  0.7142857
## 11         9             7             7 lignaria                mud  0.7777778
## 12         5             5             5 lignaria                mud  1.0000000
## 13        11            11            11 lignaria                mud  1.0000000
## 14         7             7             7 lignaria                mud  1.0000000
## 15         9             7             5   pumila chewed leaf, green  0.5555556
## 16         8             8             8   pumila chewed leaf, green  1.0000000
## 17         9             7             7   pumila chewed leaf, green  0.7777778
## 18         9             9             9 lignaria                mud  1.0000000
```

```
## 19         11            9             9   pumila      mud and leaf  0.8181818
## 20         10            3             3   pumila              leaf  0.3000000
## 21          1            1             1   pumila              leaf  1.0000000
## 22          6            5             5 lignaria               mud  0.8333333
## 23          1            1             1 lignaria               mud  1.0000000
## 24          8            8             8 lignaria               mud  1.0000000
## 25          6            6             6   pumila              leaf  1.0000000
## 26          9            8             8   pumila              leaf  0.8888889
## 27         10            5             5   pumila              leaf  0.5000000
## 28          1            0             0   pumila              leaf  0.0000000
## 29          3            3             3   pumila              leaf  1.0000000
## 30         10            9             9   pumila              leaf  0.9000000
## 31          5            1             1 lignaria               mud  0.2000000
## 32          5            1             1 lignaria               mud  0.2000000
## 33          6            6             6   pumila              leaf  1.0000000
## 34         11            9             9   pumila              leaf  0.8181818
## 35          7            7             7   pumila              leaf  1.0000000
## 36          9            8             8   pumila              leaf  0.8888889
## 37          7            7             7   pumila              leaf  1.0000000
## 38         10            9             9   pumila              leaf  0.9000000
## 39          4            2             2   pumila              leaf  0.5000000
## 40          5            5             5   pumila              leaf  1.0000000
## 41         10           10            10   pumila              leaf  1.0000000
## 42          8            8             8   pumila              leaf  1.0000000
## 43          8            5             5   pumila              leaf  0.6250000
## 44          4            4             4   pumila              leaf  1.0000000
## 45          3            2             2   pumila              leaf  0.6666667
## 46          5            5             5   pumila              leaf  1.0000000
## 47          4            3             3   pumila              leaf  0.7500000
## 48          9            9             9   pumila              leaf  1.0000000
## 49          4            4             4   pumila              leaf  1.0000000
## 50         13           11            11   pumila              leaf  0.8461538
## 51          5            4             4 lignaria               mud  0.8000000
## 52          4            3             3 lignaria               mud  0.7500000
## 53          7            7             7 lignaria               mud  1.0000000
## 54          4            2             2 lignaria               mud  0.5000000
## 55         13           13            13 lignaria               mud  1.0000000
## 56          9            9             9   pumila              leaf  1.0000000
## 57          5            5             5 lignaria               mud  1.0000000
## 58          9            9             9 lignaria               mud  1.0000000
## 59          3            1             1 lignaria               mud  0.3333333
## 60          5            5             5   pumila              leaf  1.0000000
## 61          5            5             5   pumila              leaf  1.0000000
## 62          5            5             0   pumila              leaf  0.0000000
## 63          8            7             7   pumila              leaf  0.8750000
## 64          7            7             7   pumila              leaf  1.0000000
## 65          4            4             4   pumila              leaf  1.0000000
## 66          4            4             4   pumila              leaf  1.0000000
## 67          6            6             6   pumila              leaf  1.0000000
## 68         14           12            12   pumila              leaf  0.8571429
## 69          4            4             4   pumila              leaf  1.0000000
## 70         15           12            12   pumila              leaf  0.8000000
## 71         18           13            13   pumila              leaf  0.7222222
## 72          8            8             8   pumila              leaf  1.0000000
```

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## 73          7             5             5   pumila          leaf  0.7142857
## 74          9             6             0   pumila          leaf  0.0000000
## 75          7             7             7 lignaria           mud  1.0000000
## 76          6             5             5 lignaria           mud  0.8333333
## 77          2             2             2 lignaria           mud  1.0000000
## 78         11            10            10 lignaria           mud  0.9090909
## 79          8             7             7 lignaria           mud  0.8750000
## 80         13            13            13   pumila          leaf  1.0000000
## 81         18            17            17   pumila          leaf  0.9444444
## 82          9             9             9   pumila          leaf  1.0000000
## 83          3             1             1   pumila          leaf  0.3333333
## 84          4             4             4 lignaria           mud  1.0000000
## 85          3             3             3 lignaria           mud  1.0000000
## 86         10             9             9   pumila          leaf  0.9000000
## 87          2             2             2   pumila          leaf  1.0000000
## 88          5             5             5   pumila          leaf  1.0000000
## 89          9             9             9   pumila          leaf  1.0000000
## 90          3             2             2 lignaria           mud  0.6666667
## 91          7             6             6   pumila    leaf + mud  0.8571429
## 92          8             8             8 lignaria           mud  1.0000000
## 93          6             4             4 lignaria           mud  0.6666667
## 94          4             2             2 lignaria           mud  0.5000000
## 95          7             5             5   pumila          leaf  0.7142857
## 96         12            11            11   pumila          leaf  0.9166667
## 97         14            13            13   pumila          leaf  0.9285714
## 98         12            12            12   pumila          leaf  1.0000000
## 99          4             3             3 lignaria           mud  0.7500000
## 100         4             3             3 lignaria           mud  0.7500000
## 101         3             2             2   pumila          leaf  0.6666667
## 102         5             4             4   pumila          leaf  0.8000000
## 103         6             6             6   pumila          leaf  1.0000000
## 104         2             2             2   pumila          leaf  1.0000000
## 105        11            10            10   pumila          leaf  0.9090909
## 106         9             6             6   pumila          leaf  0.6666667
## 107        13            12            12   pumila          leaf  0.9230769
## 108         7             6             6   pumila          leaf  0.8571429
## 109        15            14            14   pumila          leaf  0.9333333
## 110        19            14            14   pumila          leaf  0.7368421
## 111         9             8             8   pumila          leaf  0.8888889
## 112        10             9             9   pumila          leaf  0.9000000
## 113        12             7             7   pumila          leaf  0.5833333
## 114         5             0             0   pumila          leaf  0.0000000
## 115        13             5             5   pumila          leaf  0.3846154
## 116        20            11            11   pumila          leaf  0.5500000
## 117         9             9             9   pumila          leaf  1.0000000
## 118        12            11            11   pumila          leaf  0.9166667
## 119         5             5             5   pumila          leaf  1.0000000
## 120         8             4             4   pumila          leaf  0.5000000
## 121        14            13            13   pumila          leaf  0.9285714
## 122        13            13            13   pumila          leaf  1.0000000
## 123        15            15            15   pumila          leaf  1.0000000
## 124         1             1             1   pumila          leaf  1.0000000
## 125        11            10            10   pumila          leaf  0.9090909
## 126         5             4             4   pumila          leaf  0.8000000
```

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## 127        11             5             5   pumila            leaf  0.4545455
## 128         9             6             6   pumila            leaf  0.6666667
## 129         2             1             1   pumila            leaf  0.5000000
## 130        19            11            11   pumila            leaf  0.5789474
## 131         6             6             6   pumila            leaf  1.0000000
## 132        16            12            12   pumila            leaf  0.7500000
## 133        12            12            12   pumila            leaf  1.0000000
## 134         8             3             3   pumila            leaf  0.3750000
## 135         8             8             8   pumila            leaf  1.0000000
## 136         3             3             3   pumila            leaf  1.0000000
## 137        13            13            13   pumila            leaf  1.0000000
## 138         8             8             8   pumila            leaf  1.0000000
## 139         1             1             1   pumila            leaf  1.0000000
## 140         1             1             1   pumila            leaf  1.0000000
## 141         3             2             2   pumila            leaf  0.6666667
## 142        12             7             7   pumila            leaf  0.5833333
## 143         2             0             0   pumila            leaf  0.0000000
## 144         9             7             7   pumila            leaf  0.7777778
## 145         2             2             2 lignaria        mud+leaf  1.0000000
## 146         1             0             0   pumila            leaf  0.0000000
## 147         3             2             2   pumila            leaf  0.6666667
## 148         8             8             8   pumila            leaf  1.0000000
## 149         1             1             1   pumila            leaf  1.0000000
## 150         1             1             1 lignaria             mud  1.0000000
## 151         2             2             2   pumila            leaf  1.0000000
## 152         2             0             0 lignaria             mud  0.0000000
## 153         1             1             1   pumila            leaf  1.0000000
## 154         3             3             3   pumila            leaf  1.0000000
## 155         6             6             6   pumila            leaf  1.0000000
## 156         6             6             6 lignaria             mud  1.0000000
## 157         6             5             5   pumila            leaf  0.8333333
## 158         2             1             1   pumila            leaf  0.5000000
## 159         3             1             1 lignaria             mud  0.3333333
## 160         1             1             1   pumila            leaf  1.0000000
## 161         5             5             5   pumila            leaf  1.0000000
## 162        10             8             8   pumila            leaf  0.8000000
## 163         3             1             1   pumila            leaf  0.3333333
## 164         8             6             6   pumila            leaf  0.7500000
## 165        18             4             4   pumila            leaf  0.2222222
## 166        16            11            11   pumila            leaf  0.6875000
## 167        18            17            17   pumila            leaf  0.9444444
## 168        18            15            15   pumila            leaf  0.8333333
## 169         6             5             5   pumila            leaf  0.8333333
## 170        14            10            10   pumila            leaf  0.7142857
## 171        19            13            13   pumila            leaf  0.6842105
## 172        12            11            11   pumila            leaf  0.9166667
## 173        12             8             8   pumila            leaf  0.6666667
## 174        10             9             9   pumila            leaf  0.9000000
## 175        15            13            13   pumila            leaf  0.8666667
## 176         3             3             3   pumila            leaf  1.0000000
## 177        17            16            16   pumila            leaf  0.9411765
## 178         5             3             3   pumila            leaf  0.6000000
## 179         3             3             3   pumila            leaf  1.0000000
## 180         1             1             1   pumila            leaf  1.0000000
```

```
## 181        5            5            5 lignaria             mud  1.0000000
## 182        5            5            5   pumila            leaf  1.0000000
## 183       11           11           11   pumila            leaf  1.0000000
## 184       11           11           11    other             veg  1.0000000
## 185       14           13           13   pumila            leaf  0.9285714
## 186        4            4            4   pumila            leaf  1.0000000
## 187       15           14           14    other             mud  0.9333333
## 188        5            2            2   pumila            leaf  0.4000000
## 189        3            1            1 lignaria             mud  0.3333333
## 190        9            8            8   pumila            leaf  0.8888889
## 191        6            6            6   pumila            leaf  1.0000000
## 192       10            9            9   pumila            leaf  0.9000000
## 193        8            5            5   pumila            leaf  0.6250000
## 194        5            4            4   pumila            leaf  0.8000000
## 195        2            0            0   pumila            leaf  0.0000000
## 196        4            0            0   pumila            leaf  0.0000000
## 197        4            3            3   pumila            leaf  0.7500000
## 198        2            2            2   pumila            leaf  1.0000000
## 199        6            3            3   pumila            leaf  0.5000000
## 200        5            4            4   pumila            leaf  0.8000000
## 201        8            7            7   pumila            leaf  0.8750000
## 202        6            6            6   pumila            leaf  1.0000000
## 203       16           15           15    other            leaf  0.9375000
## 204       10           10           10   pumila            leaf  1.0000000
## 205       18           18           18   pumila            leaf  1.0000000
## 206        1            0            0   pumila            leaf  0.0000000
## 207        2            2            2   pumila            leaf  1.0000000
## 208       10            9            9   pumila            leaf  0.9000000
## 209       12           10           10   pumila            leaf  0.8333333
## 210       10           10           10   pumila            leaf  1.0000000
## 211        2            1            1   pumila            leaf  0.5000000
## 212        2            1            1   pumila            leaf  0.5000000
## 213        9            9            9   pumila            leaf  1.0000000
## 214        6            6            6   pumila            leaf  1.0000000
## 215        9            8            8   pumila            leaf  0.8888889
## 216        2            0            0   pumila            leaf  0.0000000
## 217        8            8            8   pumila            leaf  1.0000000
## 218        5            4            0   pumila            leaf  0.0000000
## 219        9            9            9   pumila            leaf  1.0000000
##     No.death death.ratio Hole_ID Block_ID   .fitted       .resid     .scresid
## 1          0  0.00000000     MB8      MB2  1.3884827  1.634770663  1.223405506
## 2          1  0.10000000     CH9      CH1  1.7992711  0.398124980  0.380027950
## 3          1  0.12500000     CH6      CH4  1.3916143  0.555171296  0.525159483
## 4          0  0.00000000     CH5      CH5  2.7743732  1.100179459  0.789864363
## 5          0  0.00000000     CH9      CH5  2.7743732  0.852195344  0.611826304
## 6          0  0.00000000    CH10      CH5  2.7743732  0.920476175  0.660847939
## 7          1  0.33333333     DF3      DF4  1.4635163 -0.597461963 -0.644673475
## 8          1  0.16666667     DF4      DF4  1.4635163  0.135367920  0.133325798
## 9          0  0.00000000     SS2      SS5  2.7280925  1.067406364  0.766873069
## 10         2  0.28571429     BP9      BP1  1.8715743 -1.055632624 -1.185694904
## 11         2  0.22222222     CO6      CO1  1.1763651  0.095955517  0.095308089
## 12         0  0.00000000     CO7      CO1  1.1763651  1.639522076  1.241768309
## 13         0  0.00000000     CO5      CO2  2.5372655  1.294002414  0.932687480
## 14         0  0.00000000     CO9      CO4  1.4295740  1.733466577  1.294556355
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## 15          4  0.44444444     VW4       VW2  0.7348495 -0.751736414 -0.771155854
## 16          0  0.00000000     VW8       VW3  1.4368296  1.847111203  1.378927398
## 17          2  0.22222222     DF4       DF5  1.5070432 -0.309579082 -0.317998222
## 18          0  0.00000000    DF10       DF3  0.9701857  2.405123711  1.846920130
## 19          2  0.18181818     SB3       SB1  0.8211742  0.935135718  0.890646818
## 20          7  0.70000000     SS3       SS3  1.2400532 -3.197892267 -3.604696740
## 21          0  0.00000000     SS7       SS3  1.2400532  0.712955562  0.537930131
## 22          1  0.16666667     SS1       SS5  2.7280925 -0.899456209 -1.075272316
## 23          0  0.00000000     BP7       BP1  1.8715743  0.535035002  0.392276958
## 24          0  0.00000000    BP10       BP1  1.8715743  1.513307513  1.109526789
## 25          0  0.00000000     VW4       VW3  1.4368296  1.599645225  1.194186157
## 26          1  0.11111111     CA7       CA3  2.1480595 -0.064120860 -0.064706339
## 27          5  0.50000000     AL7       AL4  1.4716069 -2.232978549 -2.542531190
## 28          1  1.00000000     CO8       CO1  1.1763651 -1.700099020 -1.800712711
## 29          0  0.00000000     CO1       CO3  0.9569971  1.396445370  1.073374693
## 30          1  0.10000000     CO3       CO3  0.9569971  1.382943815  1.253453739
## 31          4  0.80000000    MB10       MB2  1.3884827 -2.886329889 -3.358263321
## 32          4  0.80000000     DF8       DF3  0.9701857 -2.443591390 -2.630359710
## 33          0  0.00000000     CP8       CP1  1.2578926  1.732663060  1.305953487
## 34          2  0.18181818     CP8       CP3  1.3728822  0.170155837  0.167945873
## 35          0  0.00000000     CP9       CP3  1.3728822  1.778135496  1.331776793
## 36          1  0.11111111     CP4       CP4  3.0351715 -0.797753479 -0.935758581
## 37          0  0.00000000     CP8       CP4  3.0351715  0.810714143  0.580055961
## 38          1  0.10000000     VW3       VW5  0.8745419  1.489634788  1.348297830
## 39          2  0.50000000     VW7       VW2  0.7348495 -0.726824543 -0.751495745
## 40          0  0.00000000     SS1       SS1  2.1286371  1.060353065  0.771360374
## 41          0  0.00000000     SS4       SS1  2.1286371  1.499565685  1.090868303
## 42          0  0.00000000     SS7       SS1  2.1286371  1.341252324  0.975702272
## 43          3  0.37500000     SS8       SS1  2.1286371 -1.996439004 -2.464894509
## 44          0  0.00000000     SS3       SS2  1.9825128  1.015986877  0.742220287
## 45          1  0.33333333     SS6       SS2  1.9825128 -0.959224948 -1.127217232
## 46          0  0.00000000     SS2       SS3  1.2400532  1.594217101  1.202848340
## 47          1  0.25000000     SS3       SS3  1.2400532 -0.121027909 -0.122593544
## 48          0  0.00000000     SS4       SS3  1.2400532  2.138866685  1.613790393
## 49          0  0.00000000     SS7       SS3  1.2400532  1.425911123  1.075860262
## 50          2  0.15384615     SS8       SS3  1.2400532  0.637014456  0.609969548
## 51          1  0.20000000     SS9       SS3  1.2400532  0.132703840  0.130918669
## 52          1  0.25000000    SS10       SS3  1.2400532 -0.121027909 -0.122593544
## 53          0  0.00000000     SS2       SS4  3.1023241  0.784534586  0.560903181
## 54          2  0.50000000     SS9       SS3  1.2400532 -1.203435851 -1.321047350
## 55          0  0.00000000     SS6       SS4  3.1023241  1.069140424  0.764382189
## 56          0  0.00000000     SS7       SS4  3.1023241  0.889578604  0.636004426
## 57          0  0.00000000     SS1       SS5  2.7280925  0.795597730  0.571593437
## 58          0  0.00000000     SS2       SS5  2.7280925  1.067406364  0.766873069
## 59          2  0.66666667    CO10       CO1  1.1763651 -1.580884205 -1.758660739
## 60          0  0.00000000     CO4       CO2  2.5372655  0.872416250  0.628817771
## 61          0  0.00000000     CO3       CO3  0.9569971  1.802803220  1.385720770
## 62          5  1.00000000     CO8       CO3  0.9569971 -3.580512570 -3.608230539
## 63          1  0.12500000     CO8       CO4  1.4295740  0.514785603  0.488371364
## 64          0  0.00000000     AL3       AL4  1.4716069  1.700925434  1.267633295
## 65          0  0.00000000     AL7       AL4  1.4716069  1.285778770  0.958240701
## 66          0  0.00000000     AL8       AL4  1.4716069  1.285778770  0.958240701
## 67          0  0.00000000     AL3       AL3  1.4913228  1.560776123  1.162087927
## 68          2  0.14285714     AL7       AL3  1.4913228  0.407536442  0.394844992
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## 69          0  0.00000000     AL3       AL1  1.3664280  1.348031196  1.009982654
## 70          3  0.20000000     AL7       AL1  1.3664280  0.030837861  0.030777267
## 71          5  0.27777778     AL8       AL1  1.3664280 -0.755847923 -0.786367061
## 72          0  0.00000000    MF10       MF1  2.0629518  1.383495357  1.008278945
## 73          2  0.28571429     MF3       MF3 -0.1104356  1.296505064  1.281789337
## 74          9  1.00000000     MF7       MF3 -0.1104356 -3.392662042 -2.838837039
## 75          0  0.00000000     BP1       BP1  1.8715743  1.415569559  1.037867276
## 76          1  0.16666667     BP2       BP1  1.8715743 -0.232355044 -0.239982441
## 77          0  0.00000000     BP4       BP1  1.8715743  0.756653757  0.554763394
## 78          1  0.09090909     BP6       BP1  1.8715743  0.435937495  0.414140987
## 79          1  0.12500000    BP10       BP1  1.8715743  0.070183332  0.069550807
## 80          0  0.00000000     BP8       BP2  2.6818121  1.311932496  0.943242966
## 81          1  0.05555556     BP7       BP4  1.6645648  1.358425327  1.201463762
## 82          0  0.00000000     MB8       MB1  1.1132751  2.261118465  1.719398902
## 83          2  0.66666667     MB7       MB1  1.1132751 -1.529128565 -1.683818188
## 84          0  0.00000000     MB4       MB2  1.3884827  1.334784657  0.998906413
## 85          0  0.00000000     MB8       MB2  1.3884827  1.155957421  0.865078329
## 86          1  0.10000000     MB7       MB5  1.3881393  0.854468218  0.788673679
## 87          0  0.00000000    CA10       CA1  2.5374715  0.551709751  0.397658308
## 88          0  0.00000000     CA4       CA3  2.1480595  1.050653283  0.763905795
## 89          0  0.00000000     CA4       CA5  2.5374715  1.170353118  0.843560658
## 90          1  0.33333333     CH2       CH1  1.7992711 -0.835430076 -0.949897736
## 91          1  0.14285714     CH3       CH1  1.7992711 -0.006948196 -0.006954429
## 92          0  0.00000000     CH6       CH1  1.7992711  1.565022883  1.150371834
## 93          2  0.33333333    CH10       CH1  1.7992711 -1.181476544 -1.343358261
## 94          2  0.50000000    CH10       CH4  1.3916143 -1.340870789 -1.506655298
## 95          2  0.28571429     HM9       HM1  0.7884847  0.154120817  0.152861363
## 96          1  0.08333333     HM7       HM2  2.1610396  0.234392271  0.227302482
## 97          1  0.07142857     DF3       DF2  2.4790667  0.083783024  0.082784053
## 98          0  0.00000000     DF7       DF2  2.4790667  1.389904878  1.002924251
## 99          1  0.25000000     DF2       DF3  0.9701857  0.112394043  0.111297170
## 100         1  0.25000000     DF6       DF3  0.9701857  0.112394043  0.111297170
## 101         1  0.33333333     DF3       DF4  1.4635163 -0.597461963 -0.644673475
## 102         1  0.20000000     DF7       DF4  1.4635163 -0.068534810 -0.069086579
## 103         0  0.00000000     SB4       SB5  2.7820883  0.849011042  0.609470684
## 104         0  0.00000000     SB7       SB5  2.7820883  0.490176754  0.351878063
## 105         1  0.09090909     SB9       SB5  2.7820883 -0.428585338 -0.461580931
## 106         3  0.33333333     SB4       SB4  1.9109538 -1.578574686 -1.830652846
## 107         1  0.07692308     SB3       SB4  1.9109538  0.598465487  0.559036249
## 108         1  0.14285714     SB4       SB3  1.6039971  0.177740165  0.174089596
## 109         1  0.06666667     SB7       SB3  1.6039971  1.164905902  1.045202668
## 110         5  0.26315789     SB8       SB3  1.6039971 -1.049776248 -1.117695243
## 111         1  0.11111111    SB10       SB3  1.6039971  0.476617177  0.452487155
## 112         1  0.10000000     SB3       SB1  0.8211742  1.559605067  1.410895714
## 113         5  0.41666667     SB4       SB1  0.8211742 -0.813091814 -0.835913185
## 114         5  1.00000000     SB7       SB1  0.8211742 -3.443483894 -3.371325687
## 115         8  0.61538462     FF8       FF3  0.7133233 -2.111478133 -2.198935064
## 116         9  0.45000000     FF8       FF4  0.6324853 -0.950302981 -0.968208477
## 117         0  0.00000000     FF7       FF5  2.3028539  1.309634831  0.948555791
## 118         1  0.08333333     OR8       OR4  2.0799691  0.318215324  0.305674746
## 119         0  0.00000000     CP7       CP2  2.2027712  1.023754045  0.743291747
## 120         4  0.50000000     CP3       CP3  1.3728822 -1.872471420 -2.097658253
## 121         1  0.07142857     CP7       CP3  1.3728822  1.365420853  1.217937111
## 122         0  0.00000000     CP3       CP4  3.0351715  1.104817146  0.790483029
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## 123          0  0.00000000     CP7       CP4  3.0351715  1.186763987  0.849114982
## 124          0  0.00000000     CP9       CP4  3.0351715  0.306421144  0.219240546
## 125          1  0.09090909    CP10       CP4  3.0351715 -0.633389321 -0.714218461
## 126          1  0.20000000     VW7       VW1  1.1259963  0.238807186  0.233475513
## 127          6  0.54545455     VW8       VW1  1.1259963 -2.129245246 -2.318043189
## 128          3  0.33333333     VW3       VW2  0.7348495 -0.058837849 -0.058980325
## 129          1  0.50000000     VW4       VW2  0.7348495 -0.513942563 -0.531387738
## 130          8  0.42105263     VW3       VW3  1.4368296 -2.286575116 -2.534278563
## 131          0  0.00000000     VW3       VW4  1.5781757  1.500401028  1.112702668
## 132          4  0.25000000     VW7       VW4  1.5781757 -0.796171780 -0.838610611
## 133          0  0.00000000     VW8       VW4  1.5781757  2.121887483  1.573599205
## 134          5  0.62500000     VW8       VW5  0.8745419 -1.933307416 -2.052373487
## 135          0  0.00000000     CA7       CA1  2.5374715  1.103419502  0.795316616
## 136          0  0.00000000     CA8       CA2  2.6037748  0.654450147  0.471148824
## 137          0  0.00000000     CA3       CA3  2.1480595  1.694127514  1.231761084
## 138          0  0.00000000     CA4       CA4  2.4634130  1.143416403  0.825318648
## 139          0  0.00000000     CA7       CA5  2.5374715  0.390117706  0.281186886
## 140          0  0.00000000     CO1       CO3  0.9569971  0.806238110  0.619713168
## 141          1  0.33333333     CO3       CO3  0.9569971 -0.212058537 -0.216057991
## 142          5  0.41666667     CO4       CO3  0.9569971 -1.034200711 -1.076832323
## 143          2  1.00000000     CO3       CO4  1.4295740 -2.564535211 -2.890300891
## 144          2  0.22222222     CO4       CO4  1.4295740 -0.216877009 -0.220809515
## 145          0  0.00000000     CO6       CO4  1.4295740  0.926576860  0.691969478
## 146          1  1.00000000    CO10       CO4  1.4295740 -1.813400238 -2.043751360
## 147          1  0.33333333     MB8       MB1  1.1132751 -0.334191610 -0.345561384
## 148          0  0.00000000     MB4       MB5  1.3881393  1.887961205  1.412909626
## 149          0  0.00000000     MB7       MB5  1.3881393  0.667495085  0.499538989
## 150          0  0.00000000     CH9       CH1  1.7992711  0.553319147  0.406717862
## 151          0  0.00000000     SS3       SS2  1.9825128  0.718411211  0.524828998
## 152          2  1.00000000     SS5       SS3  1.2400532 -2.444754390 -2.628991165
## 153          0  0.00000000     SS3       SS4  3.1023241  0.296526201  0.212001475
## 154          0  0.00000000     SS4       SS4  3.1023241  0.513598447  0.367197326
## 155          0  0.00000000     SS8       SS4  3.1023241  0.726337889  0.519295439
## 156          0  0.00000000     SS4       SS5  2.7280925  0.871533647  0.626149239
## 157          1  0.16666667     MF4       MF1  2.0629518 -0.393336596 -0.417556680
## 158          1  0.50000000     MF4       MF3 -0.1104356  0.078069953  0.078129470
## 159          2  0.66666667     BP3       BP1  1.8715743 -2.127439694 -2.717103712
## 160          0  0.00000000     BP3       BP2  2.6818121  0.363864606  0.261608529
## 161          0  0.00000000     BP7       BP2  2.6818121  0.813625995  0.584974455
## 162          2  0.20000000     BP2       BP4  1.6645648 -0.342132809 -0.353124140
## 163          2  0.66666667     AL3       AL3  1.4913228 -1.834180287 -2.160011593
## 164          2  0.25000000     AL8       AL3  1.4913228 -0.464713291 -0.484066838
## 165         14  0.77777778     CP8       CP1  1.2578926 -5.015768591 -5.686612121
## 166          5  0.31250000     CP8       CP3  1.3728822 -1.039688009 -1.099038999
## 167          1  0.05555556     CP4       CP4  3.0351715 -0.190536110 -0.196601809
## 168          3  0.16666667     CP3       CP5  1.6988958 -0.140040640 -0.141492492
## 169          1  0.16666667     VW4       VW5  0.8745419  0.724777078  0.686063886
## 170          4  0.28571429     VW7       VW5  0.8745419  0.070777278  0.070573451
## 171          6  0.31578947     VW4       VW4  1.5781757 -1.538841840 -1.675413578
## 172          1  0.08333333     VW4       VW3  1.4368296  1.052295293  0.955973654
## 173          4  0.33333333     VW7       VW3  1.4368296 -1.155866254 -1.242608160
## 174          1  0.10000000     VW8       VW3  1.4368296  0.797981555  0.738879130
## 175          2  0.13333333     VW9       VW3  1.4368296  0.603528516  0.577193199
## 176          0  0.00000000     VW7       VW2  0.7348495  1.533147051  1.199471893
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## 177          1  0.05882353       VW3       VW1  1.1259963  2.048507710  1.784105612
## 178          2  0.40000000       VW4       VW1  1.1259963 -0.763497870 -0.806487594
## 179          0  0.00000000       CO7       CO3  0.9569971  1.396445370  1.073374693
## 180          0  0.00000000       SS7       SS3  1.2400532  0.712955562  0.537930131
## 181          0  0.00000000      SS10       SS3  1.2400532  1.594217101  1.202848340
## 182          0  0.00000000       SB4       SB2  2.1647238  1.042394082  0.757567273
## 183          0  0.00000000       SB3       SB5  2.7820883  1.149566386  0.825227207
## 184          0  0.00000000      SB10       SB5  2.7820883  1.149566386  0.825227207
## 185          1  0.07142857       SB3       SB4  1.9109538  0.692892053  0.641497145
## 186          0  0.00000000       SB4       SB4  1.9109538  1.050593537  0.769257342
## 187          1  0.06666667       SB1       SB3  1.6039971  1.164905902  1.045202668
## 188          3  0.60000000       SB4       SB3  1.6039971 -2.173975692 -2.590760311
## 189          2  0.66666667       DF1       DF3  0.9701857 -1.410625510 -1.520169920
## 190          1  0.11111111       CA8       CA3  2.1480595 -0.064120860 -0.064706339
## 191          0  0.00000000       FF3       FF1  2.1625331  1.143071259  0.830782866
## 192          1  0.10000000       FF3       FF3  0.7133233  1.703139546  1.540513440
## 193          3  0.37500000       FF4       FF4  0.6324853 -0.165701973 -0.166692138
## 194          1  0.20000000       FF7       FF4  0.6324853  0.722440015  0.690304204
## 195          2  1.00000000       MB4       MB1  1.1132751 -2.364158669 -2.467513898
## 196          4  1.00000000       MB7       MB5  1.3881393 -3.589890361 -4.003691492
## 197          1  0.25000000       BP4       BP5  1.5944290 -0.410958304 -0.433801656
## 198          0  0.00000000       HM4       HM2  2.1610396  0.660419576  0.480011019
## 199          3  0.50000000       VW2       VW5  0.8745419 -1.054721737 -1.105551724
## 200          1  0.20000000       VW8       VW4  1.5781757 -0.168314700 -0.171887283
## 201          1  0.12500000       CP4       CP1  1.2578926  0.700207878  0.656350561
## 202          0  0.00000000       CP7       CP1  1.2578926  1.732663060  1.305953487
## 203          1  0.06250000      CP10       CP1  1.2578926  1.743590820  1.530416489
## 204          0  0.00000000       CP7       CP4  3.0351715  0.968988738  0.693299479
## 205          0  0.00000000       CP8       CP4  3.0351715  1.300034812  0.930158859
## 206          1  1.00000000       CO3       CO3  0.9569971 -1.601253900 -1.613649753
## 207          0  0.00000000       DF8       DF4  1.4635163  0.912510520  0.680325058
## 208          1  0.10000000       HM8       HM5  2.2989339 -0.095191859 -0.096531534
## 209          2  0.16666667       HM3       HM1  0.7884847  1.154516081  1.089860152
## 210          0  0.00000000       CP8       CP1  1.2578926  2.236858392  1.685978702
## 211          1  0.50000000       CA7       CA3  2.1480595 -1.401812840 -1.828240436
## 212          1  0.50000000       CA8       CA3  2.1480595 -1.401812840 -1.828240436
## 213          0  0.00000000       CA3       CA2  2.6037748  1.133540905  0.816053702
## 214          0  0.00000000       VW3       VW4  1.5781757  1.500401028  1.112702668
## 215          1  0.11111111       CP1       CP1  1.2578926  0.860226408  0.796531003
## 216          2  1.00000000       BP7       BP4  1.6645648 -2.711388588 -3.250653320
## 217          0  0.00000000       HM4       HM5  2.2989339  1.237045885  0.896061544
## 218          5  1.00000000       HM7       HM1  0.7884847 -3.410527283 -3.316670199
## 219          0  0.00000000       HM3       HM4  2.3826633  1.260639878  0.911449243
```

The GLMM output shows that when controlling for differences in site and block characteristics, there is no evidence that there is a difference in *Osmia* spp. larvae survival among orchard and natural habitat types.

Observations	219
Dependent variable	No.surv.osmia/No.cells
Type	Mixed effects generalized linear model
Family	binomial
Link	logit

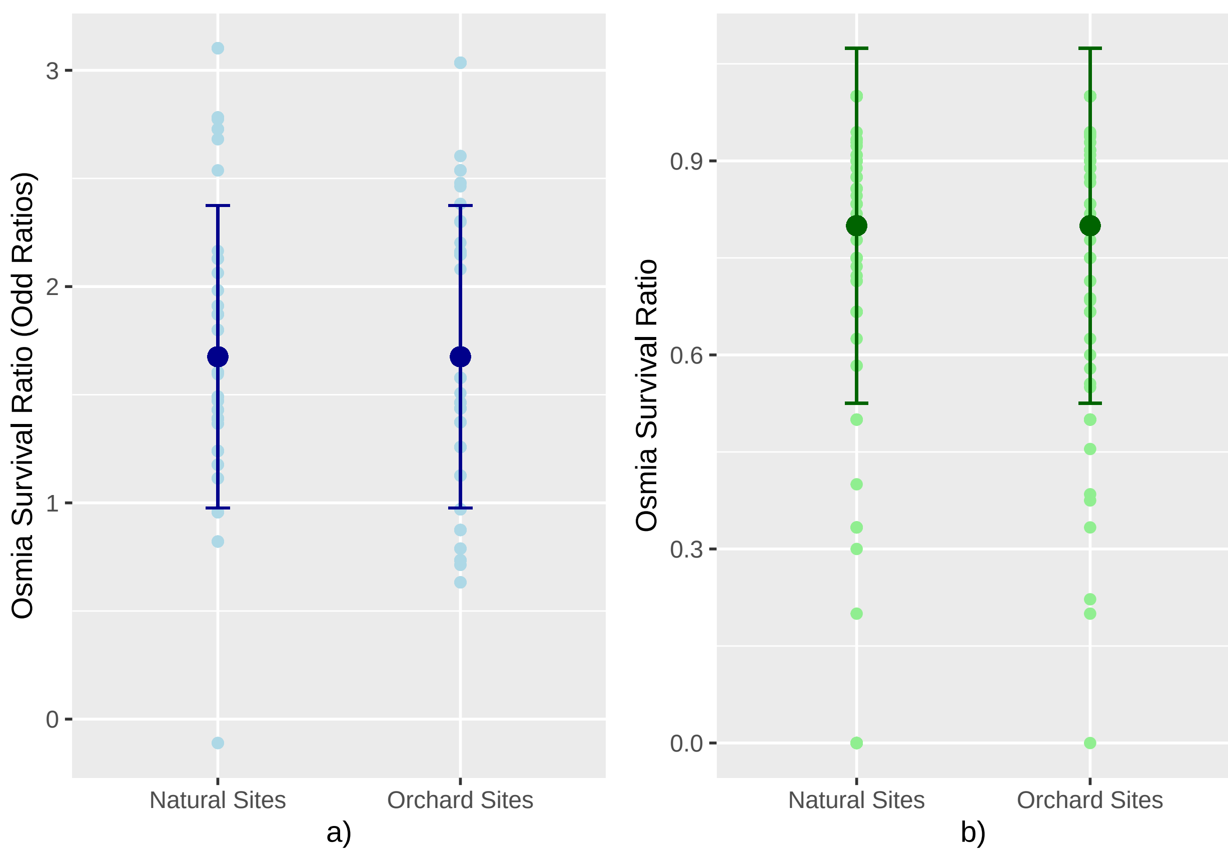


Figure 3: *Osmia* spp. survival versus habitat type with a) GLMM estimates using odds ratio and b) untransformed means ± standard deviation (raw data)

AIC	765.46
BIC	779.02
Pseudo-R^2 (fixed effects)	0.00
Pseudo-R^2 (total)	0.19

Fixed Effects					
	Est.	2.5%	97.5%	z val.	p
(Intercept)	1.78	1.34	2.21	8.03	0.00
s.typeo	0.05	-0.58	0.67	0.15	0.88

Random Effects		
Group	Parameter	Std. Dev.
Block_ID:s.ID	(Intercept)	0.84
s.ID	(Intercept)	0.25

Grouping Variables		
Group	# groups	ICC
Block_ID:s.ID	57	0.17
s.ID	15	0.02

Most importantly, the likelihood ratio testing for the predictive value of site type shows a marginal difference in AIC of 1.97 and a p-value of 0.882. Because of this, it is most likely that site type has little predictive influence on *Osmia* spp. survival.

```
## Single term deletions
##
## Model:
## No.surv.osmia/No.cells ~ s.type + (1 | s.ID/Block_ID)
##        npar    AIC      LRT Pr(Chi)
## <none>      765.46
## s.type    1 763.49 0.022051   0.882
```

3.2.1.1 Key Assumptions In terms of model fit, when comparing the mixed effect model (GLMM) with the model without the random effect of site ID (GLM) in a Wald's Chi-Square test, model fit is improved (GLMM AIC of 765.46 versus GLM AIC of 820.78). This confirms that a hierarchical model taking into account the inherent structure of the data is better suited.

```
## Data: Osmia
## Models:
## osmiaglm: No.surv.osmia/No.cells ~ s.type
## osmiaglmm: No.surv.osmia/No.cells ~ s.type + (1 | s.ID/Block_ID)
##           npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## osmiaglm     2 820.78 827.56 -408.39   816.78
## osmiaglmm    4 765.46 779.02 -378.73   757.46 59.319  2  1.315e-13 ***
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

To test the effect of nesting the random effects of site and block ID on model fit, the Wald's Chi-Square test demonstrates that the nested random value causes AIC values to increase from 198.03 to 765.46. All AIC comparisons are summarized in the table below.

	Final GLMM	Un-Nested GLMM
Intercept	1.78 ***	1.56 ***
	(CI [1.34, 2.21]	(CI [1.10, 2.02]
Orchard Site Type	0.05	0.24
	(CI [-0.58, 0.67]	(CI [-0.50, 0.99]
N	219	219
N (Block_ID:s.ID)	57	
N (s.ID)	15	15
AIC	765.46	198.03
BIC	779.02	208.20
R2 (fixed)	0.00	0.00
R2 (total)	0.19	0.00

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

```
## Data: Osmia
## Models:
## osmiaglmmtest: No.surv.osmia/No.cells ~ s.type + (1 | s.ID)
## osmiaglmm: No.surv.osmia/No.cells ~ s.type + (1 | s.ID/Block_ID)
##               npar    AIC    BIC  logLik deviance Chisq Df Pr(>Chisq)
## osmiaglmmtest    3 198.03 208.20  -96.02   192.03
## osmiaglmm        4 765.46 779.02 -378.73   757.46     0  1          1
```

However, despite this supposed improved model fit, this so-called simpler model has issues with convergence. A test checking for the singularity of the model fit (r model output below) shows that some of the constrained parameters of the random effects are equal to 0 for the un-nested model. This implies a higher probability of false positives and that the model has mis-converged due to optimization issues.

```r
tt <- getME(osmiaglmmtest,"theta")
ll <- getME(osmiaglmmtest,"lower")
min(tt[ll==0])
```

```
## [1] 0
```

When looking at the issue of over-dispersion, we find that the GLM had a deviance of 572.27 over 217 degrees of freedom. The simpler GLMM with one random effect had issues of under-dispersion with a residual deviance of 108.10 over 216 degrees of freedom. The nested GLMM had a deviance of 413.40 over 215 degrees of freedom. The final GLMM model with block ID nested within site ID as a random effect had a ratio of deviance to degrees of freedom of 1.9, close to the accepted value of 1.

```
##
## Call:
## glm(formula = No.surv.osmia/No.cells ~ s.type, family = binomial(link = "logit"),
##     data = Osmia, weights = No.cells)
##
## Deviance Residuals:
##     Min       1Q   Median       3Q      Max
## -5.6454  -0.6845   0.6313   1.4834   2.6942
##
## Coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.5839     0.0918   17.25   <2e-16 ***
## s.typeo      -0.0851     0.1290   -0.66    0.509
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## (Dispersion parameter for binomial family taken to be 1)
##
##     Null deviance: 576.71  on 218  degrees of freedom
## Residual deviance: 576.28  on 217  degrees of freedom
## AIC: 820.78
##
## Number of Fisher Scoring iterations: 4

## Residual deviance: 108.105 on 216 degrees of freedom (ratio: 0.5)

## Residual deviance: 413.402 on 215 degrees of freedom (ratio: 1.923)
```

When taking into account the fact that the nested random effect model better matches the data-set structure and the fact that it did not have any convergence warnings or issues with under-dispersion, I will choose the nested random effect model as my final model and by focusing the remaining GLMM assumptions on this final model. Therefore, returning to the initial assumptions of a GLMM that the residuals of the random effects should be normal and homoscedastic, in ***Figure 4***, the residuals are constant throughout all levels of the random effect. Moreover, the q-q plots in ***Figure 5*** show that the nested random effects of site and block ID are appropriately normal.

Having considered model fit, data structure, dispersion of the variance, issues with convergence, normality of the residuals and normality of the random effects, the GLMM with nested random-effects is the best model for my data and adequately meets the major assumptions of a GLMM.

3.2.2 Bayesian Results

Similar to the frequentist results, we find that there is not enough evidence from the data collected to show that site type has an effect on *Osmia* spp. survival since the credible interval [-0.79, 1.02] overlaps 0. This can also be surmised from ***Figure 6***.

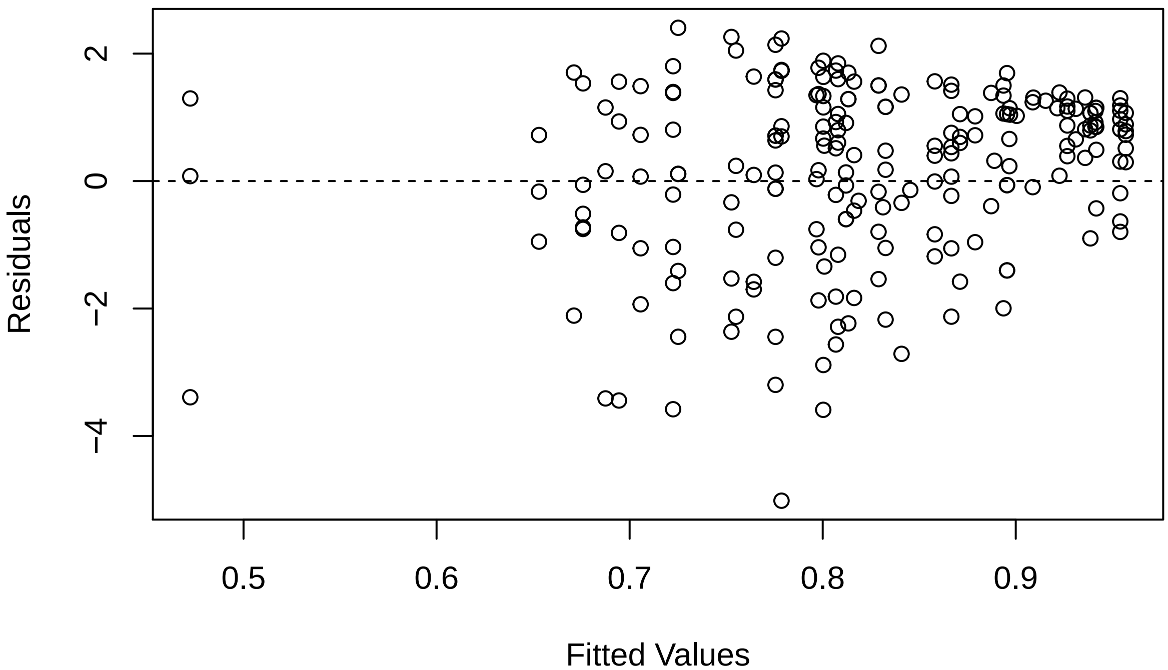


Figure 4: Residuals versus Fitted Values of Final Osmia Survival Model

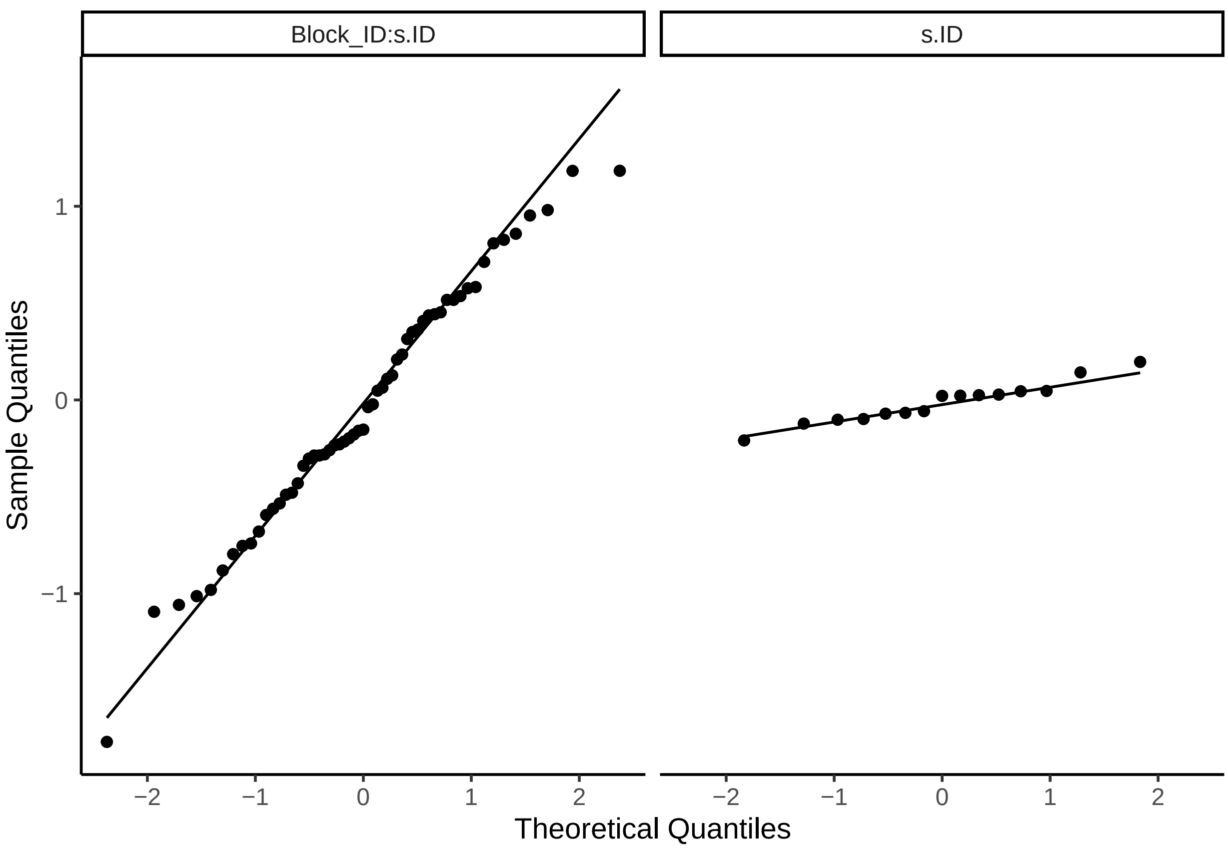
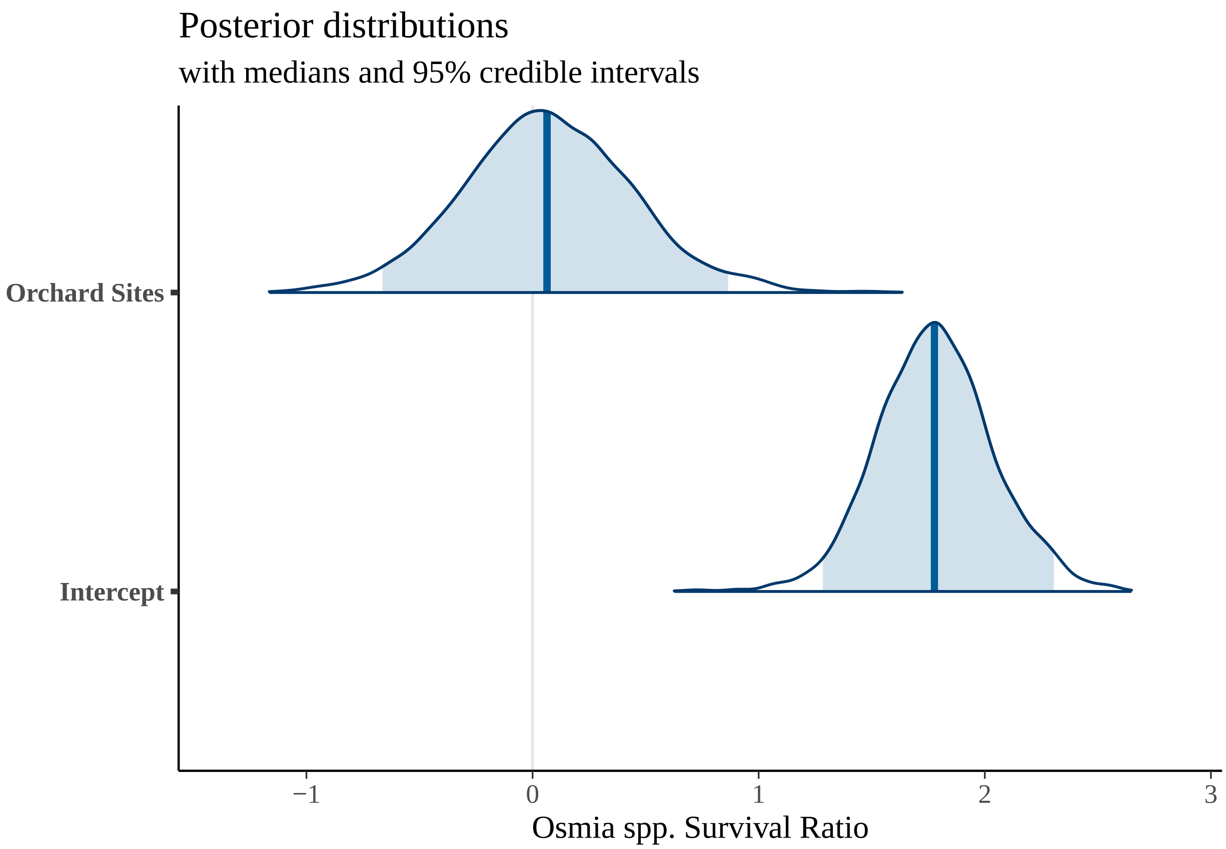


Figure 5: Q-Q Plots of Nested Random Effects of Block and Site ID (BLUPs)

Parameter	Posterior Mode	Lower Credible Interval	Upper Credible Interval
Intercept	2.02	1.42	2.67
Orchard Sites	0.08	-0.79	1.02

```
##
## SAMPLING FOR MODEL 'binomial' NOW (CHAIN 1).
## Chain 1:
## Chain 1: Gradient evaluation took 0.000178 seconds
## Chain 1: 1000 transitions using 10 leapfrog steps per transition would take 1.78 seconds.
## Chain 1: Adjust your expectations accordingly!
## Chain 1:
## Chain 1:
## Chain 1: Iteration:    1 / 2000 [  0%]  (Warmup)
## Chain 1: Iteration:  200 / 2000 [ 10%]  (Warmup)
## Chain 1: Iteration:  400 / 2000 [ 20%]  (Warmup)
## Chain 1: Iteration:  600 / 2000 [ 30%]  (Warmup)
## Chain 1: Iteration:  800 / 2000 [ 40%]  (Warmup)
## Chain 1: Iteration: 1000 / 2000 [ 50%]  (Warmup)
## Chain 1: Iteration: 1001 / 2000 [ 50%]  (Sampling)
## Chain 1: Iteration: 1200 / 2000 [ 60%]  (Sampling)
## Chain 1: Iteration: 1400 / 2000 [ 70%]  (Sampling)
## Chain 1: Iteration: 1600 / 2000 [ 80%]  (Sampling)
## Chain 1: Iteration: 1800 / 2000 [ 90%]  (Sampling)
## Chain 1: Iteration: 2000 / 2000 [100%]  (Sampling)
## Chain 1:
## Chain 1:  Elapsed Time: 4.26655 seconds (Warm-up)
## Chain 1:                1.91309 seconds (Sampling)
## Chain 1:                6.17963 seconds (Total)
## Chain 1:
##
## SAMPLING FOR MODEL 'binomial' NOW (CHAIN 2).
## Chain 2:
## Chain 2: Gradient evaluation took 8.5e-05 seconds
## Chain 2: 1000 transitions using 10 leapfrog steps per transition would take 0.85 seconds.
## Chain 2: Adjust your expectations accordingly!
## Chain 2:
## Chain 2:
## Chain 2: Iteration:    1 / 2000 [  0%]  (Warmup)
## Chain 2: Iteration:  200 / 2000 [ 10%]  (Warmup)
## Chain 2: Iteration:  400 / 2000 [ 20%]  (Warmup)
## Chain 2: Iteration:  600 / 2000 [ 30%]  (Warmup)
## Chain 2: Iteration:  800 / 2000 [ 40%]  (Warmup)
## Chain 2: Iteration: 1000 / 2000 [ 50%]  (Warmup)
## Chain 2: Iteration: 1001 / 2000 [ 50%]  (Sampling)
## Chain 2: Iteration: 1200 / 2000 [ 60%]  (Sampling)
## Chain 2: Iteration: 1400 / 2000 [ 70%]  (Sampling)
## Chain 2: Iteration: 1600 / 2000 [ 80%]  (Sampling)
## Chain 2: Iteration: 1800 / 2000 [ 90%]  (Sampling)
## Chain 2: Iteration: 2000 / 2000 [100%]  (Sampling)
## Chain 2:
## Chain 2:  Elapsed Time: 3.04245 seconds (Warm-up)
## Chain 2:                2.64024 seconds (Sampling)
## Chain 2:                5.68269 seconds (Total)
```

```
## Chain 2:
##
## SAMPLING FOR MODEL 'binomial' NOW (CHAIN 3).
## Chain 3:
## Chain 3: Gradient evaluation took 7.9e-05 seconds
## Chain 3: 1000 transitions using 10 leapfrog steps per transition would take 0.79 seconds.
## Chain 3: Adjust your expectations accordingly!
## Chain 3:
## Chain 3:
## Chain 3: Iteration:    1 / 2000 [  0%]  (Warmup)
## Chain 3: Iteration:  200 / 2000 [ 10%]  (Warmup)
## Chain 3: Iteration:  400 / 2000 [ 20%]  (Warmup)
## Chain 3: Iteration:  600 / 2000 [ 30%]  (Warmup)
## Chain 3: Iteration:  800 / 2000 [ 40%]  (Warmup)
## Chain 3: Iteration: 1000 / 2000 [ 50%]  (Warmup)
## Chain 3: Iteration: 1001 / 2000 [ 50%]  (Sampling)
## Chain 3: Iteration: 1200 / 2000 [ 60%]  (Sampling)
## Chain 3: Iteration: 1400 / 2000 [ 70%]  (Sampling)
## Chain 3: Iteration: 1600 / 2000 [ 80%]  (Sampling)
## Chain 3: Iteration: 1800 / 2000 [ 90%]  (Sampling)
## Chain 3: Iteration: 2000 / 2000 [100%]  (Sampling)
## Chain 3:
## Chain 3:  Elapsed Time: 3.40945 seconds (Warm-up)
## Chain 3:                1.86564 seconds (Sampling)
## Chain 3:                5.27509 seconds (Total)
## Chain 3:
##
## SAMPLING FOR MODEL 'binomial' NOW (CHAIN 4).
## Chain 4:
## Chain 4: Gradient evaluation took 6.8e-05 seconds
## Chain 4: 1000 transitions using 10 leapfrog steps per transition would take 0.68 seconds.
## Chain 4: Adjust your expectations accordingly!
## Chain 4:
## Chain 4:
## Chain 4: Iteration:    1 / 2000 [  0%]  (Warmup)
## Chain 4: Iteration:  200 / 2000 [ 10%]  (Warmup)
## Chain 4: Iteration:  400 / 2000 [ 20%]  (Warmup)
## Chain 4: Iteration:  600 / 2000 [ 30%]  (Warmup)
## Chain 4: Iteration:  800 / 2000 [ 40%]  (Warmup)
## Chain 4: Iteration: 1000 / 2000 [ 50%]  (Warmup)
## Chain 4: Iteration: 1001 / 2000 [ 50%]  (Sampling)
## Chain 4: Iteration: 1200 / 2000 [ 60%]  (Sampling)
## Chain 4: Iteration: 1400 / 2000 [ 70%]  (Sampling)
## Chain 4: Iteration: 1600 / 2000 [ 80%]  (Sampling)
## Chain 4: Iteration: 1800 / 2000 [ 90%]  (Sampling)
## Chain 4: Iteration: 2000 / 2000 [100%]  (Sampling)
## Chain 4:
## Chain 4:  Elapsed Time: 4.41914 seconds (Warm-up)
## Chain 4:                1.89413 seconds (Sampling)
## Chain 4:                6.31327 seconds (Total)
## Chain 4:
```



3.2.2.1 Bayesian Key Assumptions From a visual assessment of the posterior trace and density plots of the first chain (**Figure 7**), there was high evidence of autocorrelation and variability, especially for the random effects.

There was also some degree of autocorrelation since most lag iterations had autocorrelation values exceeding 0.1. Moreover, the *raftery.diag* function recommended a sample size of at least 3,746. To remedy this, for the second and final chain, sample size was increased from 1,000 to 4,000, number of iterations was increased from 13,000 to 2,020,000 and priors were adjusted (V=1, nu=1).

```
autocorr.diag(osmiabayes$Sol)
```

```
##          (Intercept)       s.typeo
## Lag 0     1.00000000  1.0000000000
## Lag 10    0.16745088  0.0761970923
## Lag 50    0.17458082  0.0962675854
## Lag 100   0.02533150 -0.0004912568
## Lag 500  -0.04219361  0.0056544326
```

```
autocorr.diag(osmiabayes$VCV)
```

```
##               s.ID Block_ID:s.ID      units
## Lag 0    1.0000000     1.0000000 1.00000000
## Lag 10   0.4400000     0.8258548 0.50503404
## Lag 50   0.3137320     0.6029269 0.12447522
## Lag 100  0.3129254     0.5180699 0.02729182
## Lag 500  0.1597343     0.5055561 0.05499515
```

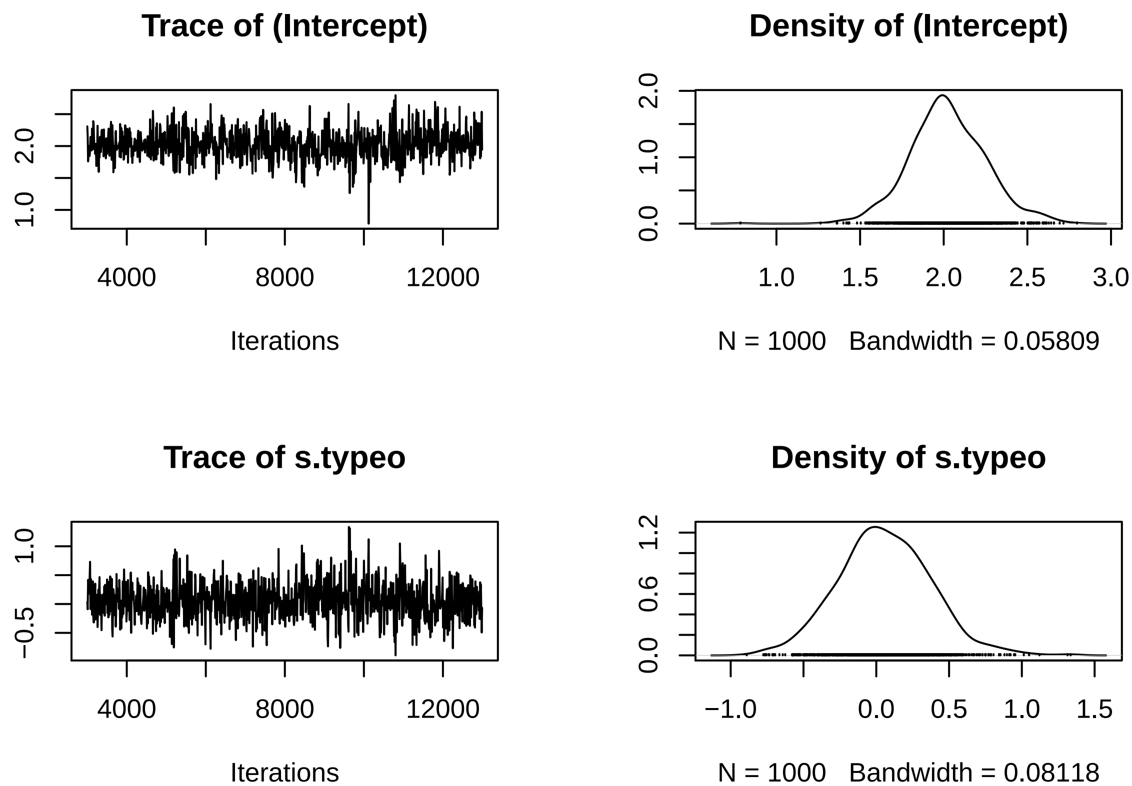


Figure 6: Initial Posterior MCMC Trace and Distribution of the Fixed Effects

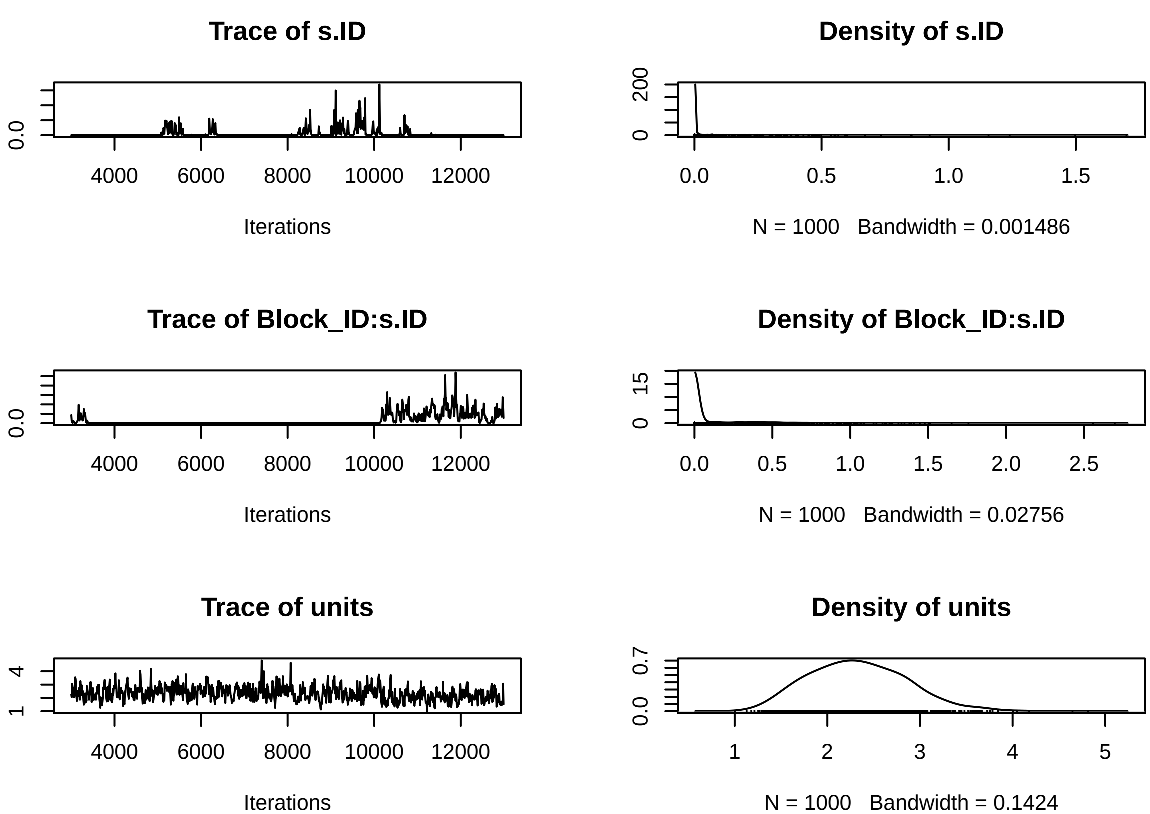


Figure 7: Initial Posterior MCMC Trace and Distribution of the Random Effects

```r
raftery.diag(osmiabayes)
```

```
##
## Quantile (q) = 0.025
## Accuracy (r) = +/- 0.005
## Probability (s) = 0.95
##
## You need a sample size of at least 3746 with these values of q, r and s
```

A visual assessment of the modified posterior trace and density plots (**Figure 8**) show that there is no identifiable pattern in the chain as what was evident in the first chain and much less proof of autocorrelation.

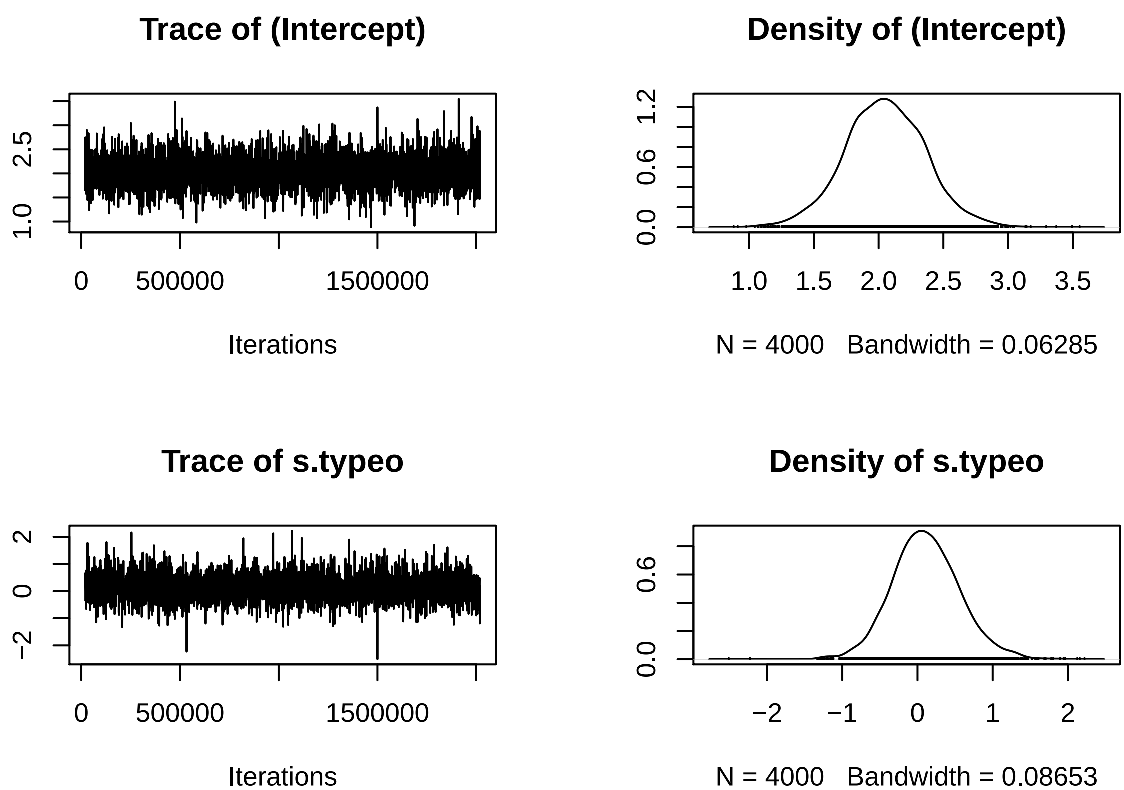


Figure 8: Final Posterior MCMC Trace and Distribution of the Fixed Effects

This is further confirmed by the diagnostic autocorrelation test in which all autocorrelation values are well below the 0.1 threshold.

```r
autocorr.diag(osmiabayesfinal$Sol)
```

```
##           (Intercept)      s.typeo
## Lag 0      1.000000000  1.000000000
## Lag 500   -0.007347109 -0.012553392
## Lag 2500  -0.026818838 -0.003098726
## Lag 5000  -0.001264728  0.006946123
## Lag 25000 -0.002187851 -0.010653274
```

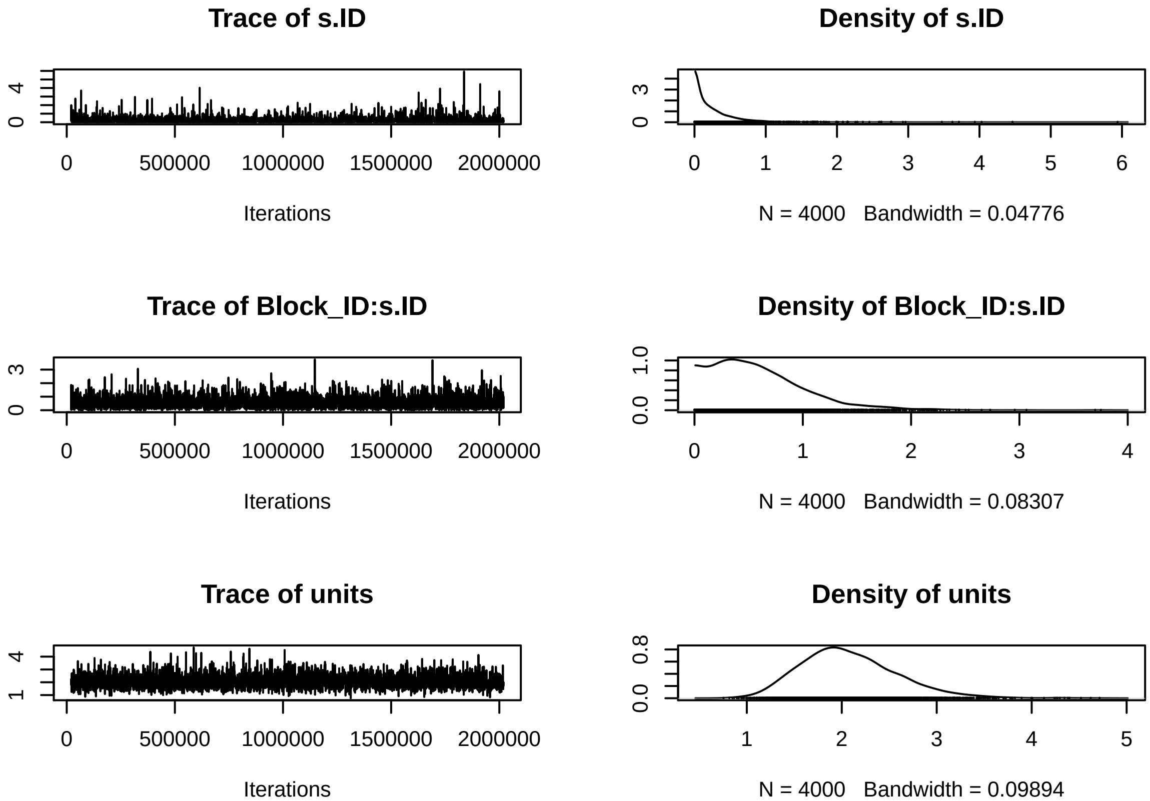


Figure 9: Final Posterior MCMC Trace and Distribution of the Random Effects

```
autocorr.diag(osmiabayesfinal$VCV)
```

```
##                  s.ID Block_ID:s.ID        units
## Lag 0      1.000000000   1.000000000  1.000000000
## Lag 500    0.007417437  -0.003859959 -0.030521443
## Lag 2500   0.009323325   0.001574388 -0.002119953
## Lag 5000  -0.006373726  -0.024457179  0.011152704
## Lag 25000 -0.007631331  -0.017282513  0.014053746
```

4. Discussion

4.1 Summary

Based on the data collected and subsequent statistical analyses, I can conclude that there is no evidence of a difference between the survival ratio of *Osmia* spp. in orchard and natural sites. This is evident when simply looking at the raw *Osmia* spp. survival ratios in natural versus orchard sites (***Figure 3b***). When correcting for differences in sites (s.ID) and blocks (Block_ID) in order to account for any noise or variation in the data, this lack of a difference among site types is still prevalent (***Figure 3a***).

However, these conclusions do not take into account the wider implications of land-use change on pollinators. For instance, species richness has been shown to be heavily influenced by percent agriculture, orchard size and most notably, sampling effort (Russo et al. 2015). Even though *Osmia* spp. survival rates in orchards have not been shown to differ from natural sites in my analysis, habitat loss due to agricultural intensification is still of major concern in the declines of native bee populations (Kline and Joshi 2020).

A possible explanation for this discrepancy in results is that the apple orchard sites included in this study are not as agriculturally intense as other fruit orchards (i.e. almond orchards in California (Koh et al. 2017)) and thus, are not as isolated from the floral and nesting resources required for wild bee population survival and growth. Thus, the difference among these orchard and natural sites are not as pronounced as in other studies.

4.2 Implications

While further investigation is needed, this could possibly indicate that the installation of nesting structures pose little risk to the development and survival of *Osmia* spp. offspring and most likely, will not act a population sink. This means that in my thesis experiment, testing the efficacy of nesting structures in orchard sites, the nesting structures for my experiment will most likely not pose an ecological threat to wild bee populations either as an ecological trap or population sink. Furthermore, the issue of promoting a resource that is potentially a population sink will most likely not have an impact on any of the conclusions that I make relating to the efficacy of the nesting structures for boosting pollinator populations.

4.3 Limitations of Analysis

Because the hierarchical nature of the data was acknowledged, I was able to avoid issues of autocorrelation within the data structure and issues of non-independent residuals which will lead to an increased rate of false positives (McNeish and Stapleton 2014). However, it must be acknowledged that the number of sites visited in the orchard and natural habitat types is very small (7 and 8, respectively), which overall, leads to bias in the results. It is typically recommended to have a minimum cluster sample size of 30 which is well below the 15 sites or clusters from this data set. Some authors even argue that mixed models become potentially untrustworthy with small sample sizes and should not be run if cluster sizes are below 10 (McNeish and Stapleton 2014). A power analysis using the *simr* package shows that the power to reject the null hypothesis of no effect of site type on *Osmia* survival given this particular set-up is 6.10% which is very low especially when considering that most studies aim for a power of 80% (Green and MacLeod 2016). This low power is most likely due to a small sample size.

```
osmia_sim <- powerSim(osmiaglmm, nsim=1000) osmia_sim
```

When it comes to a critique of the data, it would have been informative to have more data relating to the cause of death since having this value as a fixed effect would have accounted for some of the over-dispersion detected in the final GLMM. Controlling for cause of death would have also helped with recognizing overarching factors in larval mortality that are not necessarily related to habitat type but rather to normal threats to larval development common across all landscapes. This would have helped with pinpointing the true differences among habitat types which can be overshadowed by these potentially common observable factors. From a different perspective, it would have also helped to determine whether death due to parasitization is more common in orchard habitat types or natural habitat types since this could give some by-proxy insight into parasite population densities.

4.4 Future Directions

In the future, it would be useful to rerun this experiment with a larger sample size to address the issue with power. By extension, it would also be interesting to collect some information on *Osmia* spp. survival in urban and suburban habitats in addition to both natural and agricultural habitats since data on *Osmia* spp. populations in these human-dominant landscapes is scarce. Cross-referencing the likelihood of *Osmia* spp. survival in these different habitats can help with re-evaluating the usefulness of installing these nesting structures in these different habitat types from a conservation perspective. For instance, if mortality rates are high in suburban landscapes when compared to natural landscapes, nesting structures may be better suited to orchard landscapes where larval mortality has not been shown to differ from natural areas.

Moreover, it would be interesting to expand observations to include other bee and wasp genera and to document their survival. In addition, while logistically complicated, since it would involve extensive and detailed monitoring of nesting structures throughout the growing season, documenting and comparing the successful attainment of key developmental stages such as hatching, pupation and eclosion across landscape types could be an interesting extension to this question on successful *Osmia* spp. reproduction in anthropogenic environments.

Data Availability Statement

All data is available in the **Final Report GitHub Repository**.

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