Brunswick Point Peep Models

Sarah Popov

2023-02-10

Contents

Roberts Bank, Delta, BC, is situated in the great Pacific Flyway and serves as an important stopover for peeps migrating north in the spring. It therefore hosts a large seasonal population of peeps: namely, Western sandpiper (WESA) and Dunlin (DUNL), that rely on the seasonal nutritional bounty provided by the Fraser River delta.

This document describes the suite of models used to estimate yearly changes in spatial distribution and abundance of peeps in the Roberts Bank estuary.

There are two datasets used in this modelling pipeline:

1. `sr`, which contains species ratio data (WESA:DUNL)
2. `dat`, which contains bird counts + environmental covariates

For an interactive interface with the `dat` dataset used in this document, see https://popovs.shinyapps.io/peepr/.

1 Binomial species ratio model

The daily ratio of Western sandpiper (WESA) to Dunlin (DUNL) across the entire study period is first modelled using a dataset of known species ratios (species ratios are not measured during every survey).

The ratios are modelled using a binomial generalized linear mixed model (binomial GLMM). The resulting predicted ratios are then used to estimate the number of WESA vs. DUNL per day.

1.1 `sr` data summary

```
##   survey_date              wesa             dunl             total
##  Min.   :1997-04-21   Min.   :   0.0   Min.   :   0.00   Min.   :  48.0
##  1st Qu.:2005-04-21   1st Qu.: 124.5   1st Qu.:  41.25   1st Qu.: 287.2
##  Median :2009-04-25   Median : 353.5   Median :  92.00   Median : 524.5
##  Mean   :2009-09-21   Mean   : 467.5   Mean   : 176.47   Mean   : 644.0
##  3rd Qu.:2015-04-15   3rd Qu.: 714.5   3rd Qu.: 203.50   3rd Qu.: 936.2
##  Max.   :2022-05-04   Max.   :2605.0   Max.   :5000.00   Max.   :5047.0
##
##      p_wesa           p_dunl             year       julian_day
##  Min.   :  0.00   Min.   :  0.000   2006   : 23   Min.   :101.0
##  1st Qu.: 53.04   1st Qu.:  8.722   2019   : 23   1st Qu.:112.0
##  Median : 81.43   Median : 18.574   2005   : 18   Median :117.0
##  Mean   : 68.95   Mean   : 31.046   2007   : 18   Mean   :117.6
##  3rd Qu.: 91.28   3rd Qu.: 46.961   2008   : 18   3rd Qu.:123.0
##  Max.   :100.00   Max.   :100.000   2012   : 18   Max.   :137.0
##                                     (Other):204
##         dos.V1
##  Min.   :-2.2799746
##  1st Qu.:-0.7800240
##  Median :-0.0982283
##  Mean   :-0.0220027
##  3rd Qu.: 0.7199265
##  Max.   : 2.6289545
##
```

1.2 Five models are built and compared

Response variable:

- `y` - WESA:DUNL ratio

Predictor variables:

- `dos` - day of season (recentered/scaled Julian date)
- `year` - year of survey

```
## Data: sr
## Models:
## lme5: y ~ 1 + (1 | year)
## lme4: y ~ dos + (1 | year)
## lme2: y ~ dos + I(dos^2) + (1 | year)
```

```
## lme3: y ~ dos + (dos | year)
## lme1: y ~ dos + I(dos^2) + (dos + I(dos^2) | year)
##      npar   AIC   BIC logLik deviance   Chisq Df Pr(>Chisq)
## lme5    2 66919 66927 -33458    66915
## lme4    3 26358 26369 -13176    26352 40563.6  1     <2e-16 ***
## lme2    4 16609 16624  -8301    16601  9750.7  1     <2e-16 ***
## lme3    5 22611 22629 -11300    22601     0.0  1          1
## lme1    9 11158 11192  -5570    11140 11460.6  4     <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

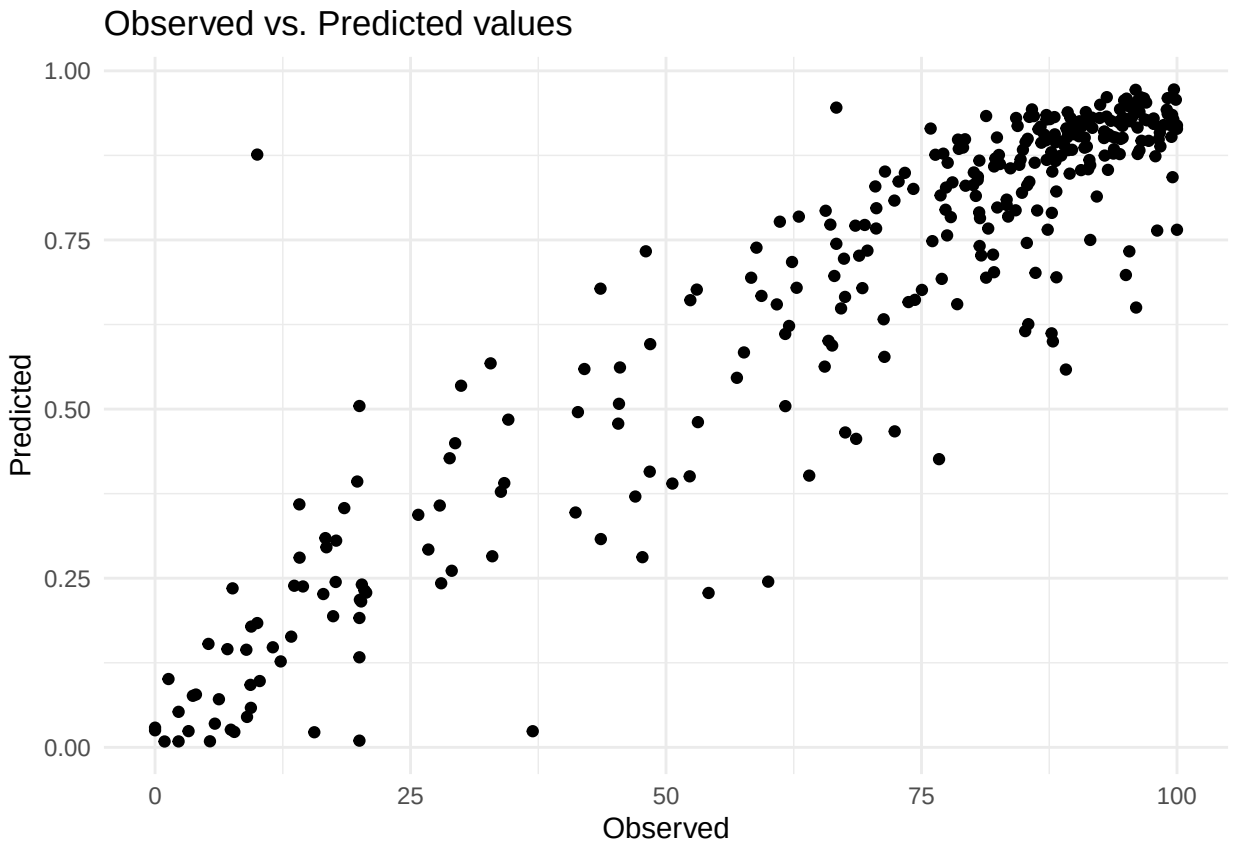
The best-fit model is `lme1`. The residuals from `lme1` are appended to the `sr` dataset and another model is re-fit in order to estimate overdispersion. Because the standard deviation of the residuals is < 1, the model is deemed an appropriate candidate for predicting daily species ratios.

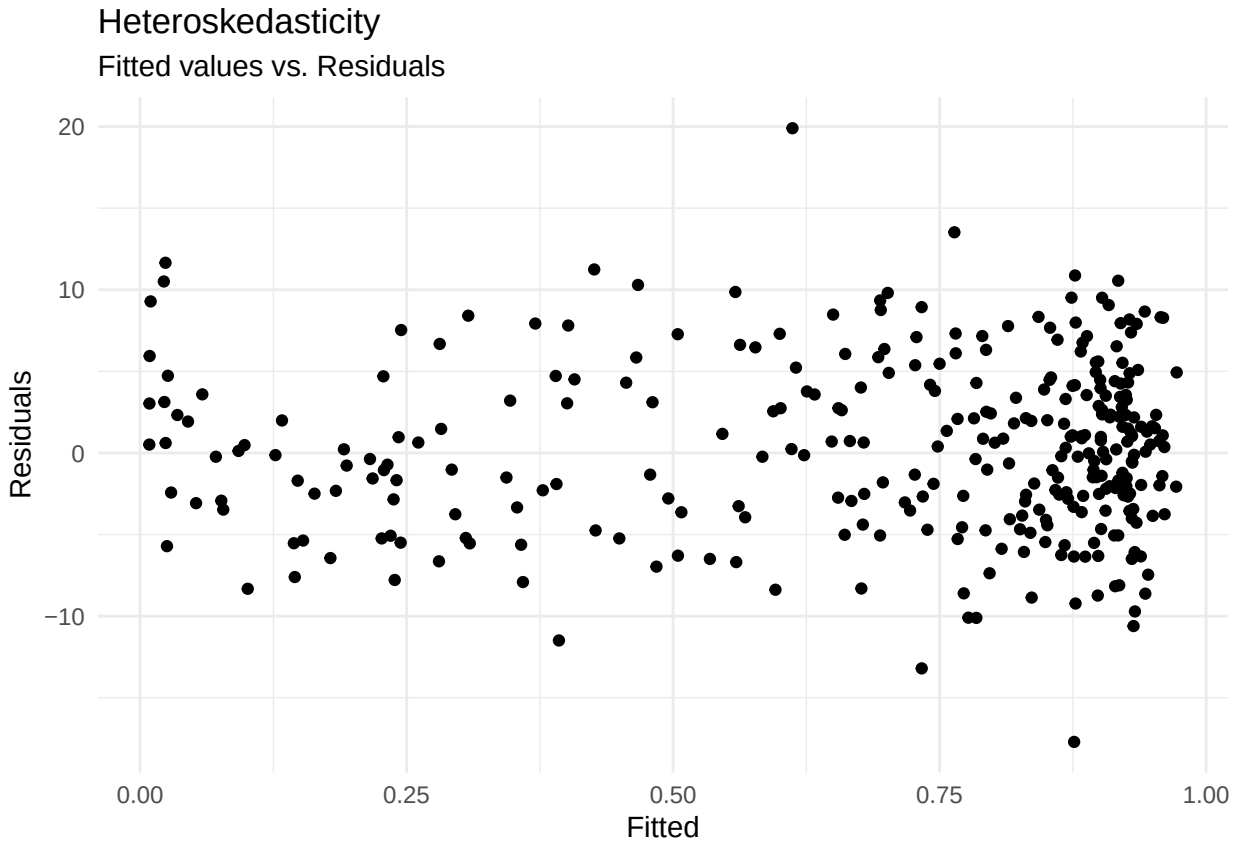
```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: y ~ dos + I(dos^2) + (dos + I(dos^2) | year) + (1 | resids)
##    Data: sr
##       AIC       BIC    logLik  deviance  df.resid
##  3449.920  3487.666 -1714.960  3429.920       312
## Random effects:
##  Groups Name        Std.Dev. Corr
##  resids (Intercept) 0.9544
##  year   (Intercept) 0.6508
##         dos         0.1729   -0.17
##         I(dos^2)    0.4248   -0.67  0.01
## Number of obs: 322, groups:  resids, 322; year, 24
## Fixed Effects:
## (Intercept)          dos     I(dos^2)
##      1.9001       1.4102      -0.8284
```

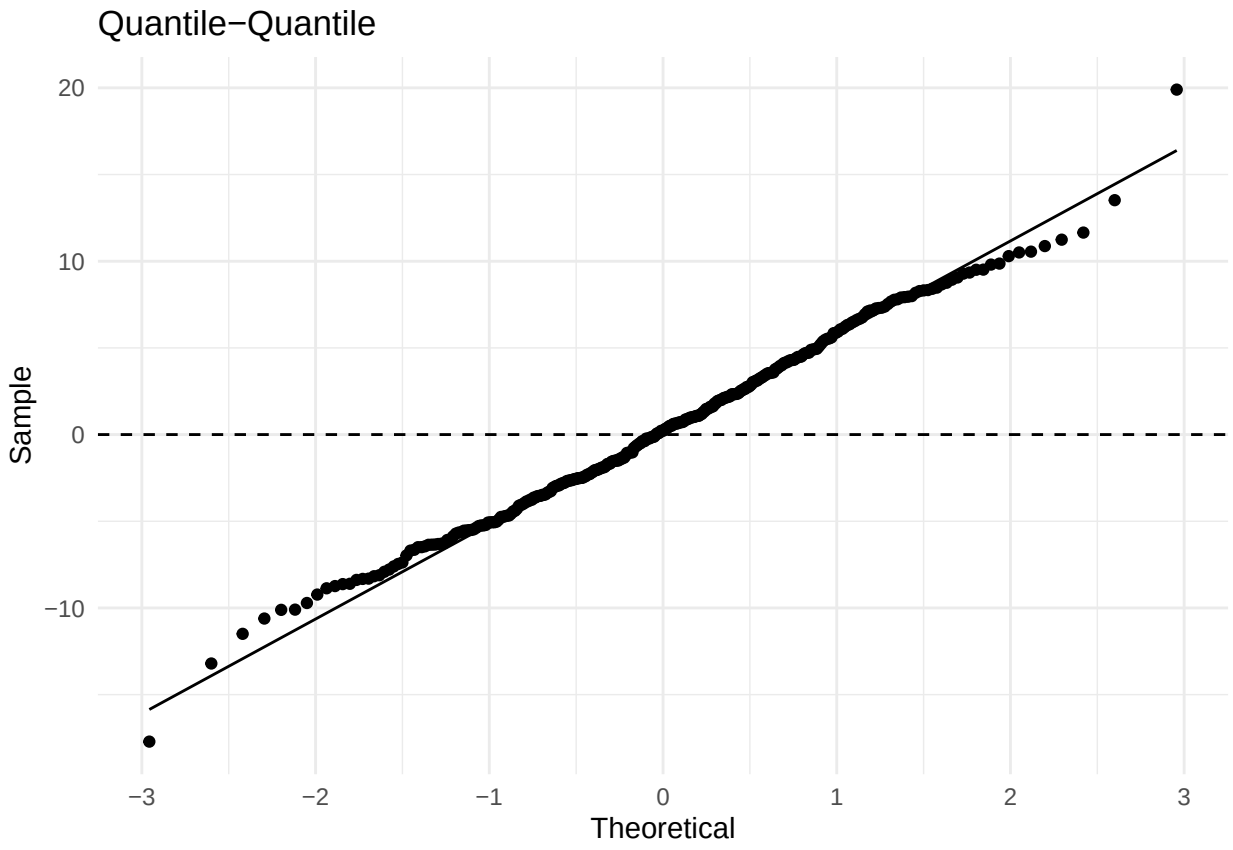
1.2.1 Summary of best fit model (lme1)

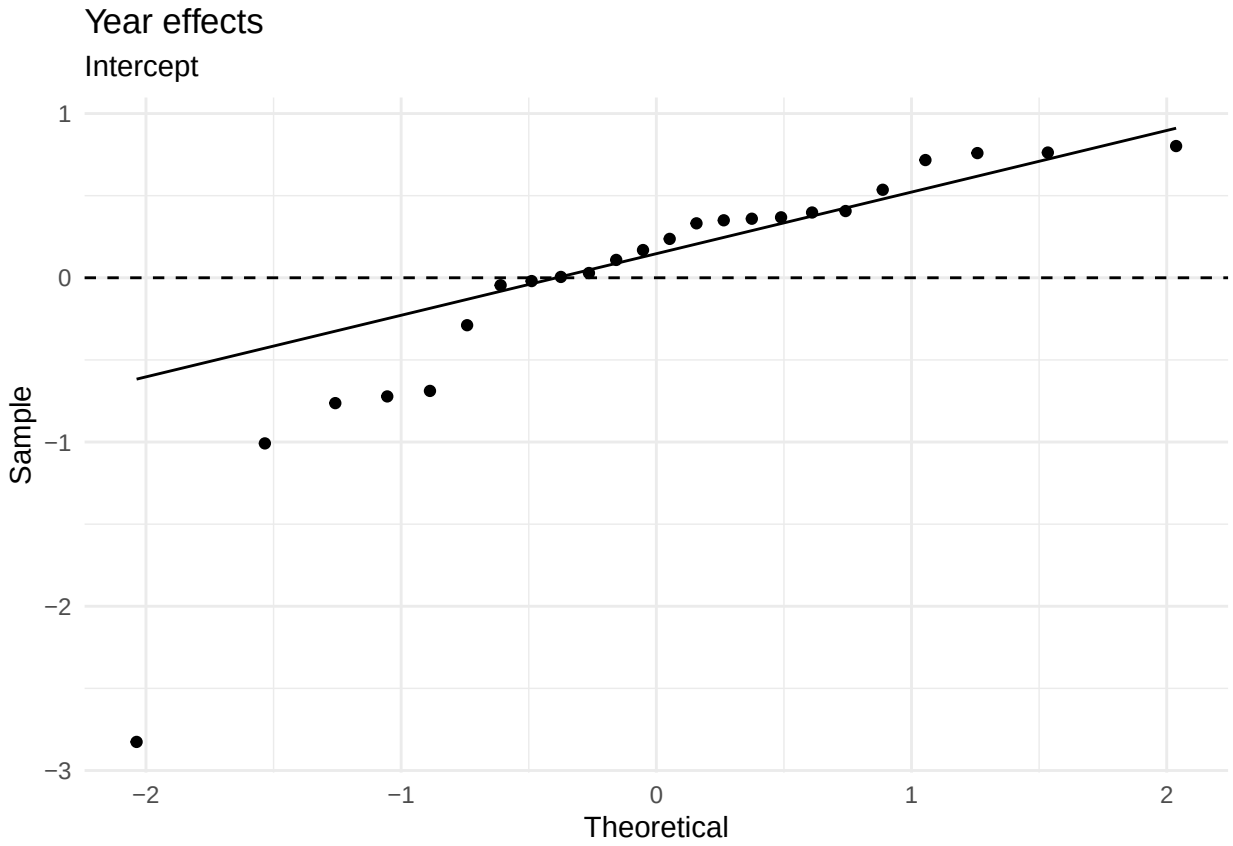
```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: y ~ dos + I(dos^2) + (dos + I(dos^2) | year)
##    Data: sr
##
##      AIC      BIC   logLik deviance df.resid
##  11157.9  11191.8  -5569.9  11139.9      313
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -23.5674  -3.4250   0.2296   3.6878  21.7593
##
## Random effects:
##  Groups Name        Variance Std.Dev. Corr
##  year   (Intercept) 0.5969   0.7726
##         dos         0.3681   0.6067    0.14
##         I(dos^2)    0.5369   0.7327   -0.73 -0.38
## Number of obs: 322, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.7377     0.1583  10.981  < 2e-16 ***
## dos           1.3146     0.1248  10.534  < 2e-16 ***
## I(dos^2)     -0.7684     0.1506  -5.101 3.38e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##          (Intr) dos
## dos       0.143
## I(dos^2) -0.729 -0.373
```

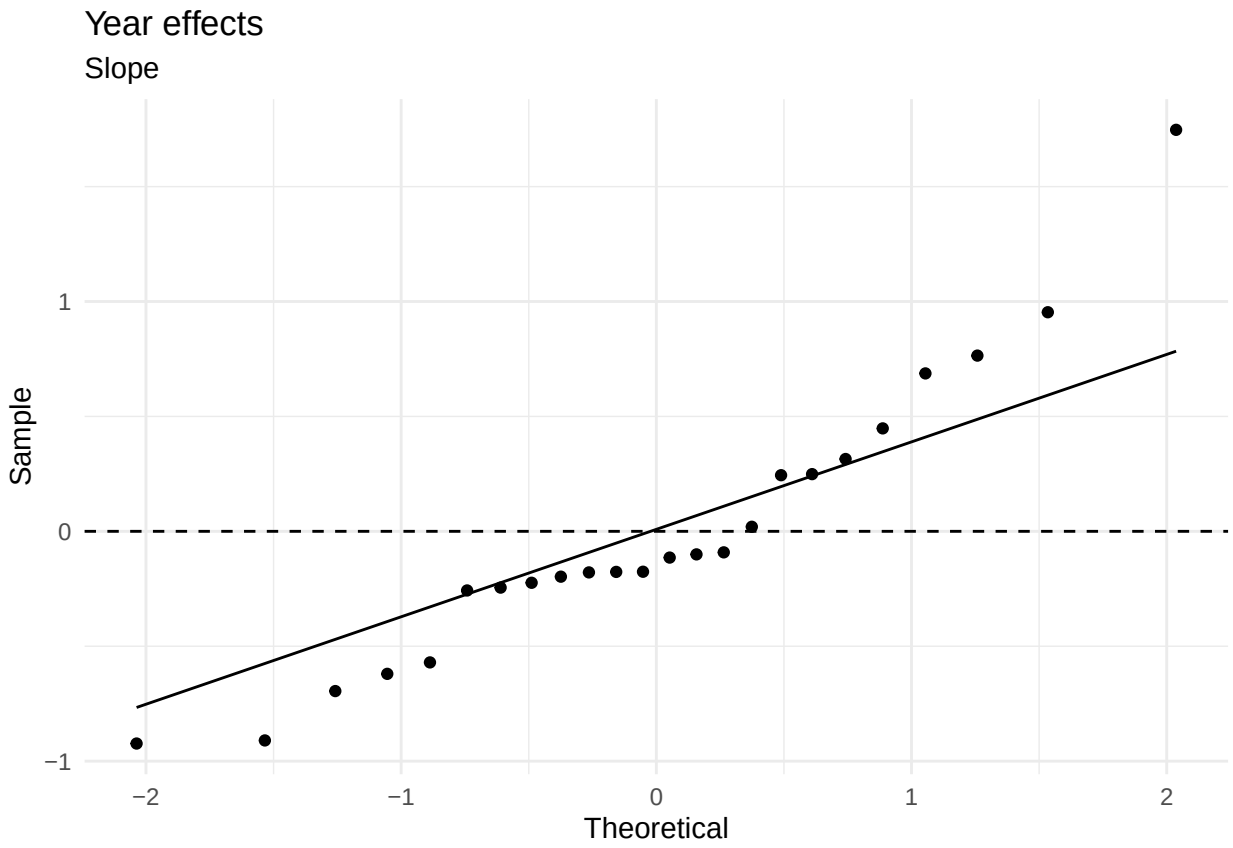
1.2.2 Check assumptions of best fit model

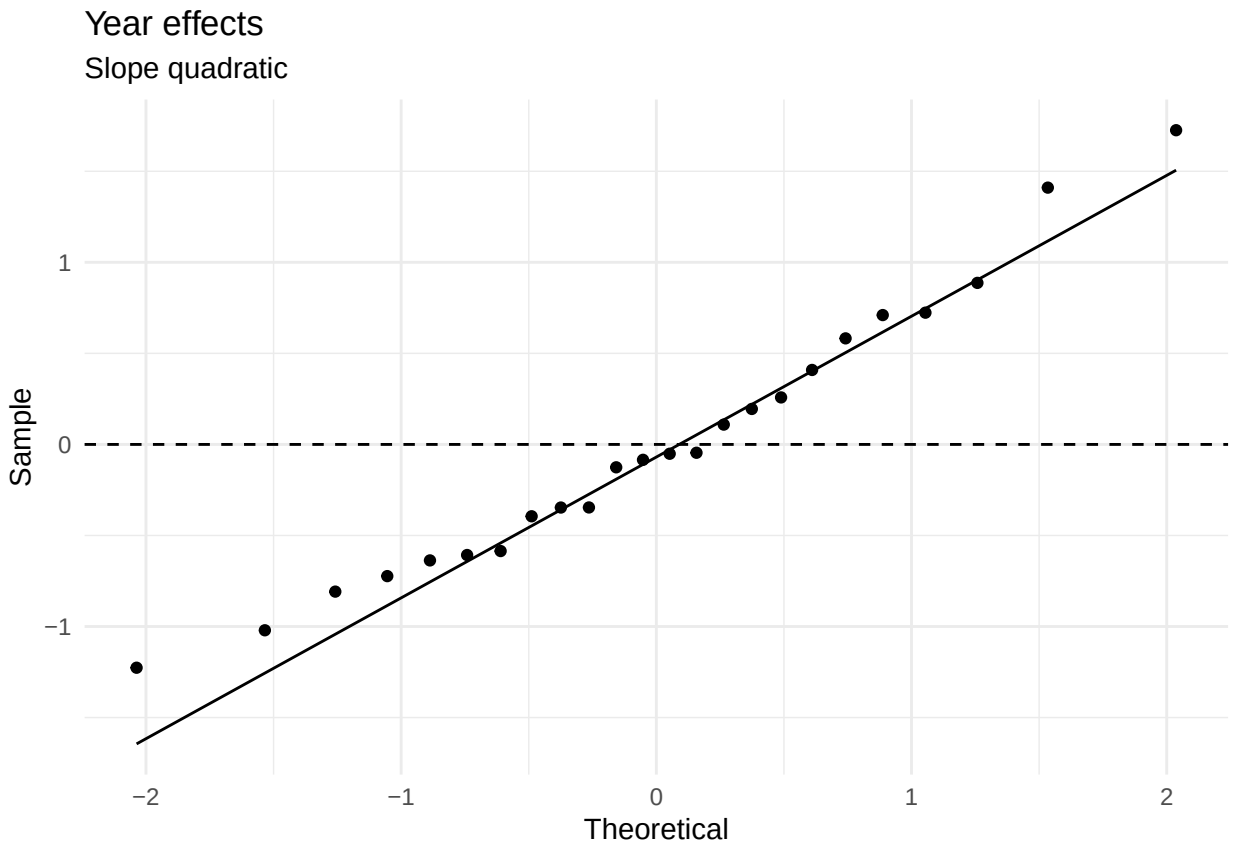



Heteroskedasticity
Fitted values vs. Residuals
Residuals
Fitted
20
10
0
−10
0.00
0.25
0.50
0.75
1.00


Quantile−Quantile
Sample
Theoretical
20
10
0
−10
−3
−2
−1
0
1
2
3


Year effects
Intercept
Sample
Theoretical
1
0
−1
−2
−3
−2
−1
0
1
2


Year effects
Slope
Sample
Theoretical
1
0
−1
−2
−1
0
1
2


Year effects
Slope quadratic
Sample
Theoretical
1
0
−1
−2
−1
0
1
2

1.3 Predict WESA/DUNL population

Using the derived binomial GLMM above, we will predict the amount of WESA and DUNL each day. For any years that are missing from the bGLMM we will assign the mean proportion of WESA:DUNL.

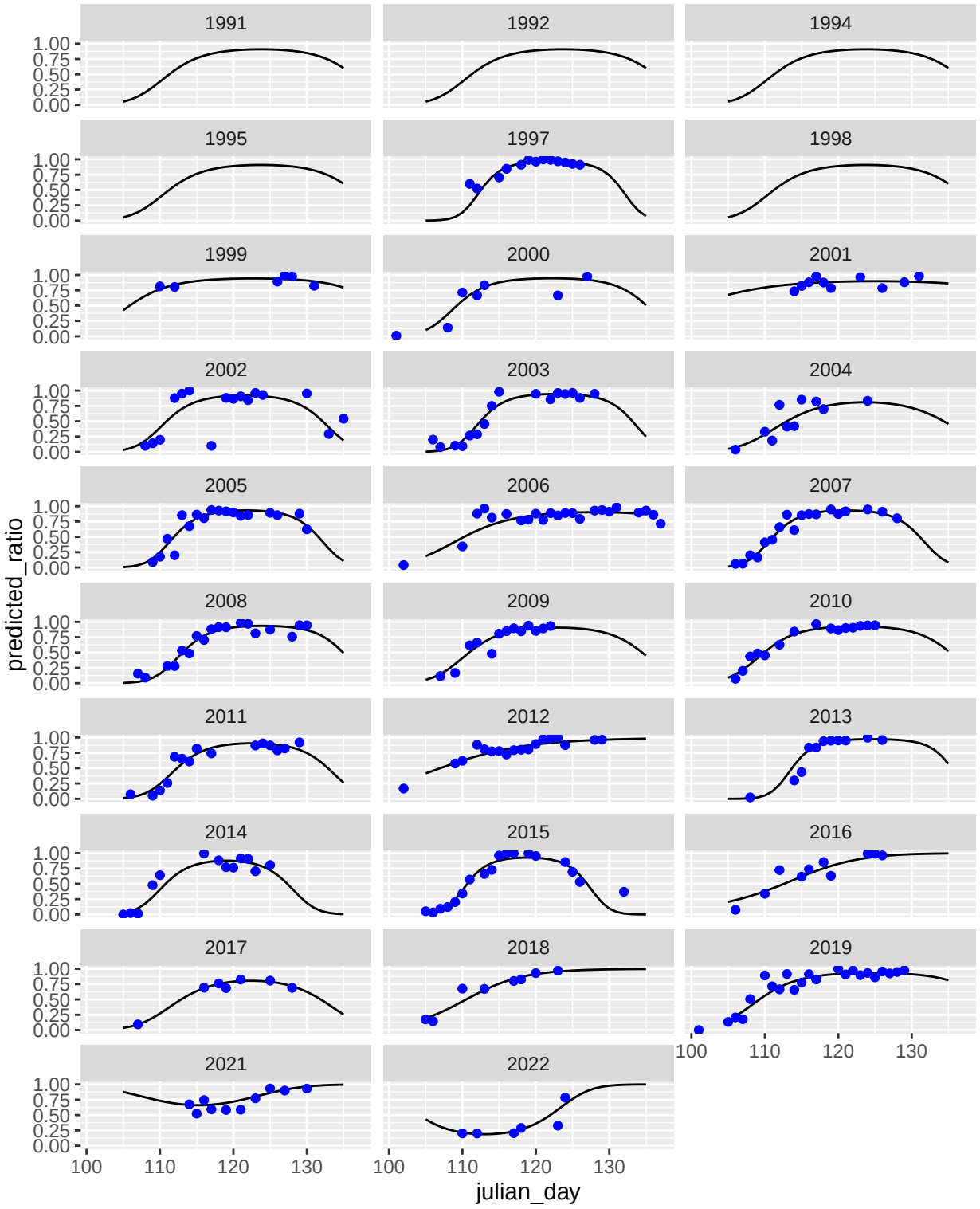


Figure 1: Yearly calculated seasonal species ratios. In years where species ratio subsample surveys were not conducted (1991, 1992, 1994, 1995, 1998), the mean species ratio curve across all years was applied.

2 Model data summary

The primary goal of this analysis is to determine whether melt flow regimes alter the north-south distribution of peeps. Birds are surveyed from a route of standardized survey stations. Any birds counted in or north of the "view corner" are labelled as `N`, while any birds counted south of the "view corner" are labelled as `S` for this analysis.[1]

The `dat` dataset, which contains survey data and associated environmental covariates, will be used in this model. The `dat` dataset can be explored in greater detail in the PeepR Shiny app.

[1] For now, this includes birds counted in Canoe Pass, but those will be excluded in a later analysis to compare results.

2.0.1 `dat` filtering

The `dat` dataset underwent some filtering steps to exclude unwanted data prior to this analysis. First, only data that was originally included in Canham et al. (2021) is extracted from the `bppeeps` database. While survey data oftentimes includes multiple sweeps, low-quality or reconnaissance sweeps were excluded from the daily totals used in Canham et al. (2021). As such, they were excluded from this dataset as well.

The total bird count for several surveys were obtained by taking the average total count from multiple sweeps. In these cases, it is difficult to obtain accurate location-level numbers because birds often moved locations between sweeps. These records are excluded for now (45 survey dates out of a total of 538).

Additionally, certain survey dates only included a total bird count for the day, but no location-level information. These records were excluded from the initial database query (24 survey dates out of a total of 538).

After excluding these surveys, the initial dataset queried from the `bppeeps` dataset included 1746 records from a total of 479. This is termed the 'full dataset' and was filtered further in `R`. The full dataset includes one survey per station per day.

Filtering step	No. survey dates	No. records	No. survey dates lost	No. records lost
Full dataset	479	1746	NA	NA
Remove NA count records	479	1742	0	-4
Exclude dates where total # of birds < 1000	453	1653	-26	-89
Exclude dates outside of survey period (<04-15 or >05-15)	440	1604	-13	-49
Exclude Canoe Pass, Intercauseway, and NA stations (e.g. location was simply 'inner mud', 'mumblies', 'flying', etc.)	438	1419	-2	-185
Exclude records where only bird count occurs in location that spans >2 stations (e.g., 'BP to CP')	434	1413	-4	-6

2.1 dat data summary after filtering

```
##       year       julian_day     survey_date          start_time
##  2019   :106   Min.   :105.0   Min.   :1997-04-21   Length:1413
##  2012   :103   1st Qu.:112.0   1st Qu.:2004-05-05   Class :character
##  2008   : 84   Median :118.0   Median :2010-04-20   Mode  :character
##  2005   : 73   Mean   :118.1   Mean   :2010-01-05
##  2015   : 70   3rd Qu.:124.0   3rd Qu.:2015-04-24
##  2013   : 68   Max.   :135.0   Max.   :2022-05-04
##  (Other):909
##            station_n             station_s     final_count         p_wesa
##  Pilings        :334   Coal Port      :  48   Min.   :     0   Min.   :  0.00
##  Coal Port      :325   View corner    :  40   1st Qu.:  1300   1st Qu.: 56.94
##  Brunswick Point:268   Bend           :  21   Median :  7000   Median : 80.69
##  34th St pullout:195   34th St pullout:  17   Mean   : 16838   Mean   : 69.35
##  View corner    :178   Pilings        :  12   3rd Qu.: 22500   3rd Qu.: 91.21
##  Bend           :113   (Other)        :   0   Max.   :222500   Max.   :100.00
##  (Other)        :  0   NA's           :1275                    NA's   :429
##   raptor_count      elev_min         elev_max      elev_median
##  Min.   :1.000   Min.   :-0.040   Min.   :3.960   Min.   :2.240
##  1st Qu.:1.000   1st Qu.: 0.820   1st Qu.:4.300   1st Qu.:3.075
##  Median :1.000   Median : 1.210   Median :4.430   Median :3.255
##  Mean   :1.792   Mean   : 1.221   Mean   :4.419   Mean   :3.238
##  3rd Qu.:2.000   3rd Qu.: 1.620   3rd Qu.:4.560   3rd Qu.:3.405
##  Max.   :8.000   Max.   : 2.420   Max.   :4.850   Max.   :3.735
##  NA's   :788
##    elev_mean       elev_range         flow       total_precip
##  Min.   :2.660   Min.   :1.870   Min.   : 996   Min.   : 0.000
##  1st Qu.:2.971   1st Qu.:2.720   1st Qu.:2480   1st Qu.: 0.000
##  Median :3.040   Median :3.210   Median :3110   Median : 0.000
##  Mean   :3.043   Mean   :3.198   Mean   :3297   Mean   : 2.198
##  3rd Qu.:3.118   3rd Qu.:3.620   3rd Qu.:4072   3rd Qu.: 2.000
##  Max.   :3.422   Max.   :4.640   Max.   :7830   Max.   :28.200
##                                  NA's   :5      NA's   :4
##    mean_temp           u                 v              windspd
##  Min.   : 3.80   Min.   :-19.8067   Min.   :-42.3467   Min.   : 5.292
##  1st Qu.: 9.30   1st Qu.: -4.1042   1st Qu.: -9.9586   1st Qu.:10.500
##  Median :10.50   Median : -0.9551   Median : -0.7814   Median :12.958
##  Mean   :10.68   Mean   : -0.6988   Mean   : -1.8068   Mean   :14.265
##  3rd Qu.:11.90   3rd Qu.:  2.6971   3rd Qu.:  7.9472   3rd Qu.:16.875
##  Max.   :17.50   Max.   : 15.0489   Max.   : 20.4541   Max.   :43.750
##
##     wind_deg       date_time_pdt                 date_time_utc
##  Min.   :-177.35   Min.   :1997-04-21 17:35:00   Min.   :1997-04-22 00:35:00
##  1st Qu.: -78.06   1st Qu.:2004-05-05 17:51:00   1st Qu.:2004-05-06 00:51:00
##  Median : -25.39   Median :2010-04-20 11:10:00   Median :2010-04-20 18:10:00
##  Mean   :  13.47   Mean   :2010-01-05 17:13:02   Mean   :2010-01-06 01:13:02
##  3rd Qu.: 117.95   3rd Qu.:2015-04-24 11:57:00   3rd Qu.:2015-04-24 18:57:00
##  Max.   : 179.93   Max.   :2022-05-04 09:00:00   Max.   :2022-05-04 16:00:00
##
##       tide            dos.V1        n_s     predicted_ratio
##  falling:864   Min.   :-1.8377454   N:893   Min.   :0.0003308
##  rising :549   1st Qu.:-0.8550379   S:520   1st Qu.:0.5722192
##                Median :-0.0127173           Median :0.8214827
```

```
##                Mean   : 0.0000000           Mean   :0.7041472
##                3rd Qu.: 0.8296034           3rd Qu.:0.9099752
##                Max.   : 2.3738580           Max.   :0.9855691
##
##  predicted_wesa   predicted_dunl     log_wesa         log_dunl
##  Min.   :     0   Min.   :    0   Min.   : 0.000   Min.   : 0.000
##  1st Qu.:   581   1st Qu.:  177   1st Qu.: 6.366   1st Qu.: 5.182
##  Median :  3998   Median : 1253   Median : 8.294   Median : 7.134
##  Mean   : 12058   Mean   : 4780   Mean   : 7.410   Mean   : 6.442
##  3rd Qu.: 14083   3rd Qu.: 4661   3rd Qu.: 9.553   3rd Qu.: 8.447
##  Max.   :208063   Max.   :82833   Max.   :12.246   Max.   :11.325
##
##       year_c.V1
##  Min.   :-1.7808702
##  1st Qu.:-0.8644382
##  Median : 0.0519938
##  Mean   : 0.0000000
##  3rd Qu.: 0.8156872
##  Max.   : 1.7321192
##
```

3 Extended Canham et al. (2021) model

In this initial analysis, the model is kept relatively simple: the exact same model as in Canham et al. (2021) is used, but a "north vs. south" term is added. The response variable will be the log-transformed count of WESA for that location (total count for that location/day * the predicted WESA ratio generated by the bGLMM above).

3.0.1 Base model

Response variable:

- `log_wesa` - Log-transformed predicted WESA count

Predictor variables:

- `year_c` - Scale-transformed survey year
- `dos` - Scale-transformed Julian date, aka Day of Season

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: log_wesa ~ year_c + dos + I(dos^2) + (dos + I(dos^2) | year)
##    Data: dat
##
## REML criterion at convergence: 6939.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4345 -0.3392  0.2425  0.6207  2.2022
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.4218   0.6495
##           dos         0.5061   0.7114   -0.10
##           I(dos^2)    0.1970   0.4438   -0.23 -0.18
##  Residual             7.4522   2.7299
## Number of obs: 1413, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)  8.65716    0.17054 15.13308  50.763  < 2e-16 ***
## year_c      -0.02303    0.14676 21.86661  -0.157    0.877
## dos          0.04903    0.17042 20.56125   0.288    0.776
## I(dos^2)    -1.33651    0.12736  9.51154 -10.494 1.54e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##          (Intr) year_c dos
## year_c    0.013
## dos      -0.068  0.017
## I(dos^2) -0.422  0.026 -0.096
```

3.0.2 Full model

NOTE: at the time of this writing, `IR` is *unavaible* in this model. I have not gotten any response from the team that manages the UBC Totem Station data. Given it was not a significant variable in Canham et al. (2021), I do not believe it is urgent to acquire this particular data.

Response variable:

- `log_wesa` - Log-transformed predicted WESA count

Predictor variables:

- `year_c` - Scale-transformed survey year
- `dos` - Scale-transformed Julian date, aka Day of Season
- `elev_range` - Tidal amplitude (m)
- `total_precip` - Total daily precipitation (mm)
- `mean_temp` - Daily mean temperature (C°)
- `flow` - Fraser River discarge (mˆ3/s)
- `u`, `v` - Westerly and Southerly wind vectors (km/h)
- `n_s` - Location ('North' or 'South')

Additionally, the dataset is reduced down to only complete cases of all predictor variables of interest (1413 -> 1404).

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## log_wesa ~ year_c + dos + I(dos^2) + scale(elev_range) + scale(total_precip) +
##     scale(mean_temp) + scale(flow) + scale(u) + scale(v) + n_s +
##     (dos + I(dos^2) | year) + (scale(flow) | n_s)
##    Data: dat2
##
## REML criterion at convergence: 6807.6
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4628 -0.3247  0.2371  0.6346  2.1111
##
## Random effects:
##  Groups   Name        Variance  Std.Dev.  Corr
##  year     (Intercept) 5.390e-01 7.342e-01
##           dos         5.071e-01 7.121e-01 -0.36
##           I(dos^2)    1.102e-01 3.320e-01  0.29 -0.15
##  n_s      (Intercept) 1.497e+01 3.869e+00
##           scale(flow) 1.204e-12 1.097e-06 1.00
##  Residual             6.920e+00 2.631e+00
## Number of obs: 1404, groups:  year, 24; n_s, 2
##
## Fixed effects:
##                       Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)          9.232e+00  3.874e+00  2.063e-08   2.383  1.00000
## year_c              -1.813e-01  1.663e-01  1.996e+01  -1.090  0.28862
## dos                  2.175e-01  1.957e-01  2.894e+01   1.111  0.27552
```

```
## I(dos^2)            -1.392e+00  1.095e-01  9.927e+00 -12.719 1.81e-07 ***
## scale(elev_range)    2.444e-01  8.186e-02  4.220e+02   2.985  0.00300 **
## scale(total_precip)  2.221e-02  7.947e-02  1.281e+03   0.279  0.77991
## scale(mean_temp)     8.993e-02  9.396e-02  7.206e+02   0.957  0.33882
## scale(flow)         -2.965e-01  1.502e-01  4.230e+01  -1.973  0.05500 .
## scale(u)             6.113e-02  9.179e-02  9.345e+02   0.666  0.50561
## scale(v)             2.485e-01  9.531e-02  1.083e+03   2.607  0.00926 **
## n_sS                -1.471e+00  5.473e+00  2.056e-08  -0.269  1.00000
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) year_c dos    I(d^2) scl(l_) scl(t_) scl(m_) scl(f) scal()
## year_c       0.000
## dos         -0.008 -0.014
## I(dos^2)    -0.007  0.045 -0.124
## scl(lv_rng)  0.000  0.026 -0.042  0.024
## scl(ttl_pr)  0.000  0.023 -0.005  0.008  0.066
## scl(mn_tmp) -0.001 -0.052 -0.161 -0.002 -0.083   0.061
## scale(flow) -0.004  0.047 -0.476  0.128  0.044   0.049   0.000
## scale(u)     0.001 -0.050  0.043 -0.067 -0.076  -0.038   0.057  -0.001
## scale(v)     0.001 -0.003  0.059 -0.061  0.038  -0.264  -0.076  -0.034  0.517
## n_sS        -0.706  0.000  0.000  0.000 -0.001   0.000   0.001   0.000  0.000
##             scl(v)
## year_c
## dos
## I(dos^2)
## scl(lv_rng)
## scl(ttl_pr)
## scl(mn_tmp)
## scale(flow)
## scale(u)
## scale(v)
## n_sS         0.000
## optimizer (nloptwrap) convergence code: 0 (OK)
## boundary (singular) fit: see help('isSingular')
```

3.0.3 Backwards step-wise selection

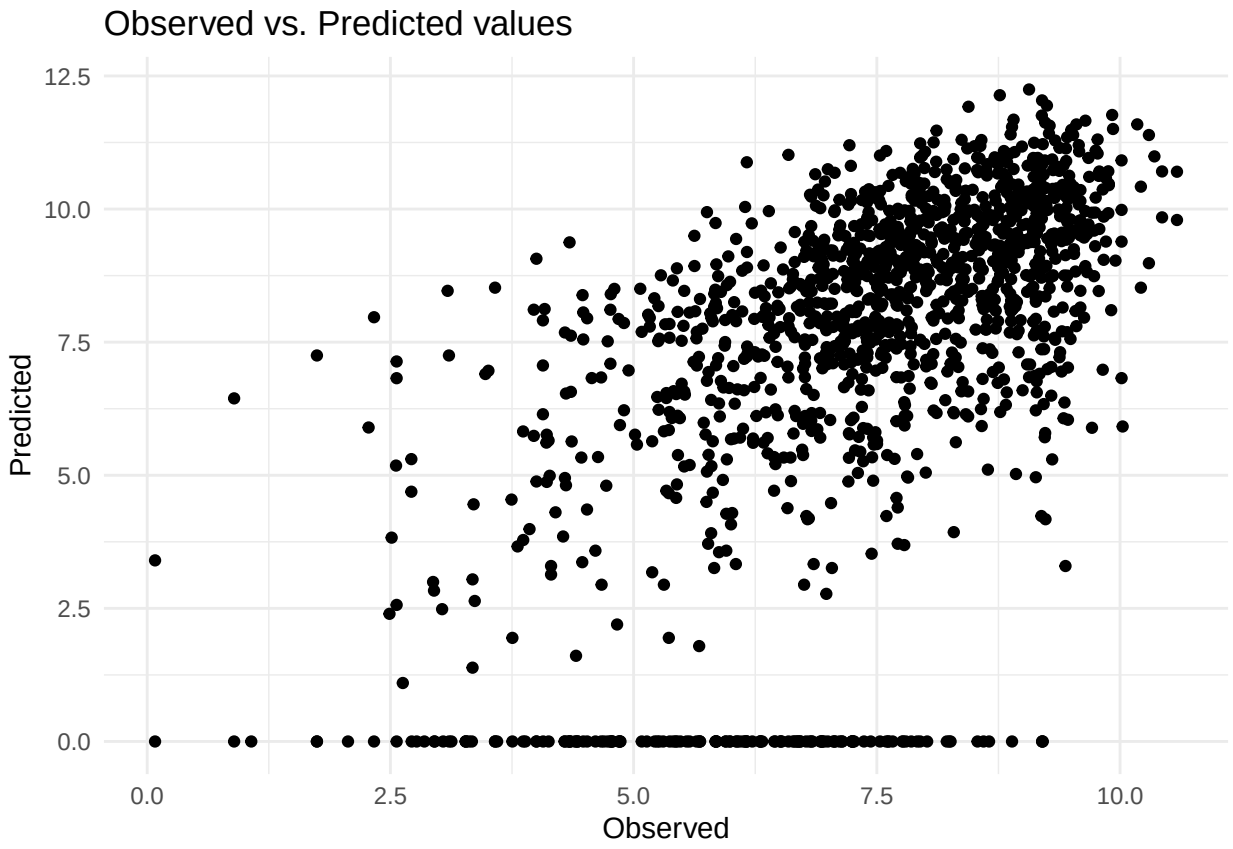
```
## Backward reduced random-effect table:
##
##                                    Eliminated npar  logLik    AIC    LRT Df
## <none>                                         21 -3403.8 6849.6
## dos in (dos + I(dos^2) | year)              0   18 -3423.5 6883.0 39.379  3
## I(dos^2) in (dos + I(dos^2) | year)         0   18 -3406.3 6848.5  4.935  3
## scale(flow) in (scale(flow) | n_s)          0   19 -3403.8 6845.6  0.000  2
##                                    Pr(>Chisq)
## <none>
## dos in (dos + I(dos^2) | year)       1.443e-08 ***
## I(dos^2) in (dos + I(dos^2) | year)     0.1766
## scale(flow) in (scale(flow) | n_s)      1.0000
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

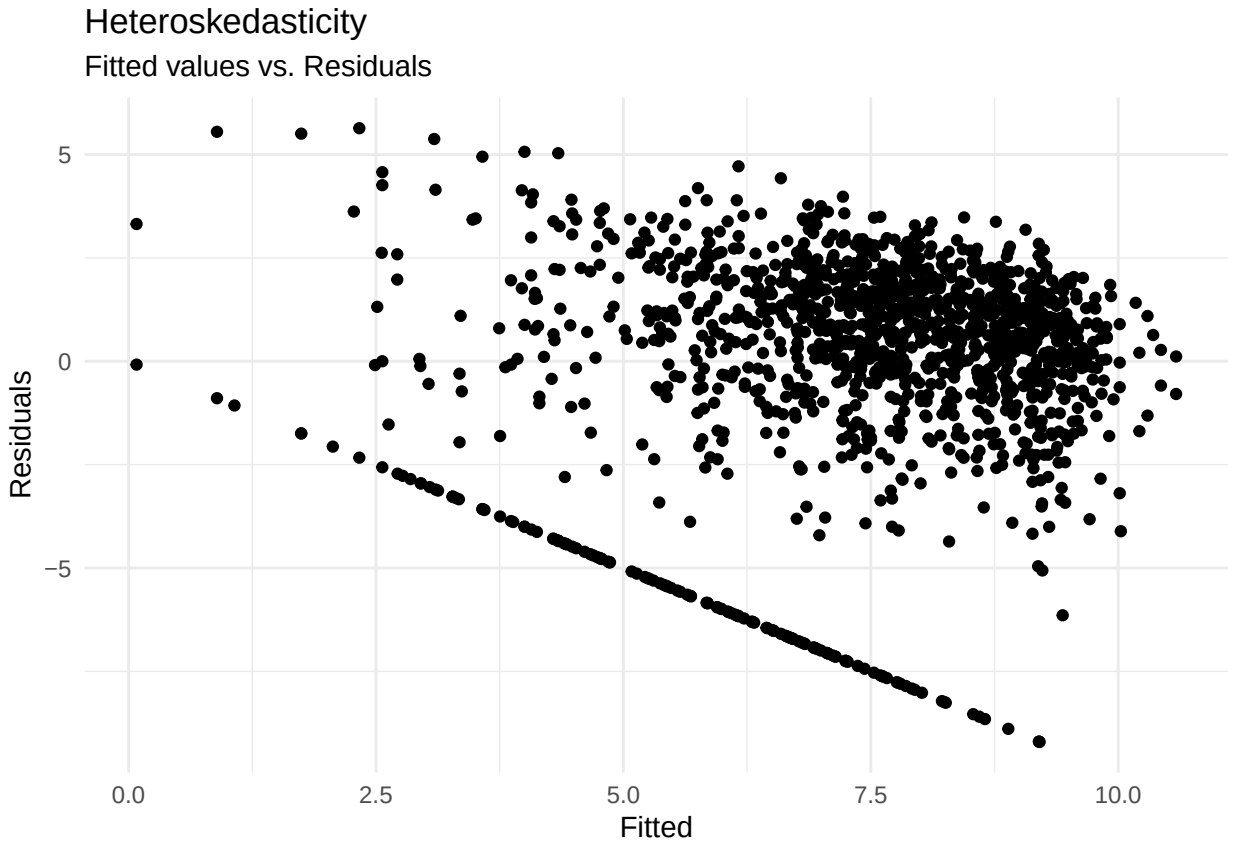
```
##
## Backward reduced fixed-effect table:
## Degrees of freedom method: Satterthwaite
##
##                     Eliminated Sum Sq Mean Sq NumDF   DenDF  F value    Pr(>F)
## n_s                          1   0.50    0.50     1    0.00   0.0723  1.000000
## scale(total_precip)          2   0.54    0.54     1 1280.21   0.0774  0.780938
## scale(u)                     3   3.19    3.19     1  935.19   0.4620  0.496842
## scale(mean_temp)             4   5.60    5.60     1  737.58   0.8102  0.368367
## scale(flow)                  5  27.81   27.81     1   11.91   4.0262  0.068045
## year_c                       0   1.56    1.56     1   21.19   0.2260  0.639351
## dos                          0   1.14    1.14     1   18.19   0.1647  0.689620
## I(dos^2)                     0 849.86  849.86     1    9.09 123.2923 1.371e-06
## scale(elev_range)            0  69.19   69.19     1  576.91  10.0370  0.001615
## scale(v)                     0  56.00   56.00     1 1191.31   8.1248  0.004442
##
## n_s
## scale(total_precip)
## scale(u)
## scale(mean_temp)
## scale(flow)          .
## year_c
## dos
## I(dos^2)             ***
## scale(elev_range)    **
## scale(v)             **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Model found:
## log_wesa ~ year_c + dos + I(dos^2) + scale(elev_range) + scale(v) + (dos + I(dos^2) | year) + (scale
```

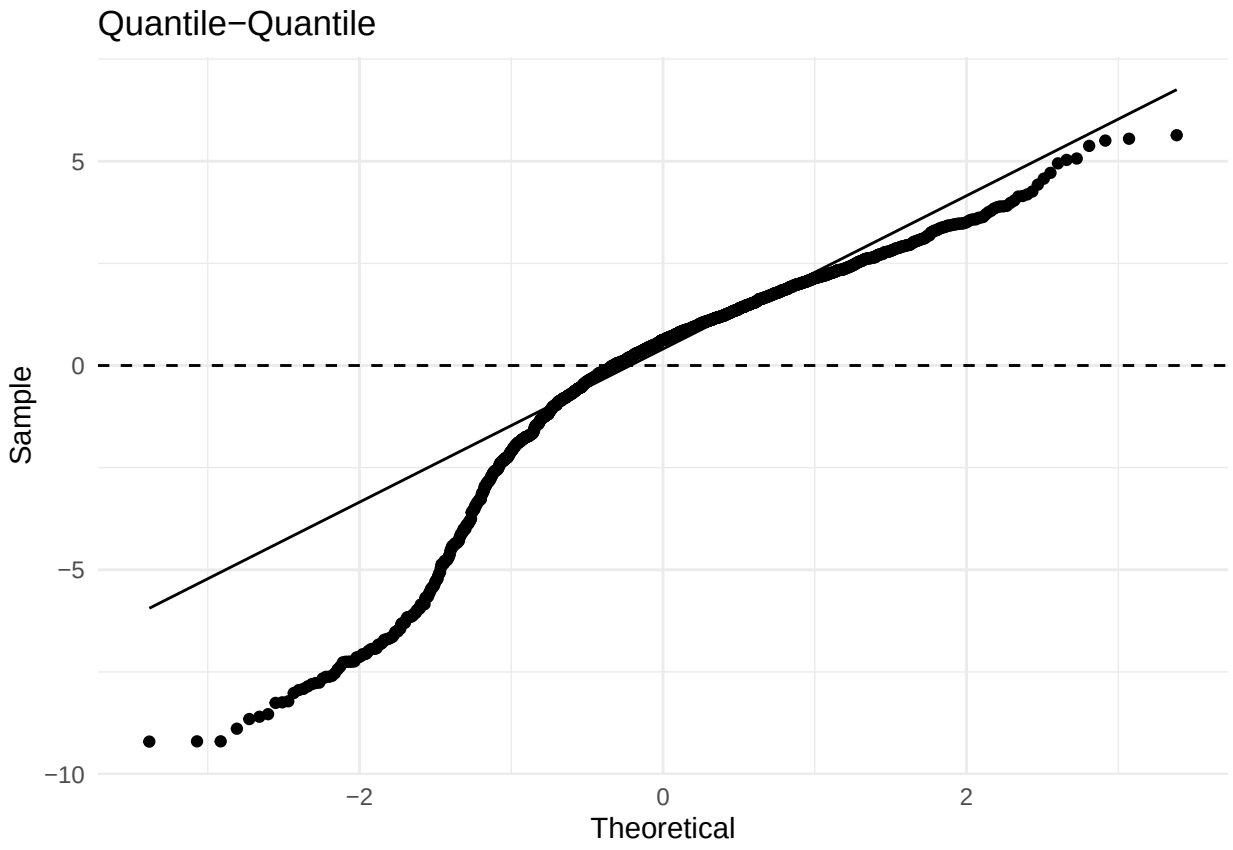
3.0.4 Summary of best-fit model

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: log_wesa ~ year_c + dos + I(dos^2) + scale(elev_range) + scale(v) +
##     (dos + I(dos^2) | year) + (scale(flow) | n_s)
##    Data: dat2
##
## REML criterion at convergence: 6804.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.5064 -0.3273  0.2375  0.6362  2.1470
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.53090  0.7286
##           dos         0.52980  0.7279   -0.21
##           I(dos^2)    0.17649  0.4201   -0.06 -0.11
##  n_s      (Intercept) 1.52850  1.2363
##           scale(flow) 0.01258  0.1121   1.00
##  Residual             6.89303  2.6255
## Number of obs: 1404, groups:  year, 24; n_s, 2
##
## Fixed effects:
##                     Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)          9.08816    0.80691    0.91543  11.263  0.06827 .
## year_c              -0.07720    0.16237   21.18598  -0.475  0.63935
## dos                  0.07224    0.17803   18.19127   0.406  0.68962
## I(dos^2)            -1.35646    0.12216    9.08827 -11.104 1.37e-06 ***
## scale(elev_range)    0.26066    0.08228  576.91090   3.168  0.00162 **
## scale(v)             0.22237    0.07801 1191.30902   2.850  0.00444 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) year_c dos    I(d^2) scl(_)
## year_c      -0.012
## dos          0.212  0.004
## I(dos^2)    -0.121  0.029 -0.063
## scl(lv_rng) -0.025  0.011 -0.044  0.019
## scale(v)     0.009  0.020  0.012 -0.026  0.105
## optimizer (nloptwrap) convergence code: 0 (OK)
## boundary (singular) fit: see help('isSingular')
```

3.0.5 Check assumptions of best fit model




Heteroskedasticity
Fitted values vs. Residuals
Residuals
5
0
−5
0.0
2.5
5.0
7.5
10.0
Fitted


Quantile−Quantile
Sample
5
0
−5
−10
−2
0
2
Theoretical

4 Exploring mechanism (flow) vs. time (year)

Given the Canham extended model has some issues, the next step is to run two models with a slightly simpler approach. First, we want to see what the baseline trend is in north-south distributions - from plotting the data it appears that the birds prefer the north. We are also still interested in seeing if the discharge (`flow`) has an impact on the north-south distribution of peeps. In addition, we are interested in seeing any temporal changes in this distribution.

Three simpler models can get at these questions:

1. The base model: log_wesa ~ n_s + dos + I(dos^2) + (dos + I(dos^2) | year)
2. The 'mechanism' model: log_wesa ~ n_s * scale(flow) + dos + I(dos^2) + (dos + I(dos^2) | year)
3. The 'temporal' model: log_wesa ~ n_s * year_c + dos + I(dos^2) + (dos + I(dos^2) | year)

4.1 Data changes

These simpler models necessitate further data aggregation. We are primarily interested in N vs S distribution of peeps: therefore, the data are grouped by N/S such that there are two data points per survey date: number of peeps in the northern stations (Canoe Pass, Brunswick Point, Bend, Pilings, View corner) vs southern (34th St pullout, Coal Port). Any NA values in our variables of interest are also removed.

```
##   year        dos n_s  log_wesa log_dunl flow    year_c
## 1 1997 -0.9915388   N  8.171599 9.258464 3430 -1.684594
## 2 1997 -0.9915388   S  0.000000 0.000000 3430 -1.684594
## 3 1997 -0.8528390   N  8.585973 8.941938 3670 -1.684594
## 4 1997 -0.8528390   S  0.000000 0.000000 3670 -1.684594
## 5 1997 -0.4367394   N 11.024253 9.599541 4160 -1.684594
## 6 1997 -0.4367394   S 10.681206 9.256460 4160 -1.684594
```

```
##       year            dos.V1        n_s        log_wesa         log_dunl
##  2019   : 51   Min.   :-1.8237379   N:426   Min.   : 0.000   Min.   : 0.000
##  2015   : 47   1st Qu.:-0.8528390   S:412   1st Qu.: 7.671   1st Qu.: 6.334
##  2012   : 46   Median :-0.0206399           Median : 9.098   Median : 7.931
##  2008   : 45   Mean   : 0.0013734           Mean   : 8.215   Mean   : 7.227
##  2005   : 44   3rd Qu.: 0.8115592           3rd Qu.:10.217   3rd Qu.: 9.176
##  1999   : 42   Max.   : 2.3372576           Max.   :12.250   Max.   :11.387
##  (Other):563
##       flow           year_c.V1
##  Min.   : 996   Min.   :-1.6845940
##  1st Qu.:2500   1st Qu.:-0.9182889
##  Median :3130   Median : 0.0012772
##  Mean   :3311   Mean   :-0.0040266
##  3rd Qu.:4030   3rd Qu.: 0.7675822
##  Max.   :7830   Max.   : 1.8404093
##
```

4.2 The base model

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: log_wesa ~ n_s + dos + I(dos^2) + (dos + I(dos^2) | year)
##    Data: mt_dat
##
```

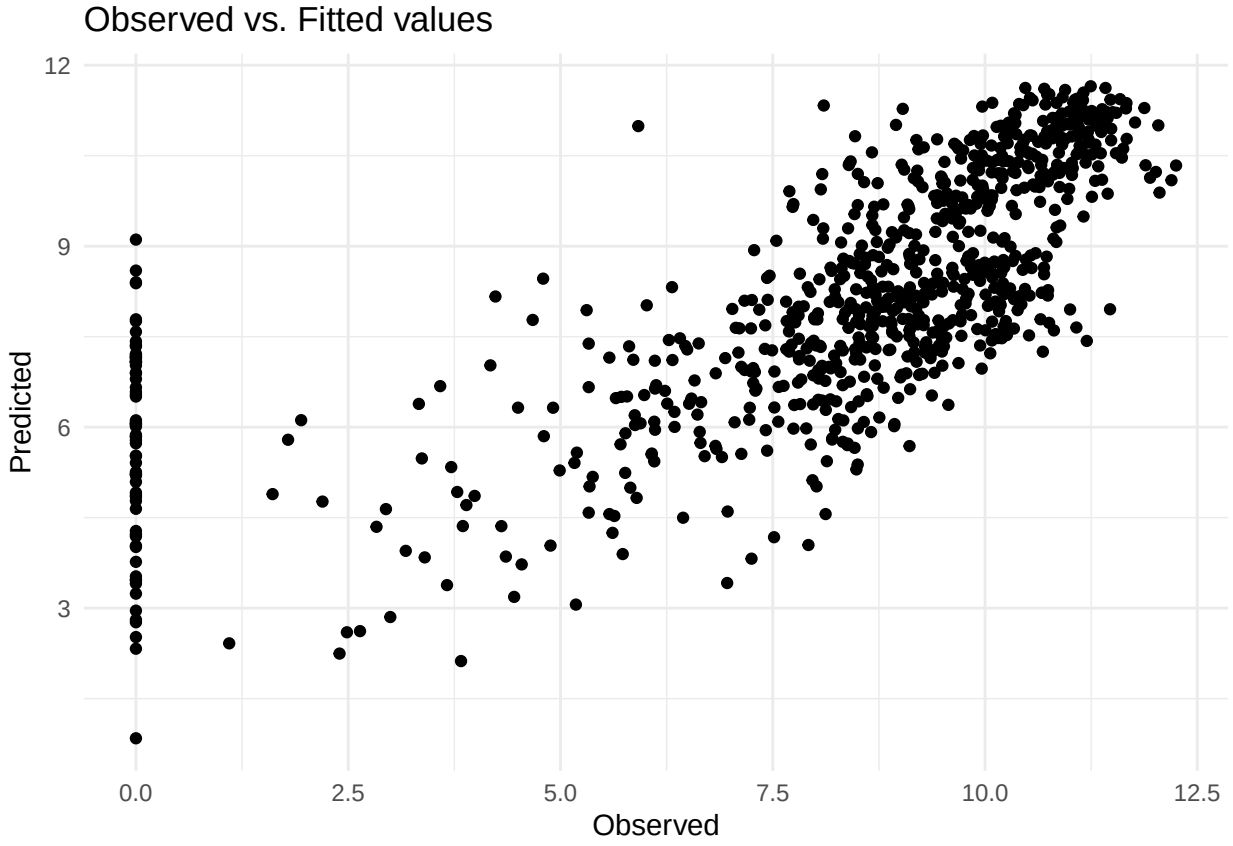
```
## REML criterion at convergence: 3799.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.0409 -0.2174  0.1190  0.5819  1.7493
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3106   0.5573
##           dos         0.4333   0.6582   -0.22
##           I(dos^2)    0.2092   0.4574   -0.22 -0.07
##  Residual             4.9545   2.2259
## Number of obs: 838, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error t value
## (Intercept)  10.9155     0.1774  61.538
## n_sS         -2.7998     0.1540 -18.183
## dos           0.1218     0.1638   0.744
## I(dos^2)     -1.4470     0.1327 -10.906
##
## Correlation of Fixed Effects:
##          (Intr) n_sS   dos
## n_sS     -0.428
## dos      -0.122 -0.002
## I(dos^2) -0.403  0.000 -0.024
```

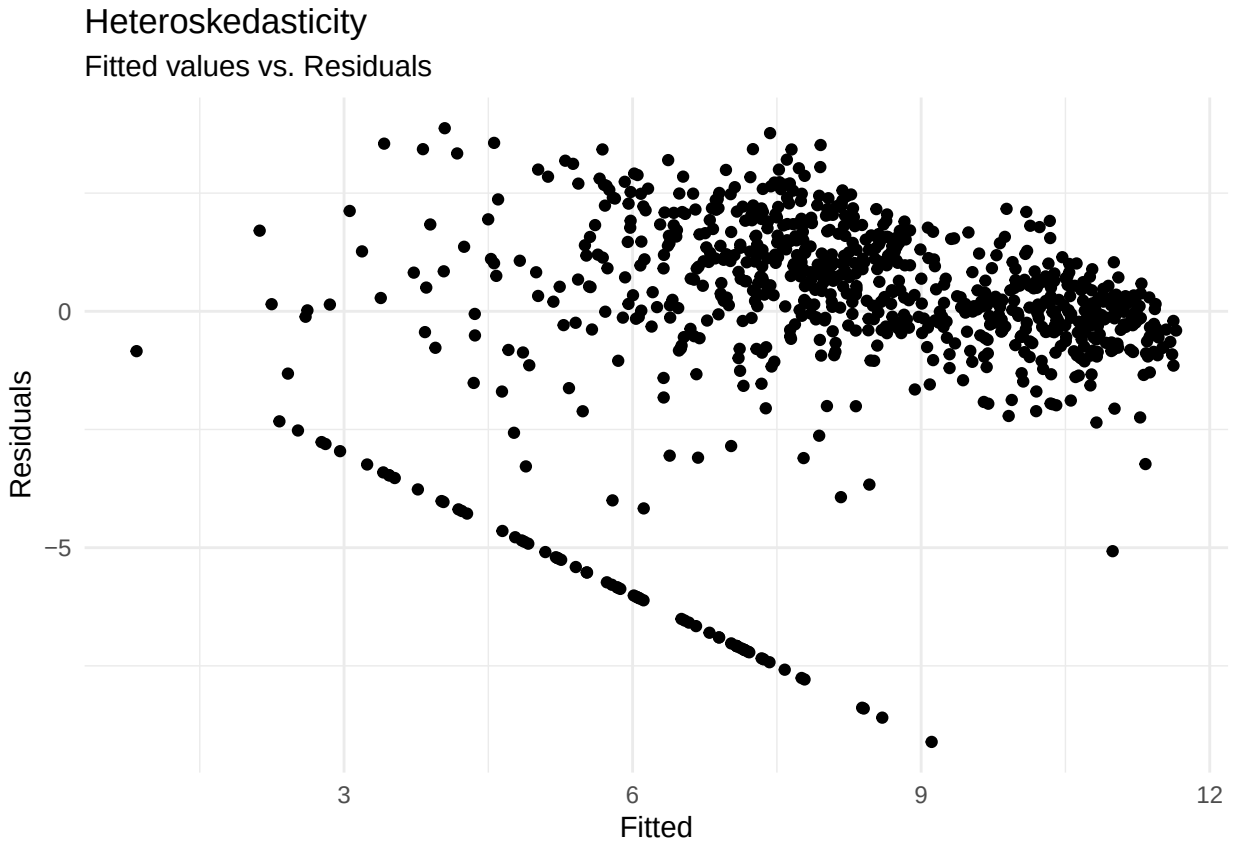
4.3 The 'mechanism' model

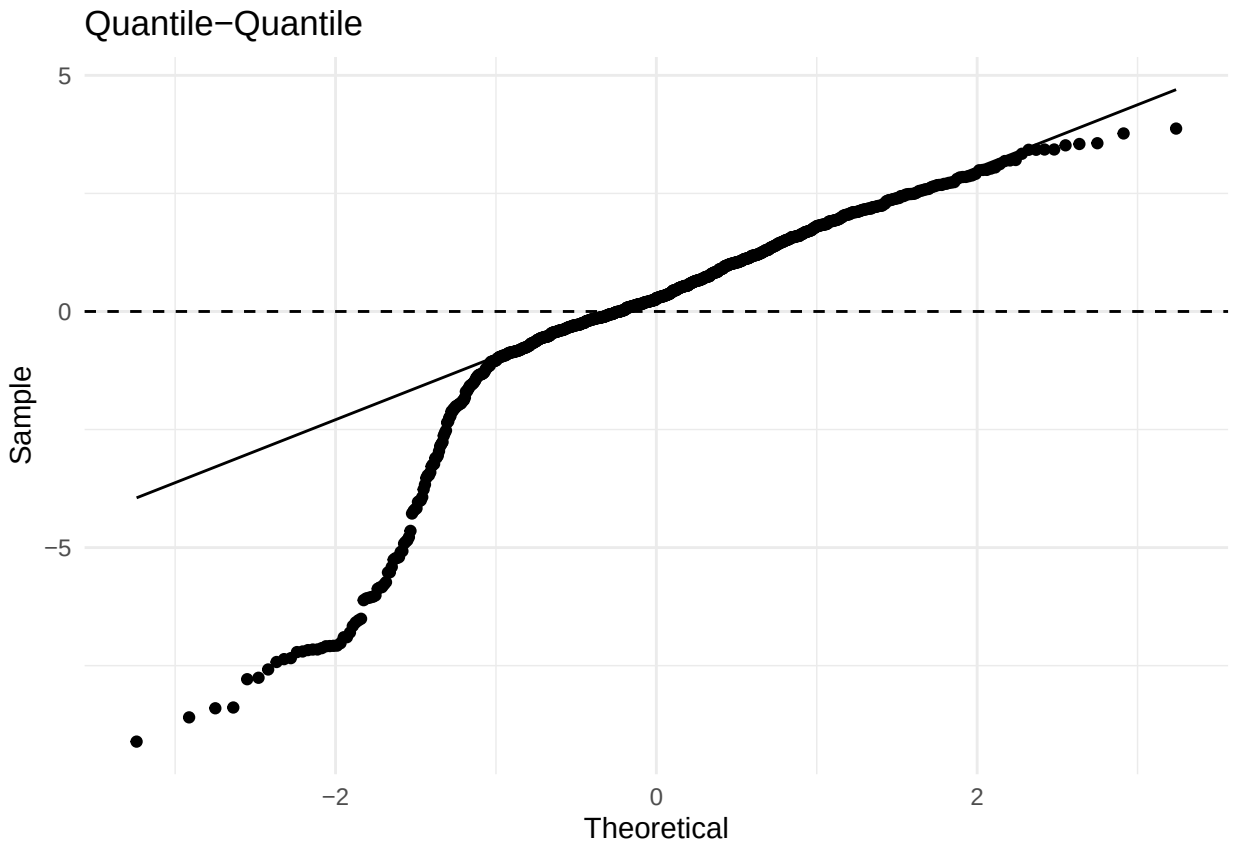
```
## Linear mixed model fit by REML ['lmerMod']
## Formula: log_wesa ~ n_s * scale(flow) + dos + I(dos^2) + (dos + I(dos^2) |
##     year)
##    Data: mt_dat
##
## REML criterion at convergence: 3797.9
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.1012 -0.2358  0.1270  0.5743  1.7439
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3429   0.5856
##           dos         0.4424   0.6651   -0.25
##           I(dos^2)    0.1831   0.4279   -0.20 -0.15
##  Residual             4.9329   2.2210
## Number of obs: 838, groups:  year, 24
##
## Fixed effects:
##                  Estimate Std. Error t value
## (Intercept)       10.9491     0.1816  60.276
## n_sS              -2.8012     0.1536 -18.232
## scale(flow)       -0.2167     0.1635  -1.326
```

```
## dos                0.3244     0.1893   1.713
## I(dos^2)          -1.4784     0.1286 -11.493
## n_sS:scale(flow)  -0.1798     0.1537  -1.170
##
## Correlation of Fixed Effects:
##             (Intr) n_sS   scl(f) dos    I(d^2)
## n_sS        -0.418
## scale(flow) -0.081  0.004
## dos         -0.072 -0.004 -0.439
## I(dos^2)    -0.400  0.001  0.102 -0.122
## n_sS:scl(f) -0.003  0.000 -0.460 -0.002  0.006
```

4.3.1 Diagnostic plots



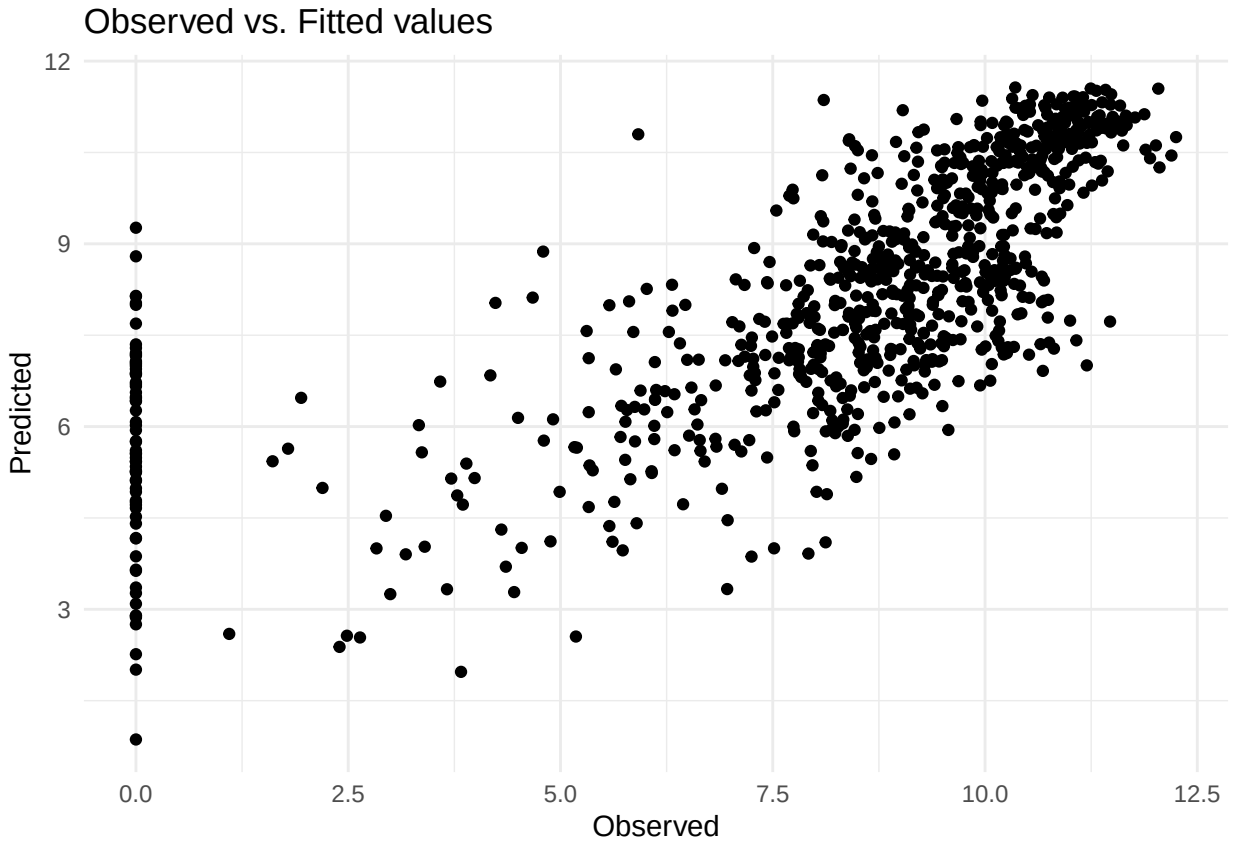

Heteroskedasticity
Fitted values vs. Residuals
Residuals
0
−5
3
6
9
12
Fitted

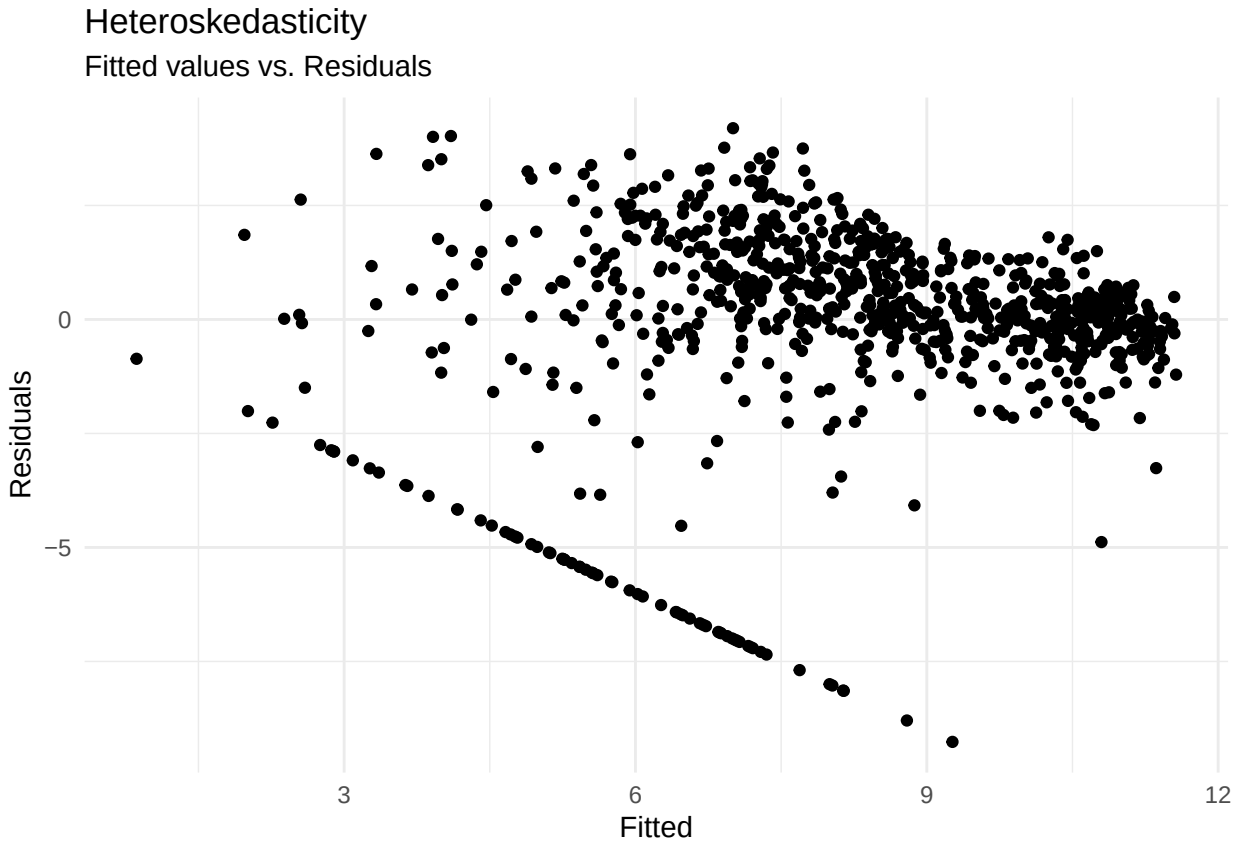

Quantile−Quantile
Sample
5
0
−5
−2
0
2
Theoretical

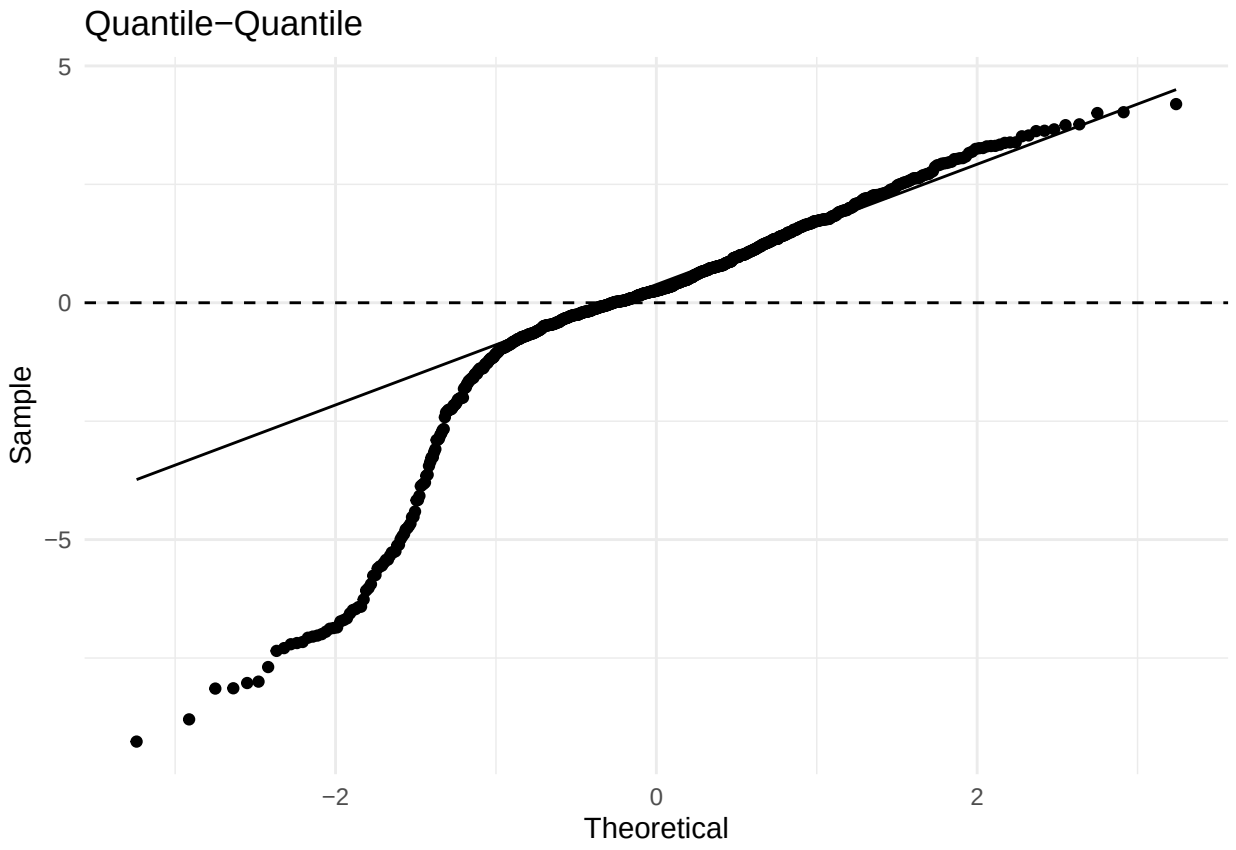
4.4 The 'temporal' model

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: log_wesa ~ n_s * year_c + dos + I(dos^2) + (dos + I(dos^2) |
##     year)
##    Data: mt_dat
##
## REML criterion at convergence: 3791.1
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.1880 -0.2140  0.1141  0.5607  1.8960
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3195   0.5652
##           dos         0.4372   0.6612    0.07
##           I(dos^2)    0.2223   0.4715   -0.39 -0.09
##  Residual             4.8934   2.2121
## Number of obs: 838, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error t value
## (Intercept) 10.90165    0.17792  61.272
## n_sS        -2.79605    0.15304 -18.271
## year_c      -0.02216    0.15210  -0.146
## dos          0.11382    0.16398   0.694
## I(dos^2)    -1.43994    0.13450 -10.706
## n_sS:year_c  0.50406    0.15343   3.285
##
## Correlation of Fixed Effects:
##             (Intr) n_sS   year_c dos    I(d^2)
## n_sS        -0.424
## year_c      -0.015 -0.002
## dos          0.036 -0.002  0.022
## I(dos^2)    -0.480  0.000  0.001 -0.031
## n_sS:year_c -0.003  0.005 -0.496 -0.003  0.004
```

4.4.1 Diagnostic plots




Heteroskedasticity
Fitted values vs. Residuals
Residuals
0
−5
3
6
9
12
Fitted


Quantile−Quantile
Sample
5
0
−5
−2
0
2
Theoretical

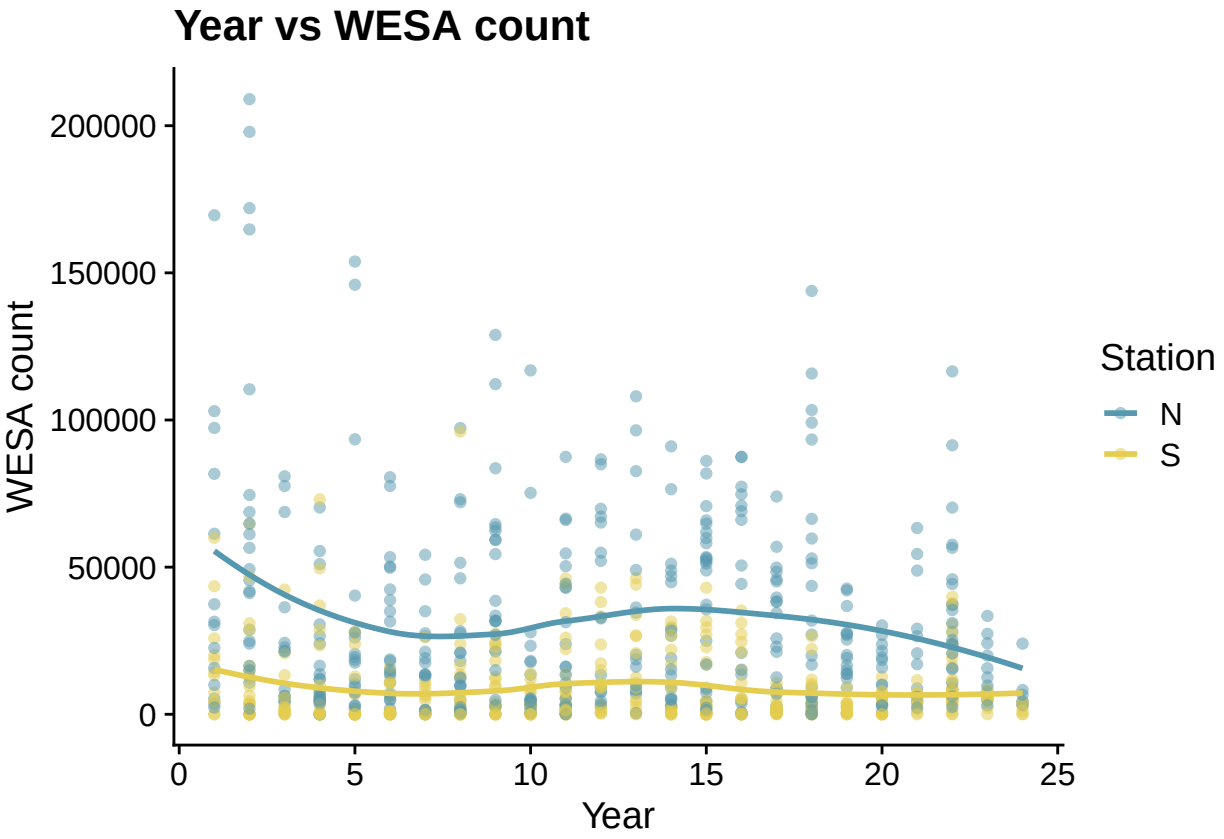
4.5 Comparing the three

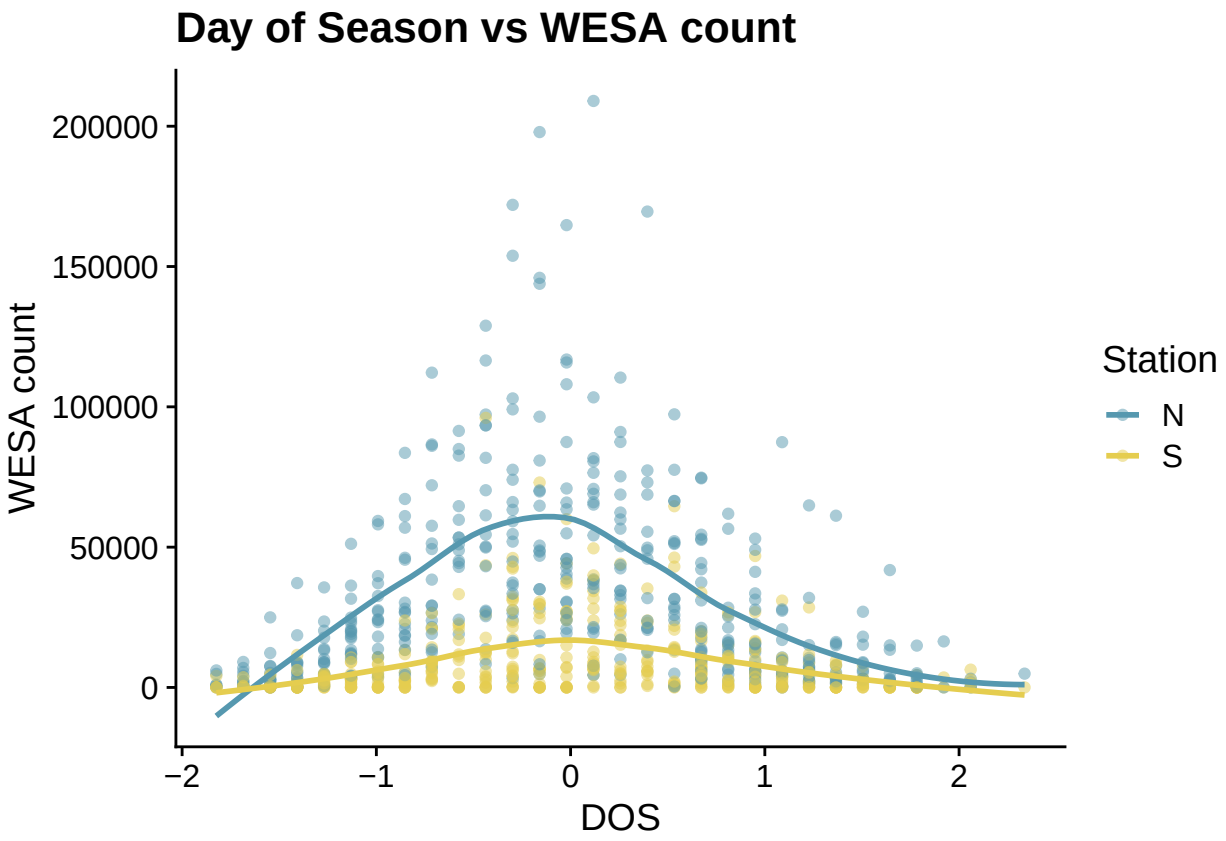
```
## Data: mt_dat
## Models:
## base_model: log_wesa ~ n_s + dos + I(dos^2) + (dos + I(dos^2) | year)
## mech_model: log_wesa ~ n_s * scale(flow) + dos + I(dos^2) + (dos + I(dos^2) | year)
## temp_model: log_wesa ~ n_s * year_c + dos + I(dos^2) + (dos + I(dos^2) | year)
##            npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## base_model   11 3813.5 3865.5 -1895.7   3791.5
## mech_model   13 3811.8 3873.3 -1892.9   3785.8 5.6259  2    0.06003 .
## temp_model   13 3804.8 3866.3 -1889.4   3778.8 7.0270  0
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

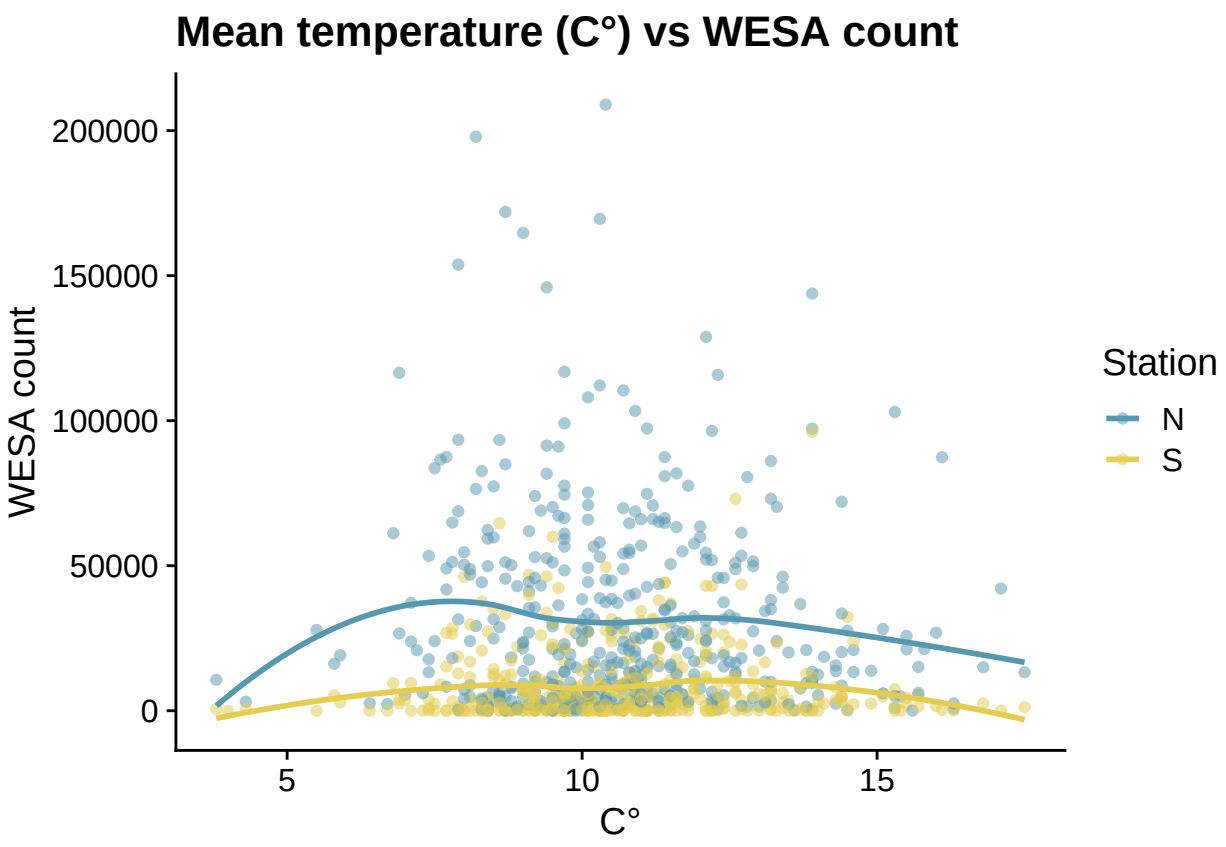
5 Final WESA model

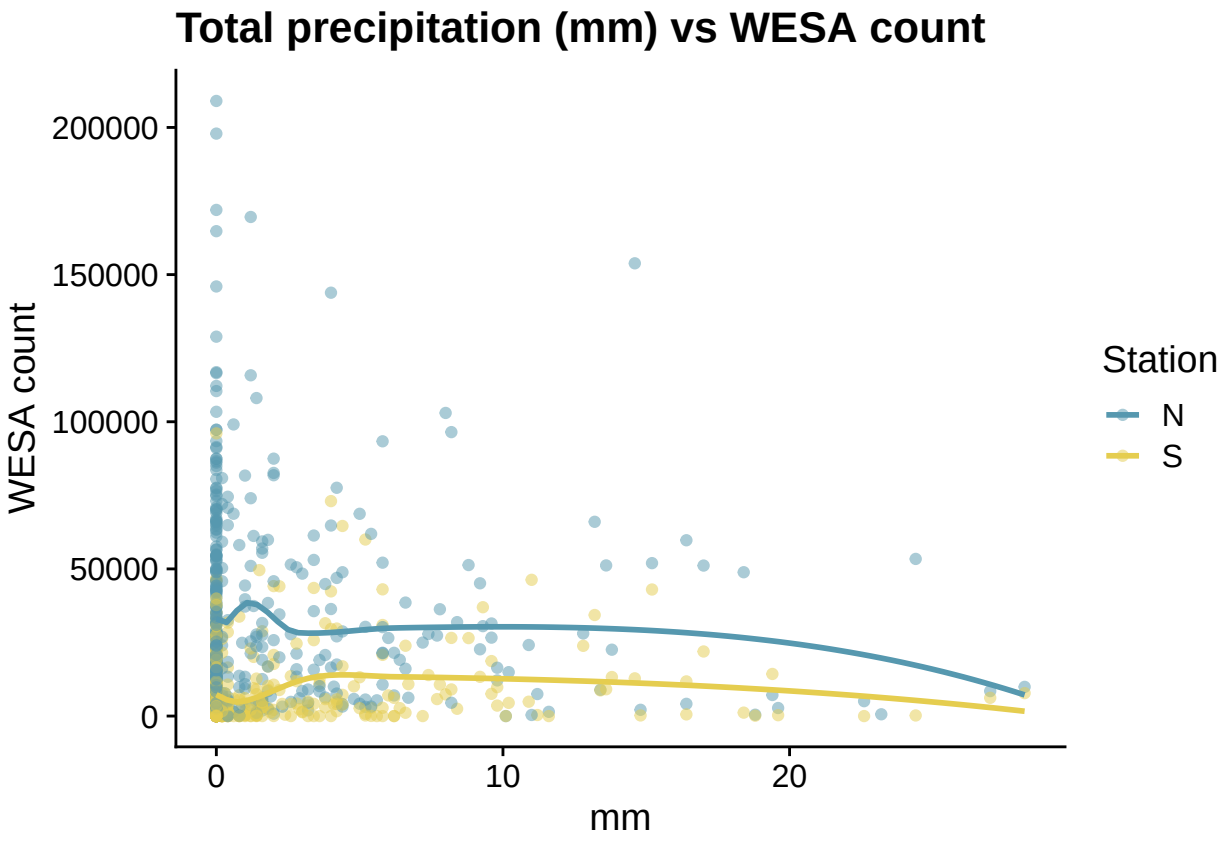
5.1 WESA vs. variable plots

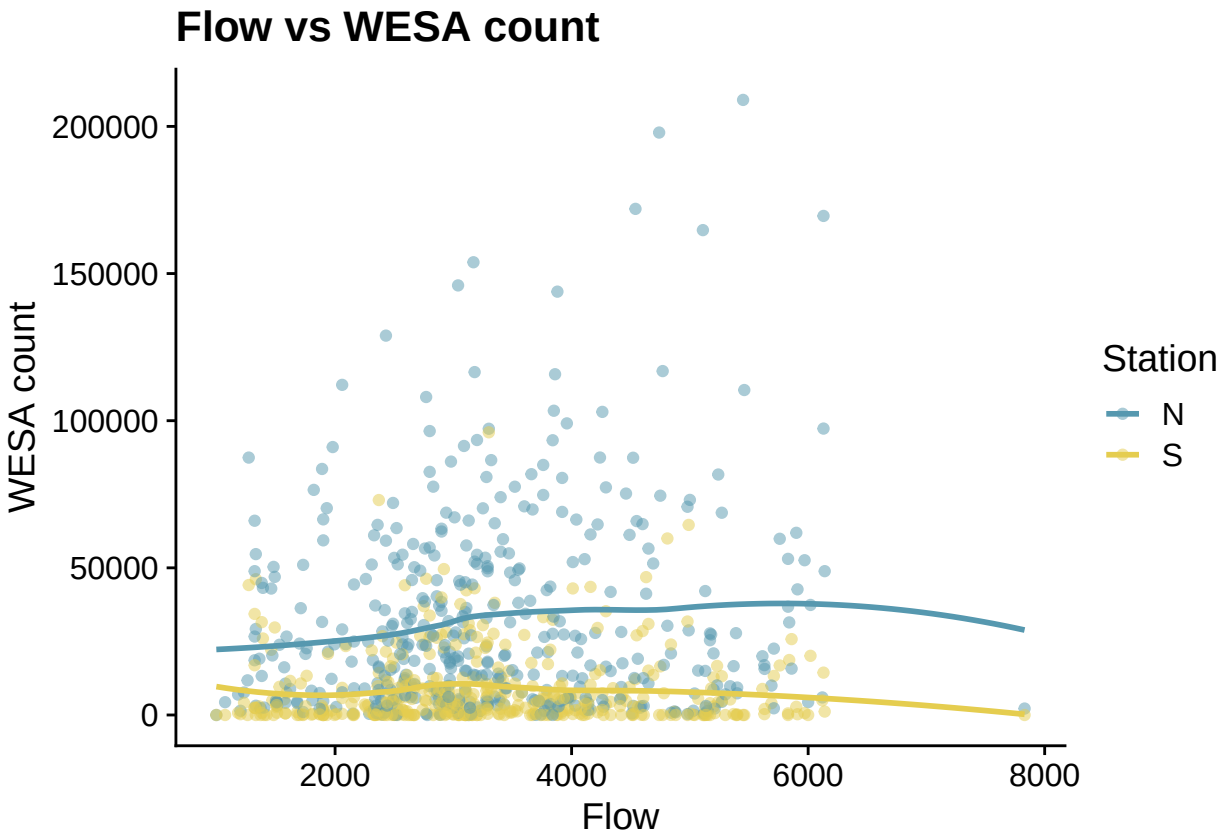
5.2 WESA vs. variable plots

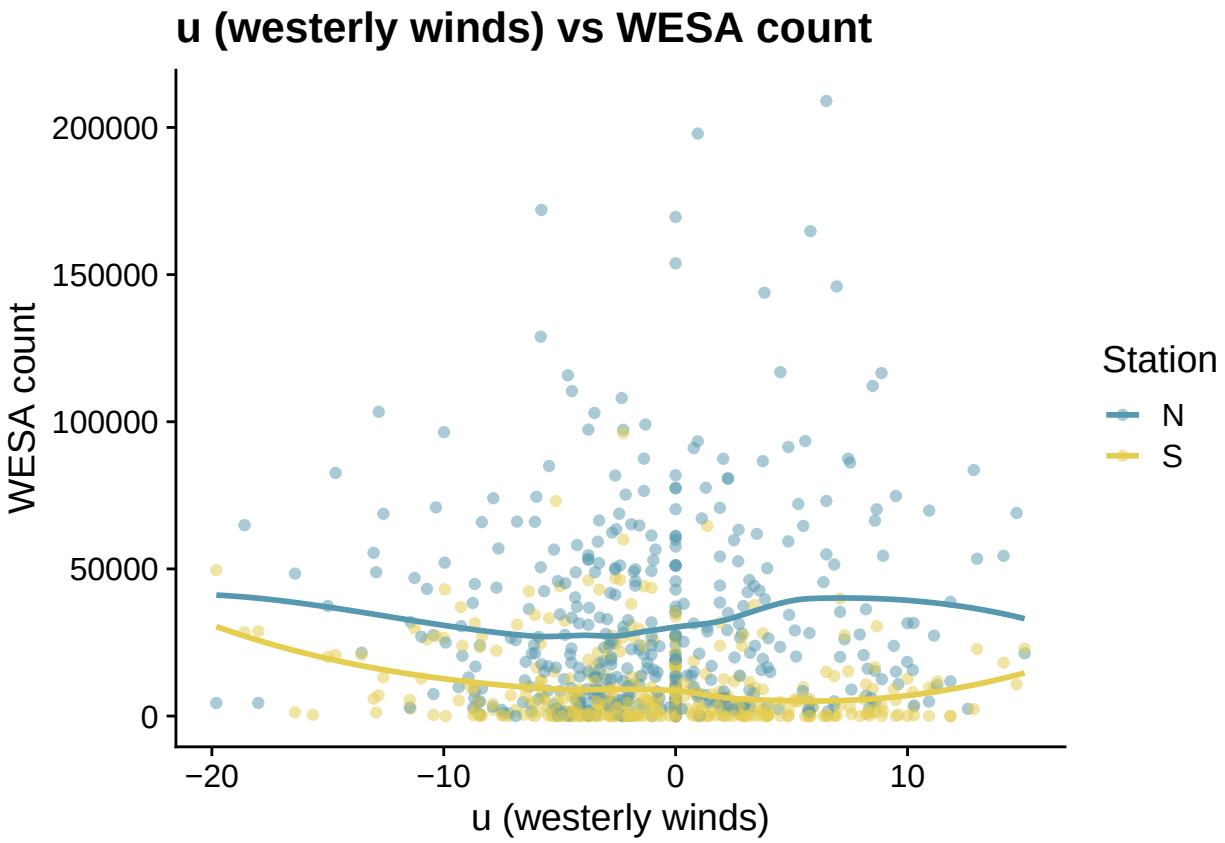


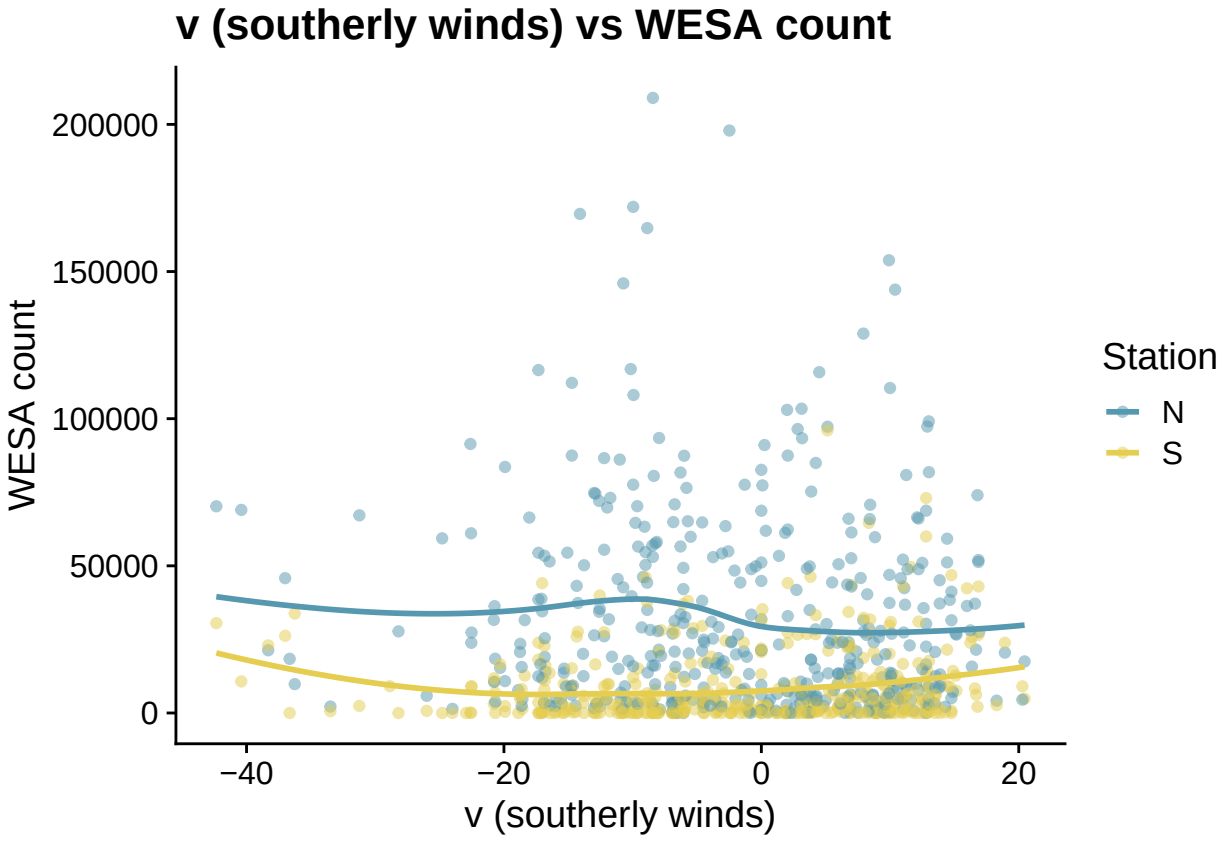

Day of Season vs WESA count
WESA count
200000
150000
100000
50000
0
−2
−1
0
1
2
DOS
Station
N
S

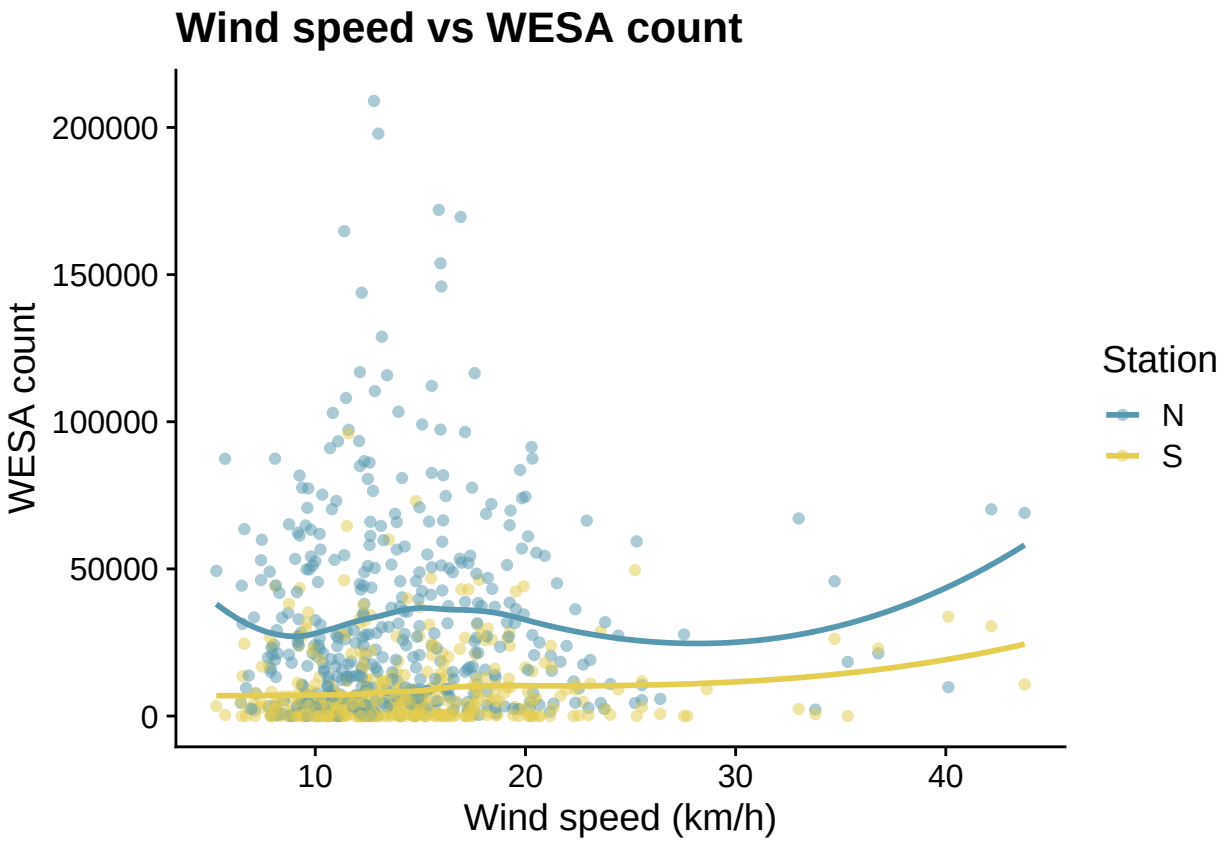

Mean temperature (C°) vs WESA count
WESA count
200000
150000
100000
50000
0
5
10
15
C°
Station
N
S

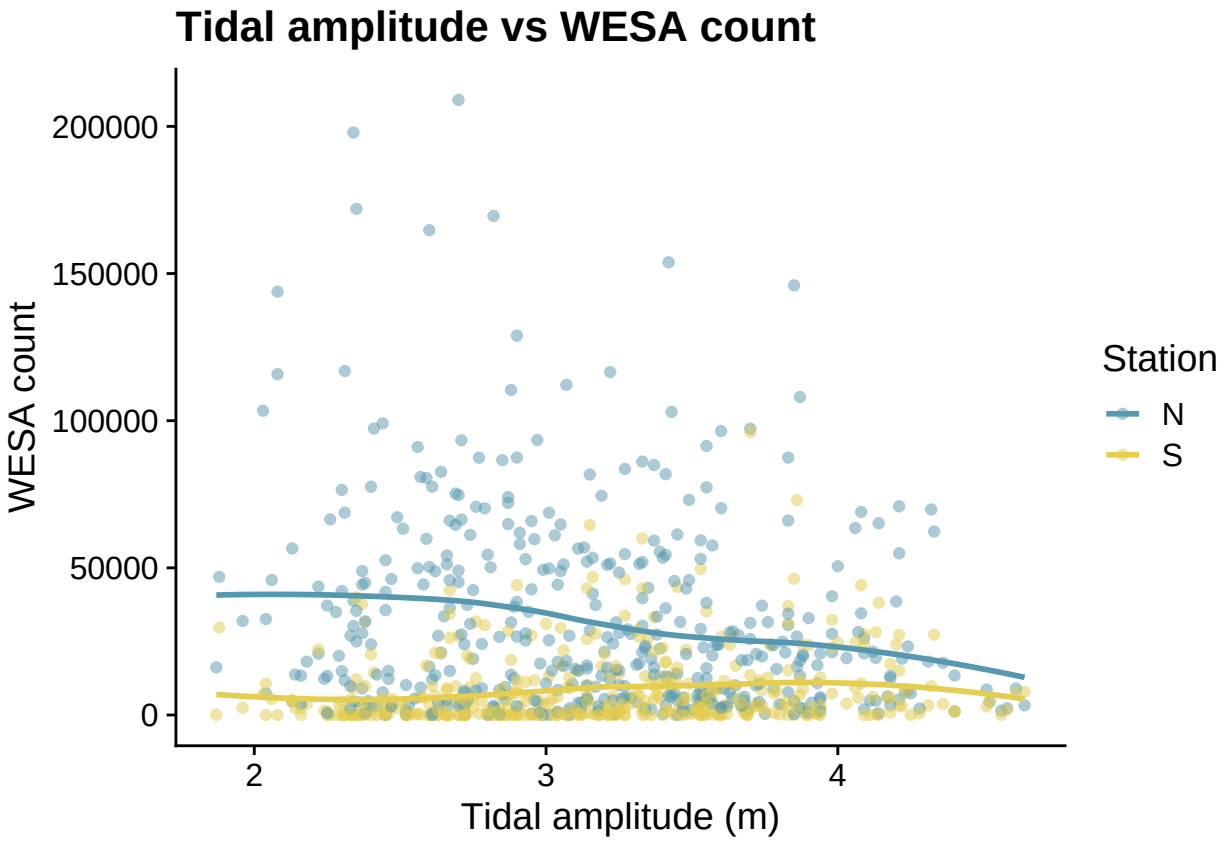

Total precipitation (mm) vs WESA count
WESA count
200000
150000
100000
50000
0
0
10
20
mm
Station
N
S

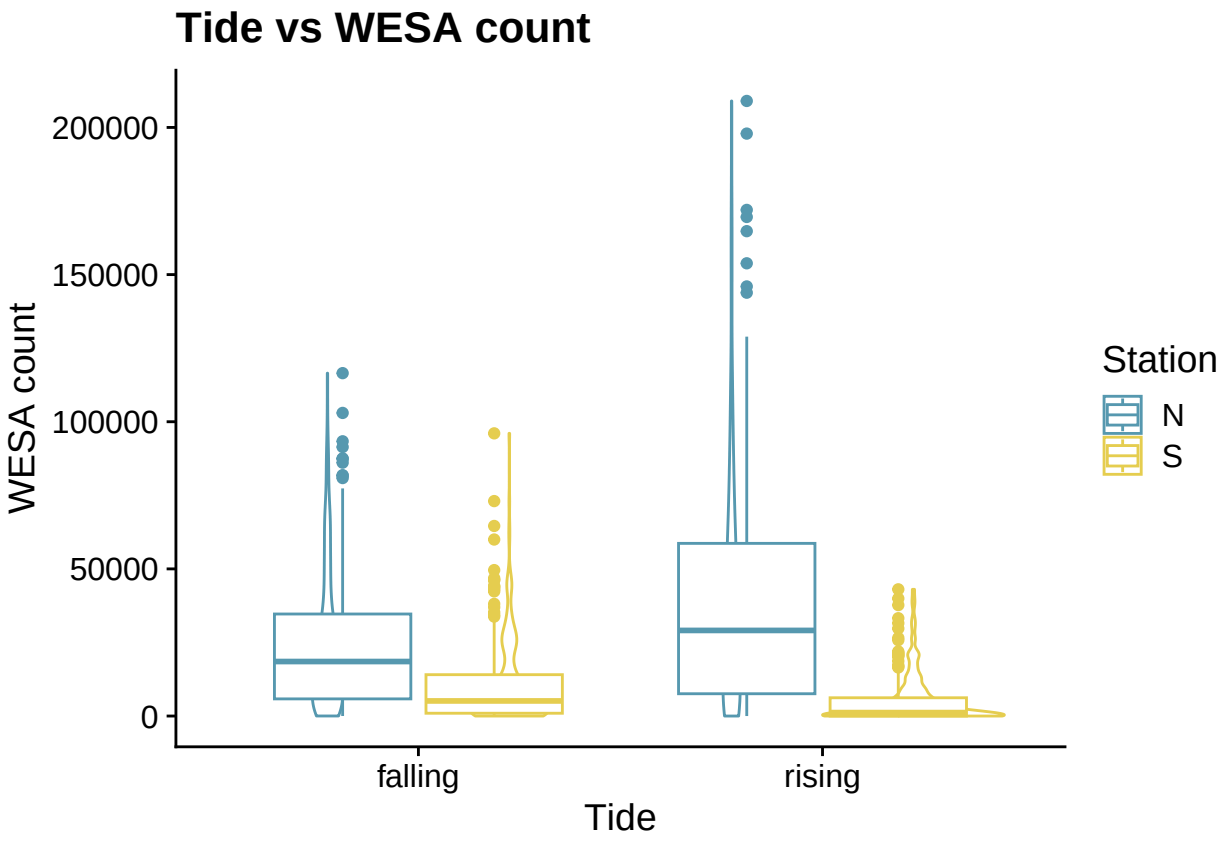

Flow vs WESA count
WESA count
200000
150000
100000
50000
0
2000
4000
6000
8000
Flow
Station
N
S


u (westerly winds) vs WESA count
WESA count
200000
150000
100000
50000
0
−20
−10
0
10
u (westerly winds)
Station
N
S


v (southerly winds) vs WESA count
WESA count
200000
150000
100000
50000
0
−40
−20
0
20
v (southerly winds)
Station
N
S


Wind speed vs WESA count
WESA count
200000
150000
100000
50000
0
10
20
30
40
Wind speed (km/h)
Station
N
S


Tidal amplitude vs WESA count
WESA count
200000
150000
100000
50000
0
2
3
4
Tidal amplitude (m)
Station
N
S


Tide vs WESA count
WESA count
200000
150000
100000
50000
0
falling
rising
Tide
Station
N
S

5.3 WESA model

5.3.1 Full model

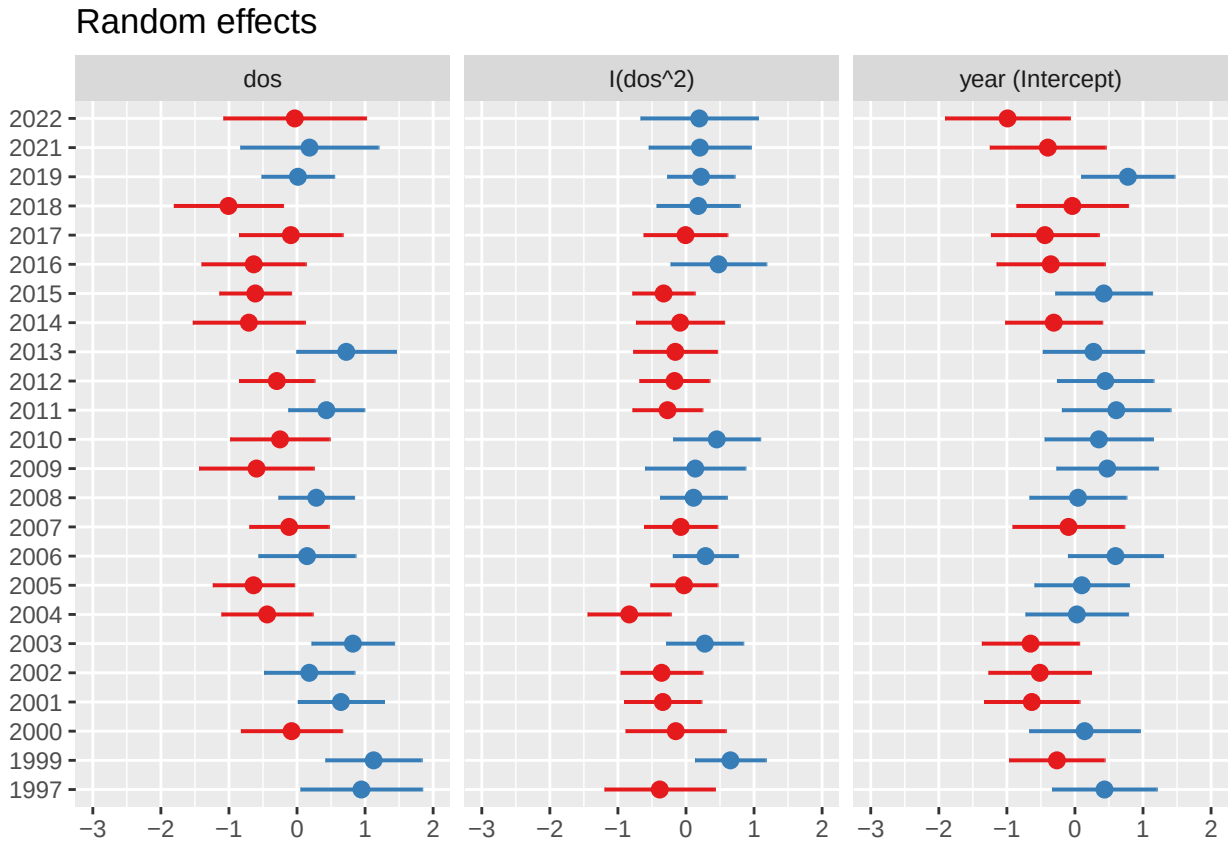
```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: f
##    Data: lme_dat
##
## REML criterion at convergence: 3713.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.0440 -0.3083  0.1175  0.5719  2.1984
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.4238   0.6510
##           dos         0.4711   0.6864   -0.11
##           I(dos^2)    0.1662   0.4077   -0.27  0.09
##  Residual             4.3853   2.0941
## Number of obs: 836, groups:  year, 24
##
## Fixed effects:
##                          Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)              10.89804    0.18582  25.40186  58.648  < 2e-16 ***
## scale(total_precip)       0.13716    0.07895 807.88273   1.737   0.0827 .
## scale(mean_temp)          0.15400    0.09656 571.67772   1.595   0.1113
## n_sS                     -2.81457    0.14507 753.05294 -19.401  < 2e-16 ***
## scale(flow)              -0.14315    0.16534  90.07778  -0.866   0.3889
## scale(elev_range)        -0.06224    0.11102 764.73454  -0.561   0.5752
## scale(u)                  0.12354    0.10948 805.52774   1.128   0.2595
## scale(windspd)            0.02800    0.10727 794.38552   0.261   0.7942
## dos                       0.17974    0.19473  31.80447   0.923   0.3629
## I(dos^2)                 -1.43928    0.12313  14.61704 -11.689 8.21e-09 ***
## year_c                    0.17951    0.14639  20.88733   1.226   0.2337
## n_sS:scale(flow)         -0.23005    0.14584 752.21403  -1.577   0.1151
## n_sS:scale(elev_range)    0.99542    0.14557 752.32018   6.838 1.66e-11 ***
## n_sS:scale(u)            -0.67368    0.14727 752.94711  -4.574 5.58e-06 ***
## n_sS:scale(windspd)       0.21682    0.14693 753.11067   1.476   0.1404
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

5.3.2 Backwards stepwise selection

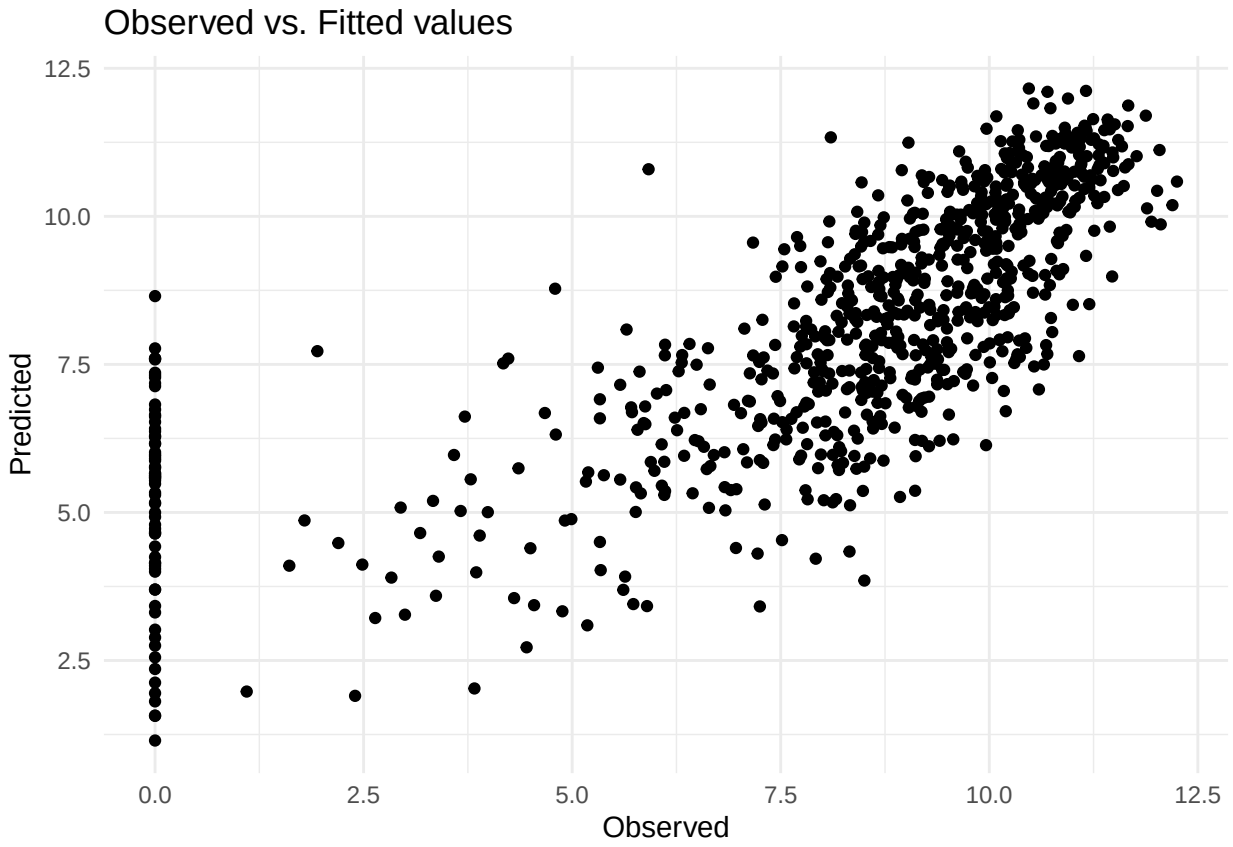
```
## Backward reduced random-effect table:
##
##                                    Eliminated npar  logLik    AIC     LRT Df
## <none>                                         22 -1856.8 3757.7
## dos in (dos + I(dos^2) | year)              0   19 -1870.0 3778.1 26.3957  3
## I(dos^2) in (dos + I(dos^2) | year)         0   19 -1859.9 3757.8  6.1667  3
##                                    Pr(>Chisq)
## <none>
```

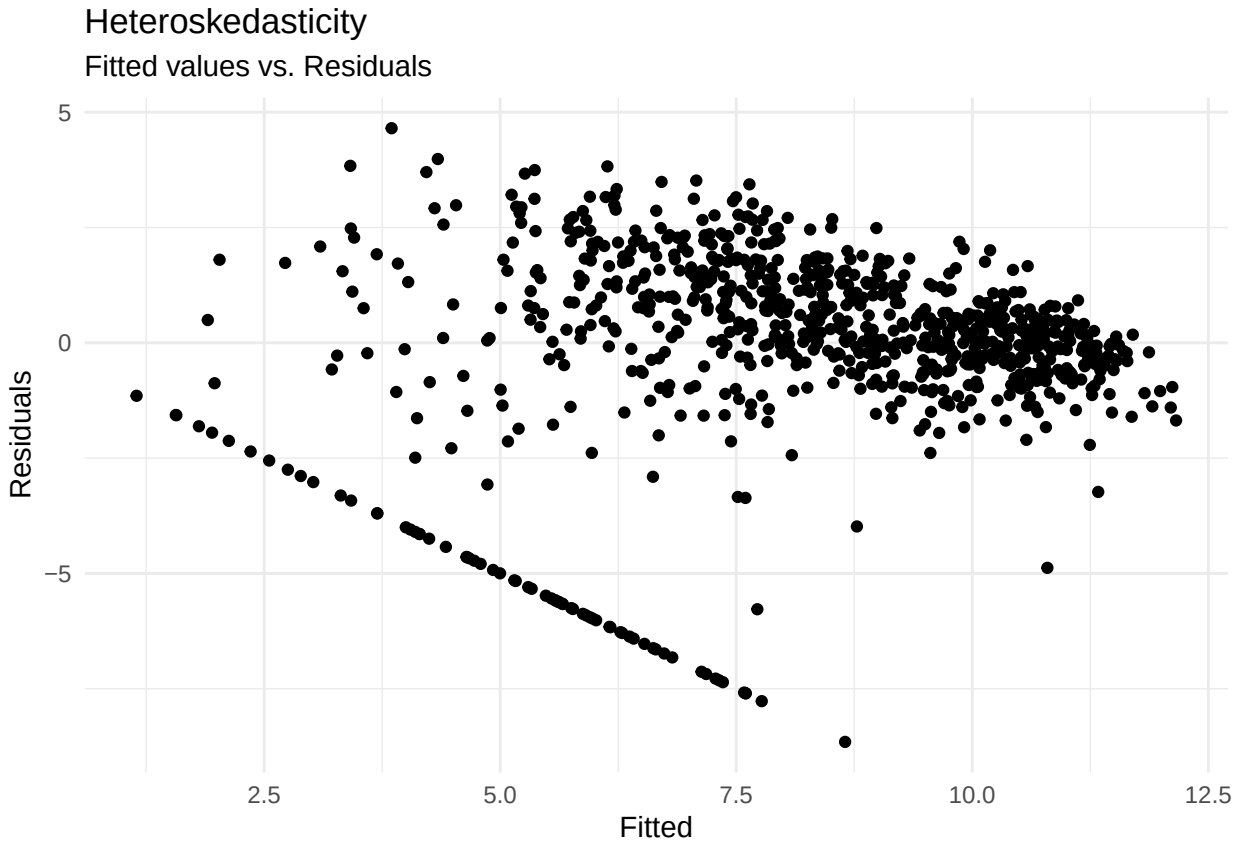
```
## dos in (dos + I(dos^2) | year)        7.88e-06 ***
## I(dos^2) in (dos + I(dos^2) | year)     0.1038
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Backward reduced fixed-effect table:
## Degrees of freedom method: Satterthwaite
##
##                       Eliminated Sum Sq Mean Sq NumDF  DenDF  F value    Pr(>F)
## n_s:scale(windspd)             1   9.55    9.55     1 753.11   2.1777   0.14044
## scale(mean_temp)               2  11.13   11.13     1 572.79   2.5339   0.11197
## scale(windspd)                 3  11.81   11.81     1 760.57   2.6837   0.10179
## n_s:scale(flow)                4  12.37   12.37     1 753.69   2.8051   0.09438
## scale(flow)                    5  13.06   13.06     1  56.44   2.9569   0.09099
## scale(total_precip)            6  15.28   15.28     1 812.91   3.4524   0.06352
## dos                            0   0.38    0.38     1  20.00   0.0863   0.77200
## I(dos^2)                       0 522.29  522.29     1  14.88 117.7187 1.834e-08
## year_c                         0   9.36    9.36     1  21.63   2.1094   0.16075
## n_s:scale(elev_range)          0 208.93  208.93     1 756.28  47.0903 1.412e-11
## n_s:scale(u)                   0  80.97   80.97     1 756.86  18.2490 2.185e-05
##
## n_s:scale(windspd)
## scale(mean_temp)
## scale(windspd)
## n_s:scale(flow)       .
## scale(flow)           .
## scale(total_precip)   .
## dos
## I(dos^2)              ***
## year_c
## n_s:scale(elev_range) ***
## n_s:scale(u)          ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Model found:
## log_wesa ~ n_s + scale(elev_range) + scale(u) + dos + I(dos^2) + year_c + (dos + I(dos^2) | year) + r
```

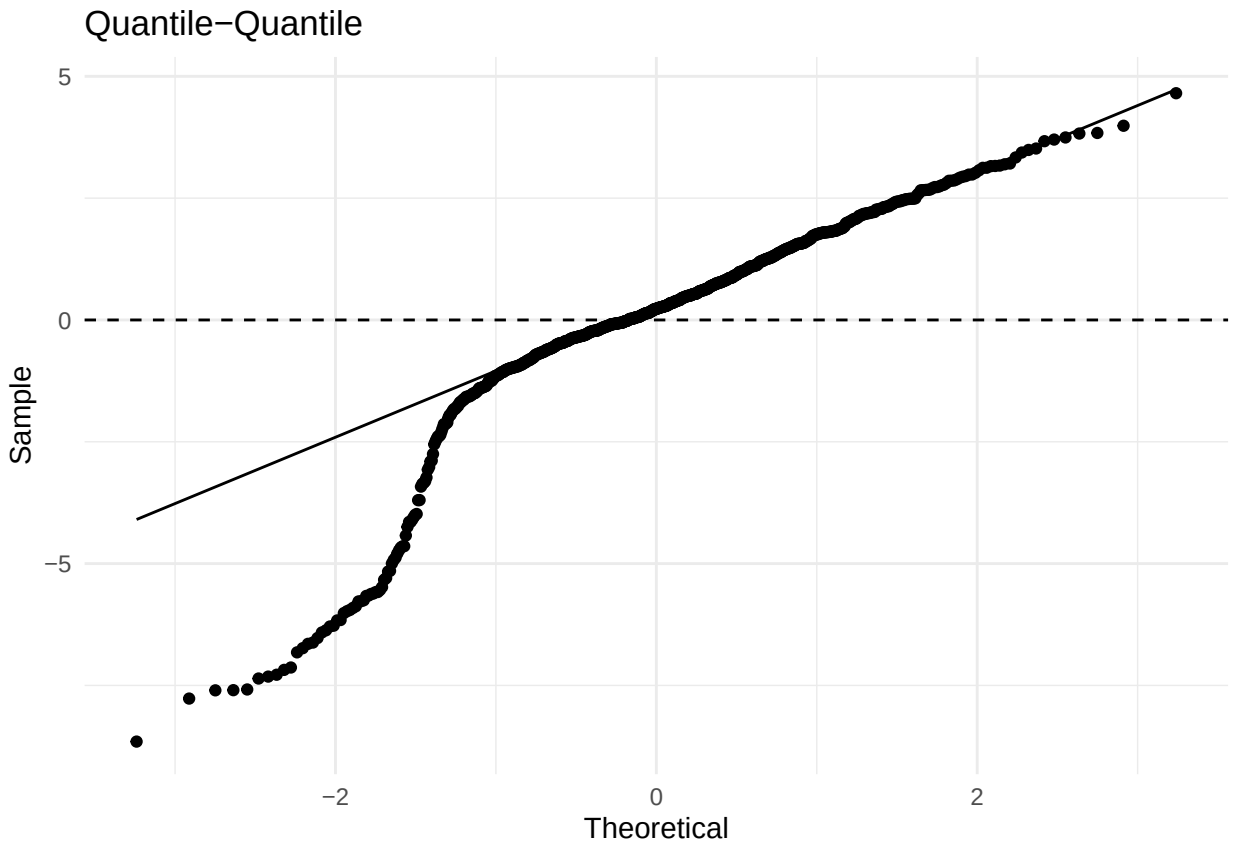

Final WESA model − standardized fixed effect sizes
n_sS
scale(elev_range)
scale(u)
dos
I(dos^2)
year_c
n_sS:scale(elev_range)
n_sS:scale(u)
−2
−1.5
−1
−0.5
0
0.5
1
Estimates

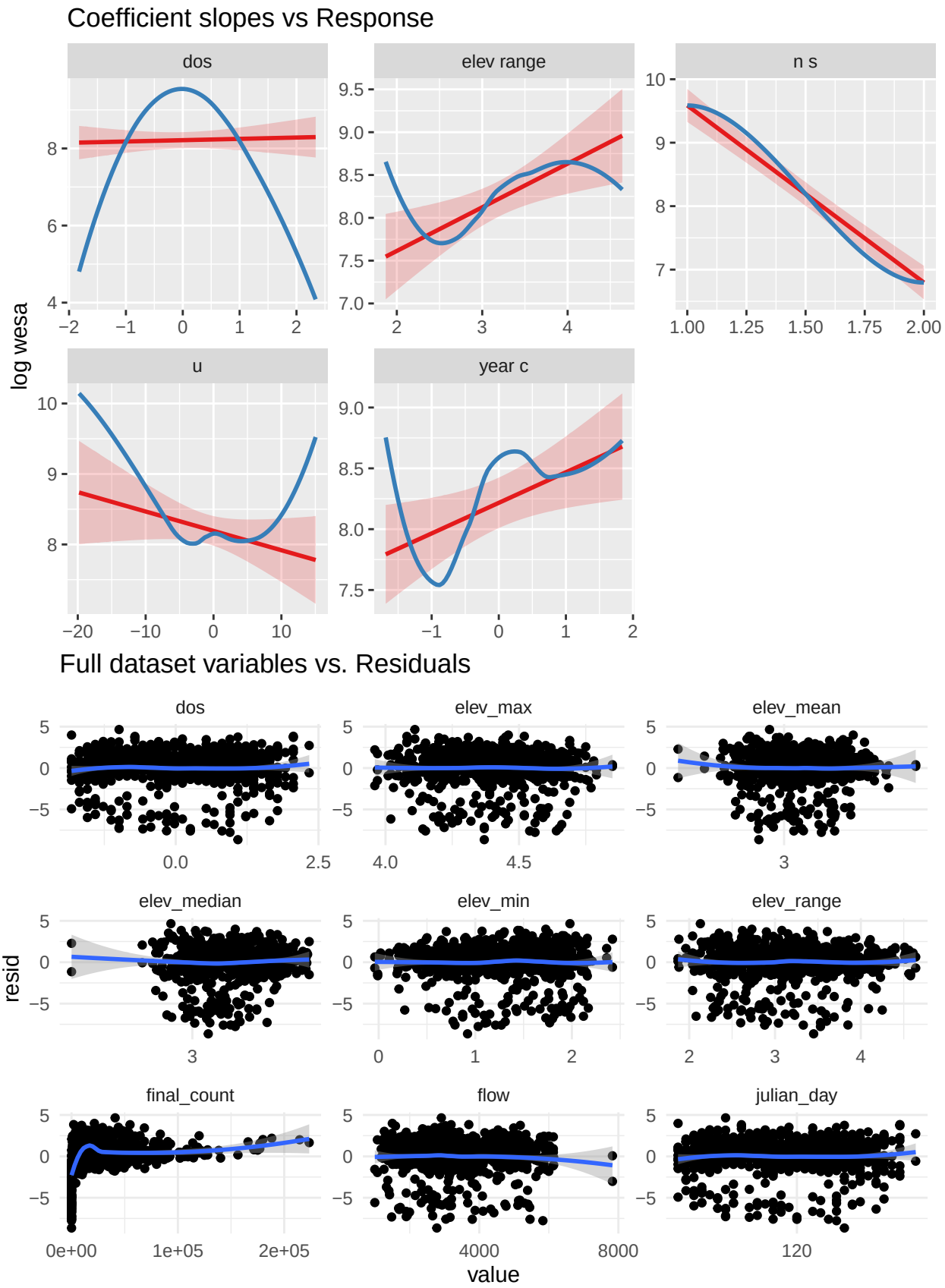

Random effects
dos
I(dos^2)
year (Intercept)
2022
2021
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1997
−3
−2
−1
0
1
2

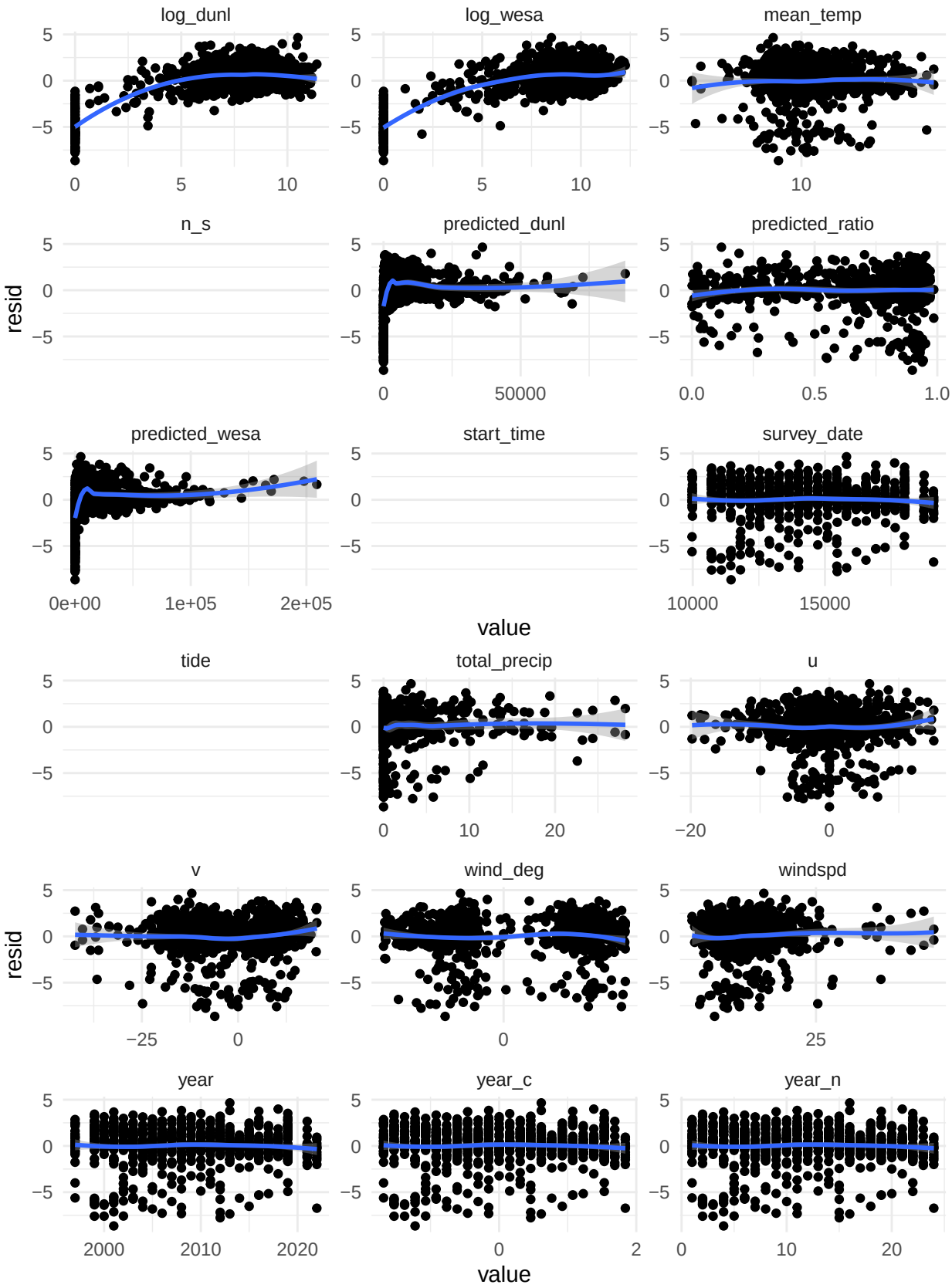
5.4 Final model diagnostics




Heteroskedasticity
Fitted values vs. Residuals
Residuals
Fitted
5
0
−5
2.5
5.0
7.5
10.0
12.5


Quantile−Quantile
Sample
Theoretical
5
0
−5
−2
0
2

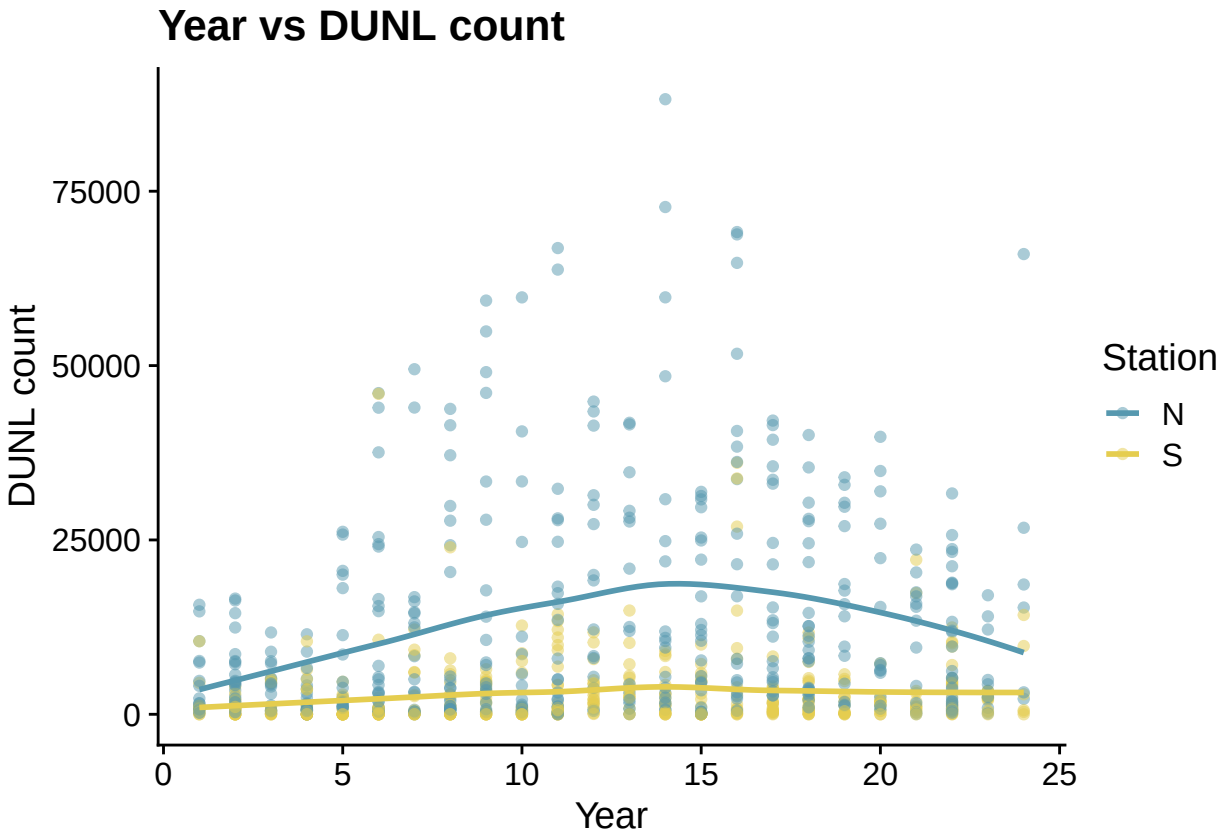

Coefficient slopes vs Response
dos
elev range
n s
u
year c
log wesa
Full dataset variables vs. Residuals
dos
elev_max
elev_mean
elev_median
elev_min
elev_range
final_count
flow
julian_day
resid
value

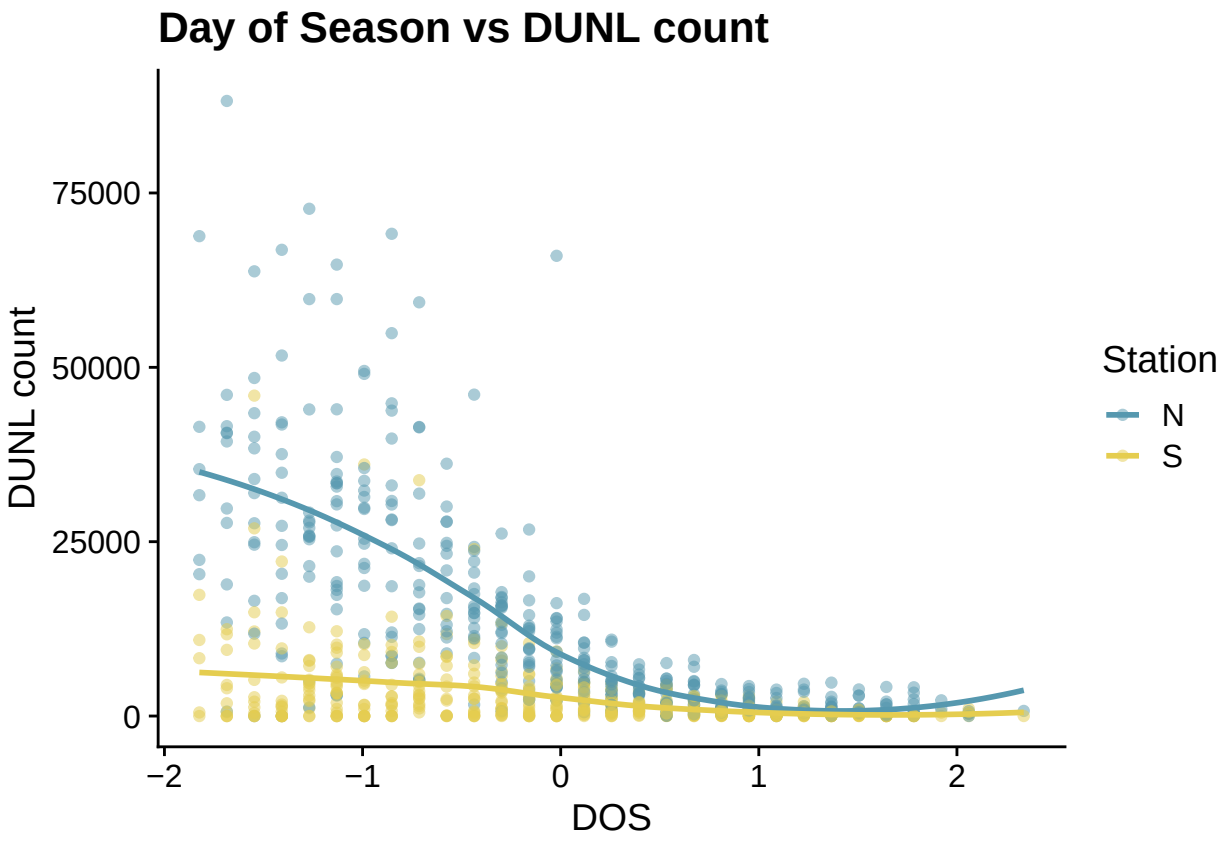

log_dunl
log_wesa
mean_temp
n_s
predicted_dunl
predicted_ratio
predicted_wesa
start_time
survey_date
tide
total_precip
u
v
wind_deg
windspd
year
year_c
year_n
resid
value

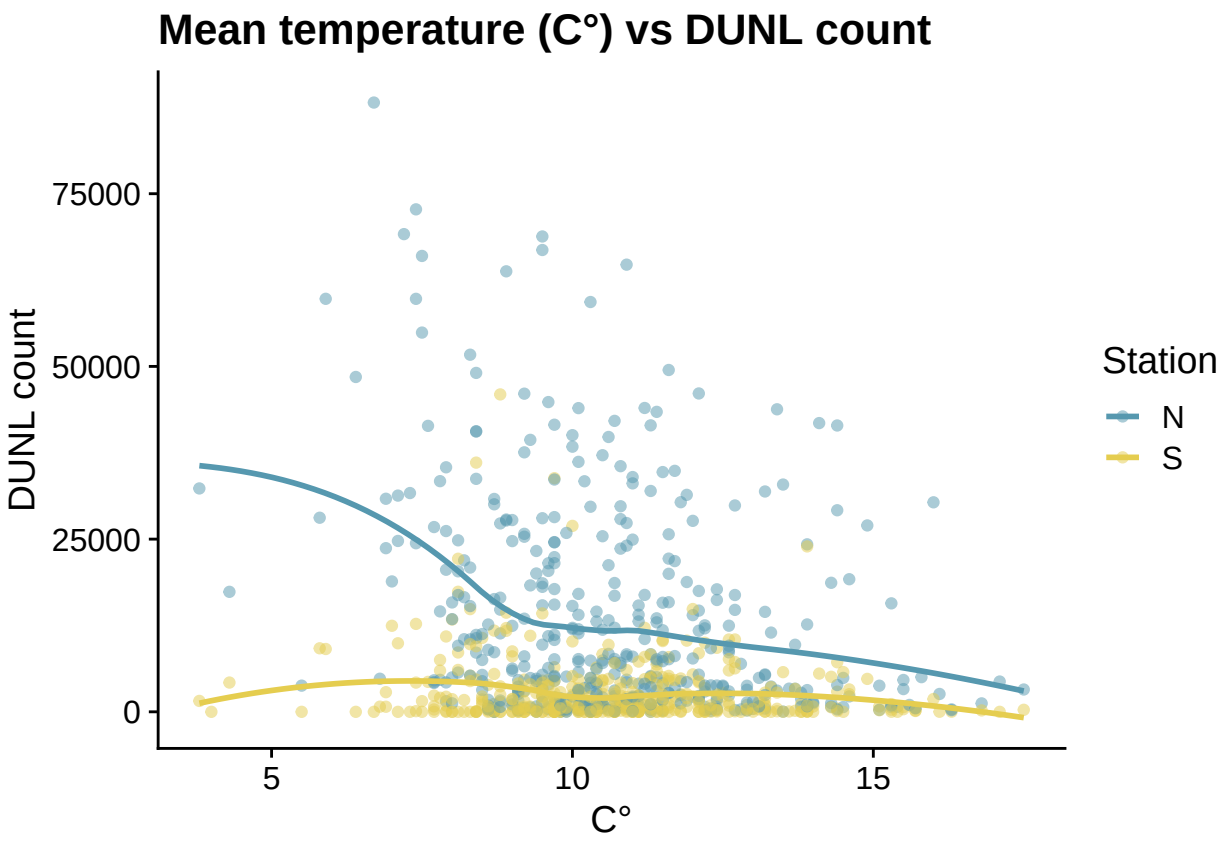
6 Final DUNL model

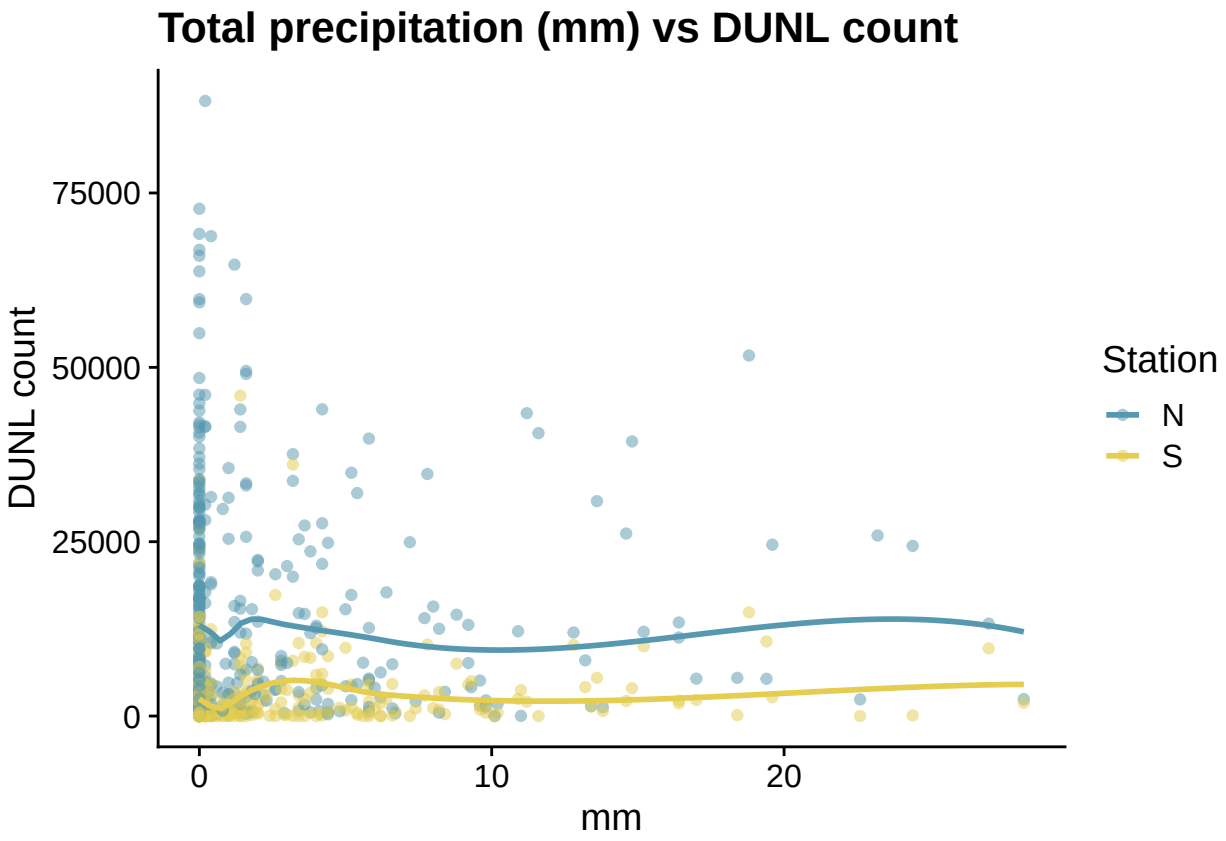
6.1 DUNL vs. variable plots

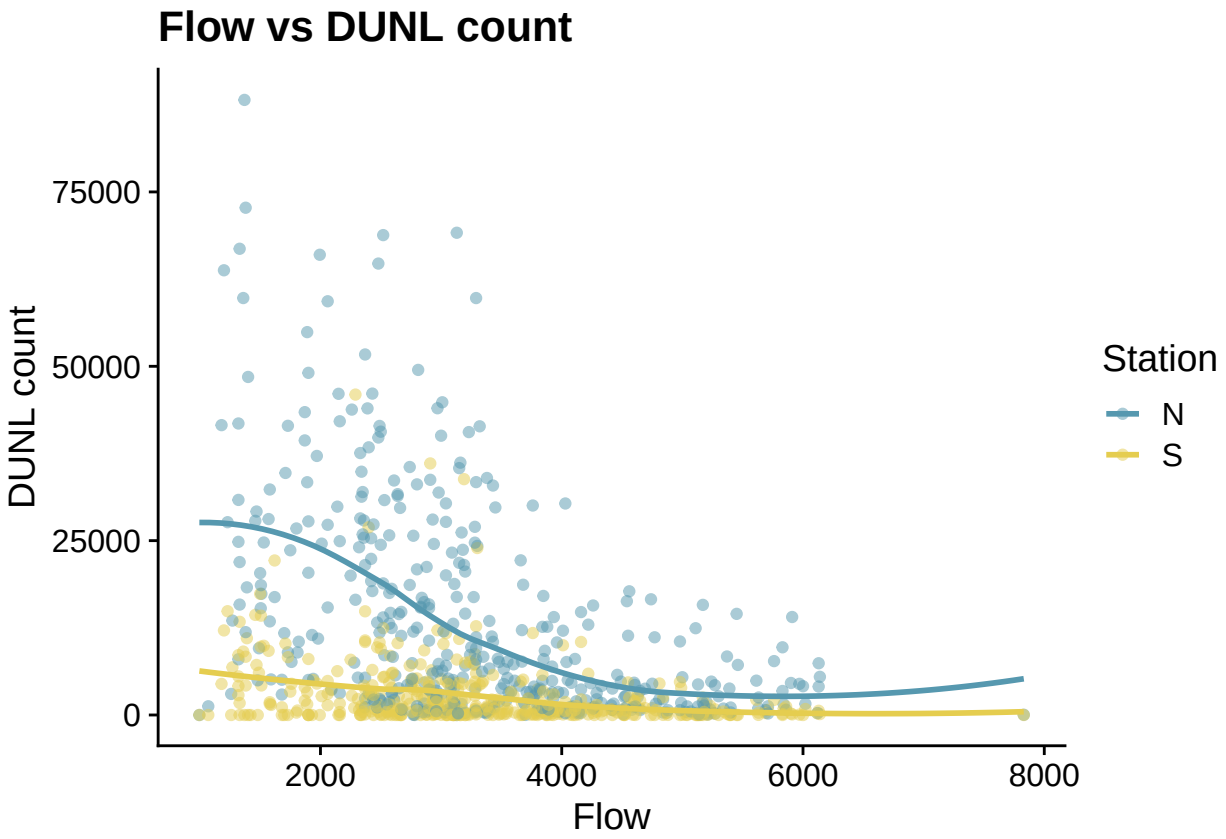
6.2 DUNL vs. variable plots

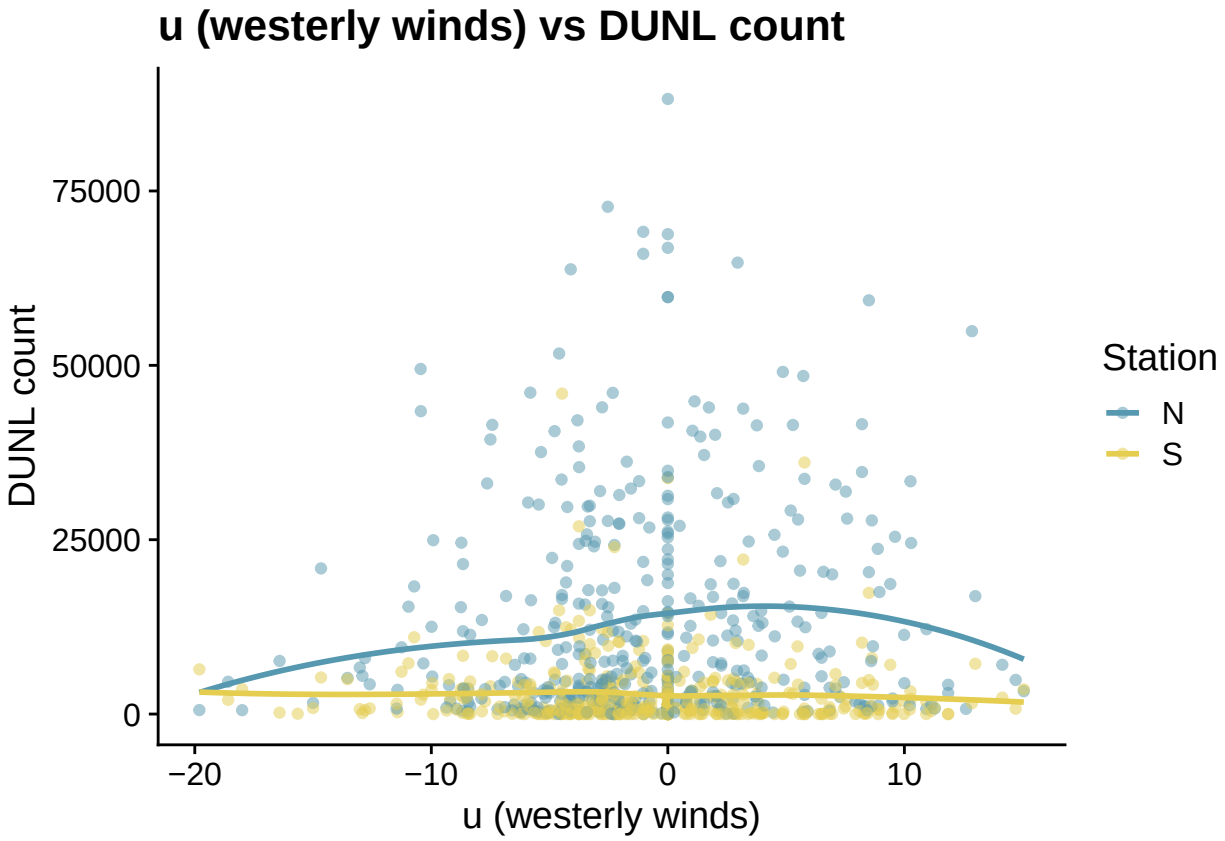


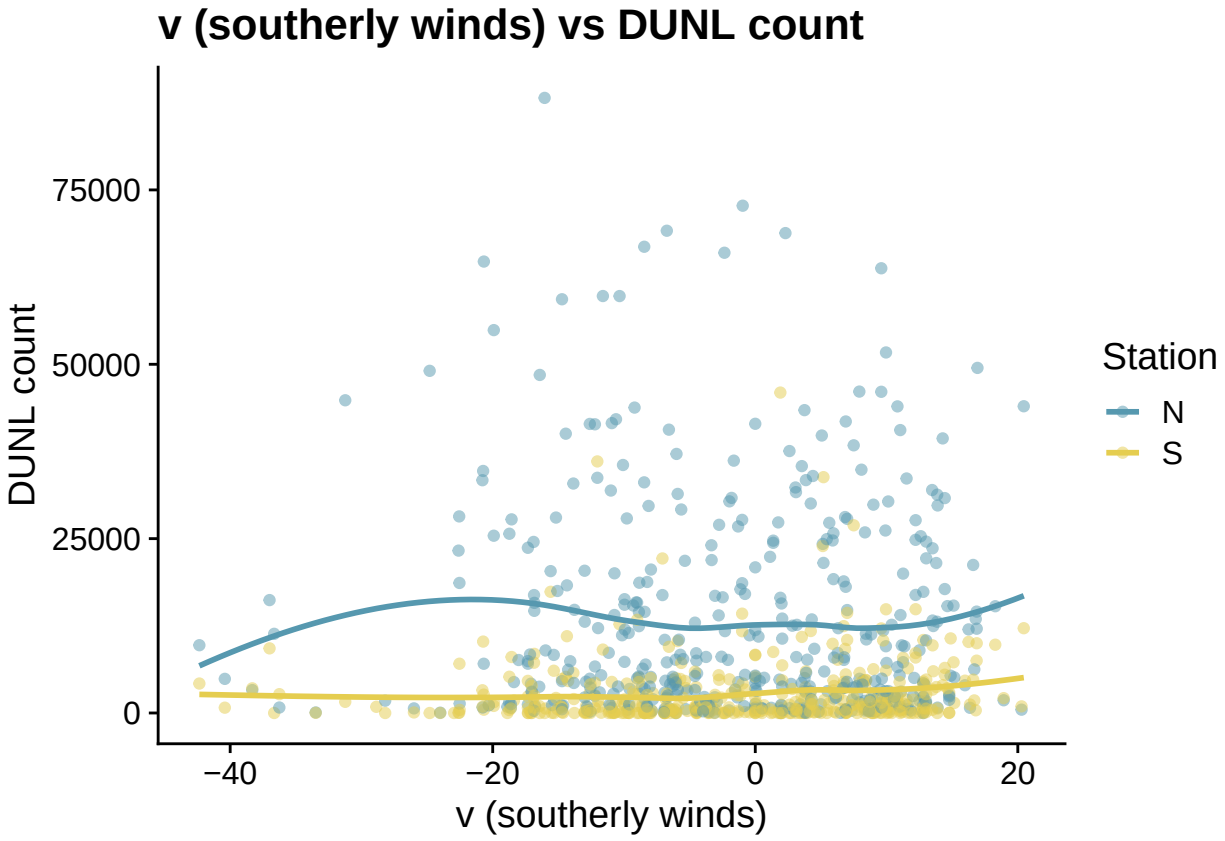

Day of Season vs DUNL count
DUNL count
75000
50000
25000
0
−2
−1
0
1
2
DOS
Station
N
S

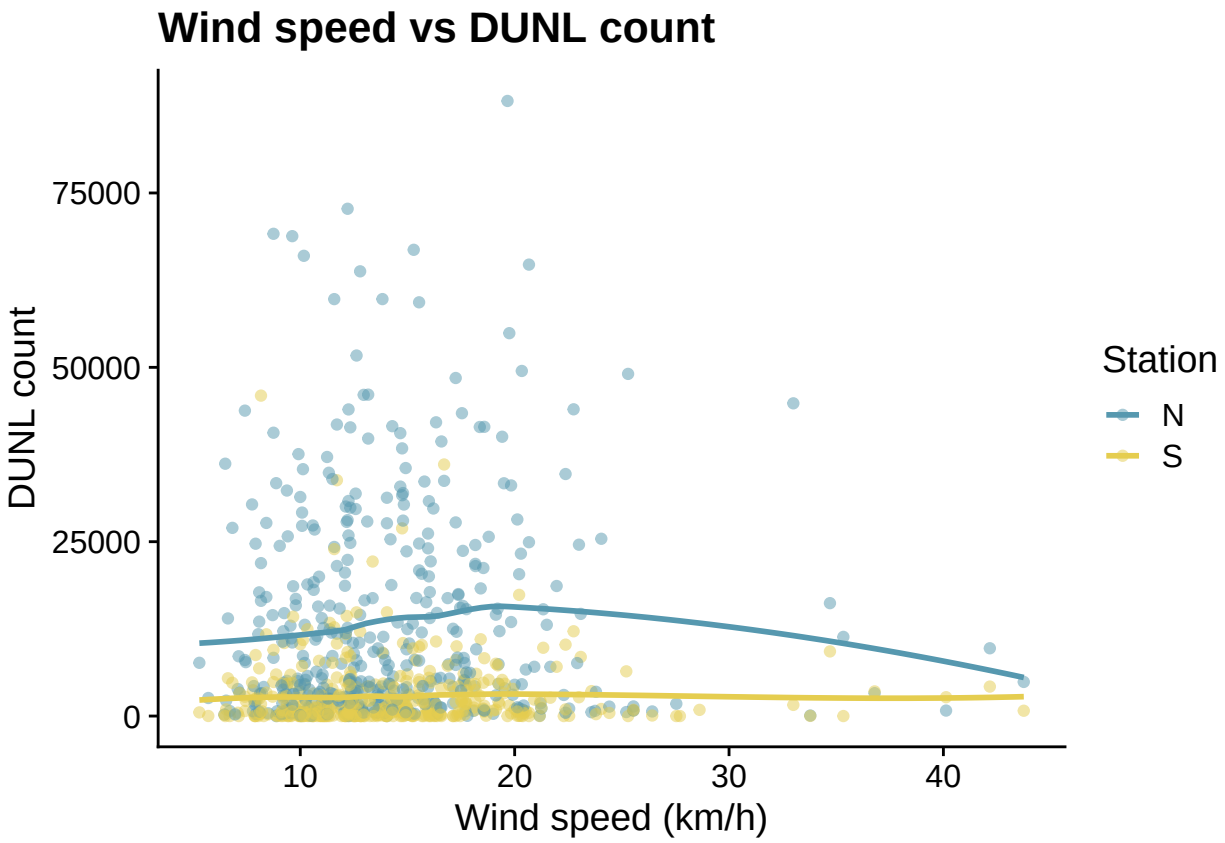

Mean temperature (C°) vs DUNL count
DUNL count
75000
50000
25000
0
5
10
15
C°
Station
N
S

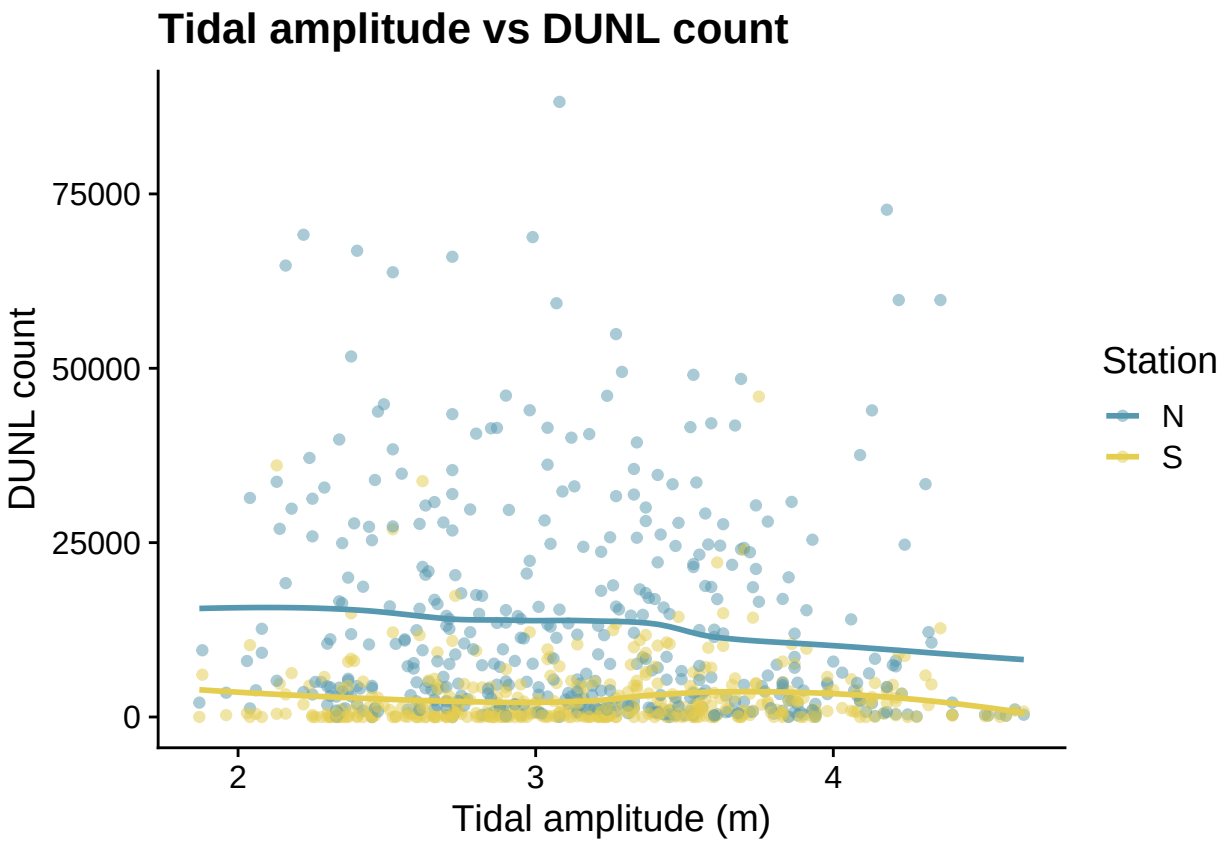

Total precipitation (mm) vs DUNL count
DUNL count
75000
50000
25000
0
0
10
20
mm
Station
N
S

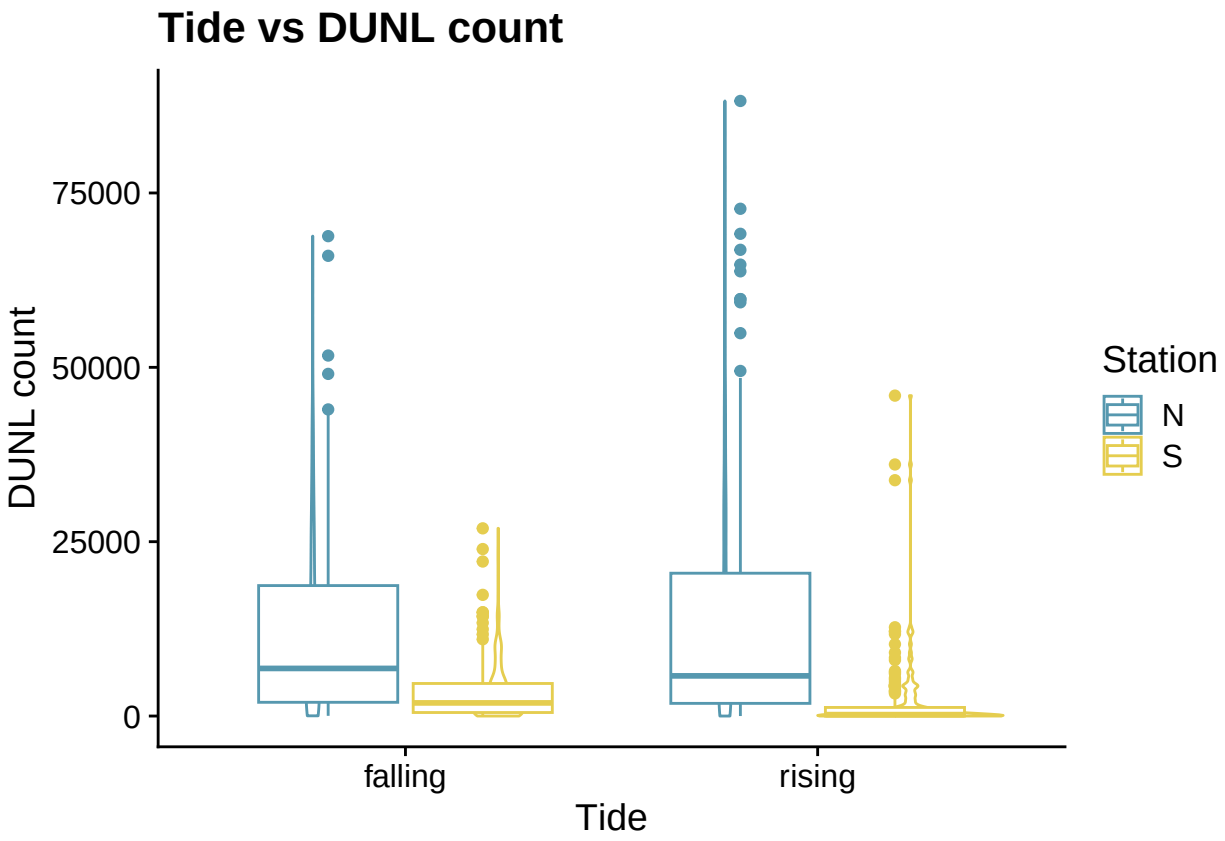

Flow vs DUNL count
DUNL count
75000
50000
25000
0
2000
4000
6000
8000
Flow
Station
N
S


u (westerly winds) vs DUNL count
DUNL count
75000
50000
25000
0
−20
−10
0
10
u (westerly winds)
Station
N
S


v (southerly winds) vs DUNL count
DUNL count
75000
50000
25000
0
−40
−20
0
20
v (southerly winds)
Station
N
S


Wind speed vs DUNL count
DUNL count
75000
50000
25000
0
10
20
30
40
Wind speed (km/h)
Station
N
S


Tidal amplitude vs DUNL count
DUNL count
75000
50000
25000
0
2
3
4
Tidal amplitude (m)
Station
N
S


Tide vs DUNL count
DUNL count
75000
50000
25000
0
falling
rising
Tide
Station
N
S

6.3 DUNL model

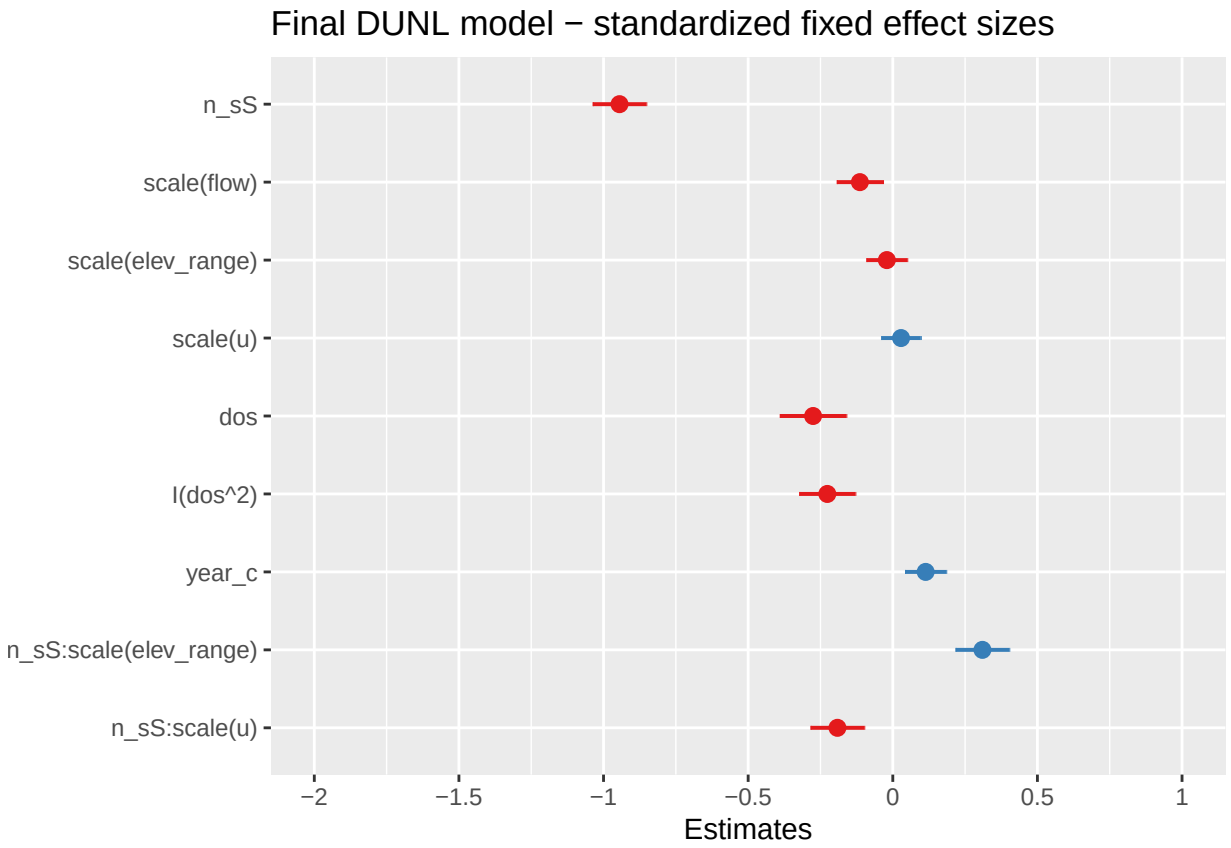
6.3.1 Full model

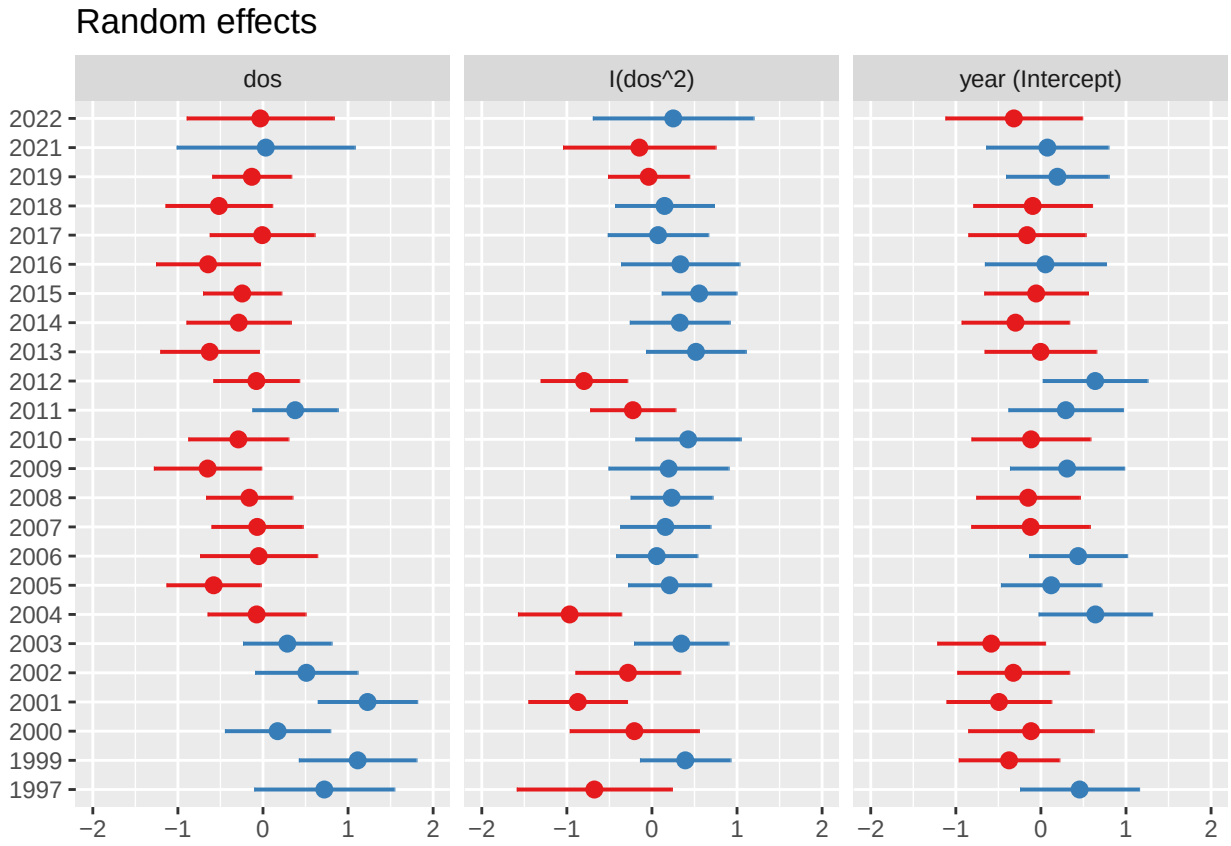
```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: f
##    Data: lme_dat
##
## REML criterion at convergence: 3584.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.9058 -0.3163  0.0892  0.5942  2.3154
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.2302   0.4798
##           dos         0.3674   0.6062   -0.22
##           I(dos^2)    0.2890   0.5376   -0.51 -0.34
##  Residual             3.7670   1.9409
## Number of obs: 836, groups:  year, 24
##
## Fixed effects:
##                          Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)              9.07467    0.15500  32.39324  58.547  < 2e-16 ***
## scale(total_precip)      0.11755    0.07285 805.54172   1.614 0.107001
## scale(mean_temp)         0.09866    0.08588 414.43568   1.149 0.251313
## n_sS                    -2.69568    0.13443 758.86154 -20.052  < 2e-16 ***
## scale(flow)             -0.31158    0.13468  77.12212  -2.314 0.023361 *
## scale(elev_range)       -0.05587    0.10292 791.42724  -0.543 0.587408
## scale(u)                 0.10496    0.10114 804.10291   1.038 0.299703
## scale(windspd)          -0.01379    0.09924 796.87209  -0.139 0.889514
## dos                     -0.81151    0.16914  26.99264  -4.798 5.25e-05 ***
## I(dos^2)                -0.64090    0.13919  19.68513  -4.604 0.000178 ***
## year_c                   0.31529    0.10539  24.08537   2.992 0.006316 **
## n_sS:scale(flow)        -0.02402    0.13515 758.35843  -0.178 0.858956
## n_sS:scale(elev_range)   0.87568    0.13490 758.30295   6.491 1.54e-10 ***
## n_sS:scale(u)           -0.57380    0.13645 758.88214  -4.205 2.92e-05 ***
## n_sS:scale(windspd)      0.18643    0.13617 758.69574   1.369 0.171375
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

6.3.2 Backwards stepwise selection

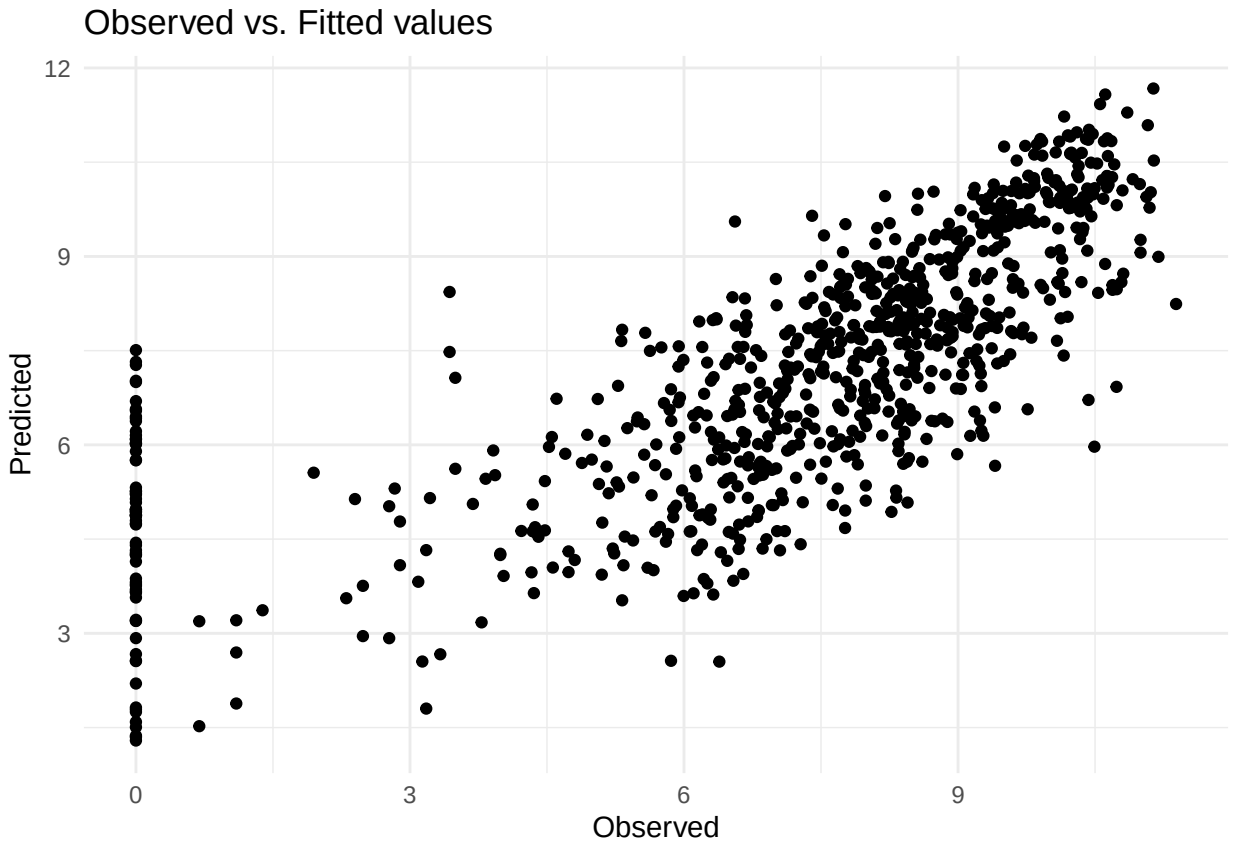
```
## Backward reduced random-effect table:
##
##                                     Eliminated npar  logLik    AIC    LRT Df
## <none>                                          22 -1792.1 3628.2
## dos in (dos + I(dos^2) | year)               0   19 -1804.3 3646.7 24.447  3
## I(dos^2) in (dos + I(dos^2) | year)          0   19 -1803.2 3644.4 22.178  3
##                                     Pr(>Chisq)
## <none>
```

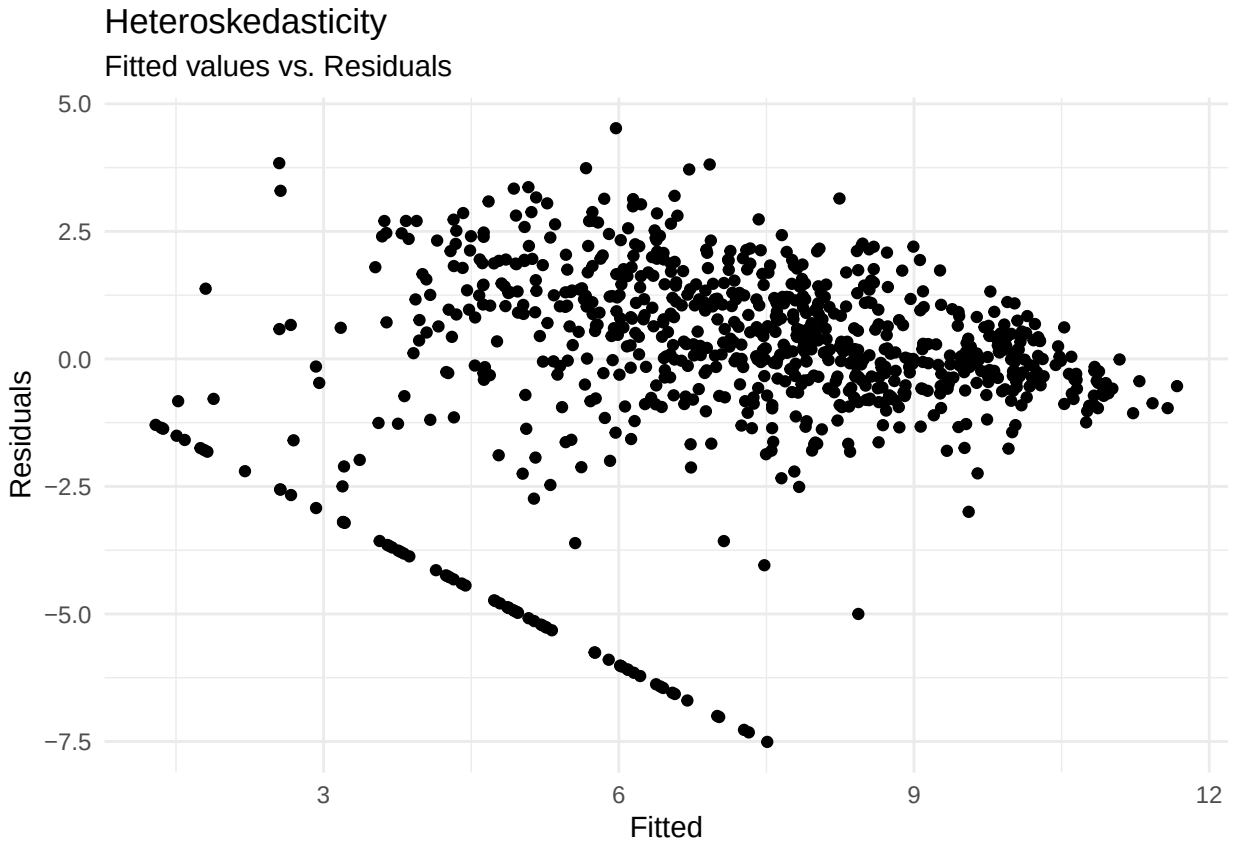
```
## dos in (dos + I(dos^2) | year)       2.015e-05 ***
## I(dos^2) in (dos + I(dos^2) | year)  5.990e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Backward reduced fixed-effect table:
## Degrees of freedom method: Satterthwaite
##
##                       Eliminated  Sum Sq Mean Sq NumDF  DenDF F value    Pr(>F)
## n_s:scale(flow)                1   0.119   0.119     1 758.36  0.0316 0.8589560
## scale(mean_temp)               2   4.981   4.981     1 415.04  1.3240 0.2505458
## n_s:scale(windspd)             3   7.154   7.154     1 760.22  1.8988 0.1686206
## scale(windspd)                 4   4.202   4.202     1 777.51  1.1140 0.2915398
## scale(total_precip)            5  10.307  10.307     1 807.65  2.7316 0.0987721
## scale(flow)                    0  29.502  29.502     1  42.79  7.8106 0.0077432
## dos                            0  83.947  83.947     1  26.80 22.2252 6.673e-05
## I(dos^2)                       0  79.366  79.366     1  19.20 21.0123 0.0001979
## year_c                         0  37.098  37.098     1  22.93  9.8216 0.0046676
## n_s:scale(elev_range)          0 162.260 162.260     1 762.83 42.9586 1.029e-10
## n_s:scale(u)                   0  61.912  61.912     1 763.24 16.3914 5.678e-05
##
## n_s:scale(flow)
## scale(mean_temp)
## n_s:scale(windspd)
## scale(windspd)
## scale(total_precip)   .
## scale(flow)           **
## dos                   ***
## I(dos^2)              ***
## year_c                **
## n_s:scale(elev_range) ***
## n_s:scale(u)          ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Model found:
## log_dunl ~ n_s + scale(flow) + scale(elev_range) + scale(u) + dos + I(dos^2) + year_c + (dos + I(dos
```

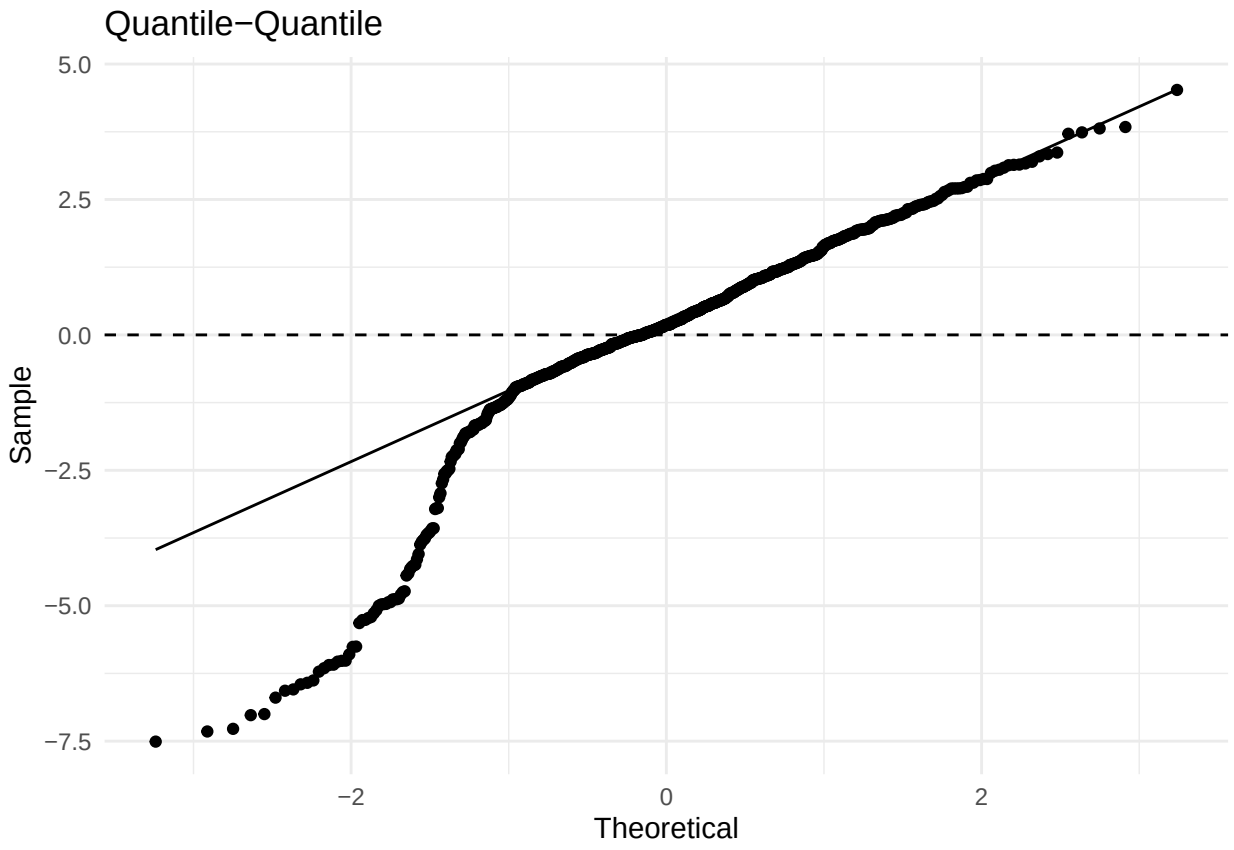

Final DUNL model − standardized fixed effect sizes
n_sS
scale(flow)
scale(elev_range)
scale(u)
dos
I(dos^2)
year_c
n_sS:scale(elev_range)
n_sS:scale(u)
−2
−1.5
−1
−0.5
0
0.5
1
Estimates

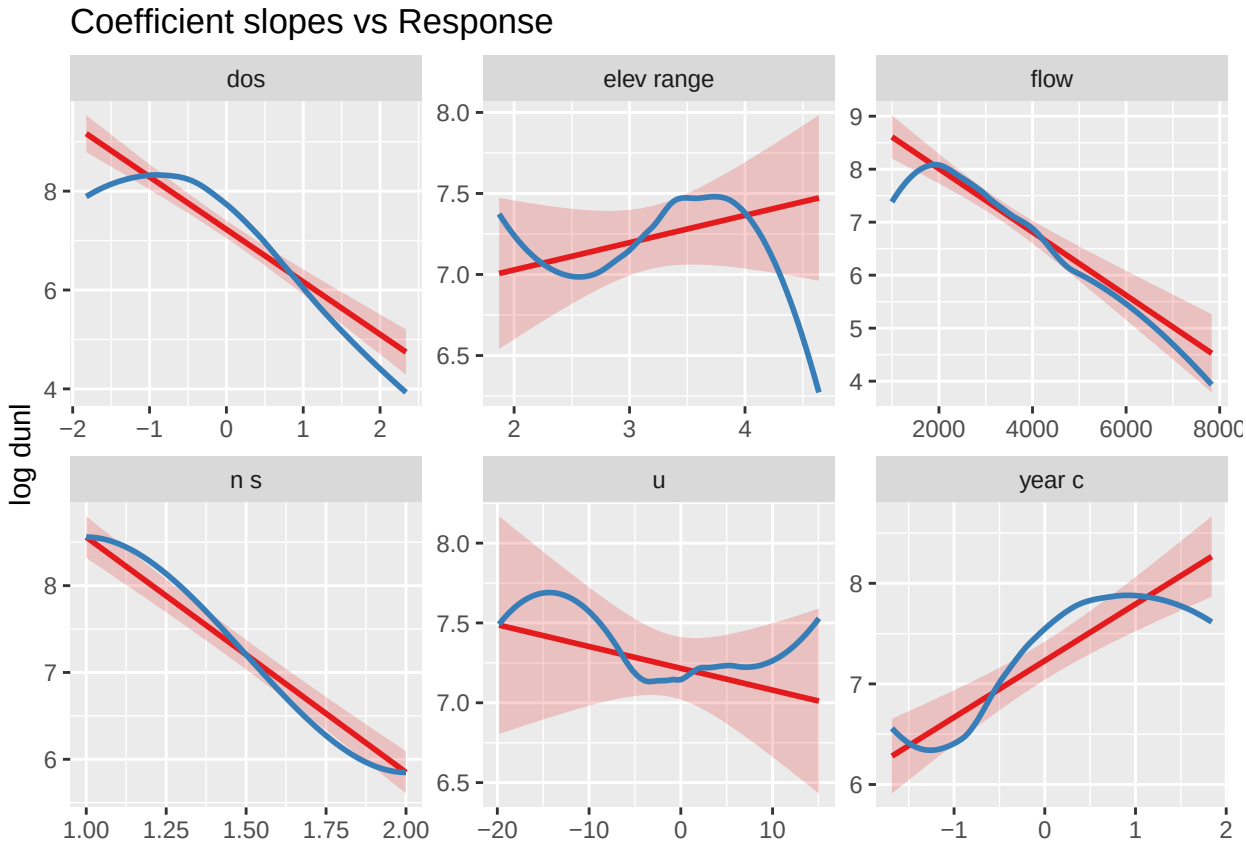

Random effects
dos
I(dos^2)
year (Intercept)
2022
2021
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1997
−2
−1
0
1
2

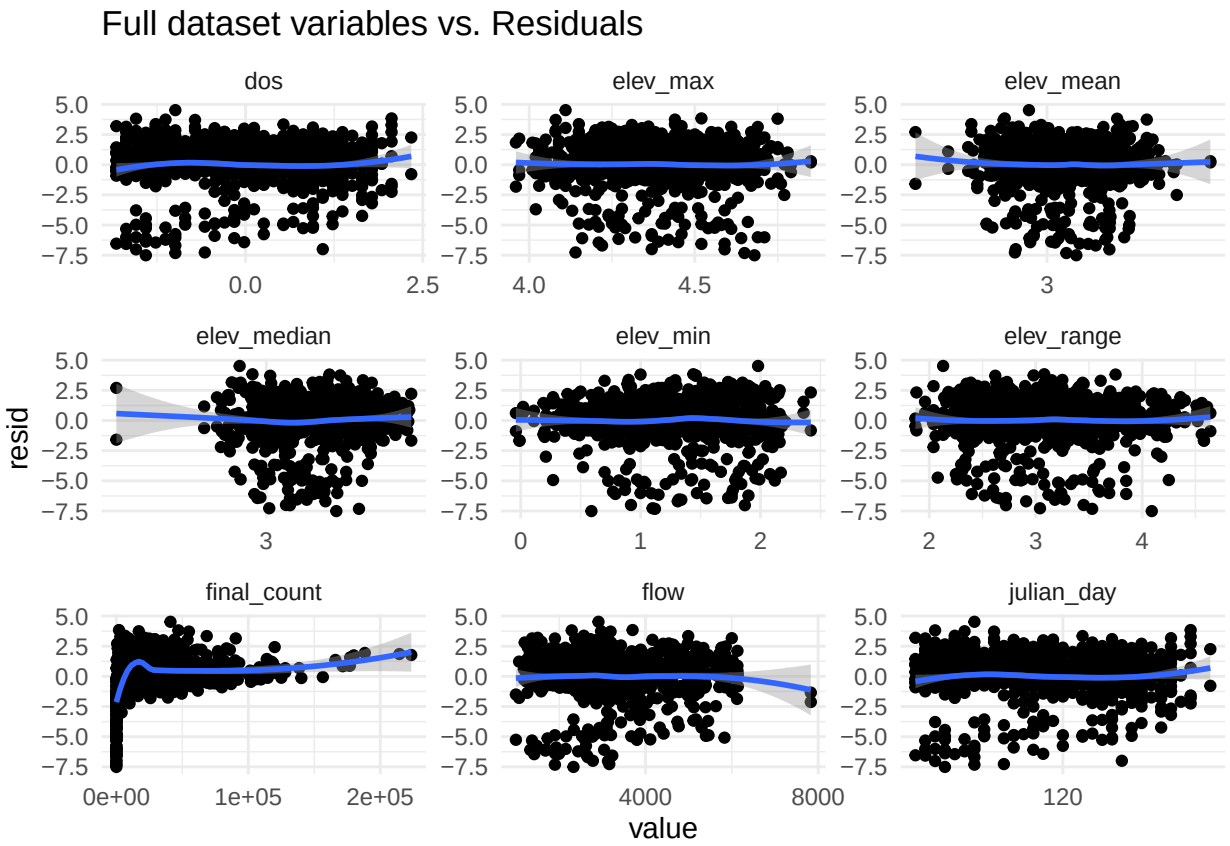
6.4 Final model diagnostics

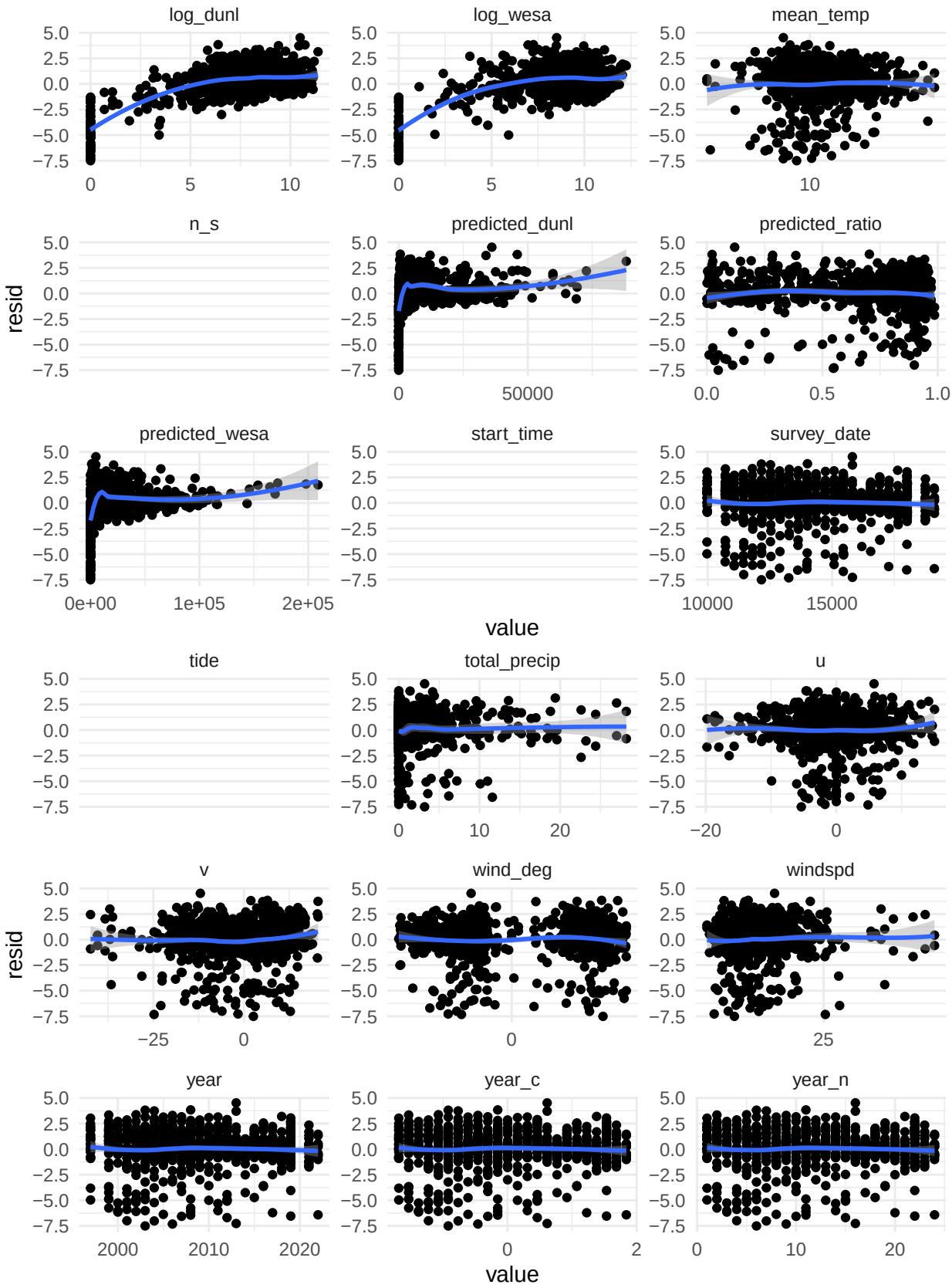



Heteroskedasticity
Fitted values vs. Residuals
Residuals
Fitted
5.0
2.5
0.0
−2.5
−5.0
−7.5
3
6
9
12


Quantile−Quantile
Sample
Theoretical
5.0
2.5
0.0
−2.5
−5.0
−7.5
−2
0
2


Coefficient slopes vs Response
dos
elev range
flow
n s
u
year c
log dunl


Full dataset variables vs. Residuals
dos
elev_max
elev_mean
elev_median
elev_min
elev_range
final_count
flow
julian_day
resid
value


log_dunl
log_wesa
mean_temp
n_s
predicted_dunl
predicted_ratio
predicted_wesa
start_time
survey_date
tide
total_precip
u
v
wind_deg
windspd
year
year_c
year_n
resid
value

7 Yearly trends in peep population

The original Canham et al. (2021) paper provided yearly population trends of WESA and DUNL at Brunswick Point. These same population trends are extended here with 2020-2022 data, using the same population models derived in the original paper (i.e., no north vs. south component). Values represent population indices (with 95% confidence intervals) calculated as predicted values for each year from final models for each species, with independent variables held at median values for each year. Daily total counts (not broken down by survey station) are used as the data for this model.

WESA model:

$log(WESA) \sim year + dos + I(dos^2) + scale(elev.range) + scale(flow) + scale(u) + (dos + I(dos^2)|year)$

DUNL model:

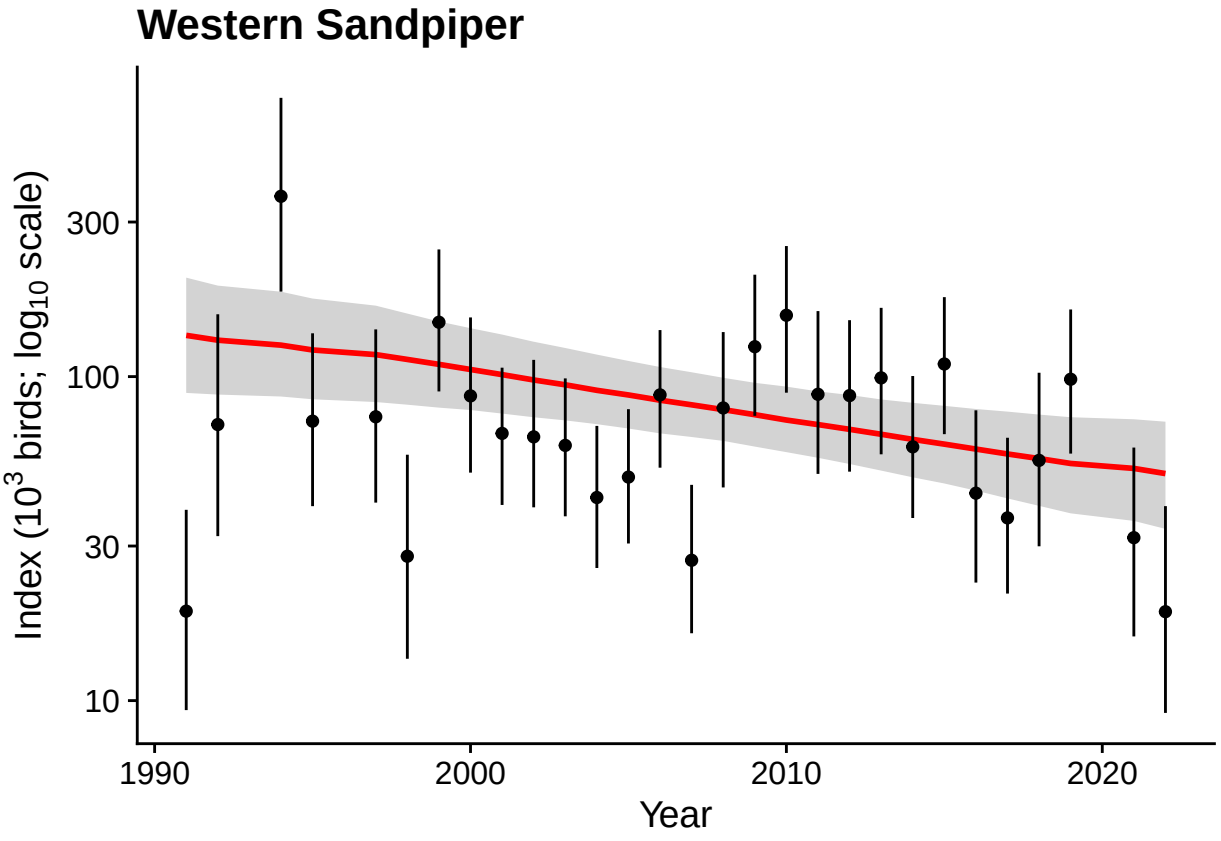
$log(DUNL) \sim year + dos + I(dos^2) + scale(elev.range) + scale(flow) + scale(u) + (dos + I(dos^2)|year)$

7.1 WESA population trend

Western sandpiper populations continue to show yearly declines in population. Since 1991, western sandpiper populations have fallen by 62.5% (-2.2% per annum). In the last ten years the rate of decline has slowed. Since 2012, western sandpiper populations have fallen by 27% (-0.9% per annum).

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## log_wesa ~ year_c + dos + I(dos^2) + scale(elev_range) + scale(flow) +
##     scale(u) + (dos + I(dos^2) | year)
##    Data: dt
## Control: lme4::lmerControl(optimizer = "bobyqa")
##
## REML criterion at convergence: 1368.8
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.5659 -0.3638  0.0501  0.4639  2.9835
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3168   0.5628
##           dos         0.3875   0.6225    0.19
##           I(dos^2)    0.3256   0.5706   -0.36  0.13
##  Residual             0.5649   0.7516
## Number of obs: 513, groups:  year, 29
##
## Fixed effects:
##                    Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)        11.25963    0.11695  21.05803  96.280  < 2e-16 ***
## year_c             -0.26055    0.09608  25.58475  -2.712  0.01179 *
## dos                -0.35263    0.14122  35.73022  -2.497  0.01727 *
## I(dos^2)           -1.61297    0.11568  24.63154 -13.944 3.44e-13 ***
## scale(elev_range)  -0.12398    0.03965 462.70123  -3.127  0.00188 **
## scale(flow)        -0.19699    0.09291 119.65754  -2.120  0.03605 *
## scale(u)            0.07340    0.03698 443.55600   1.985  0.04776 *
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) year_c dos    I(d^2) scl(_) scl(f)
## year_c       0.033
## dos          0.170 -0.027
## I(dos^2)    -0.409 -0.003  0.065
## scl(lv_rng) -0.015 -0.014 -0.049  0.009
## scale(flow) -0.081  0.110 -0.455  0.043  0.061
## scale(u)    -0.005 -0.003 -0.003  0.002 -0.077  0.068
```



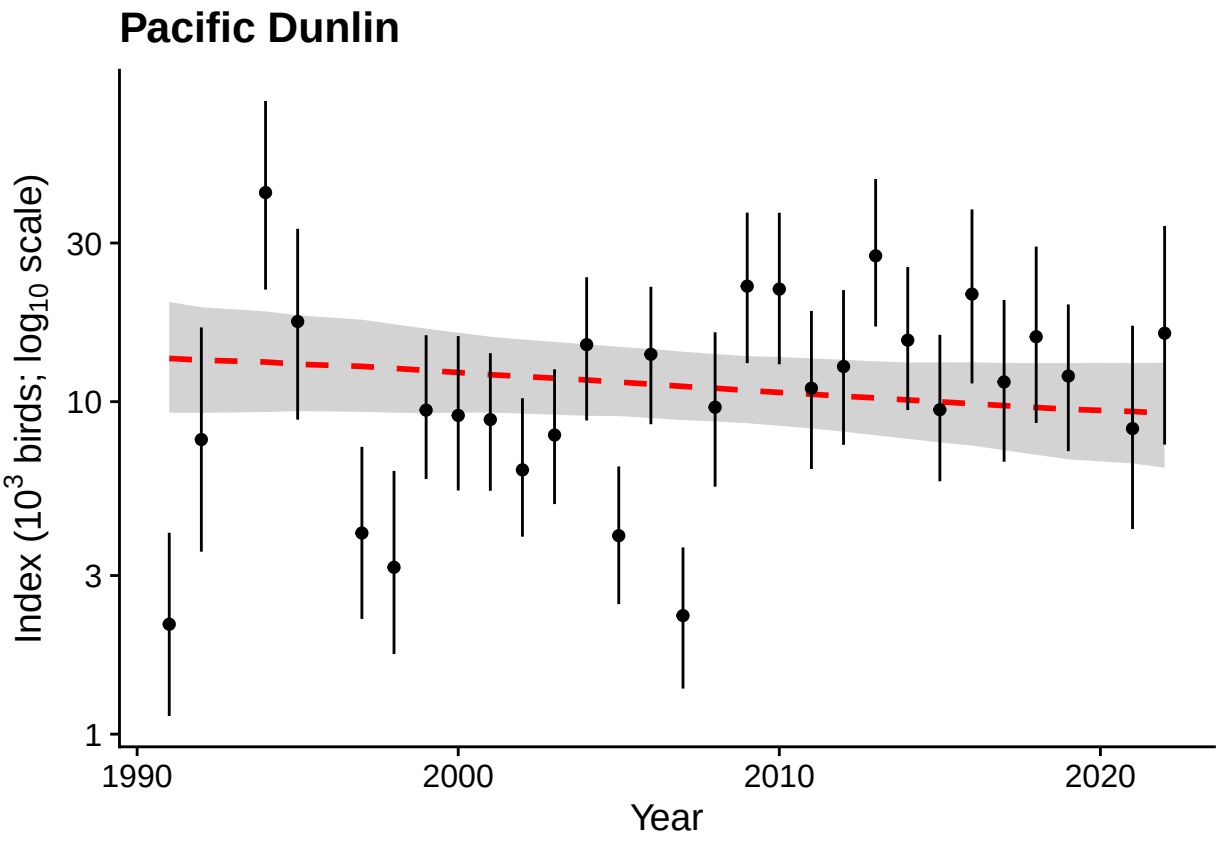
7.2 DUNL population trend

As in the original Canham paper, however, `year` remains insignificant in the DUNL model.

Pacific Dunlin populations continue to show yearly declines in population, though the trend is not statistically significant. Since 1991, Pacific Dunline populations have fallen by 32.4% (-1.1% per annum). In the last ten years the rate of decline has slowed. Since 2012, Pacific Dunline populations have fallen by 11.8% (-0.4% per annum).

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## log_dunl ~ year_c + dos + I(dos^2) + scale(elev_range) + scale(flow) +
##     scale(u) + (dos + I(dos^2) | year)
##    Data: dt
```

```
## Control: lme4::lmerControl(optimizer = "bobyqa")
##
## REML criterion at convergence: 1342.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.9607 -0.3995  0.0388  0.4567  2.9302
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3471   0.5892
##           dos         0.4707   0.6861    0.00
##           I(dos^2)    0.4234   0.6507   -0.69  0.18
##  Residual             0.5294   0.7276
## Number of obs: 513, groups:  year, 29
##
## Fixed effects:
##                     Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)          9.26902    0.12062  23.85827  76.848  < 2e-16 ***
## year_c              -0.10402    0.08158  28.01040  -1.275 0.212745
## dos                 -1.32980    0.14952  35.69018  -8.894 1.39e-10 ***
## I(dos^2)            -0.72078    0.12913  25.60351  -5.582 7.68e-06 ***
## scale(elev_range)   -0.12978    0.03863 459.69967  -3.360 0.000845 ***
## scale(flow)         -0.24995    0.08684 102.81184  -2.878 0.004863 **
## scale(u)             0.07435    0.03575 446.20883   2.080 0.038119 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) year_c dos    I(d^2) scl(_) scl(f)
## year_c       0.026
## dos          0.026 -0.020
## I(dos^2)    -0.679 -0.010  0.122
## scl(lv_rng) -0.016 -0.003 -0.050  0.007
## scale(flow) -0.073  0.103 -0.414  0.038  0.075
## scale(u)    -0.004 -0.006  0.003  0.002 -0.077  0.058
```


Pacific Dunlin
Index (10^3 birds; $\log_{10}$ scale)
30
10
3
1
1990
2000
2010
2020
Year