Brunswick Point Peep Models

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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.   :   0.0   Min.   :  48.0
##  1st Qu.:2005-04-20   1st Qu.: 126.8   1st Qu.:  42.0   1st Qu.: 287.2
##  Median :2009-04-23   Median : 355.0   Median :  93.0   Median : 524.5
##  Mean   :2009-09-05   Mean   : 470.1   Mean   : 176.7   Mean   : 646.8
##  3rd Qu.:2015-04-16   3rd Qu.: 719.0   3rd Qu.: 203.5   3rd Qu.: 943.8
##  Max.   :2022-05-04   Max.   :2605.0   Max.   :5000.0   Max.   :5047.0
##
##      p_wesa           p_dunl            year       julian_day
##  Min.   :  0.00   Min.   :  0.00   2006   : 23   Min.   :101.0
##  1st Qu.: 53.04   1st Qu.:  8.83   2019   : 23   1st Qu.:112.0
##  Median : 81.32   Median : 18.68   2005   : 18   Median :117.0
##  Mean   : 68.94   Mean   : 31.06   2007   : 18   Mean   :117.6
##  3rd Qu.: 91.17   3rd Qu.: 46.96   2008   : 18   3rd Qu.:123.0
##  Max.   :100.00   Max.   :100.00   2012   : 18   Max.   :137.0
##                                    (Other):200
##         dos.V1
##  Min.   :-2.2763470
##  1st Qu.:-0.7798519
##  Median :-0.0996268
##  Mean   :-0.0221924
##  3rd Qu.: 0.7166433
##  Max.   : 2.6212735
##
```

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 64756 64764 -32376    64752
## lme4    3 25804 25815 -12899    25798 38954.1  1     <2e-16 ***
## lme2    4 16295 16310  -8144    16287  9510.6  1     <2e-16 ***
## lme3    5 22521 22540 -11255    22511     0.0  1          1
## lme1    9 11083 11117  -5532    11065 11446.2  4     <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

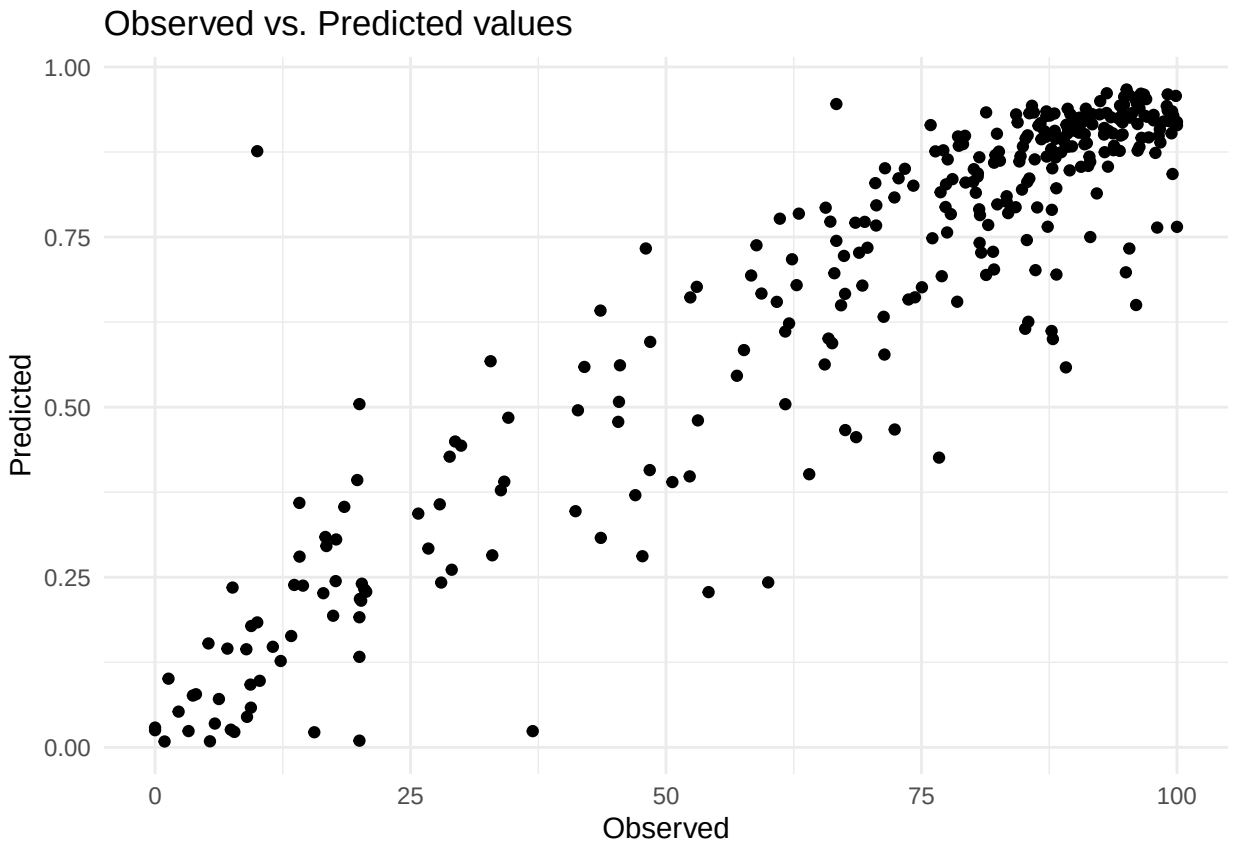
The best-fit model is `lme1`. The residuals from `lme1` are appended to the `sr` dataset and another model is re-fit in order to estimate overdispersion. Because the standard deviation of the residuals is < 1, the model is deemed an appropriate candidate for predicting daily species ratios.

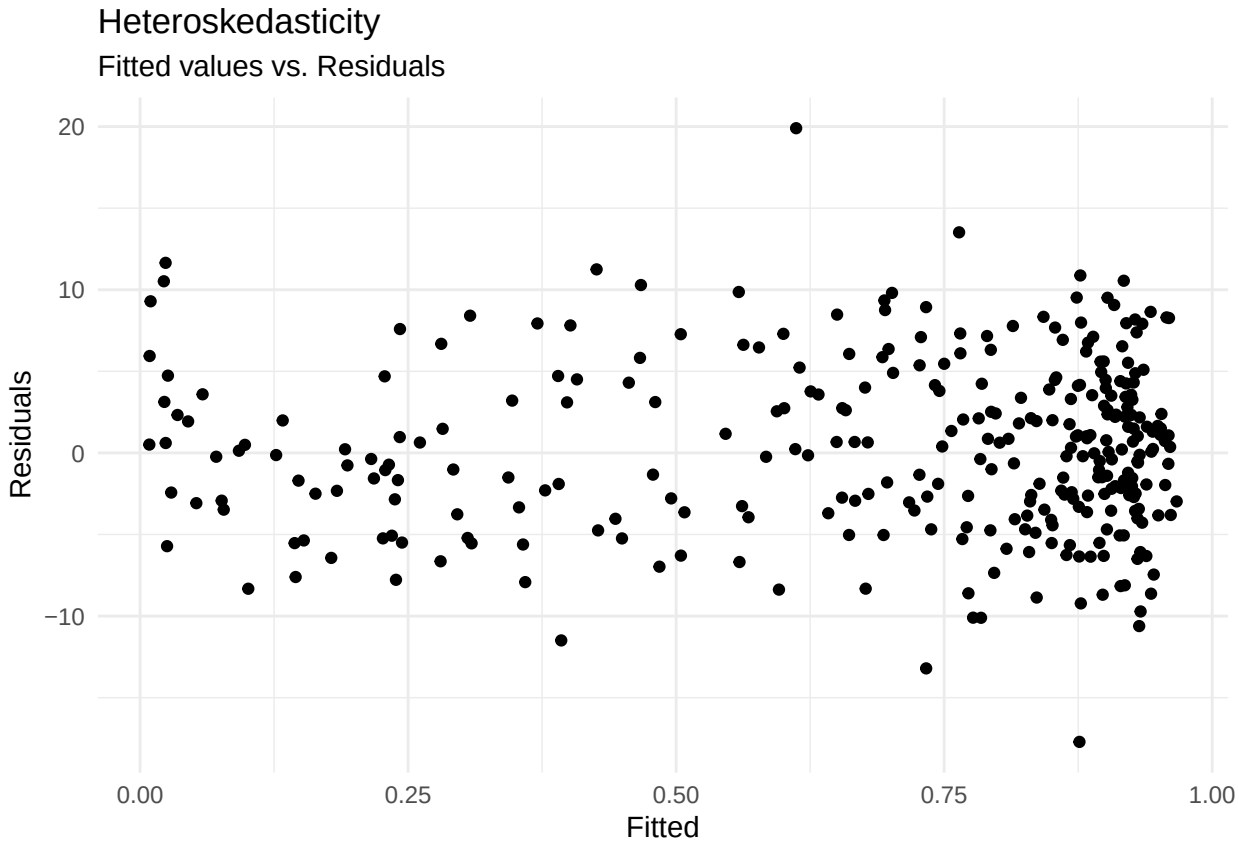
```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: y ~ dos + I(dos^2) + (dos + I(dos^2) | year) + (1 | resids)
##    Data: sr
##       AIC       BIC    logLik  deviance  df.resid
##  3409.879  3447.499 -1694.939  3389.879       308
## Random effects:
##  Groups Name        Std.Dev. Corr
##  resids (Intercept) 0.94716
##  year   (Intercept) 0.65139
##         dos         0.06454  -1.00
##         I(dos^2)    0.41479  -0.65  0.68
## Number of obs: 318, groups:  resids, 318; year, 24
## Fixed Effects:
## (Intercept)          dos     I(dos^2)
##      1.8826       1.3770      -0.8085
```

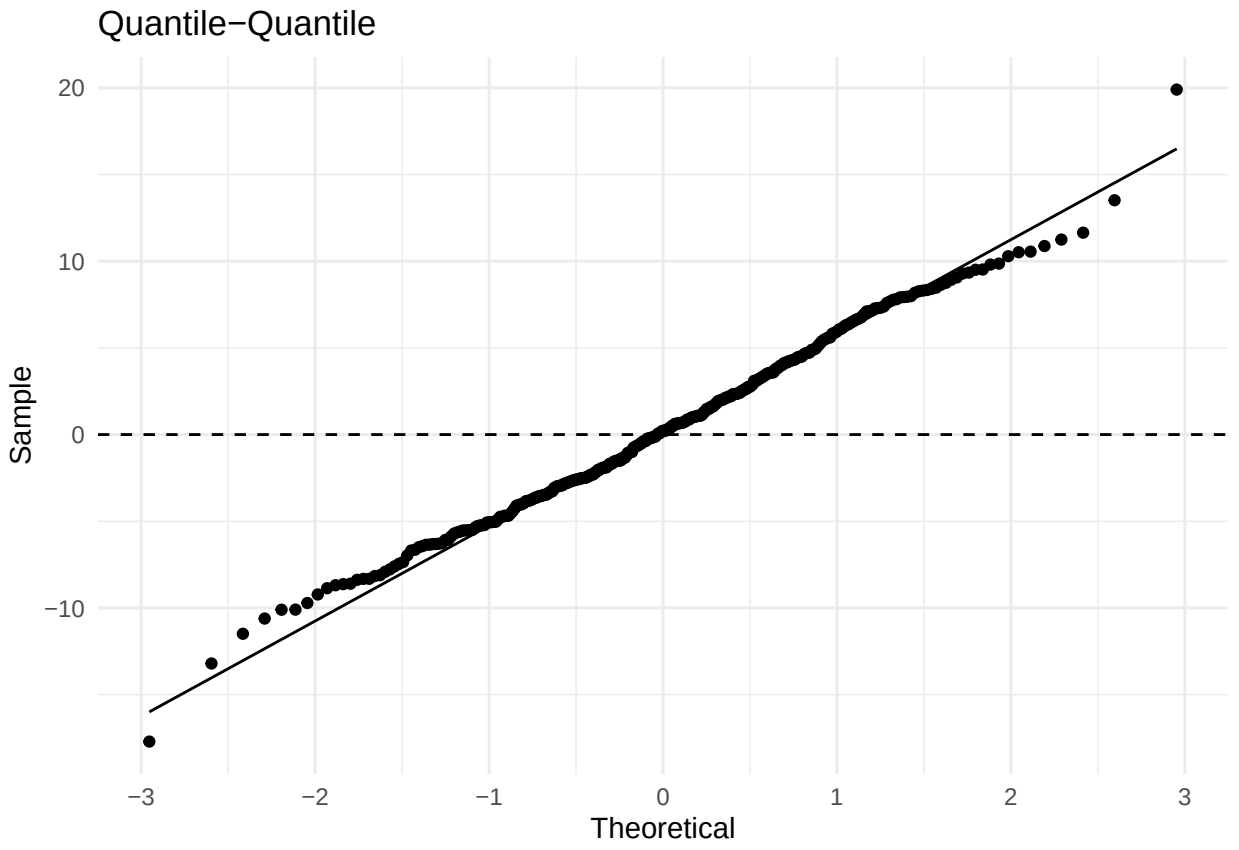
1.2.1 Summary of best fit model (lme1)

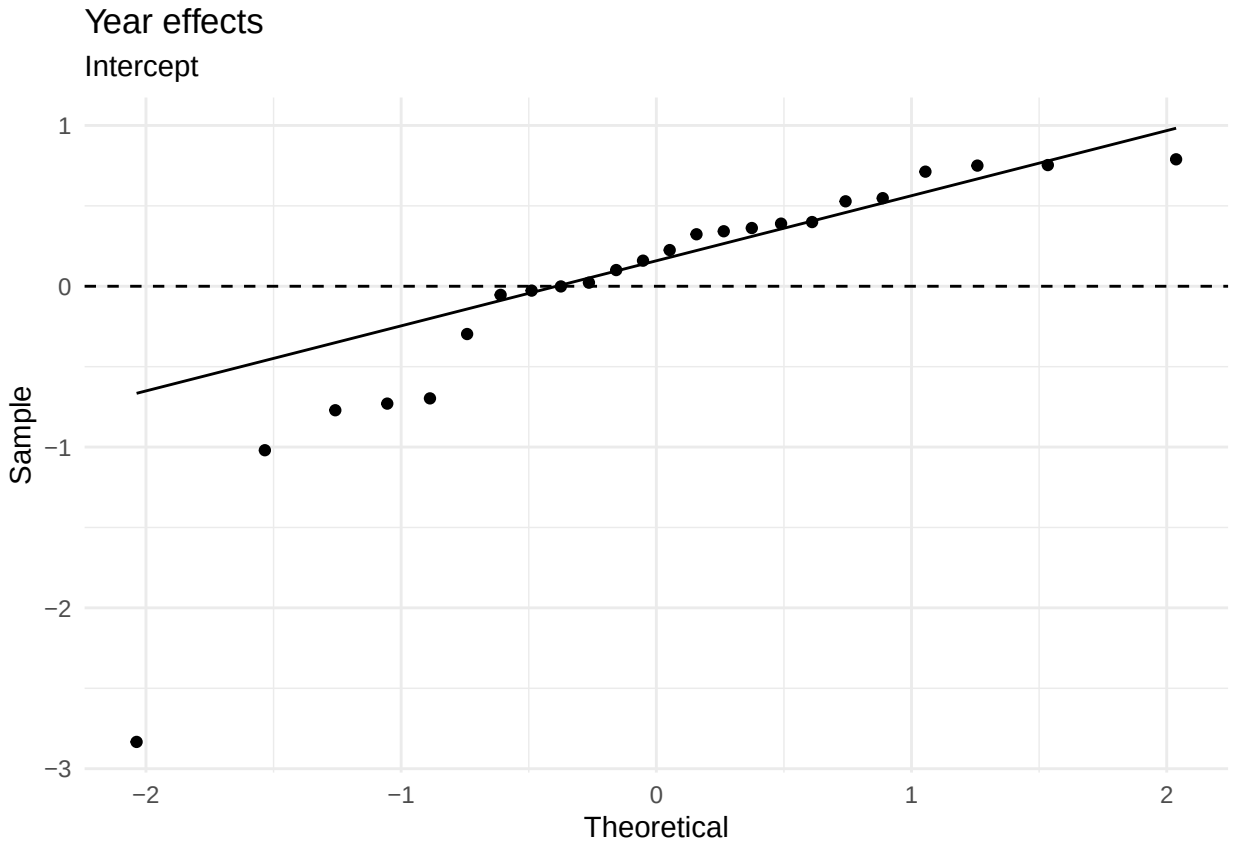
```
## Generalized linear mixed model fit by maximum likelihood (Laplace
##   Approximation) [glmerMod]
##  Family: binomial  ( logit )
## Formula: y ~ dos + I(dos^2) + (dos + I(dos^2) | year)
##    Data: sr
##
##      AIC      BIC   logLik deviance df.resid
##  11082.7  11116.6  -5532.4  11064.7      309
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -23.5674  -3.5412   0.2172   3.6901  21.7396
##
## Random effects:
##  Groups Name        Variance Std.Dev. Corr
##  year   (Intercept) 0.6045   0.7775
##         dos         0.4629   0.6803    0.18
##         I(dos^2)    0.6650   0.8155   -0.71 -0.53
## Number of obs: 318, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   1.7477     0.1593  10.974  < 2e-16 ***
## dos           1.3365     0.1398   9.558  < 2e-16 ***
## I(dos^2)     -0.8168     0.1676  -4.874 1.09e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##          (Intr) dos
## dos       0.177
## I(dos^2) -0.705 -0.522
```

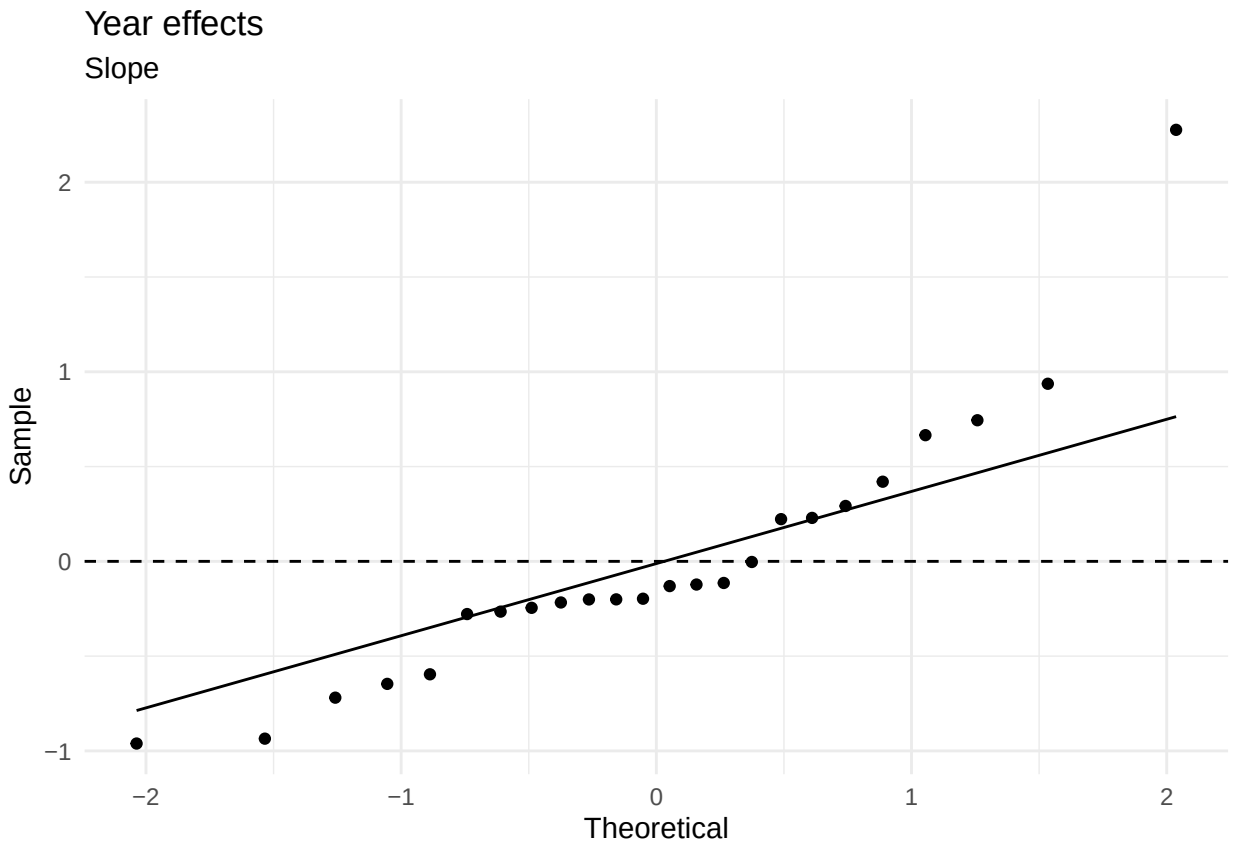
1.2.2 Check assumptions of best fit model

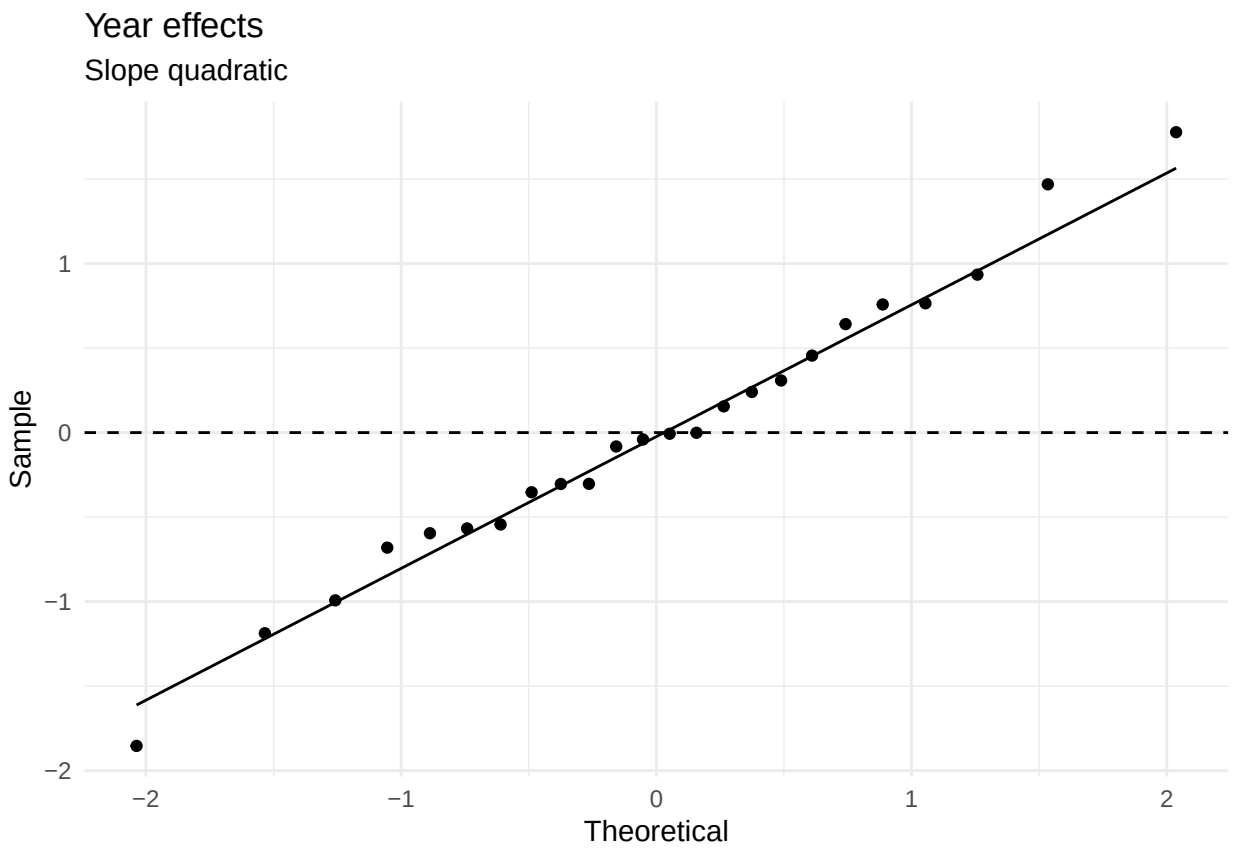



Heteroskedasticity
Fitted values vs. Residuals
Residuals
Fitted
20
10
0
−10
0.00
0.25
0.50
0.75
1.00


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

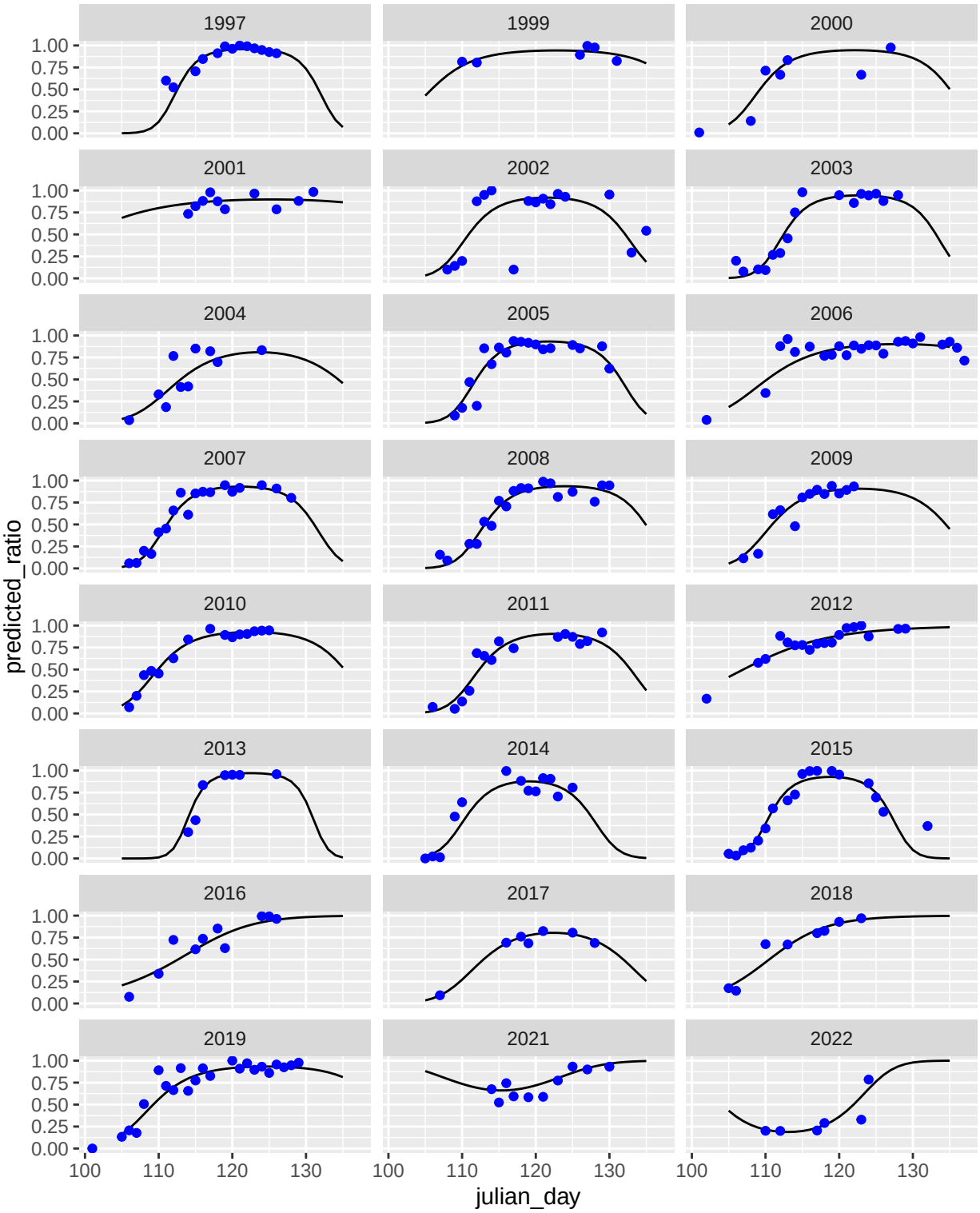

Year effects
Intercept
Sample
Theoretical
1
0
−1
−2
−3
−2
−1
0
1
2


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


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



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 1727 records from a total of 469. 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	469	1727	NA	NA
Remove NA count records	469	1722	0	-5
Exclude dates where total # of birds < 1000	443	1633	-26	-89
Exclude dates outside of survey period (<04-15 or >05-15)	430	1584	-13	-49
Exclude Intercauseway and NA stations (e.g. location was simply 'inner mud', 'mumblies', 'flying', etc.)	429	1477	-1	-107
Exclude records where only bird count occurs in location that spans >2 stations (e.g., 'BP to CP')	426	1471	-3	-6

2.1 dat data summary after filtering

```
##   survey_date          start_time                  station_n
##  Min.   :1997-04-21   Length:1471        Pilings        :331
##  1st Qu.:2004-04-26   Class :character   Coal Port      :326
##  Median :2009-04-28   Mode  :character   Brunswick Point:269
##  Mean   :2009-09-28                      34th St pullout:189
##  3rd Qu.:2015-04-19                      View corner    :170
##  Max.   :2022-05-04                      Bend           :111
##                                          (Other)        : 75
##            station_s     final_count         p_wesa        raptor_count
##  Coal Port      :  48   Min.   :     0   Min.   :  0.00   Min.   :1.000
##  View corner    :  40   1st Qu.:  1138   1st Qu.: 53.12   1st Qu.:1.000
##  Bend           :  21   Median :  6500   Median : 80.66   Median :1.000
##  34th St pullout:  17   Mean   : 16333   Mean   : 69.34   Mean   :1.812
##  Pilings        :  12   3rd Qu.: 21250   3rd Qu.: 91.18   3rd Qu.:2.000
##  (Other)        :   1   Max.   :222500   Max.   :100.00   Max.   :8.000
##  NA's           :1332                    NA's   :458      NA's   :818
##     elev_min          elev_max     elev_median      elev_mean
##  Min.   :-0.040   Min.   :3.96   Min.   :2.240   Min.   :2.660
##  1st Qu.: 0.830   1st Qu.:4.30   1st Qu.:3.072   1st Qu.:2.971
##  Median : 1.210   Median :4.43   Median :3.255   Median :3.038
##  Mean   : 1.223   Mean   :4.42   Mean   :3.238   Mean   :3.043
##  3rd Qu.: 1.620   3rd Qu.:4.56   3rd Qu.:3.410   3rd Qu.:3.120
##  Max.   : 2.420   Max.   :4.85   Max.   :3.735   Max.   :3.422
##
##    elev_range          flow       total_precip     mean_temp
##  Min.   :1.870   Min.   : 996   Min.   : 0.00   Min.   : 3.80
##  1st Qu.:2.720   1st Qu.:2490   1st Qu.: 0.00   1st Qu.: 9.30
##  Median :3.210   Median :3110   Median : 0.00   Median :10.50
##  Mean   :3.197   Mean   :3291   Mean   : 2.11   Mean   :10.68
##  3rd Qu.:3.610   3rd Qu.:4070   3rd Qu.: 2.00   3rd Qu.:11.90
##  Max.   :4.640   Max.   :7830   Max.   :28.20   Max.   :17.50
##                  NA's   :5      NA's   :4
##        u                  v              windspd          wind_deg
##  Min.   :-19.8067   Min.   :-42.3467   Min.   : 5.292   Min.   :-177.35
##  1st Qu.: -3.8203   1st Qu.: -9.7841   1st Qu.:10.521   1st Qu.: -77.27
##  Median : -0.9551   Median : -0.4341   Median :12.958   Median : -24.09
##  Mean   : -0.7154   Mean   : -1.7433   Mean   :14.309   Mean   :  14.30
##  3rd Qu.:  2.5179   3rd Qu.:  8.1678   3rd Qu.:16.896   3rd Qu.: 116.65
##  Max.   : 15.0489   Max.   : 20.4541   Max.   :43.750   Max.   : 179.93
##
##       year       julian_day          dos.V1        n_s
##  2019   :106   Min.   :105.0   Min.   :-1.8553478   N:956
##  2012   :104   1st Qu.:112.0   1st Qu.:-0.8711370   S:515
##  2008   : 90   Median :118.0   Median :-0.0275277
##  2001   : 80   Mean   :118.2   Mean   : 0.0000000
##  2005   : 80   3rd Qu.:124.0   3rd Qu.: 0.8160816
##  2015   : 70   Max.   :135.0   Max.   : 2.3626986
##  (Other):941
```

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: 7302.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.2987 -0.3248  0.2468  0.6247  2.1576
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3804   0.6168
##           dos         0.5523   0.7432   -0.12
##           I(dos^2)    0.1273   0.3568   -0.13 -0.04
##  Residual             7.9024   2.8111
## Number of obs: 1471, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)  8.57114    0.16581 15.94079  51.693  < 2e-16 ***
## year_c      -0.02345    0.14500 22.31502  -0.162    0.873
## dos         -0.04050    0.17635 19.23766  -0.230    0.821
## I(dos^2)    -1.32114    0.11598 11.08207 -11.391 1.85e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##          (Intr) year_c dos
## year_c   -0.014
## dos      -0.078  0.017
## I(dos^2) -0.398  0.026 -0.007
```

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 (1471 -> 1462).

```
## 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: 7182.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4130 -0.3223  0.2407  0.6394  2.1634
##
## Random effects:
##  Groups   Name        Variance  Std.Dev.  Corr
##  year     (Intercept) 4.460e-01 6.679e-01
##           dos         6.103e-01 7.812e-01 -0.22
##           I(dos^2)    6.387e-02 2.527e-01  0.46 -0.04
##  n_s      (Intercept) 6.145e+00 2.479e+00
##           scale(flow) 1.082e-09 3.289e-05 1.00
##  Residual             7.421e+00 2.724e+00
## Number of obs: 1462, groups:  year, 24; n_s, 2
##
## Fixed effects:
##                       Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)            9.10629    2.48556 1383.39733   3.664 0.000258 ***
## year_c                -0.11093    0.16058   20.78506  -0.691 0.497335
## dos                    0.08759    0.20620   26.92175   0.425 0.674382
```

```
## I(dos^2)              -1.38697    0.10097   11.70827 -13.737 1.41e-08 ***
## scale(elev_range)      0.25045    0.08231  484.67379   3.043 0.002471 **
## scale(total_precip)    0.03184    0.08023 1297.14887   0.397 0.691563
## scale(mean_temp)       0.13624    0.09490  694.28100   1.436 0.151569
## scale(flow)           -0.24502    0.14872   41.26802  -1.648 0.107043
## scale(u)               0.08265    0.09278  825.77108   0.891 0.373329
## scale(v)               0.23498    0.09595 1091.10794   2.449 0.014485 *
## n_sS                  -1.40193    3.50904 1369.17555  -0.400 0.689573
## ---
## 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      -0.001
## dos         -0.006 -0.012
## I(dos^2)    -0.012  0.032 -0.074
## scl(lv_rng)  0.000  0.025 -0.039  0.015
## scl(ttl_pr)  0.000  0.024 -0.011  0.026  0.045
## scl(mn_tmp) -0.001 -0.042 -0.149  0.007 -0.081   0.064
## scale(flow) -0.007  0.041 -0.444  0.135  0.050   0.043  -0.009
## scale(u)     0.003 -0.056  0.044 -0.075 -0.089  -0.038   0.062  -0.004
## scale(v)     0.002 -0.011  0.063 -0.069  0.039  -0.260  -0.079  -0.035  0.514
## n_sS        -0.706  0.000  0.000  0.000 -0.002   0.000   0.001  -0.001  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

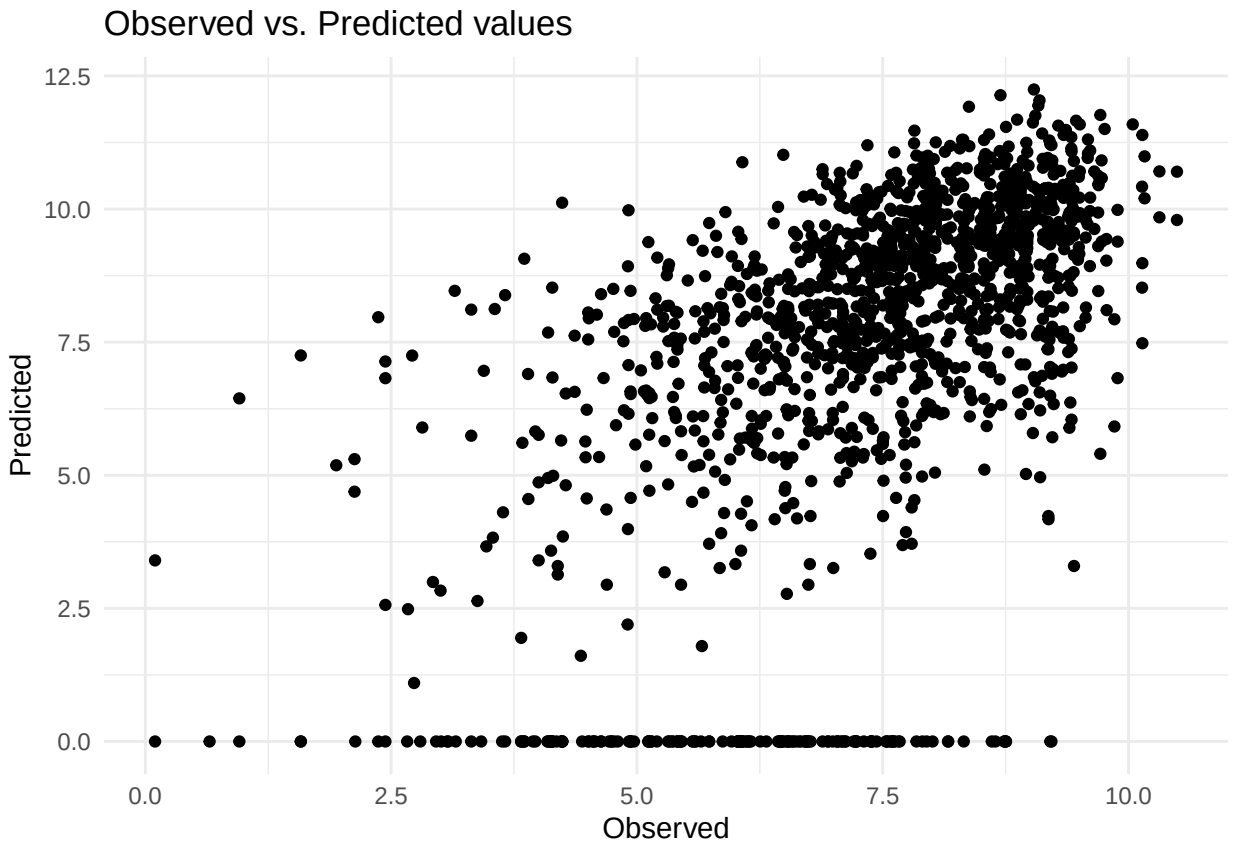
```
## Backward reduced random-effect table:
##
##                                    Eliminated npar  logLik    AIC    LRT Df
## <none>                                         21 -3591.2 7224.4
## dos in (dos + I(dos^2) | year)              0   18 -3611.2 7258.4 40.033  3
## I(dos^2) in (dos + I(dos^2) | year)         0   18 -3592.9 7221.8  3.355  3
## scale(flow) in (scale(flow) | n_s)          0   19 -3591.2 7220.4  0.000  2
##                                    Pr(>Chisq)
## <none>
## dos in (dos + I(dos^2) | year)       1.048e-08 ***
## I(dos^2) in (dos + I(dos^2) | year)       0.34
## scale(flow) in (scale(flow) | n_s)        1.00
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

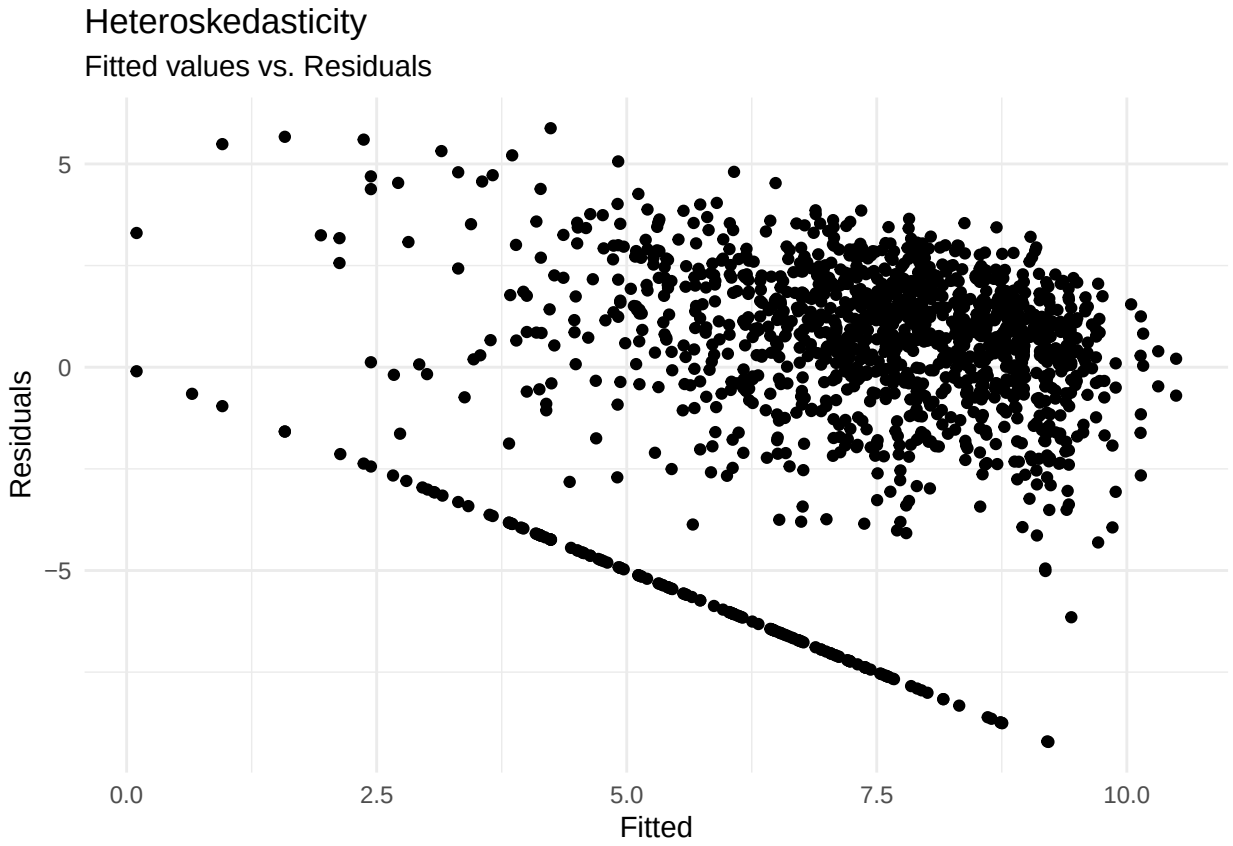
```
##
## Backward reduced fixed-effect table:
## Degrees of freedom method: Satterthwaite
##
##                     Eliminated  Sum Sq Mean Sq NumDF   DenDF  F value    Pr(>F)
## scale(total_precip)          1    1.17    1.17     1 1297.15   0.1575  0.691563
## n_s                          2    0.69    0.69     1 1370.49   0.0928  0.760725
## scale(u)                     3    6.14    6.14     1  823.09   0.8279  0.363157
## scale(mean_temp)             4   13.67   13.67     1  711.85   1.8445  0.174857
## scale(flow)                  5   21.38   21.38     1   18.61   2.8839  0.106132
## year_c                       0    0.50    0.50     1   21.79   0.0671  0.798097
## dos                          0    0.30    0.30     1   19.63   0.0403  0.842911
## I(dos^2)                     0 1066.28 1066.28     1   12.04 144.0700 4.663e-08
## scale(elev_range)            0   80.14   80.14     1  688.01  10.8282  0.001051
## scale(v)                     0   49.87   49.87     1 1189.52   6.7387  0.009551
##
## scale(total_precip)
## n_s
## 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
```

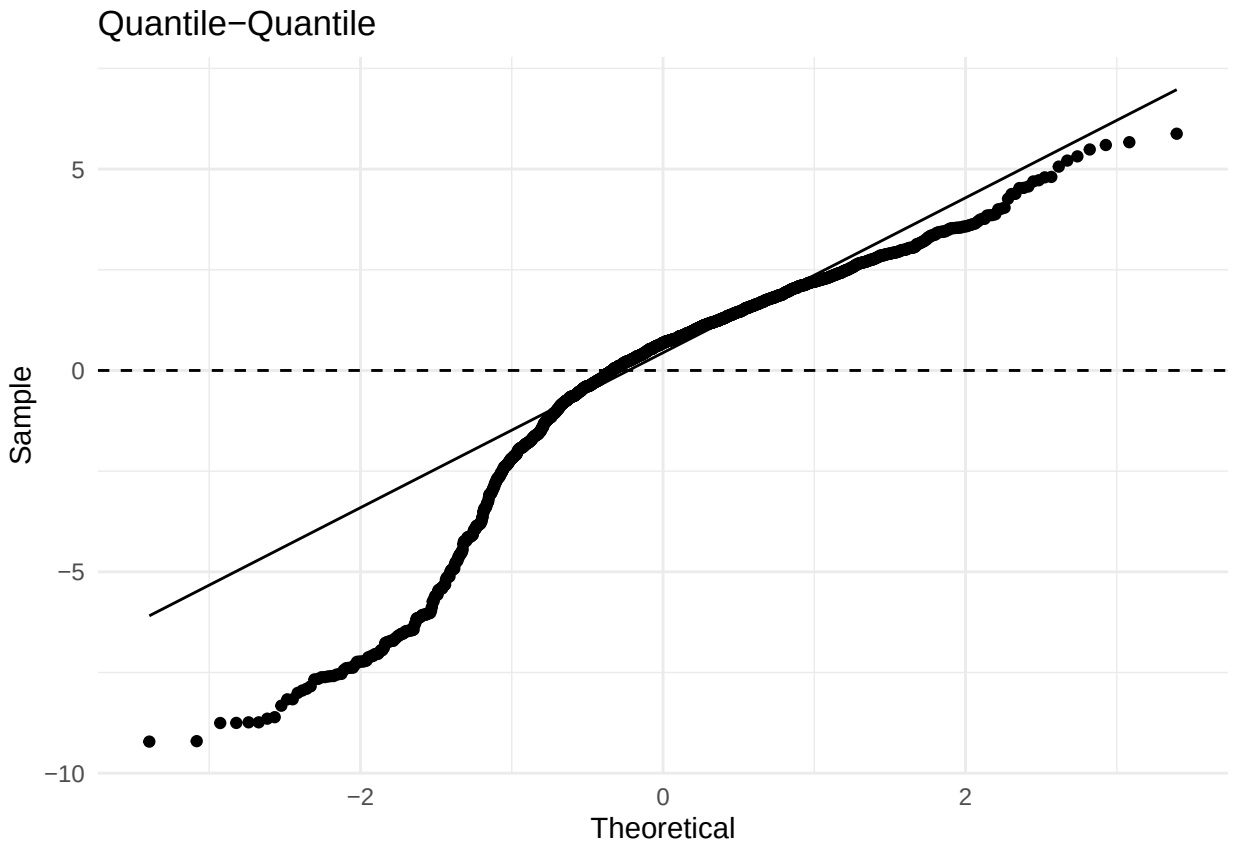
3.0.4 Summary of best-fit model

```
## 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: 7179.9
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.3876 -0.3149  0.2521  0.6390  2.1610
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.472474 0.68737
##           dos         0.634054 0.79628  -0.16
##           I(dos^2)    0.116392 0.34116   0.03  0.02
##  n_s      (Intercept) 1.013085 1.00652
##           scale(flow) 0.001794 0.04235  1.00
##  Residual             7.401143 2.72050
## Number of obs: 1462, groups:  year, 24; n_s, 2
##
## Fixed effects:
##                     Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)          8.55731    0.72403    1.11667  11.819  0.04136 *
## year_c              -0.04111    0.15874   21.79071  -0.259  0.79810
## dos                 -0.03736    0.18606   19.63071  -0.201  0.84291
## I(dos^2)            -1.34797    0.11230   12.03937 -12.003 4.66e-08 ***
## scale(elev_range)    0.27225    0.08273  688.00994   3.291  0.00105 **
## scale(v)             0.20483    0.07890 1189.52245   2.596  0.00955 **
## ---
## 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      -0.008
## dos          0.069  0.008
## I(dos^2)    -0.095  0.024  0.020
## scl(lv_rng) -0.013  0.011 -0.033  0.013
## scale(v)     0.004  0.019  0.015 -0.027  0.110
## 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. We are 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.

Two simpler models can get at these questions:

1. The 'mechanism' model: `log_wesa ~ n_s * scale(flow) + dos + I(dos^2) + (dos + I(dos^2) | year)`
2. 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 survey_date julian_day        dos start_time n_s final_count
## 1 1997  1997-04-21        111 -1.0204526      17:35   N       14030
## 2 1997  1997-04-21        111 -1.0204526      18:05   S           0
## 3 1997  1997-04-22        112 -0.8808935      00:00   N       13000
## 4 1997  1997-04-22        112 -0.8808935      17:25   S           0
## 5 1997  1997-04-25        115 -0.4622159      09:15   N       76100
## 6 1997  1997-04-25        115 -0.4622159      09:00   S       54000
##   predicted_wesa predicted_dunl  log_wesa log_dunl   p_wesa predicted_ratio
## 1           3506          10524  8.162516 9.261509 60.00000       0.2499045
## 2              0              0  0.000000 0.000000 60.00000       0.2499045
## 3           5328           7672  8.580919 8.945463 52.31788       0.4098783
## 4              0              0  0.000000 0.000000 52.31788       0.4098783
## 5          61335          14765 11.024122 9.600083 70.58319       0.8059765
## 6          43523          10477 10.681068 9.257033 70.58319       0.8059765
##   raptor_count elev_min elev_max elev_median elev_mean elev_range flow
## 1            1     1.60     4.13       3.170  3.056667       2.53 3430
## 2            1     1.60     4.13       3.170  3.056667       2.53 3430
## 3           NA     1.42     4.28       3.235  3.109167       2.86 3670
## 4           NA     1.42     4.28       3.235  3.109167       2.86 3670
## 5           NA     0.89     4.34       3.155  3.003750       3.45 4160
## 6           NA     0.89     4.34       3.155  3.003750       3.45 4160
##   total_precip mean_temp         u         v  windspd  wind_deg year_n
## 1          0.0       8.3  2.952019 -6.894400 12.45833 -37.88846      1
## 2          0.0       8.3  2.952019 -6.894400 12.45833 -37.88846      1
## 3          5.6      10.7 -2.325784  3.963163 11.16667 147.32756      1
## 4          5.6      10.7 -2.325784  3.963163 11.16667 147.32756      1
## 5          3.4      12.7 -1.041889  7.000000  9.25000  92.45501      1
## 6          3.4      12.7 -1.041889  7.000000  9.25000  92.45501      1
##      year_c
## 1 -1.663883
## 2 -1.663883
## 3 -1.663883
## 4 -1.663883
```

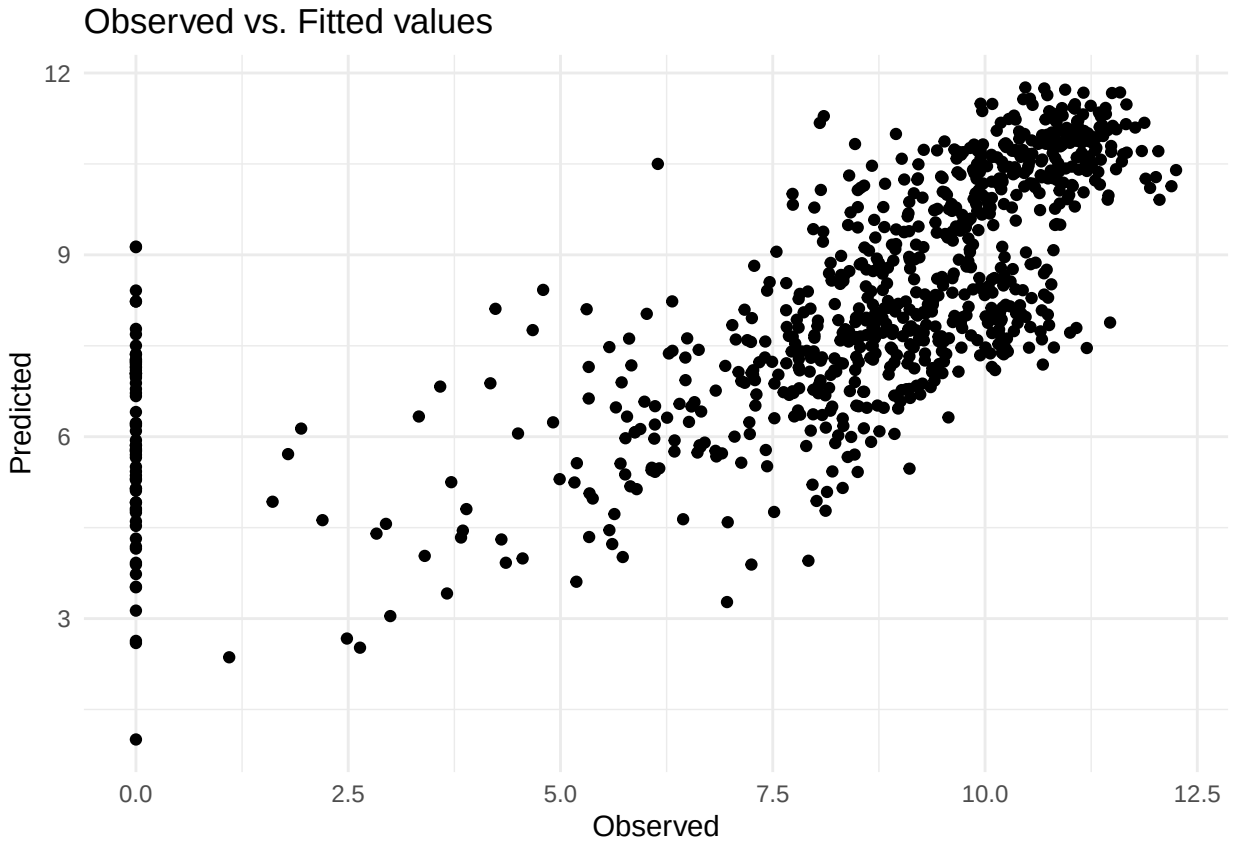
```
## 5 -1.663883
## 6 -1.663883

##       year      survey_date           julian_day           dos.V1
##  2019   : 51   Min.   :1997-04-21   Min.   :105.0   Min.   :-1.8578077
##  2012   : 46   1st Qu.:2003-05-04   1st Qu.:112.0   1st Qu.:-0.8808935
##  2008   : 45   Median :2008-05-09   Median :118.0   Median :-0.0435384
##  2015   : 45   Mean   :2009-03-11   Mean   :118.3   Mean   :-0.0008058
##  2005   : 44   3rd Qu.:2014-10-24   3rd Qu.:124.0   3rd Qu.: 0.7938166
##  1999   : 42   Max.   :2022-05-04   Max.   :135.0   Max.   : 2.3289675
##  (Other):550
##   start_time        n_s      final_count     predicted_wesa   predicted_dunl
##  Length:823         N:419   Min.   :     0   Min.   :     0   Min.   :     0
##  Class :character   S:404   1st Qu.:  4000   1st Qu.:  2298   1st Qu.:   557
##  Mode  :character           Median : 16100   Median :  9116   Median :  2752
##                             Mean   : 29125   Mean   : 20961   Mean   :  8163
##                             3rd Qu.: 43000   3rd Qu.: 27900   3rd Qu.:  9560
##                             Max.   :223500   Max.   :208942   Max.   :100284
##
##     log_wesa         log_dunl          p_wesa       predicted_ratio
##  Min.   : 0.000   Min.   : 0.000   Min.   :  0.00   Min.   :0.008502
##  1st Qu.: 7.740   1st Qu.: 6.324   1st Qu.: 53.04   1st Qu.:0.577486
##  Median : 9.118   Median : 7.920   Median : 81.08   Median :0.833322
##  Mean   : 8.284   Mean   : 7.223   Mean   : 69.25   Mean   :0.707910
##  3rd Qu.:10.236   3rd Qu.: 9.165   3rd Qu.: 91.49   3rd Qu.:0.908682
##  Max.   :12.250   Max.   :11.516   Max.   :100.00   Max.   :0.985180
##                                    NA's   :277
##   raptor_count    elev_min         elev_max     elev_median      elev_mean
##  Min.   :1.0   Min.   :-0.040   Min.   :3.96   Min.   :2.240   Min.   :2.660
##  1st Qu.:1.0   1st Qu.: 0.865   1st Qu.:4.30   1st Qu.:3.080   1st Qu.:2.973
##  Median :1.0   Median : 1.240   Median :4.43   Median :3.255   Median :3.041
##  Mean   :1.8   Mean   : 1.235   Mean   :4.42   Mean   :3.240   Mean   :3.047
##  3rd Qu.:2.0   3rd Qu.: 1.640   3rd Qu.:4.56   3rd Qu.:3.405   3rd Qu.:3.121
##  Max.   :8.0   Max.   : 2.420   Max.   :4.85   Max.   :3.735   Max.   :3.422
##  NA's   :457
##    elev_range         flow       total_precip      mean_temp
##  Min.   :1.870   Min.   : 996   Min.   : 0.000   Min.   : 3.80
##  1st Qu.:2.710   1st Qu.:2520   1st Qu.: 0.000   1st Qu.: 9.30
##  Median :3.190   Median :3140   Median : 0.000   Median :10.50
##  Mean   :3.185   Mean   :3322   Mean   : 2.069   Mean   :10.71
##  3rd Qu.:3.600   3rd Qu.:4060   3rd Qu.: 2.000   3rd Qu.:12.00
##  Max.   :4.640   Max.   :7830   Max.   :28.200   Max.   :17.50
##
##        u                 v              windspd          wind_deg
##  Min.   :-19.807   Min.   :-42.347   Min.   : 5.292   Min.   :-177.35
##  1st Qu.: -4.104   1st Qu.: -9.642   1st Qu.:10.625   1st Qu.: -76.58
##  Median : -1.042   Median :  0.000   Median :13.000   Median : -10.15
##  Mean   : -0.802   Mean   : -1.522   Mean   :14.249   Mean   :  15.34
##  3rd Qu.:  2.367   3rd Qu.:  8.391   3rd Qu.:16.729   3rd Qu.: 118.55
##  Max.   : 15.049   Max.   : 20.454   Max.   :43.750   Max.   : 179.93
##
##      year_n           year_c.V1
##  Min.   : 1.00   Min.   :-1.6638826
##  1st Qu.: 6.00   1st Qu.:-0.9010314
```

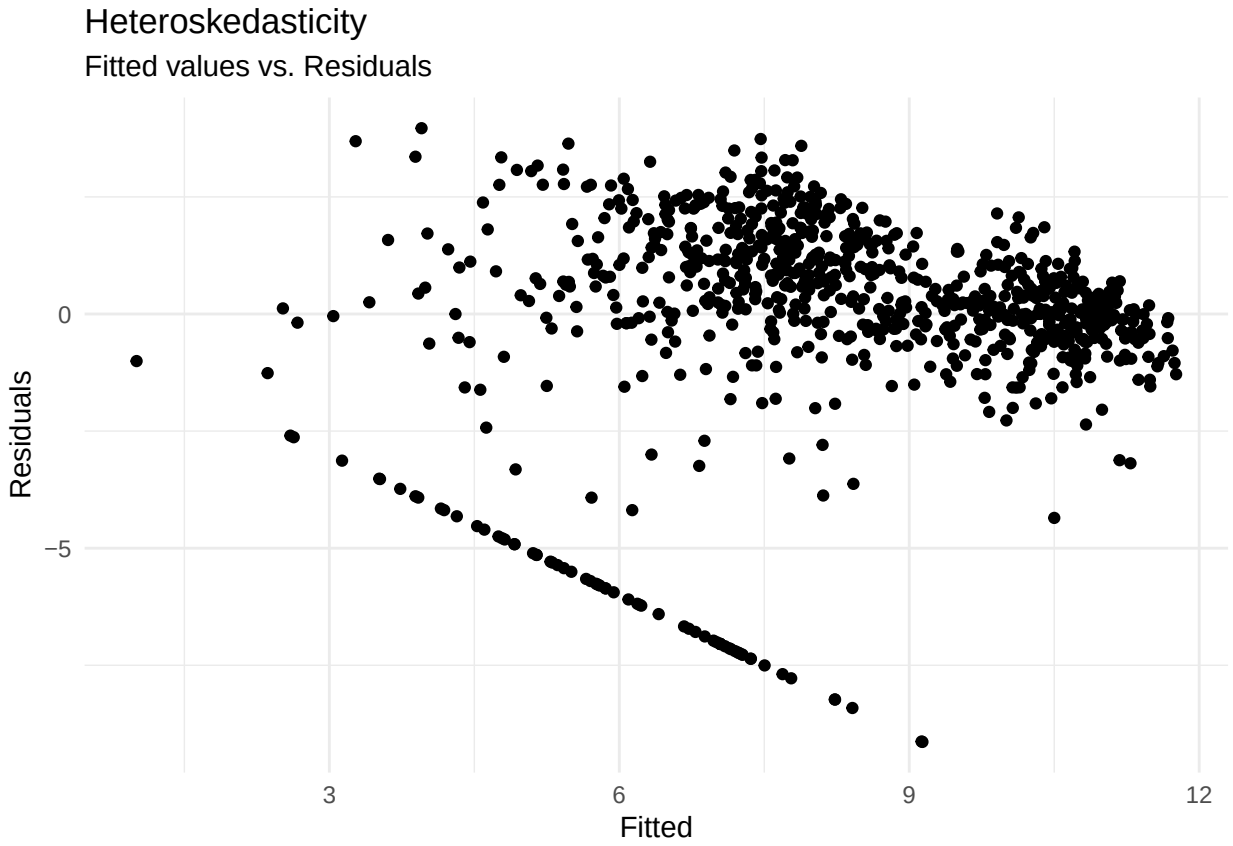
```
##  Median :11.00   Median :-0.1381803
##  Mean   :11.86   Mean   :-0.0063730
##  3rd Qu.:17.50   3rd Qu.: 0.8535262
##  Max.   :24.00   Max.   : 1.8452327
##
```

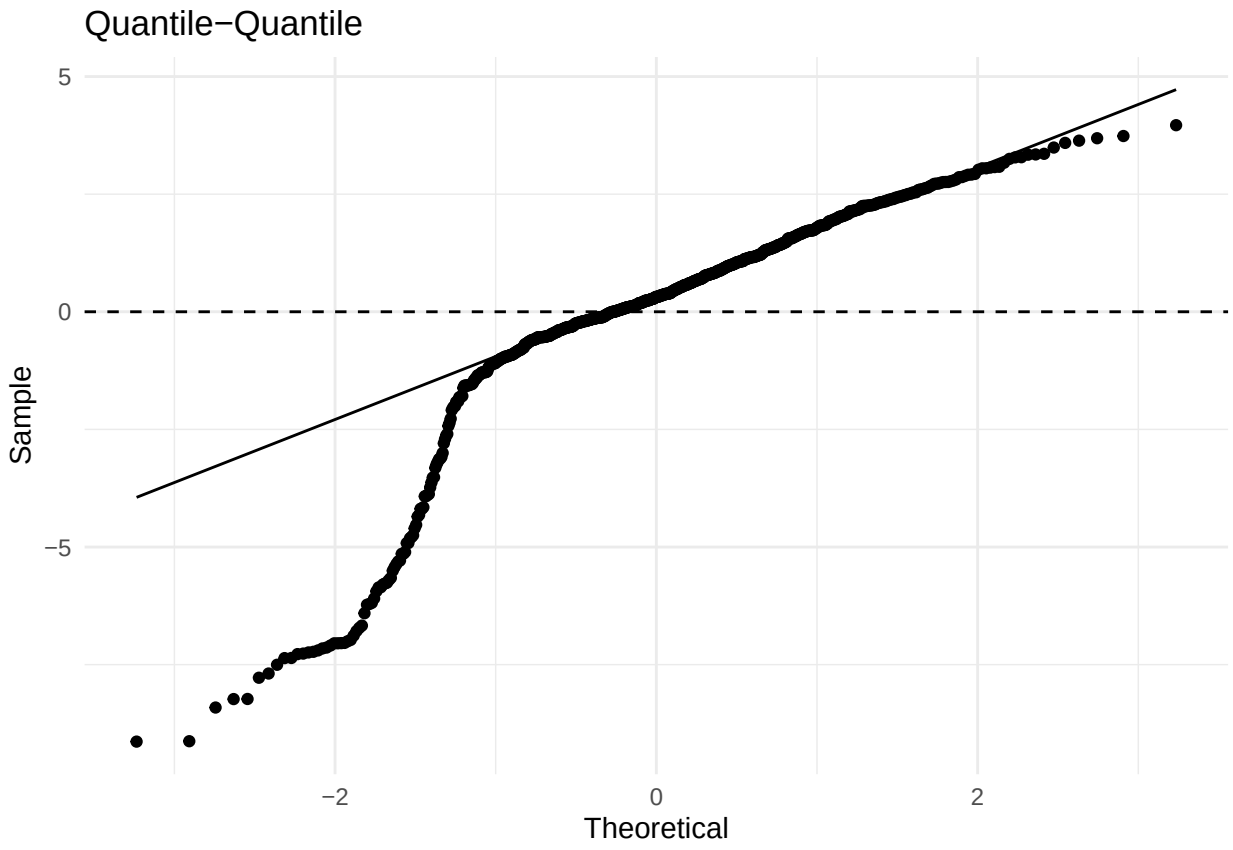
4.2 The 'mechanism' model

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: log_wesa ~ n_s * scale(flow) + dos + I(dos^2) + (dos + I(dos^2) |
##     year)
##    Data: dat3
##
## REML criterion at convergence: 3744.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.0428 -0.2276  0.1400  0.5718  1.7551
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.26220  0.5121
##           dos         0.47129  0.6865   -0.31
##           I(dos^2)    0.04913  0.2217   -0.08  0.59
##  Residual             5.10678  2.2598
## Number of obs: 823, groups:  year, 24
##
## Fixed effects:
##                  Estimate Std. Error t value
## (Intercept)      10.95996    0.17388  63.030
## n_sS             -2.91429    0.15768 -18.482
## scale(flow)      -0.24031    0.16048  -1.497
## dos               0.10666    0.18943   0.563
## I(dos^2)         -1.37393    0.10280 -13.365
## n_sS:scale(flow) -0.06884    0.15777  -0.436
##
## Correlation of Fixed Effects:
##             (Intr) n_sS   scl(f) dos    I(d^2)
## n_sS        -0.444
## scale(flow) -0.086  0.003
## dos         -0.098 -0.002 -0.406
## I(dos^2)    -0.426 -0.002  0.113  0.167
## n_sS:scl(f) -0.002  0.000 -0.481 -0.001  0.009
```

4.2.1 Diagnostic plots



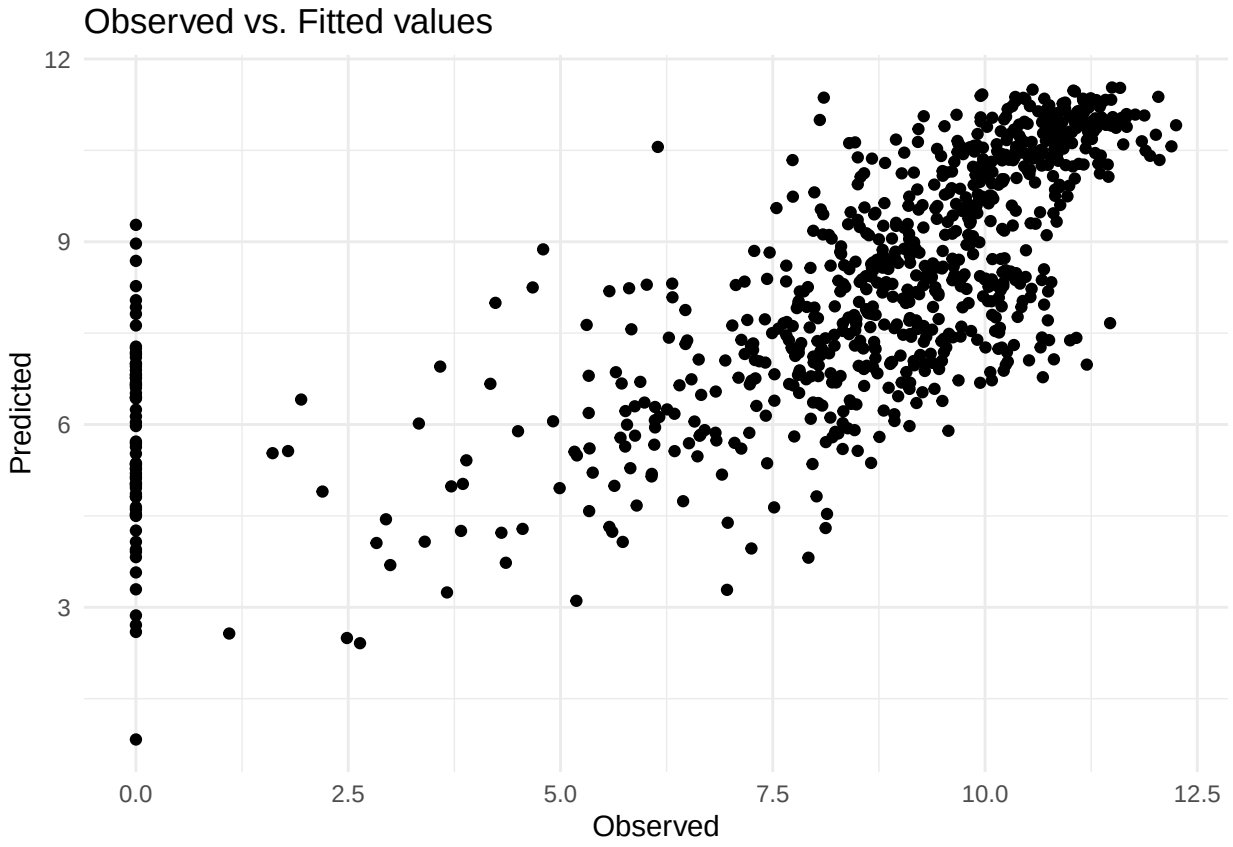

Heteroskedasticity
Fitted values vs. Residuals
Residuals
0
−5
3
6
9
12
Fitted

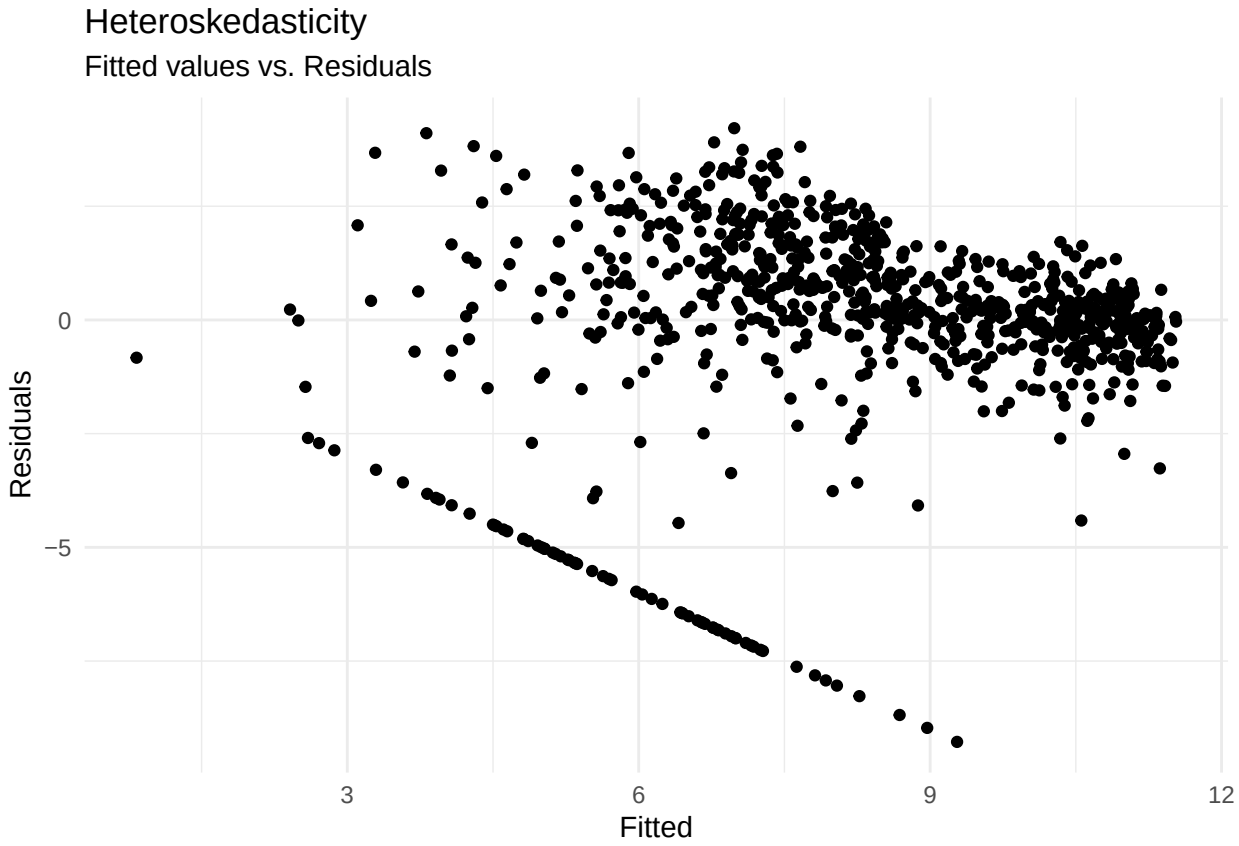

Quantile−Quantile
Sample
5
0
−5
−2
0
2
Theoretical

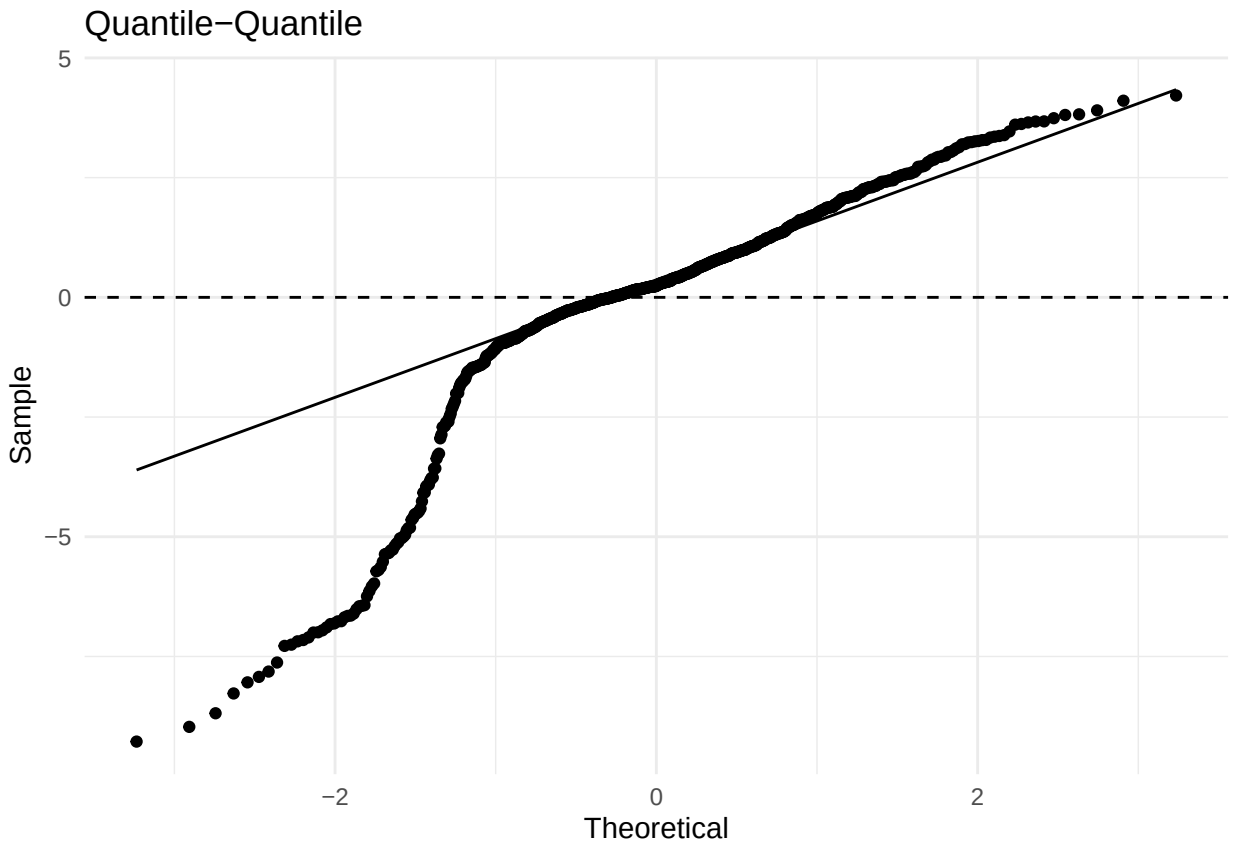
4.3 The 'temporal' model

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: log_wesa ~ n_s * year_c + dos + I(dos^2) + (dos + I(dos^2) |
##     year)
##    Data: dat3
##
## REML criterion at convergence: 3733.6
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.1323 -0.2056  0.1068  0.5320  1.8776
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.25123  0.5012
##           dos         0.46676  0.6832   -0.02
##           I(dos^2)    0.07833  0.2799   -0.29  0.56
##  Residual             5.04042  2.2451
## Number of obs: 823, groups:  year, 24
##
## Fixed effects:
##             Estimate Std. Error t value
## (Intercept) 10.91398    0.17126  63.727
## n_sS        -2.90810    0.15666 -18.563
## year_c      -0.04480    0.14707  -0.305
## dos         -0.07831    0.16730  -0.468
## I(dos^2)    -1.33924    0.10807 -12.393
## n_sS:year_c  0.56111    0.15710   3.572
##
## Correlation of Fixed Effects:
##             (Intr) n_sS   year_c dos    I(d^2)
## n_sS        -0.448
## year_c      -0.011 -0.003
## dos         -0.021  0.000  0.031
## I(dos^2)    -0.472 -0.003 -0.010  0.299
## n_sS:year_c -0.005  0.007 -0.524 -0.004  0.004
```

4.3.1 Diagnostic plots




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

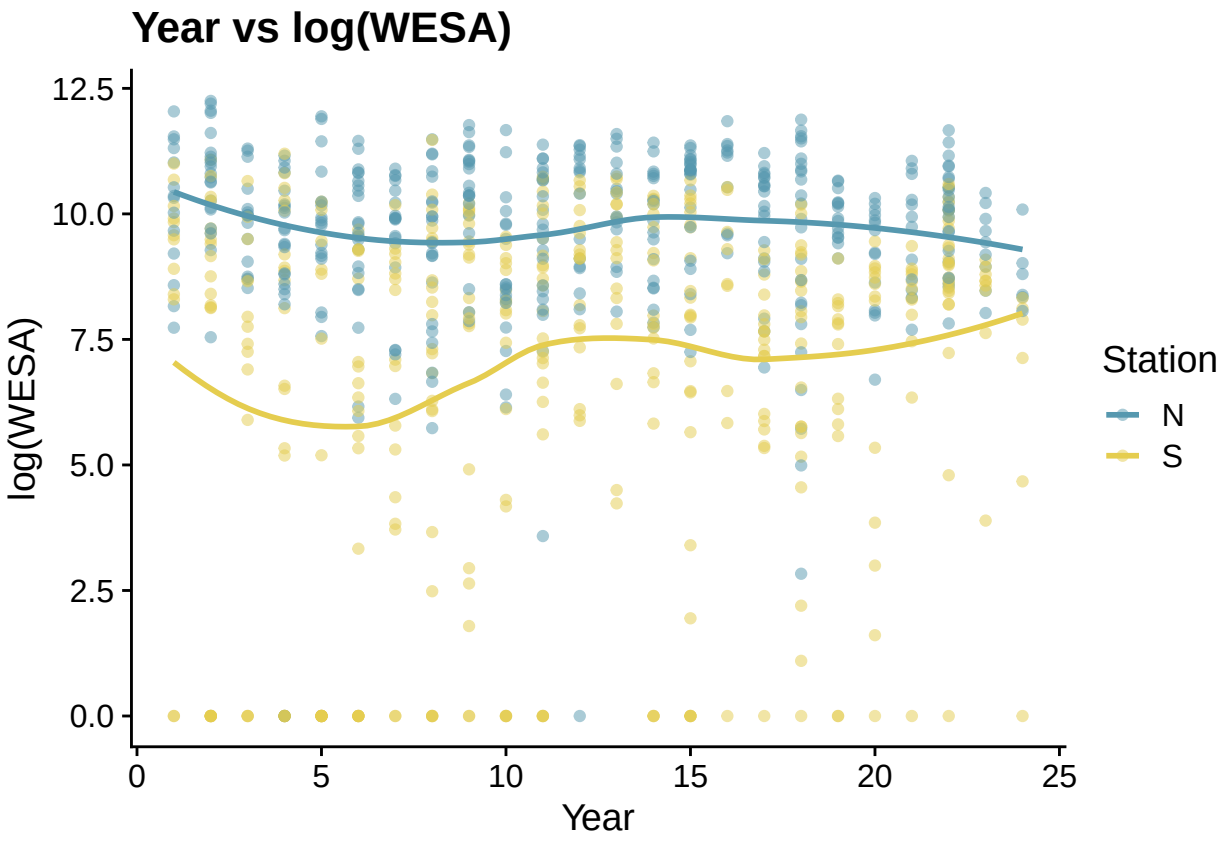

Quantile−Quantile
Sample
5
0
−5
−2
0
2
Theoretical

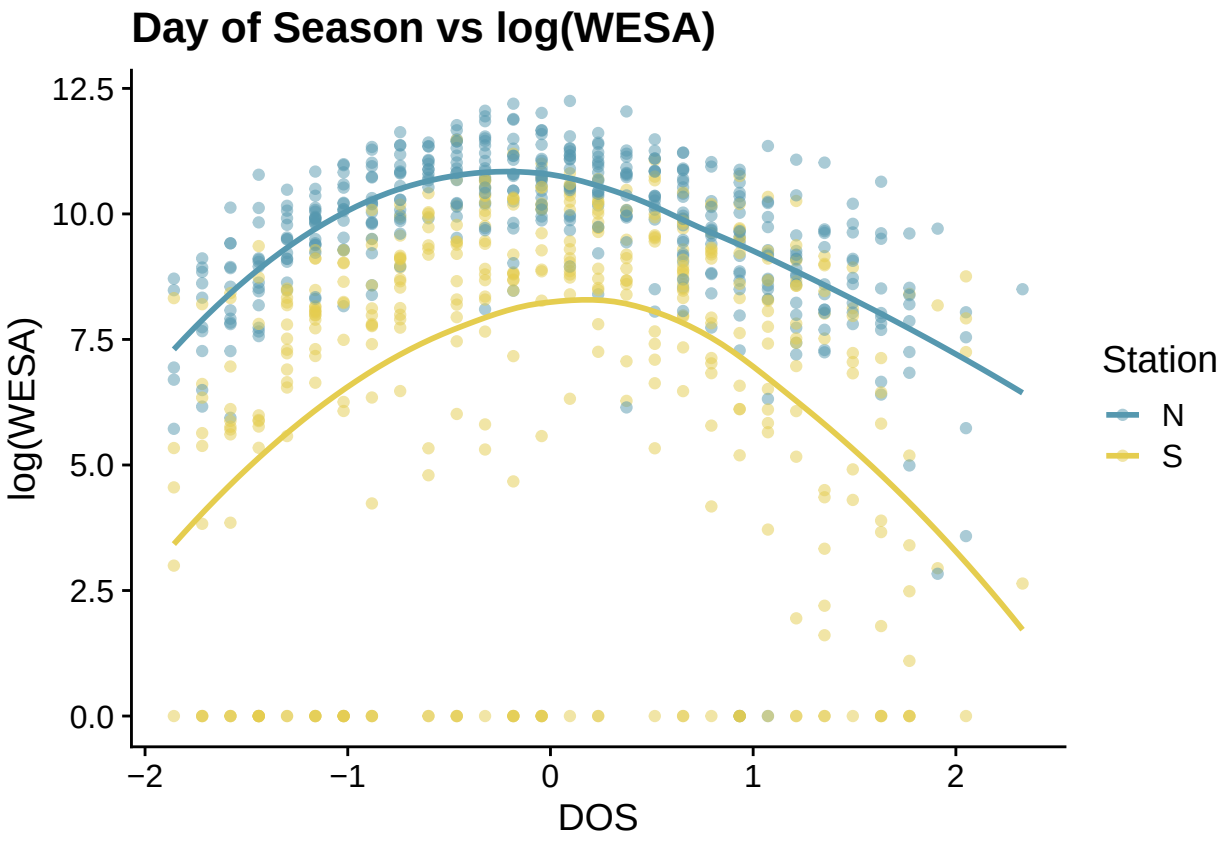
4.4 Comparing the two

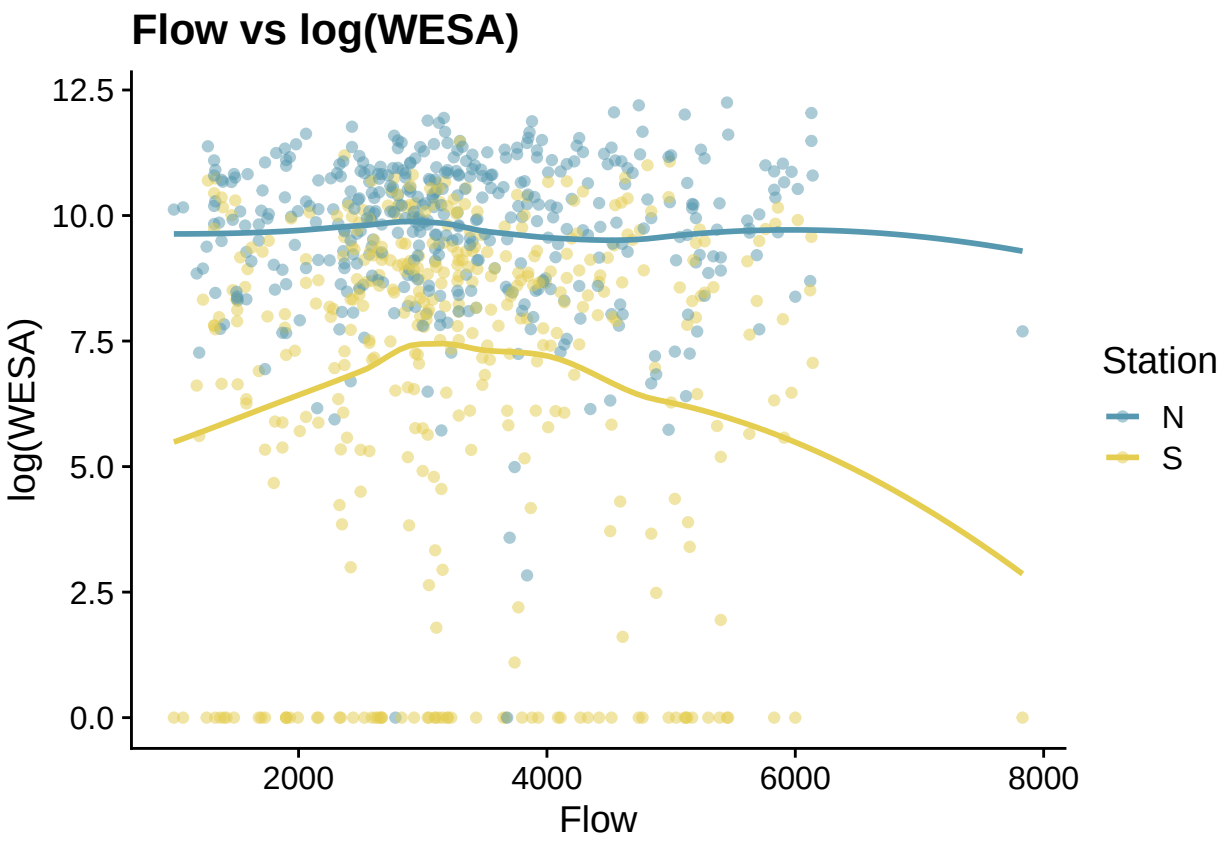
```
## Data: dat3
## Models:
## mech_model: log_wesa ~ n_s * scale(flow) + dos + I(dos^2) + (dos + I(dos^2) | year)
## temp_model: log_wesa ~ n_s * year_c + dos + I(dos^2) + (dos + I(dos^2) | year)
##            npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## mech_model   13 3757.7 3819.0 -1865.9   3731.7
## temp_model   13 3746.6 3807.9 -1860.3   3720.6 11.108  0
```

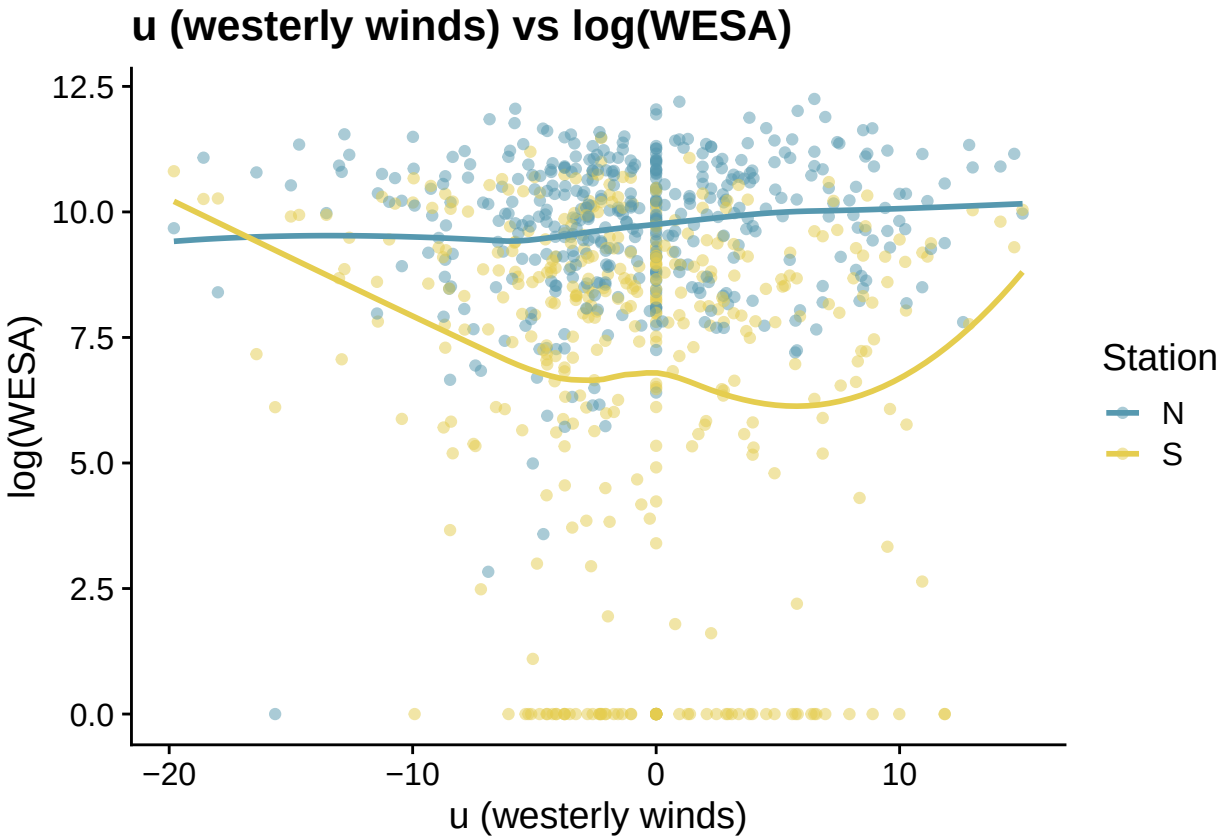
5 Final WESA model

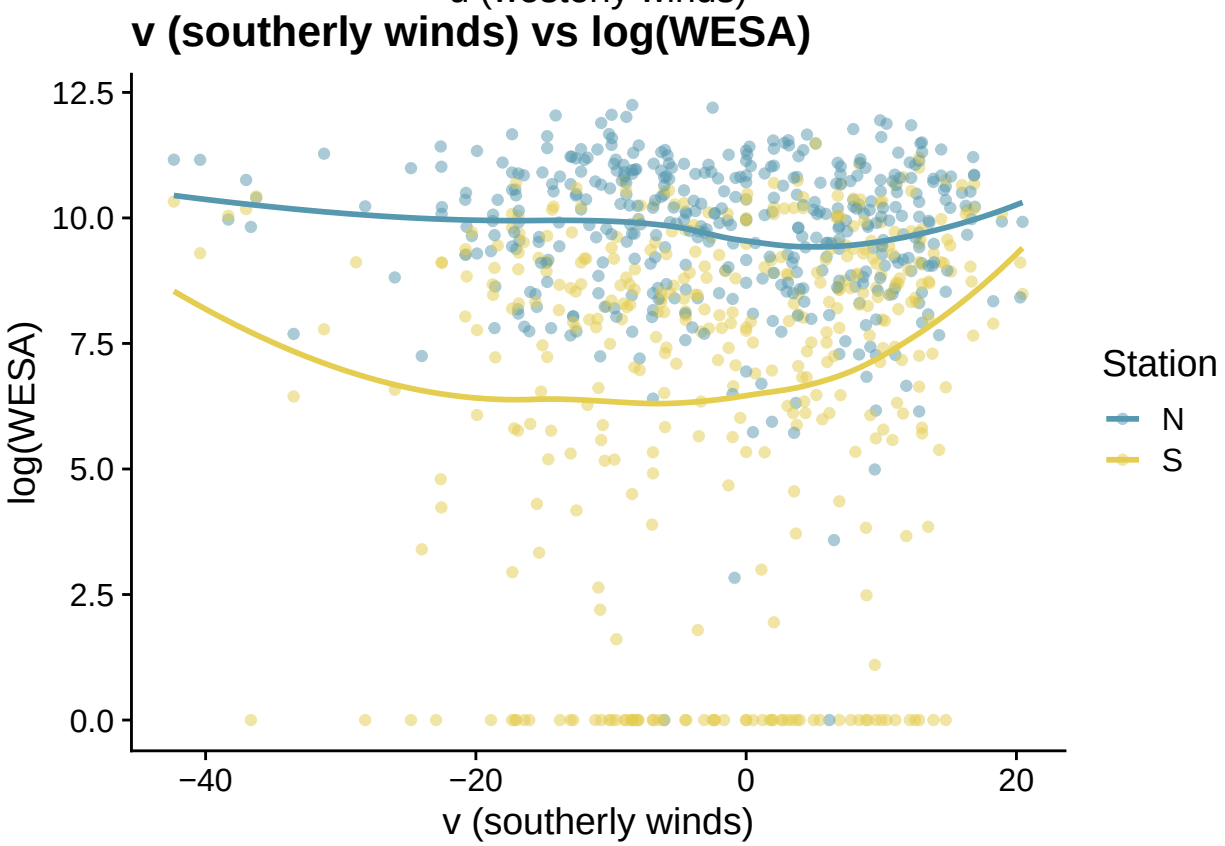
5.1 WESA vs. variable plots

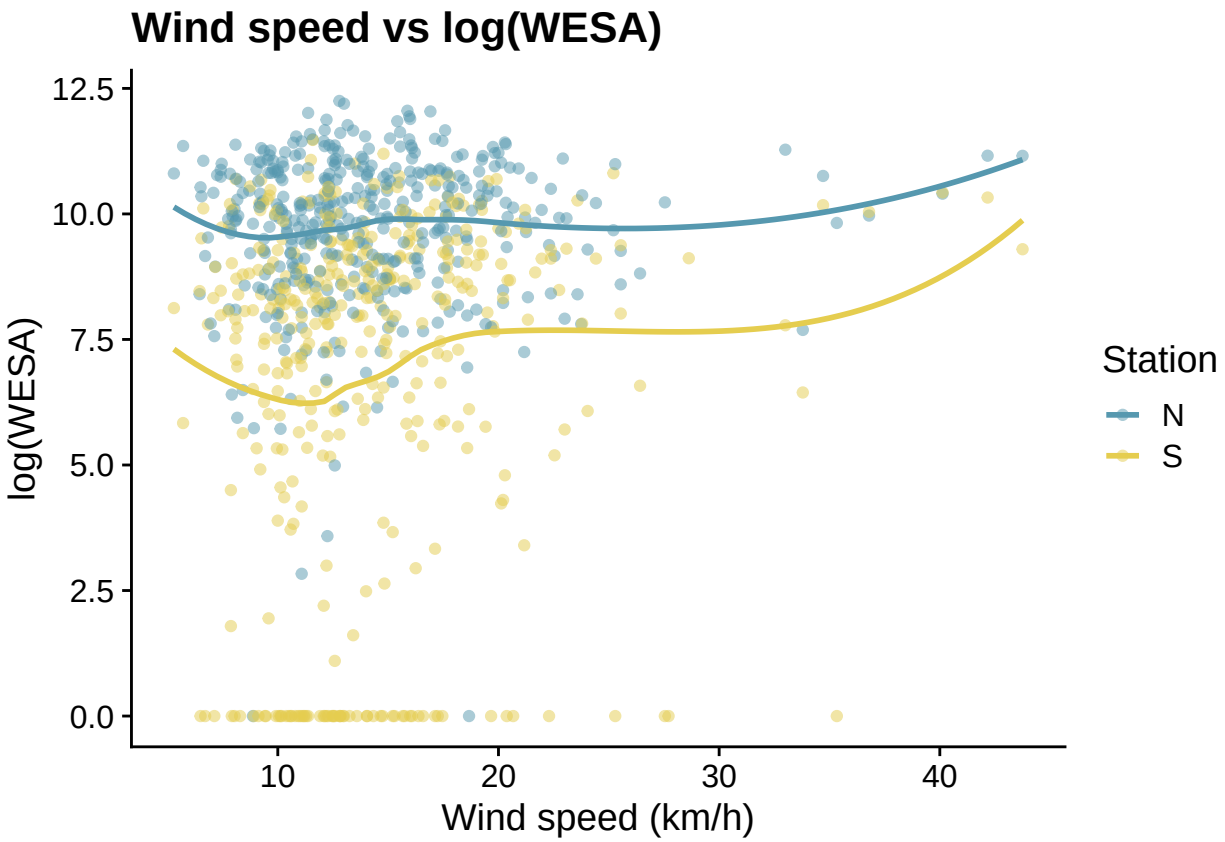


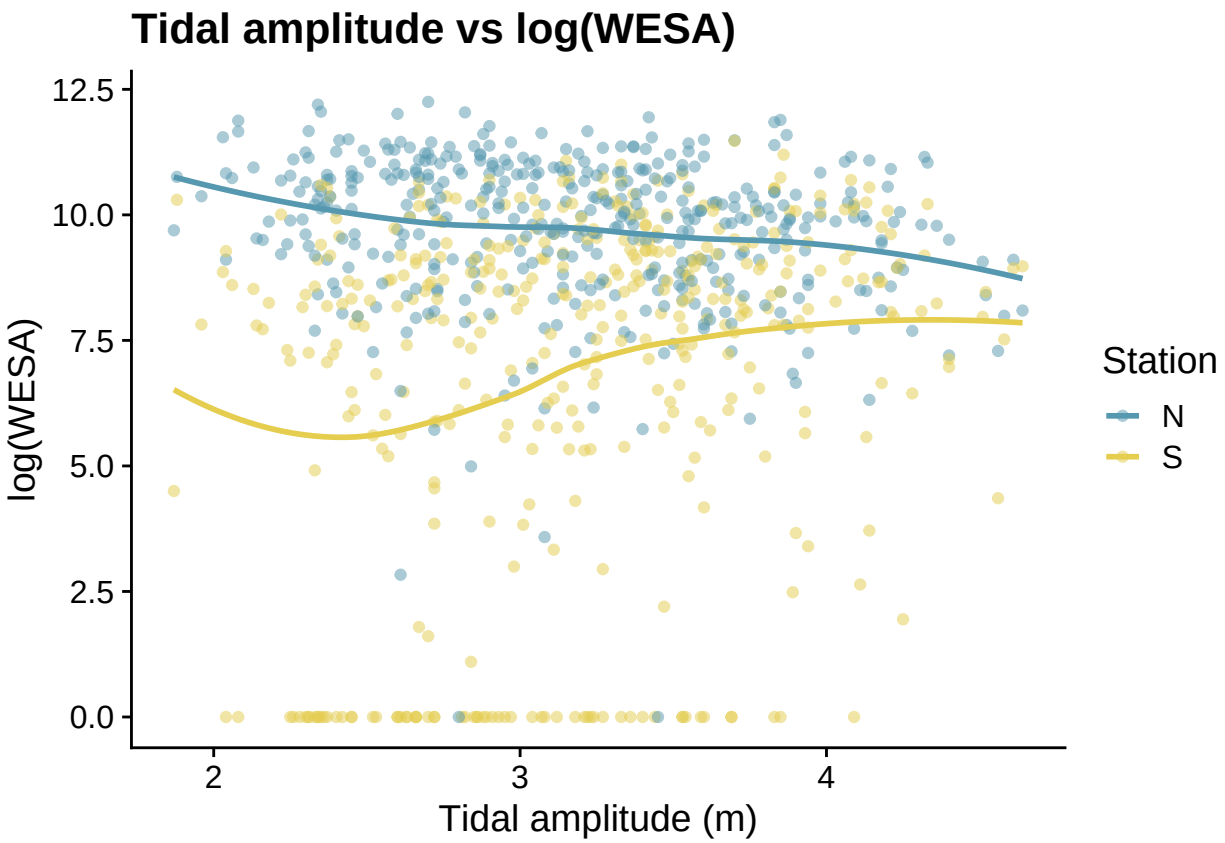

Day of Season vs log(WESA)
log(WESA)
12.5
10.0
7.5
5.0
2.5
0.0
−2
−1
0
1
2
DOS
Station
N
S


Flow vs log(WESA)
log(WESA)
12.5
10.0
7.5
5.0
2.5
0.0
2000
4000
6000
8000
Flow
Station
N
S


u (westerly winds) vs log(WESA)
log(WESA)
12.5
10.0
7.5
5.0
2.5
0.0
−20
−10
0
10
u (westerly winds)
Station
N
S


v (southerly winds) vs log(WESA)
log(WESA)
12.5
10.0
7.5
5.0
2.5
0.0
−40
−20
0
20
v (southerly winds)
Station
N
S


Wind speed vs log(WESA)
log(WESA)
12.5
10.0
7.5
5.0
2.5
0.0
10
20
30
40
Wind speed (km/h)
Station
N
S


Tidal amplitude vs log(WESA)
log(WESA)
12.5
10.0
7.5
5.0
2.5
0.0
2
3
4
Tidal amplitude (m)
Station
N
S

5.2 WESA model

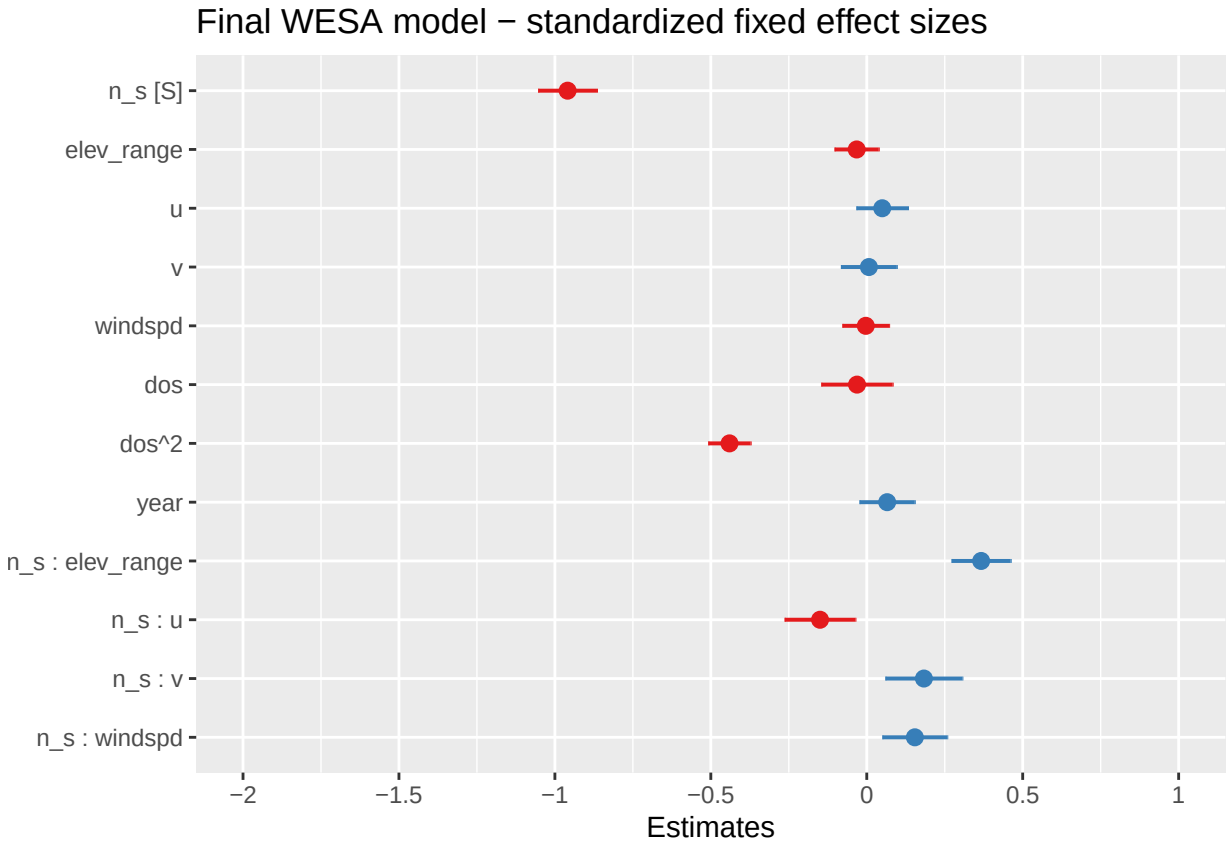
5.2.1 Full model

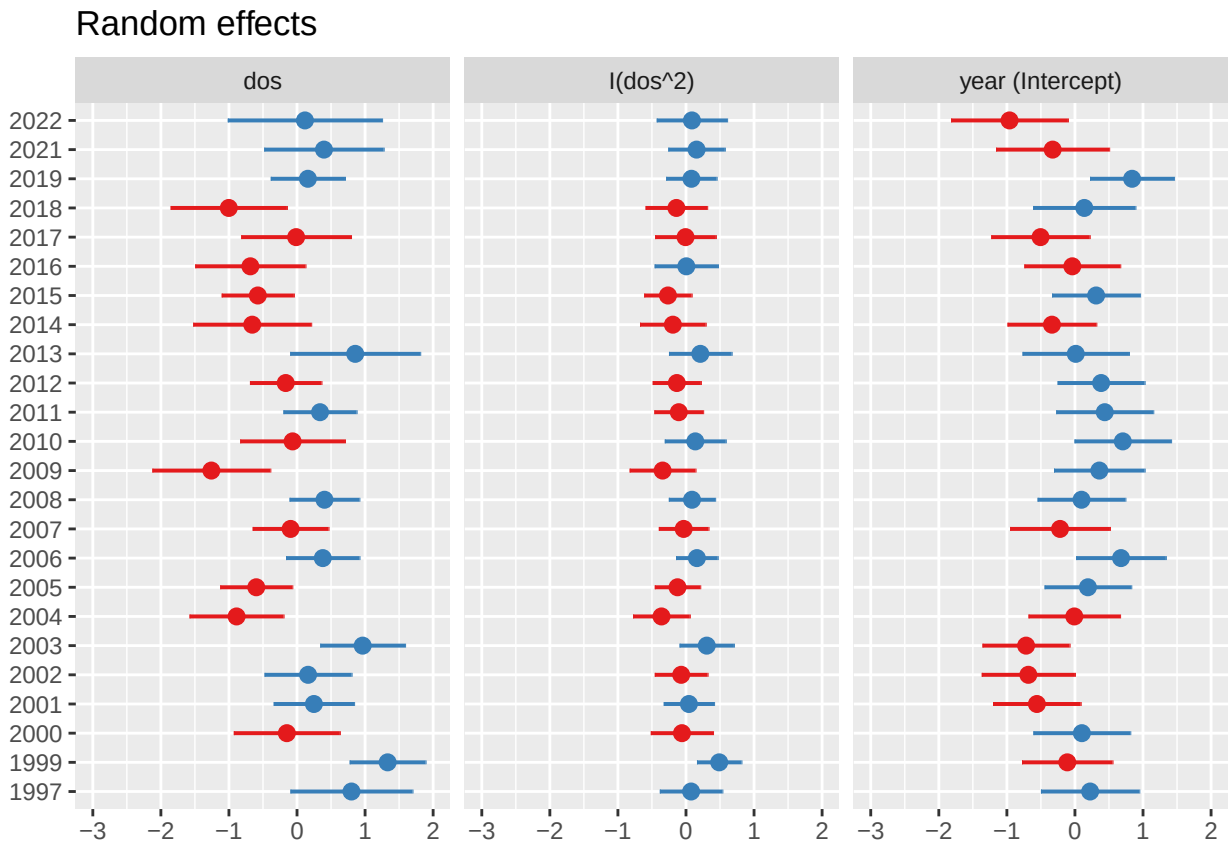
```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## "log_wesa ~ n_s*scale(flow) + n_s*scale(elev_range) + n_s*scale(u) + n_s*scale(v) + n_s*scale(windsp
##    Data: dat3
##
## REML criterion at convergence: 3645.9
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.2143 -0.2964  0.1061  0.5668  2.1699
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.40916  0.6397
##           dos         0.56288  0.7503   -0.19
##           I(dos^2)    0.05842  0.2417   -0.28  0.72
##  Residual             4.38790  2.0947
## Number of obs: 823, groups:  year, 24
##
## Fixed effects:
##                          Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)             10.930360   0.184098  25.276326  59.372  < 2e-16 ***
## n_sS                    -2.927783   0.146196 738.629067 -20.026  < 2e-16 ***
## scale(flow)             -0.231610   0.162326  89.064901  -1.427  0.15713
## scale(elev_range)       -0.105303   0.109812 662.018332  -0.959  0.33794
## scale(u)                 0.154439   0.128462 774.260380   1.202  0.22965
## scale(v)                 0.031740   0.139251 779.094862   0.228  0.81976
## scale(windspd)          -0.007841   0.116143 775.508353  -0.068  0.94619
## dos                      0.080552   0.198923  28.285788   0.405  0.68857
## I(dos^2)                -1.368286   0.100038  15.304719 -13.678 5.45e-10 ***
## year_c                   0.184449   0.143744  19.459908   1.283  0.21450
## n_sS:scale(flow)        -0.084143   0.147250 738.058295  -0.571  0.56788
## n_sS:scale(elev_range)   1.119289   0.147184 738.188463   7.605 8.70e-14 ***
## n_sS:scale(u)           -0.466105   0.177009 737.799263  -2.633  0.00863 **
## n_sS:scale(v)            0.552910   0.191881 738.403236   2.882  0.00407 **
## n_sS:scale(windspd)      0.462816   0.161862 739.870872   2.859  0.00436 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

5.2.2 Backwards stepwise selection

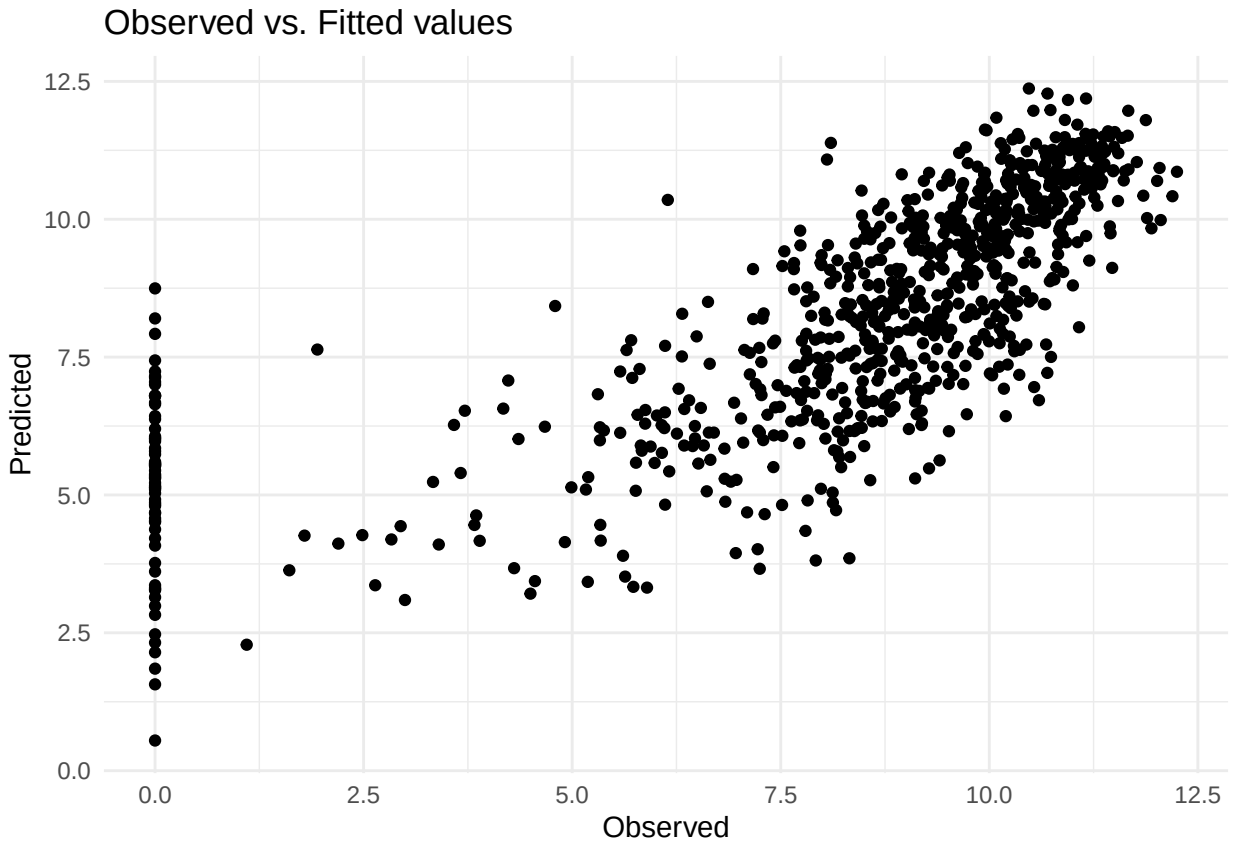
```
## Backward reduced random-effect table:
##
##                                    Eliminated npar  logLik    AIC    LRT Df
## <none>                                         22 -1823.0 3689.9
## dos in (dos + I(dos^2) | year)              0   19 -1838.9 3715.8 31.822  3
## I(dos^2) in (dos + I(dos^2) | year)         0   19 -1824.8 3687.5  3.601  3
##                                    Pr(>Chisq)
```

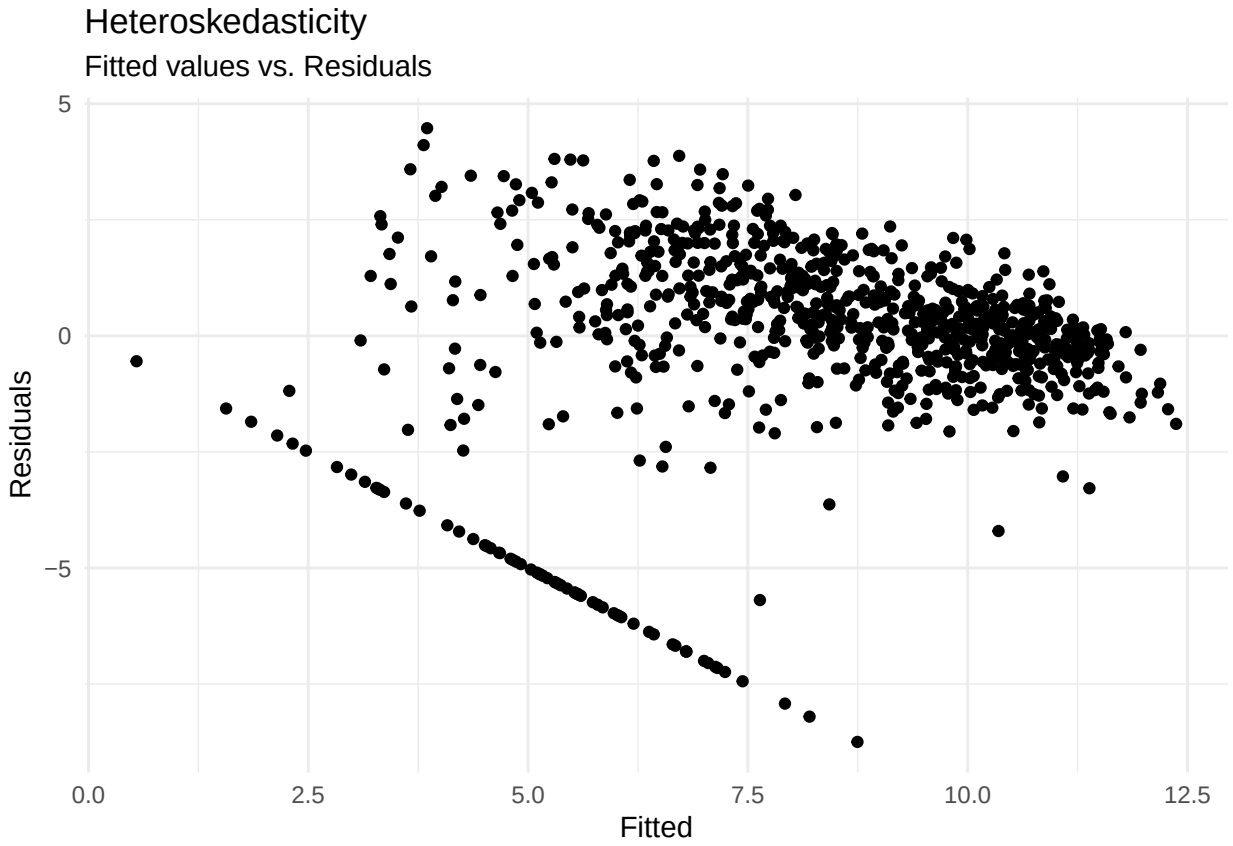
```
## <none>
## dos in (dos + I(dos^2) | year)       5.705e-07 ***
## I(dos^2) in (dos + I(dos^2) | year)     0.3079
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Backward reduced fixed-effect table:
## Degrees of freedom method: Satterthwaite
##
##                       Eliminated Sum Sq Mean Sq NumDF  DenDF  F value    Pr(>F)
## n_s:scale(flow)                1   1.43    1.43     1 738.06   0.3265  0.567881
## scale(flow)                    2  15.43   15.43     1  58.31   3.5200  0.065641
## dos                            0   1.32    1.32     1  19.60   0.3005  0.589751
## I(dos^2)                       0 710.84  710.84     1  15.56 161.7215 1.249e-09
## year_c                         0   9.24    9.24     1  21.40   2.1023  0.161573
## n_s:scale(elev_range)          0 253.55  253.55     1 738.71  57.6849 9.317e-14
## n_s:scale(u)                   0  29.50   29.50     1 738.12   6.7111  0.009771
## n_s:scale(v)                   0  37.36   37.36     1 738.82   8.4998  0.003659
## n_s:scale(windspd)             0  37.22   37.22     1 740.19   8.4682  0.003722
##
## n_s:scale(flow)
## scale(flow)           .
## dos
## I(dos^2)              ***
## year_c
## n_s:scale(elev_range) ***
## n_s:scale(u)          **
## n_s:scale(v)          **
## n_s:scale(windspd)    **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Model found:
## log_wesa ~ n_s + scale(elev_range) + scale(u) + scale(v) + scale(windspd) + dos + I(dos^2) + year_c +
```

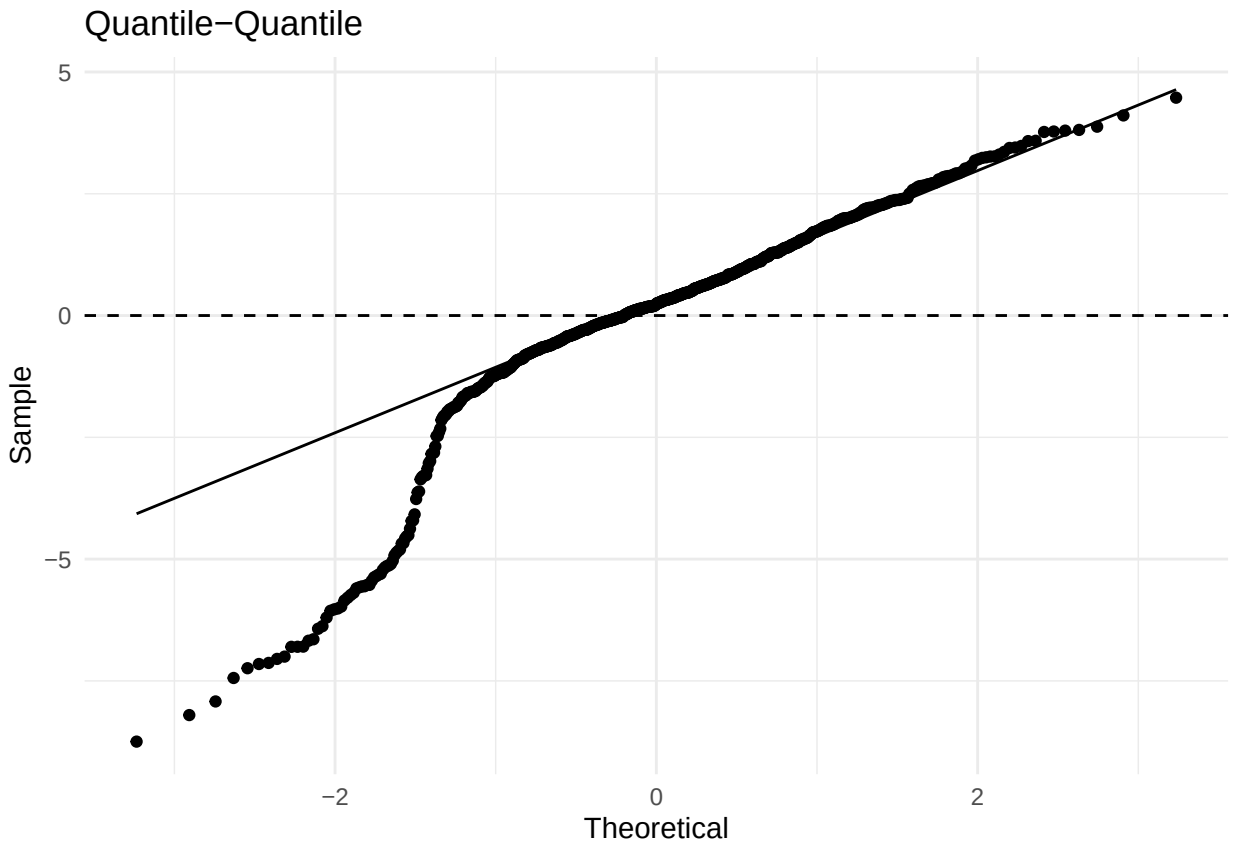

Final WESA model − standardized fixed effect sizes
n_s [S]
elev_range
u
v
windspd
dos
dos^2
year
n_s : elev_range
n_s : u
n_s : v
n_s : windspd
−2
−1.5
−1
−0.5
0
0.5
1
Estimates

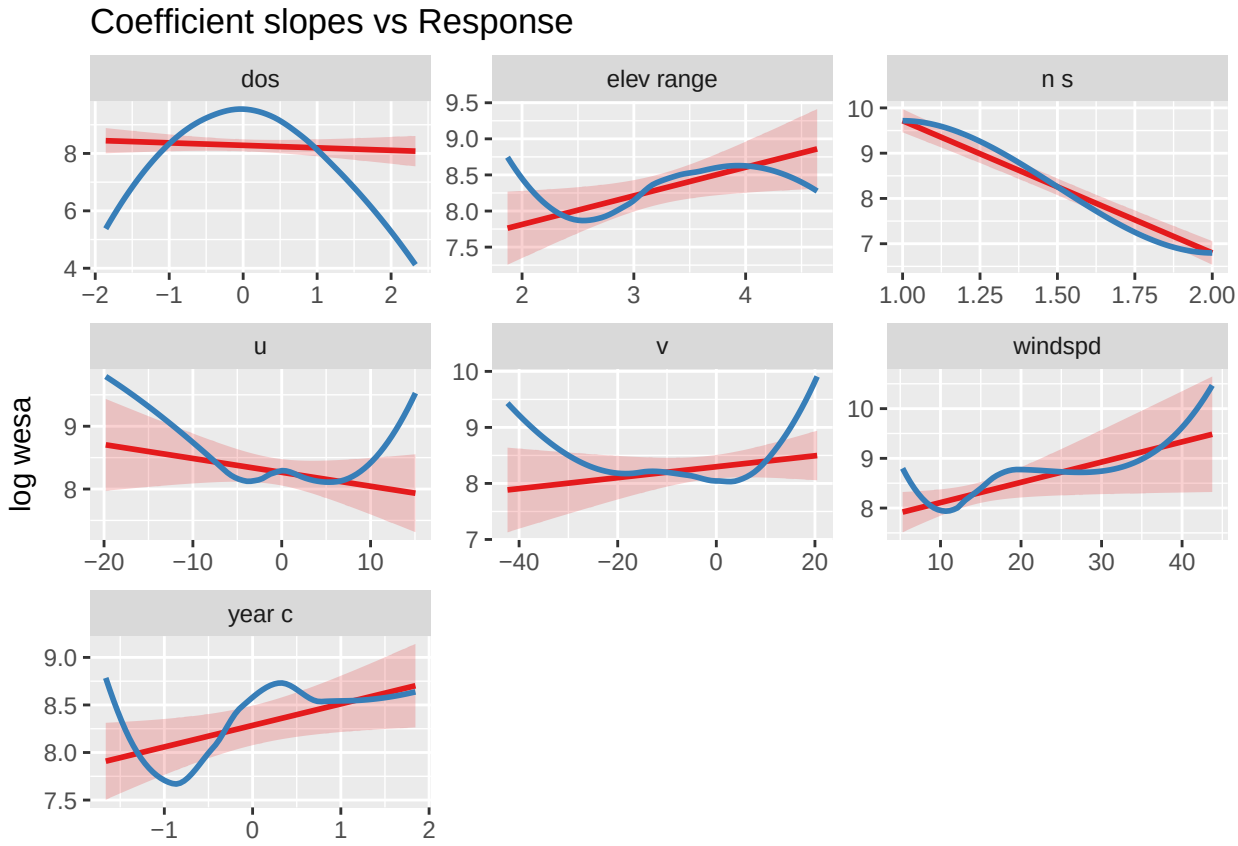

Random effects
dos
I(dos^2)
year (Intercept)
2022
2021
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1997
−3
−2
−1
0
1
2

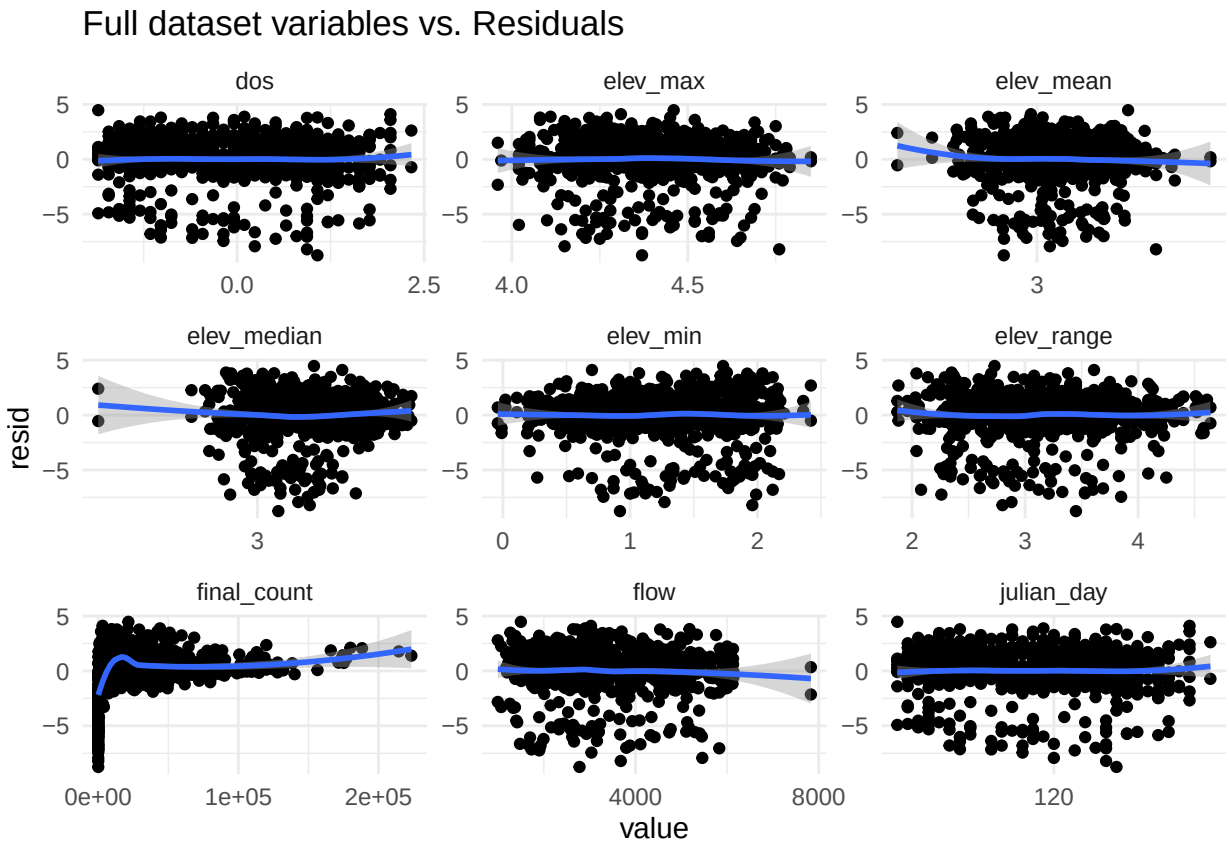
5.3 Final model diagnostics

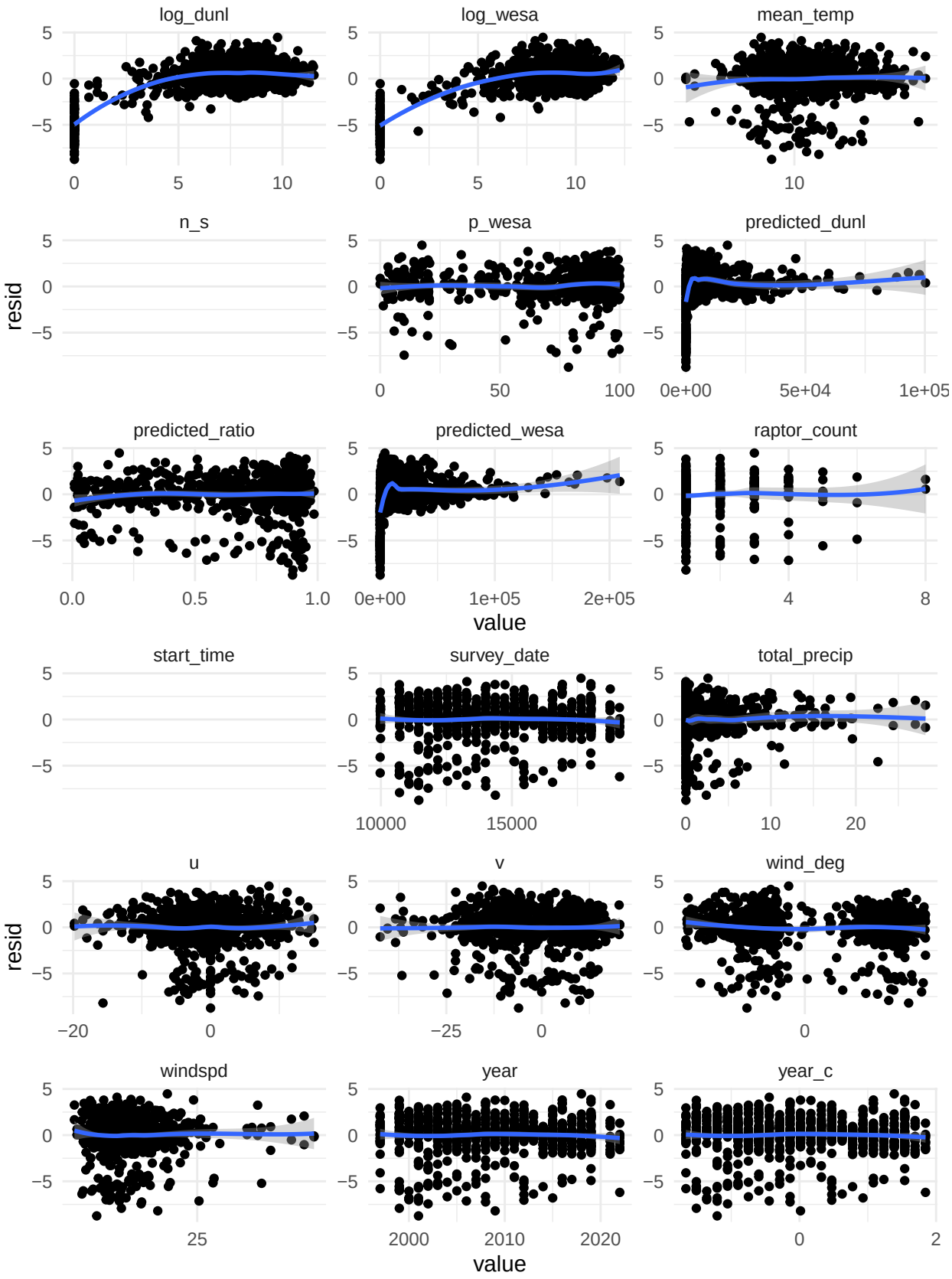



Heteroskedasticity
Fitted values vs. Residuals
Residuals
Fitted
5
0
−5
0.0
2.5
5.0
7.5
10.0
12.5


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

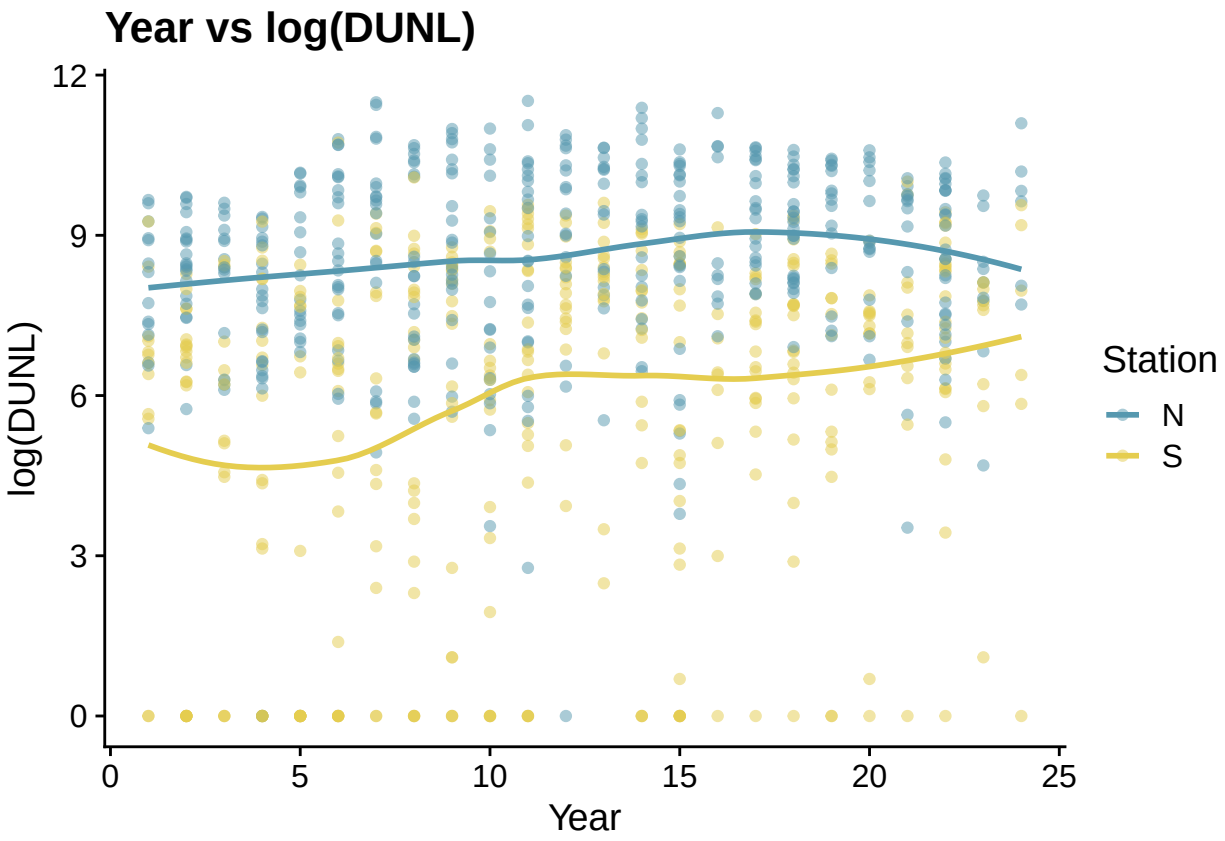

Coefficient slopes vs Response
dos
elev range
n s
u
v
windspd
year c
log wesa

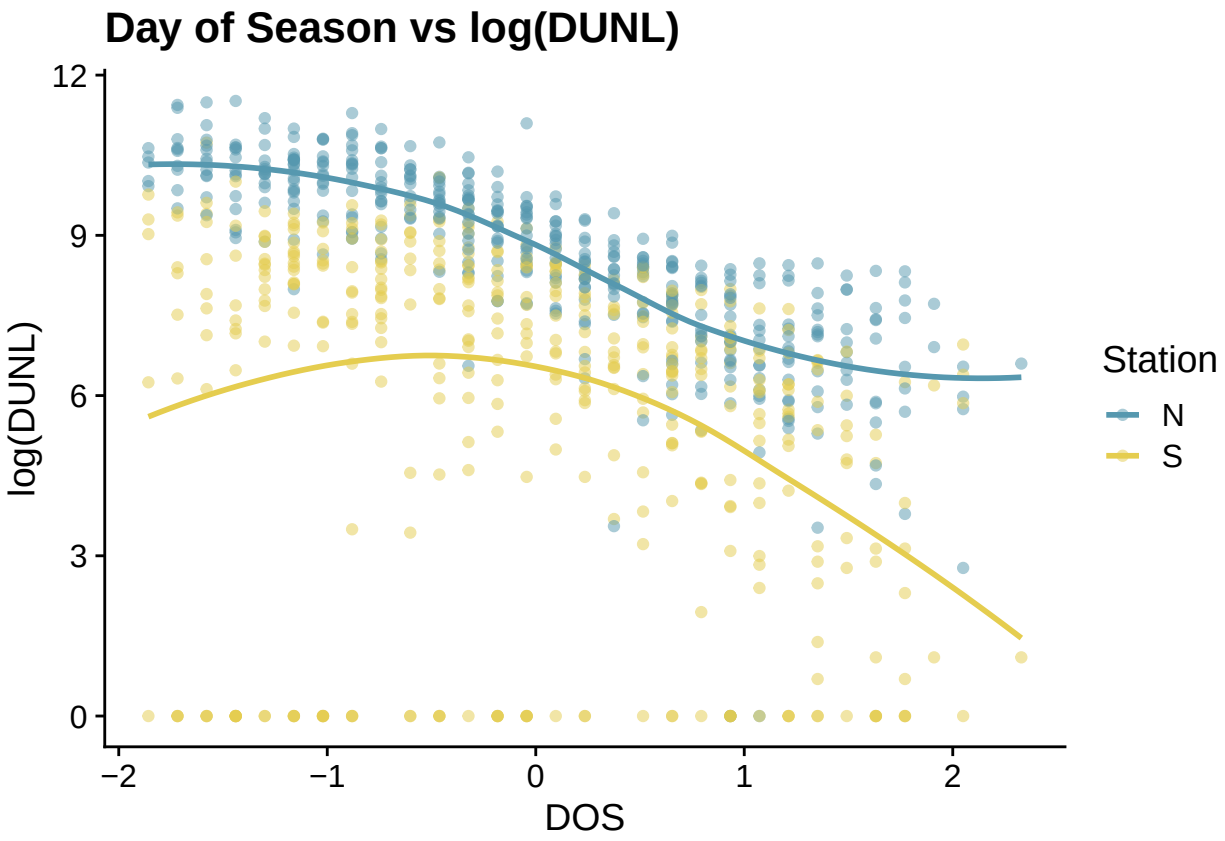

Full dataset variables vs. Residuals
dos
elev_max
elev_mean
elev_median
elev_min
elev_range
final_count
flow
julian_day
resid
value

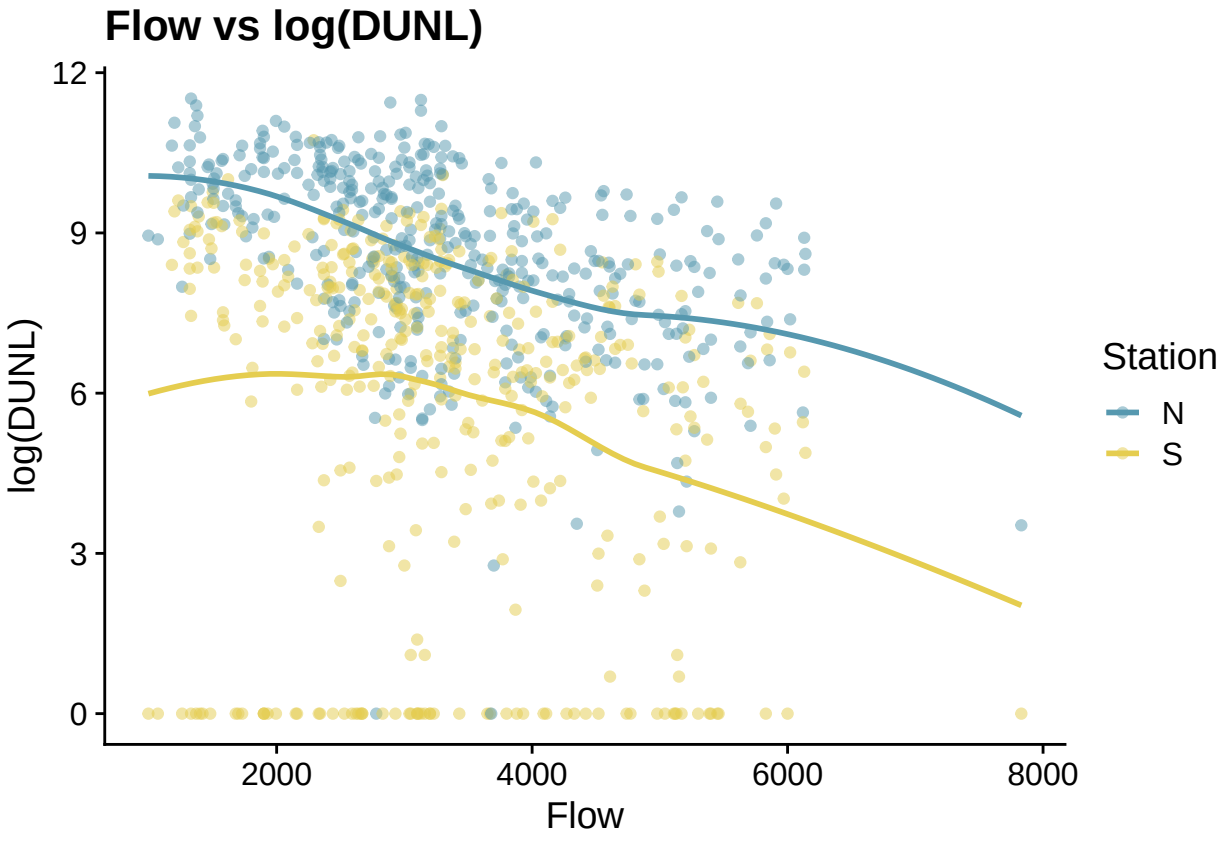

log_dunl
log_wesa
mean_temp
n_s
p_wesa
predicted_dunl
predicted_ratio
predicted_wesa
raptor_count
start_time
survey_date
total_precip
u
v
wind_deg
windspd
year
year_c
resid
value

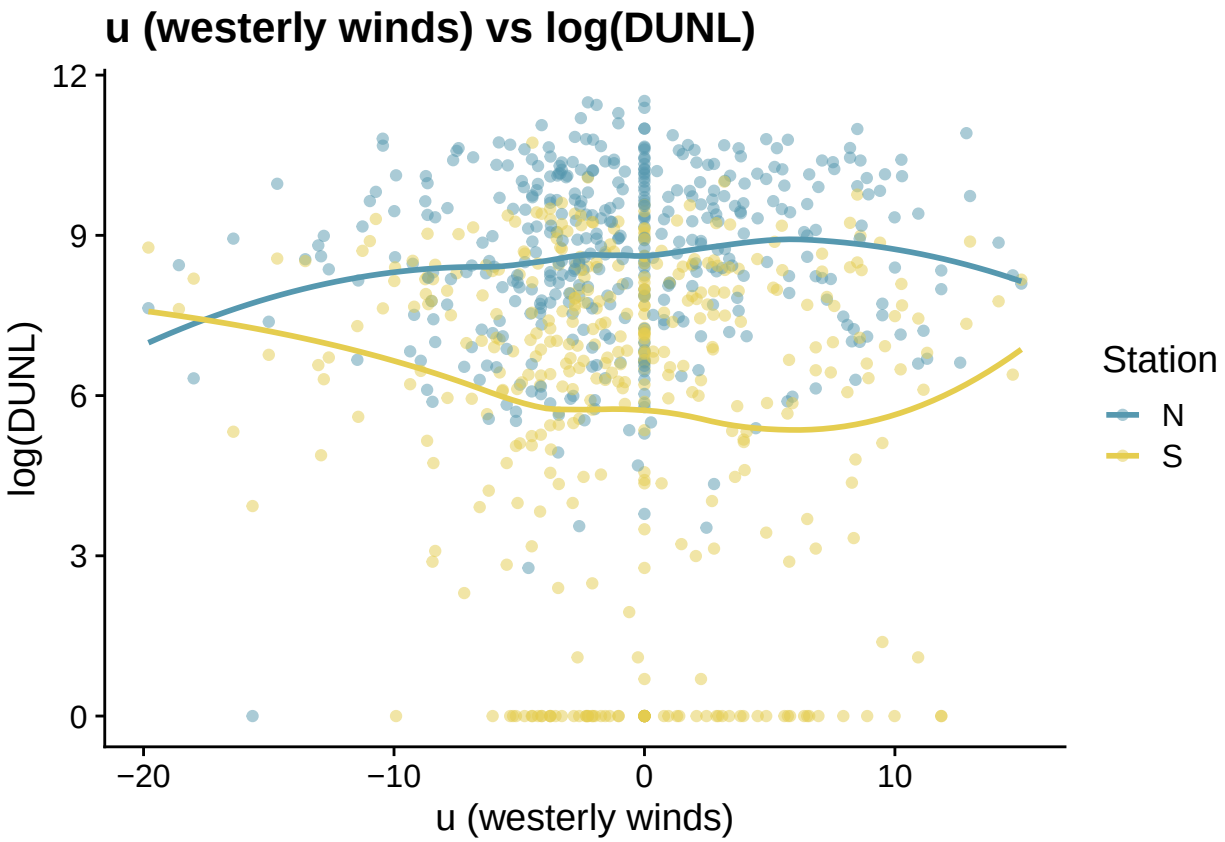
6 Final DUNL model

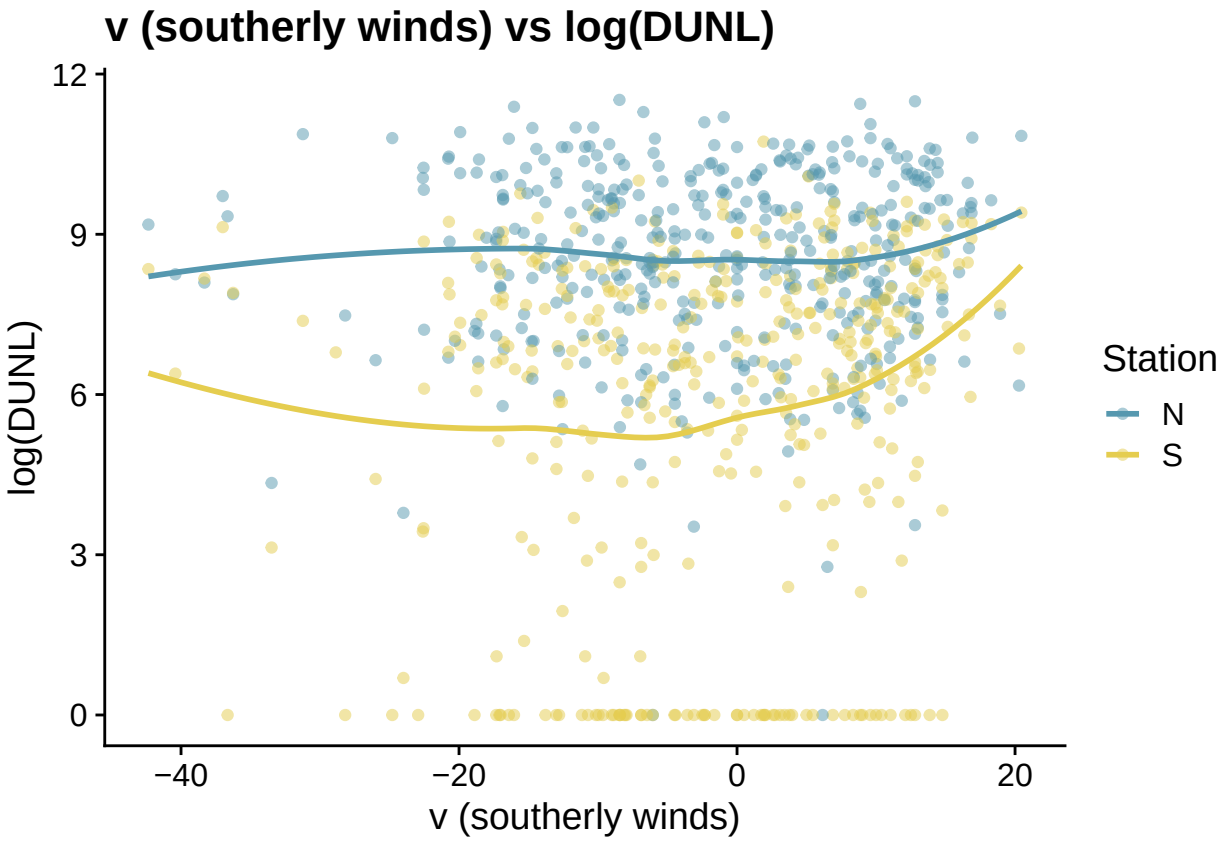
6.1 DUNL vs. variable plots

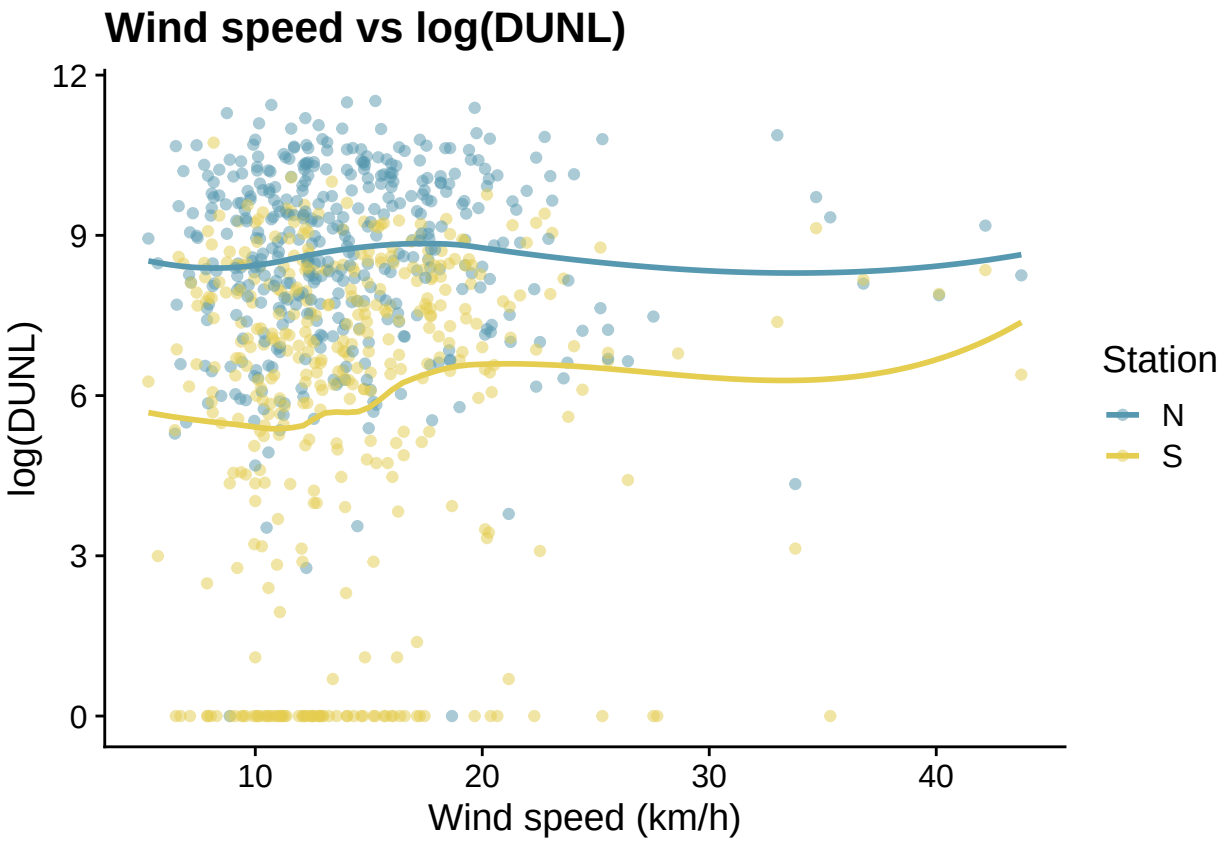


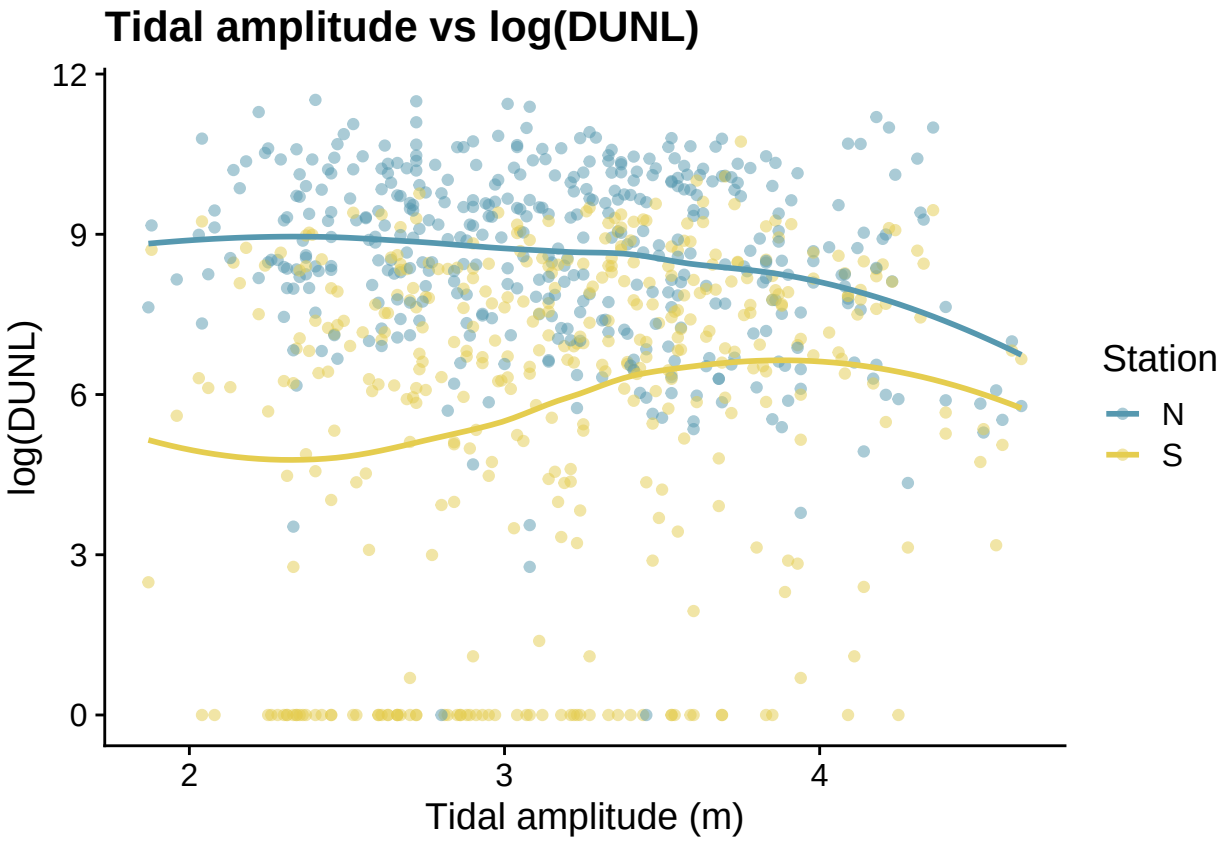

Day of Season vs log(DUNL)
log(DUNL)
12
9
6
3
0
−2
−1
0
1
2
DOS
Station
N
S


Flow vs log(DUNL)
log(DUNL)
12
9
6
3
0
2000
4000
6000
8000
Flow
Station
N
S


u (westerly winds) vs log(DUNL)
log(DUNL)
12
9
6
3
0
−20
−10
0
10
u (westerly winds)
Station
N
S


v (southerly winds) vs log(DUNL)
log(DUNL)
12
9
6
3
0
−40
−20
0
20
v (southerly winds)
Station
N
S


Wind speed vs log(DUNL)
log(DUNL)
12
9
6
3
0
10
20
30
40
Wind speed (km/h)
Station
N
S


Tidal amplitude vs log(DUNL)
log(DUNL)
12
9
6
3
0
2
3
4
Tidal amplitude (m)
Station
N
S

6.2 DUNL model

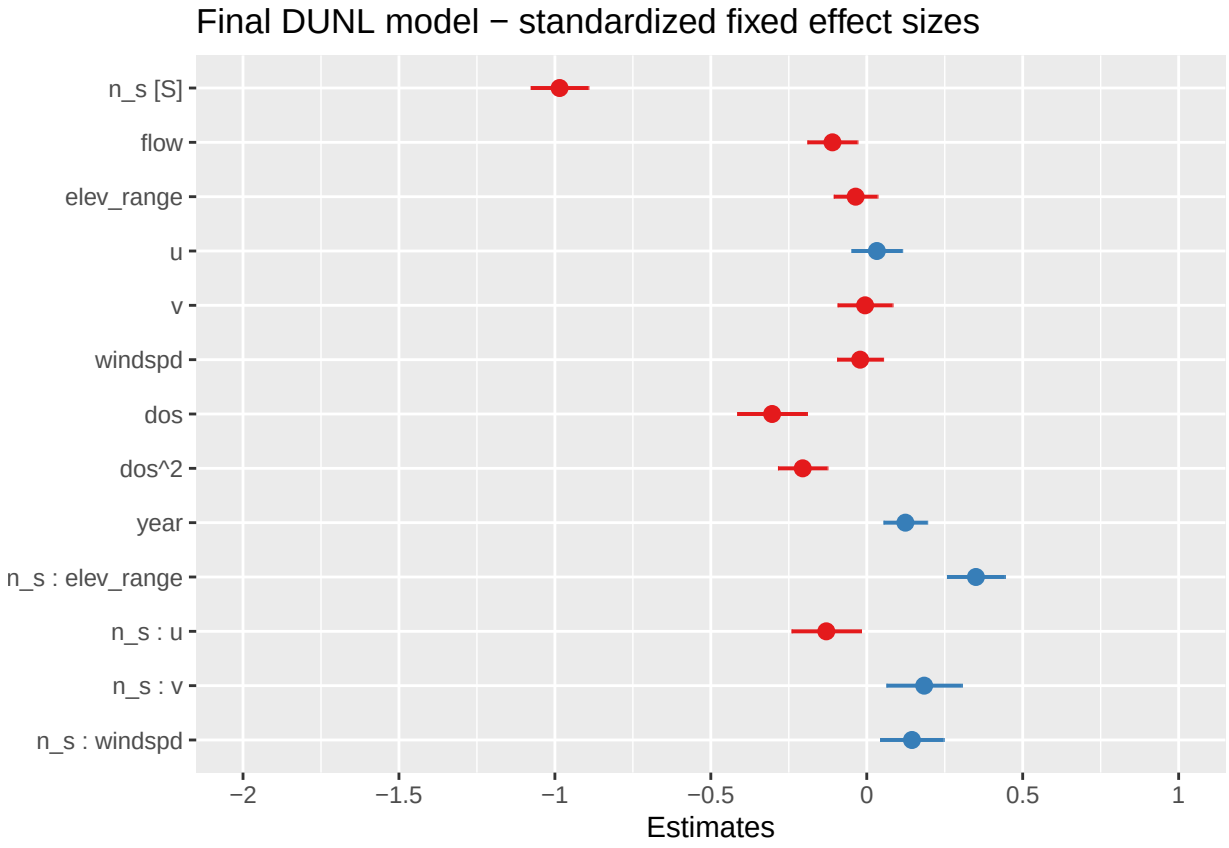
6.2.1 Full model

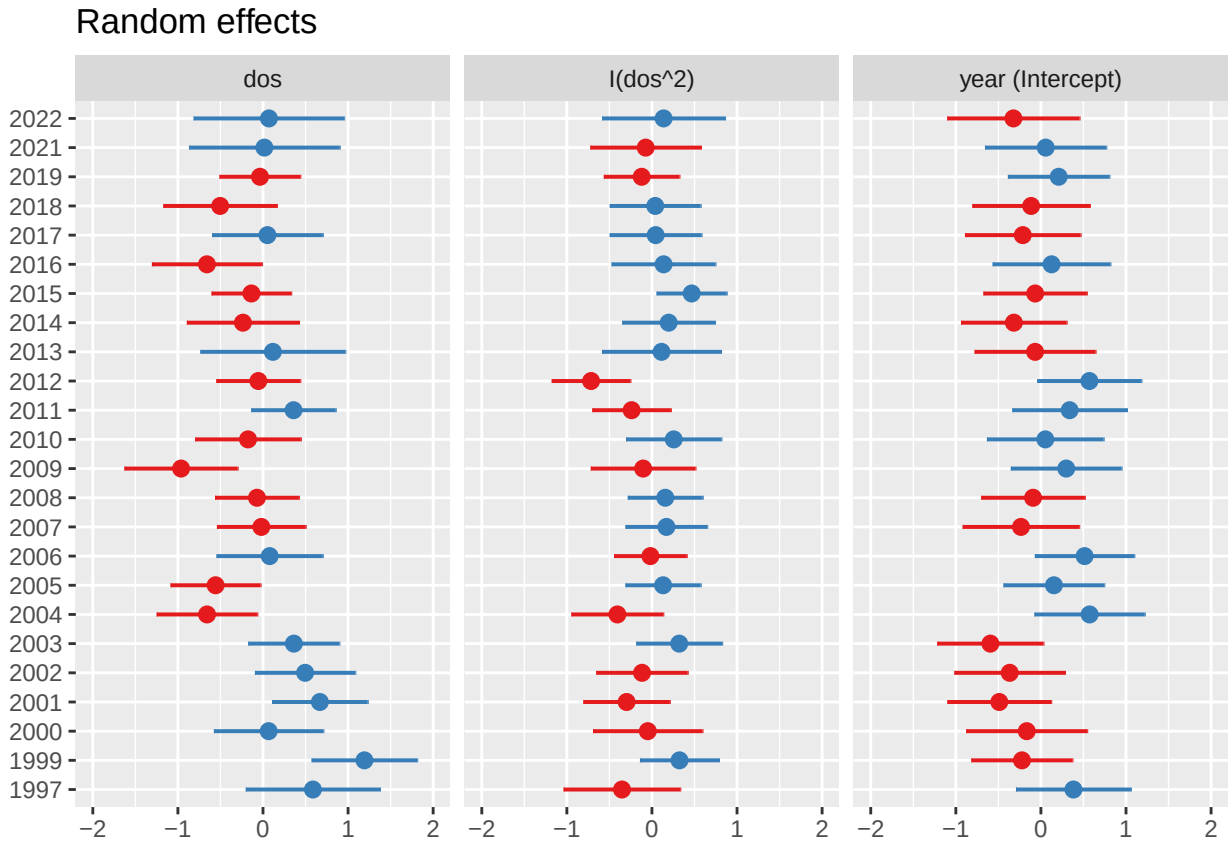
```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## "log_dunl ~ n_s*scale(flow) + n_s*scale(elev_range) + n_s*scale(u) + n_s*scale(v) + n_s*scale(windsp
##    Data: dat3
##
## REML criterion at convergence: 3503.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.7595 -0.3217  0.1066  0.5931  2.2032
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.2260   0.4754
##           dos         0.3355   0.5792   -0.27
##           I(dos^2)    0.1507   0.3882   -0.61  0.02
##  Residual             3.7019   1.9240
## Number of obs: 823, groups:  year, 24
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)              9.08764    0.15393  32.69644  59.038  < 2e-16 ***
## n_sS                    -2.81293    0.13428 745.29435 -20.948  < 2e-16 ***
## scale(flow)             -0.36901    0.13394  79.76843  -2.755  0.00727 **
## scale(elev_range)       -0.10177    0.10194 782.04887  -0.998  0.31843
## scale(u)                 0.08623    0.11838 792.08268   0.728  0.46658
## scale(v)                -0.02025    0.12817 789.79617  -0.158  0.87451
## scale(windspd)          -0.06444    0.10709 790.99022  -0.602  0.54754
## dos                     -0.86746    0.16245  27.76925  -5.340 1.12e-05 ***
## I(dos^2)                -0.58502    0.11516  21.06177  -5.080 4.92e-05 ***
## year_c                   0.35374    0.10197  23.75414   3.469  0.00201 **
## n_sS:scale(flow)         0.11244    0.13523 745.03029   0.831  0.40598
## n_sS:scale(elev_range)   0.99966    0.13518 745.23157   7.395 3.81e-13 ***
## n_sS:scale(u)           -0.35775    0.16259 744.25827  -2.200  0.02809 *
## n_sS:scale(v)            0.53410    0.17627 744.67632   3.030  0.00253 **
## n_sS:scale(windspd)      0.42252    0.14870 745.67061   2.841  0.00461 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

6.2.2 Backwards stepwise selection

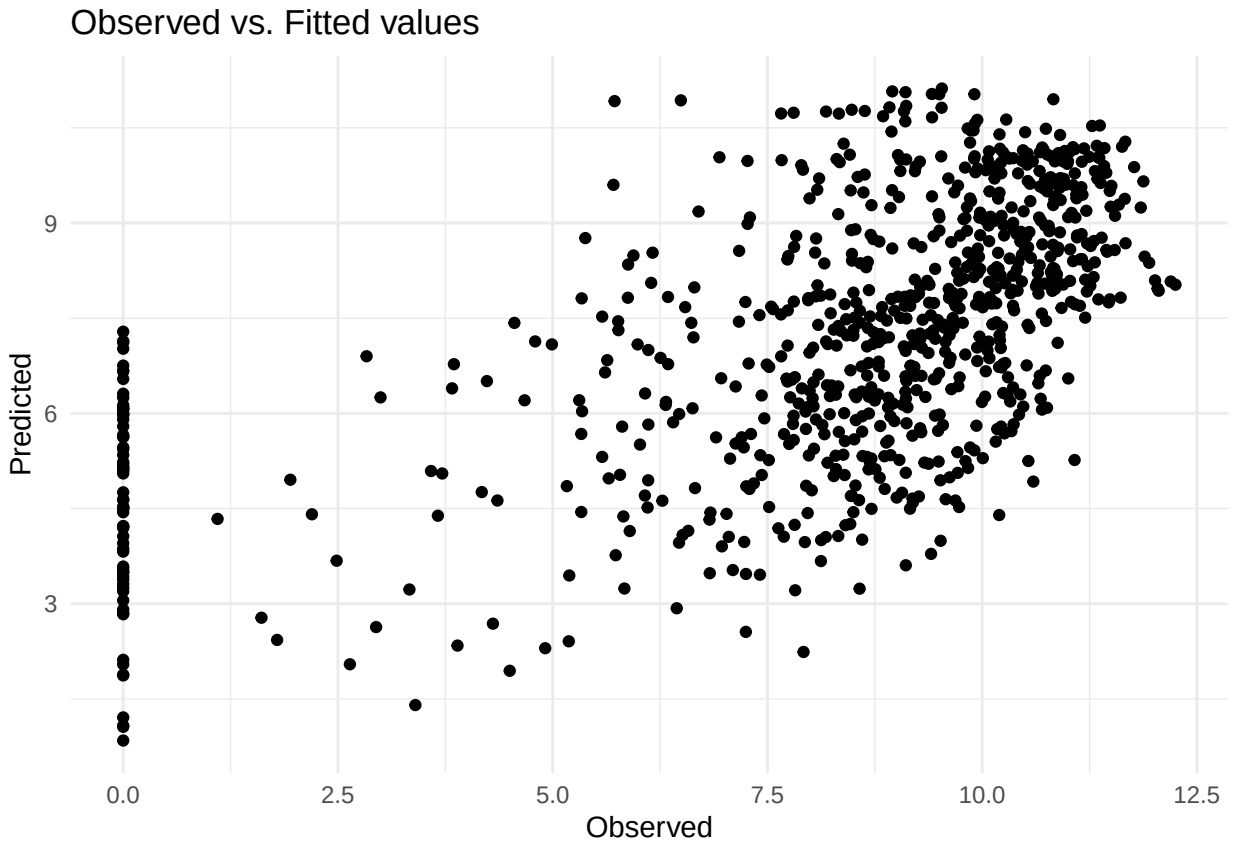
```
## Backward reduced random-effect table:
##
##                                    Eliminated npar  logLik    AIC    LRT Df
## <none>                                         22 -1751.7 3547.4
## dos in (dos + I(dos^2) | year)              0   19 -1765.3 3568.7 27.303  3
## I(dos^2) in (dos + I(dos^2) | year)         0   19 -1756.7 3551.4 10.015  3
##                                    Pr(>Chisq)
```

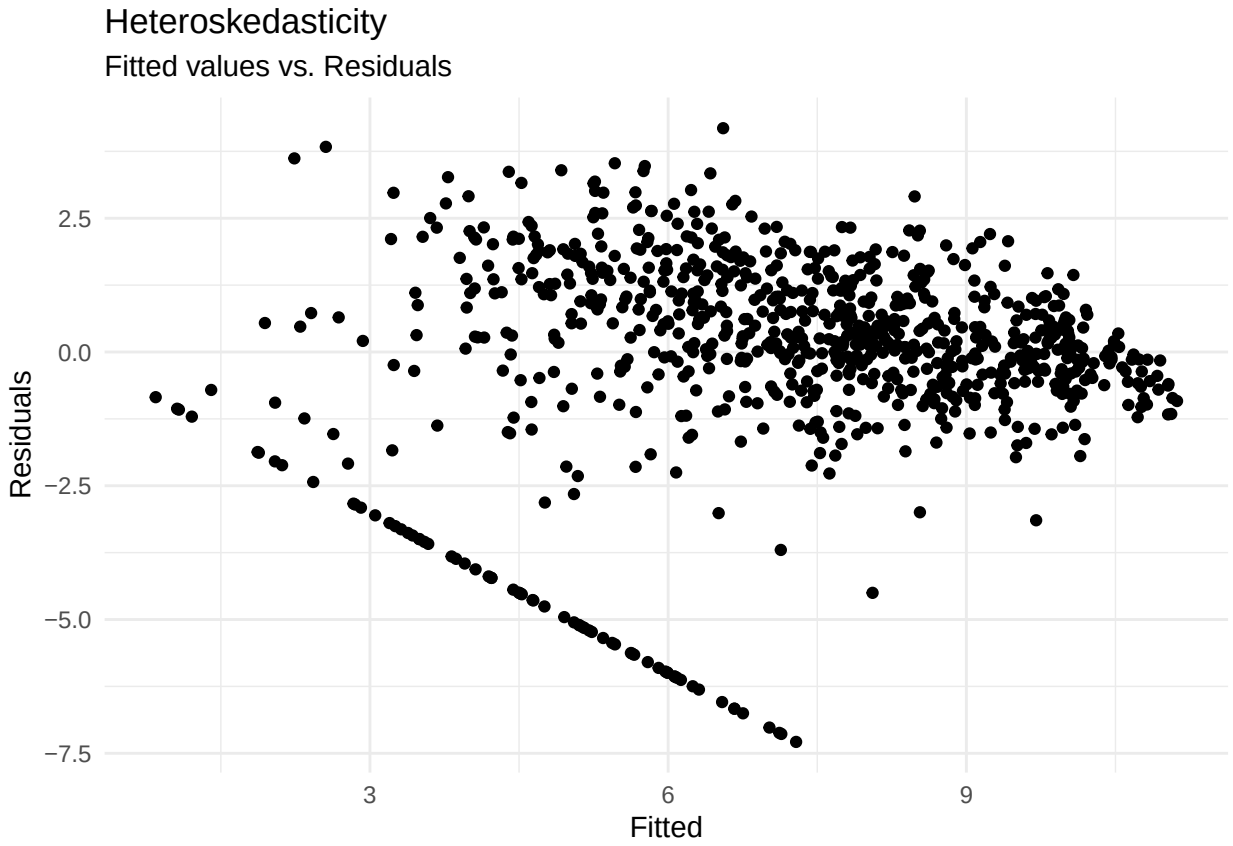
```
## <none>
## dos in (dos + I(dos^2) | year)       5.085e-06 ***
## I(dos^2) in (dos + I(dos^2) | year)    0.01844 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Backward reduced fixed-effect table:
## Degrees of freedom method: Satterthwaite
##
##                       Eliminated  Sum Sq Mean Sq NumDF  DenDF F value    Pr(>F)
## n_s:scale(flow)                1   2.559   2.559     1 745.03  0.6913  0.405978
## scale(flow)                    0  26.903  26.903     1  46.75  7.2703  0.009715
## dos                            0 105.481 105.481     1  27.79 28.5050 1.123e-05
## I(dos^2)                       0  95.648  95.648     1  21.05 25.8477 4.879e-05
## year_c                         0  44.722  44.722     1  23.75 12.0855  0.001974
## n_s:scale(elev_range)          0 202.397 202.397     1 746.23 54.6954 3.791e-13
## n_s:scale(u)                   0  19.401  19.401     1 745.19  5.2429  0.022316
## n_s:scale(v)                   0  33.047  33.047     1 745.67  8.9305  0.002897
## n_s:scale(windspd)             0  28.803  28.803     1 746.67  7.7836  0.005407
##
## n_s:scale(flow)
## scale(flow)           **
## dos                   ***
## I(dos^2)              ***
## year_c                **
## n_s:scale(elev_range) ***
## n_s:scale(u)          *
## n_s:scale(v)          **
## n_s:scale(windspd)    **
## ---
## 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) + scale(v) + scale(windspd) + dos + I(dos
```

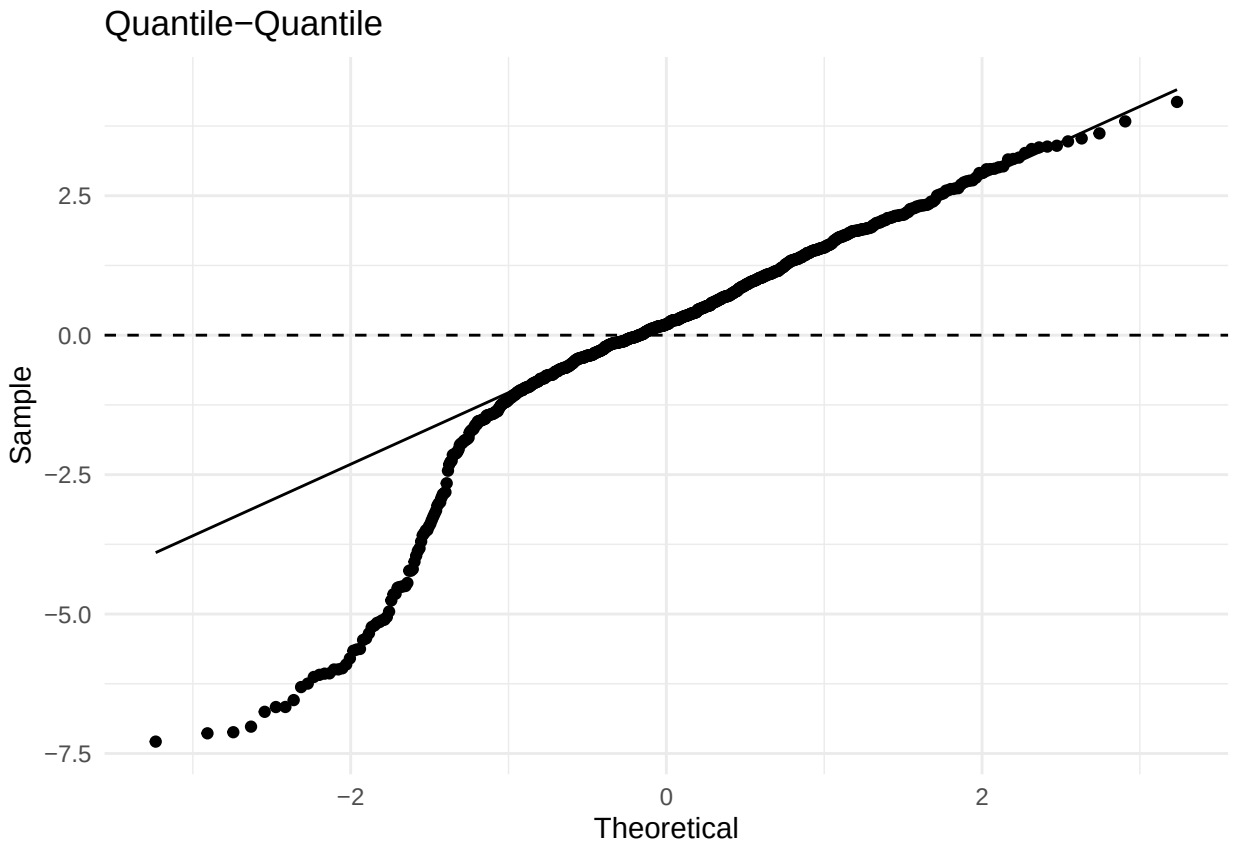

Final DUNL model − standardized fixed effect sizes
n_s [S]
flow
elev_range
u
v
windspd
dos
dos^2
year
n_s : elev_range
n_s : u
n_s : v
n_s : windspd
−2
−1.5
−1
−0.5
0
0.5
1
Estimates

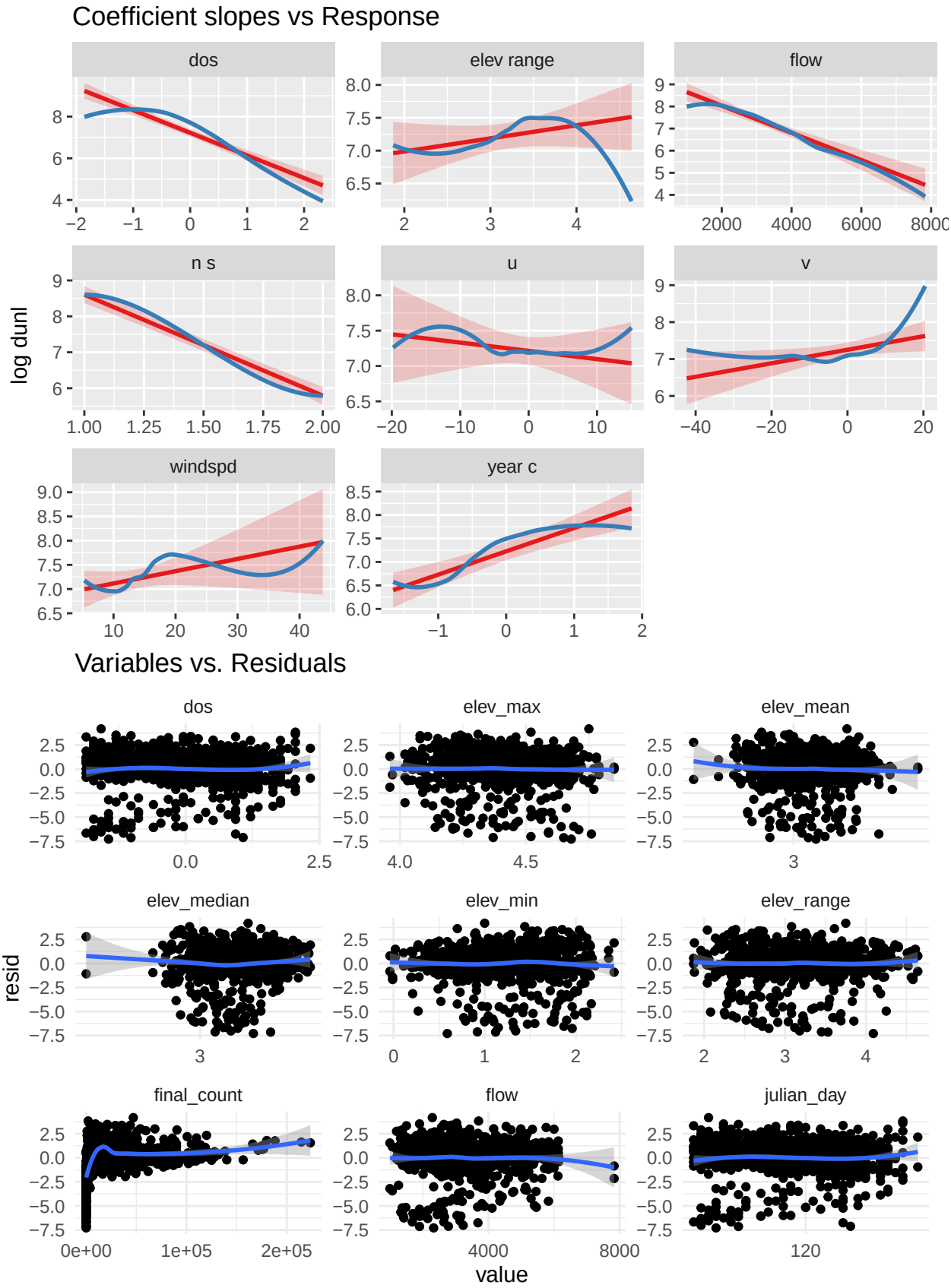

Random effects
dos
I(dos^2)
year (Intercept)
2022
2021
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1997
−2
−1
0
1
2

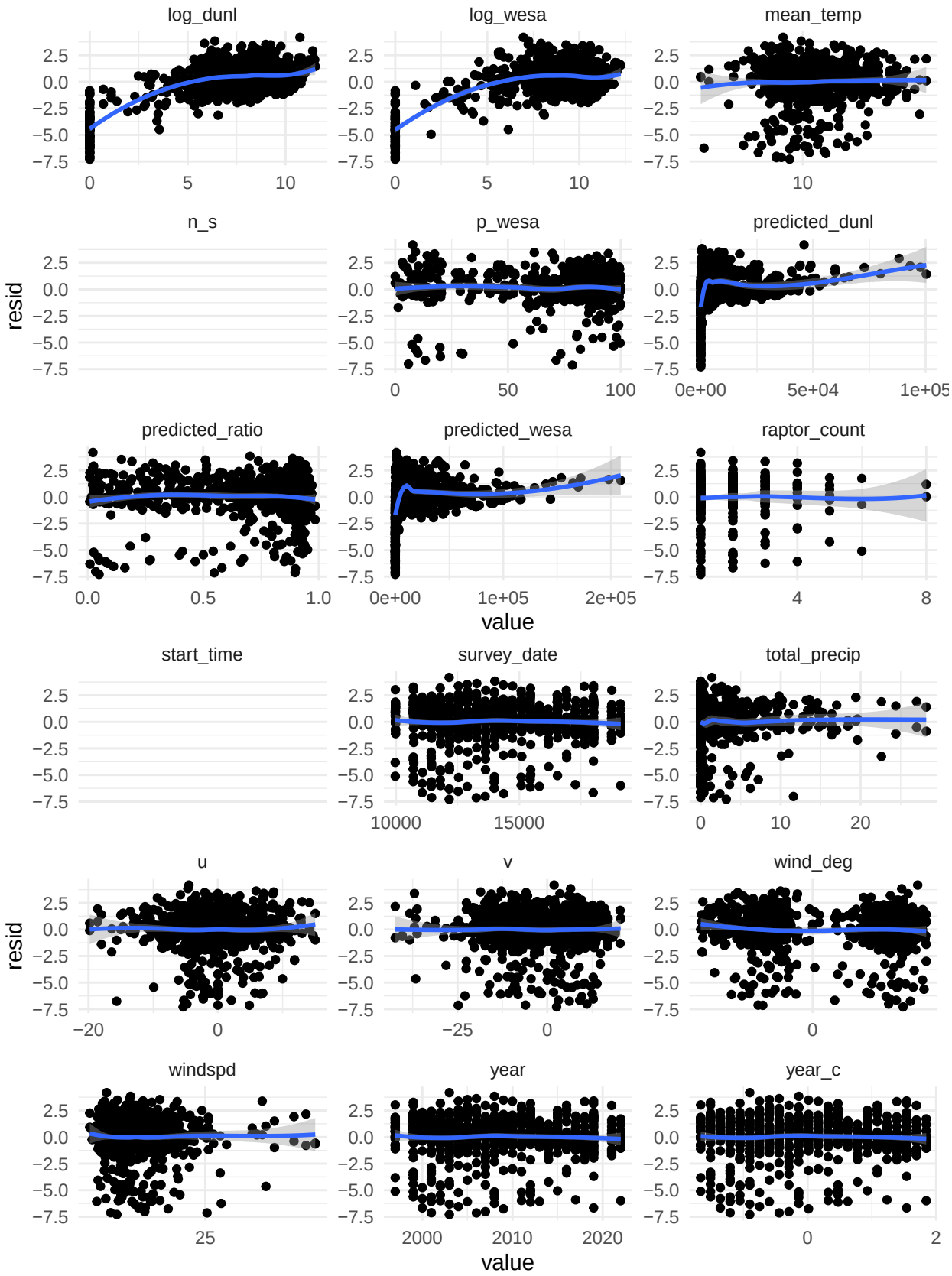
6.3 Final model diagnostics




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


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


Coefficient slopes vs Response
dos
elev range
flow
n s
u
v
windspd
year c
log dunl
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
p_wesa
predicted_dunl
predicted_ratio
predicted_wesa
raptor_count
start_time
survey_date
total_precip
u
v
wind_deg
windspd
year
year_c
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 orginal 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; differences between the original Canham data is that this dataset only goes back to 1994 (rather than 1991) and goes up to 2022 (rather than 2019).

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 Yearly population trend model summaries

The westerly wind vector, `u`, is not significant in either model, deviating from the original Canham paper. As in the original Canham paper, however, `year` remains insignificant in the DUNL model.

7.1.1 WESA

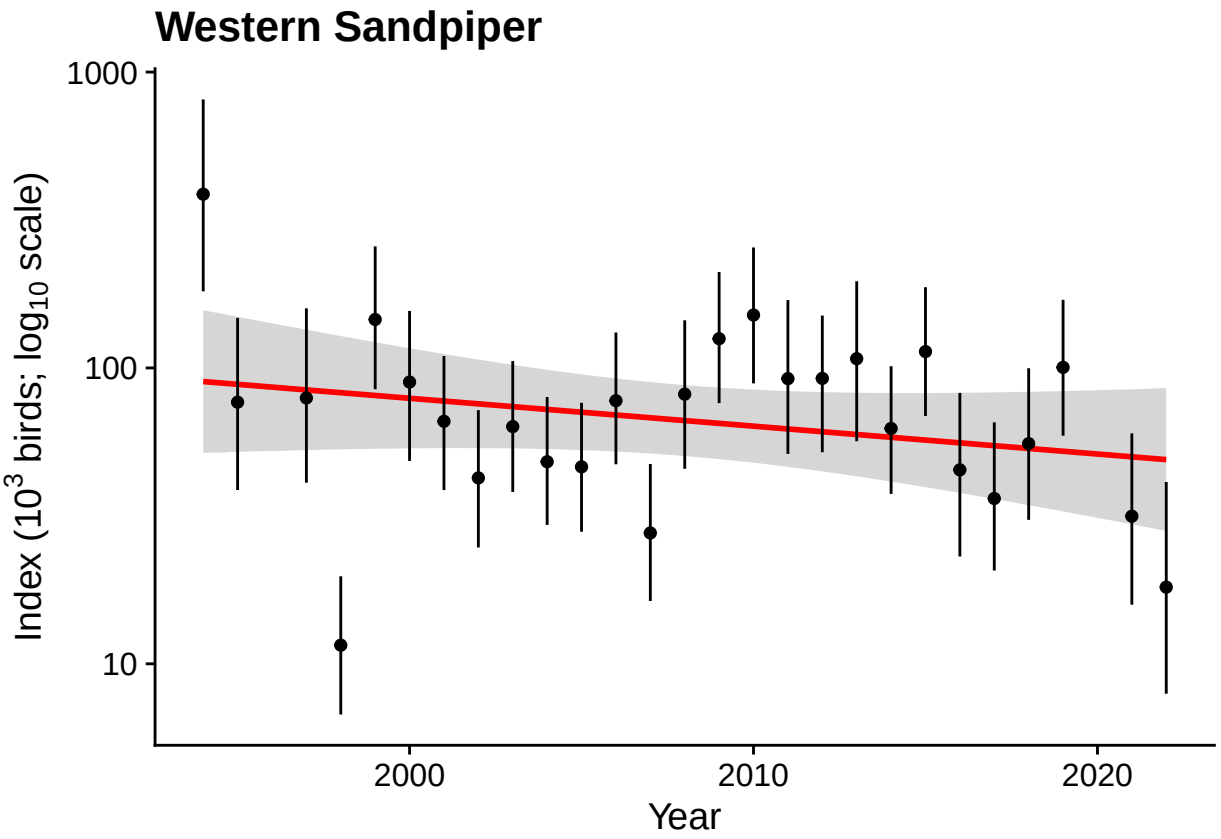
```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## log_wesa ~ year_c + dos + I(dos^2) + scale(elev_range) + scale(flow) +
##     scale(u) + (dos + I(dos^2) | year)
##    Data: dt
## Control: lme4::lmerControl(optimizer = "bobyqa")
##
## REML criterion at convergence: 1256.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.6828 -0.3770  0.0445  0.4588  3.0829
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3393   0.5825
##           dos         0.4120   0.6418    0.21
##           I(dos^2)    0.3483   0.5901   -0.33  0.15
##  Residual             0.5510   0.7423
## Number of obs: 474, groups:  year, 26
##
## Fixed effects:
##                    Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)        11.25075    0.12571  18.27449  89.498  < 2e-16 ***
## year_c             -0.28230    0.10505  21.12458  -2.687  0.01375 *
## dos                -0.52333    0.14966  30.99909  -3.497  0.00145 **
## I(dos^2)           -1.64309    0.12550  19.60208 -13.093 3.81e-11 ***
## scale(elev_range)  -0.10934    0.04025 427.05983  -2.716  0.00687 **
```

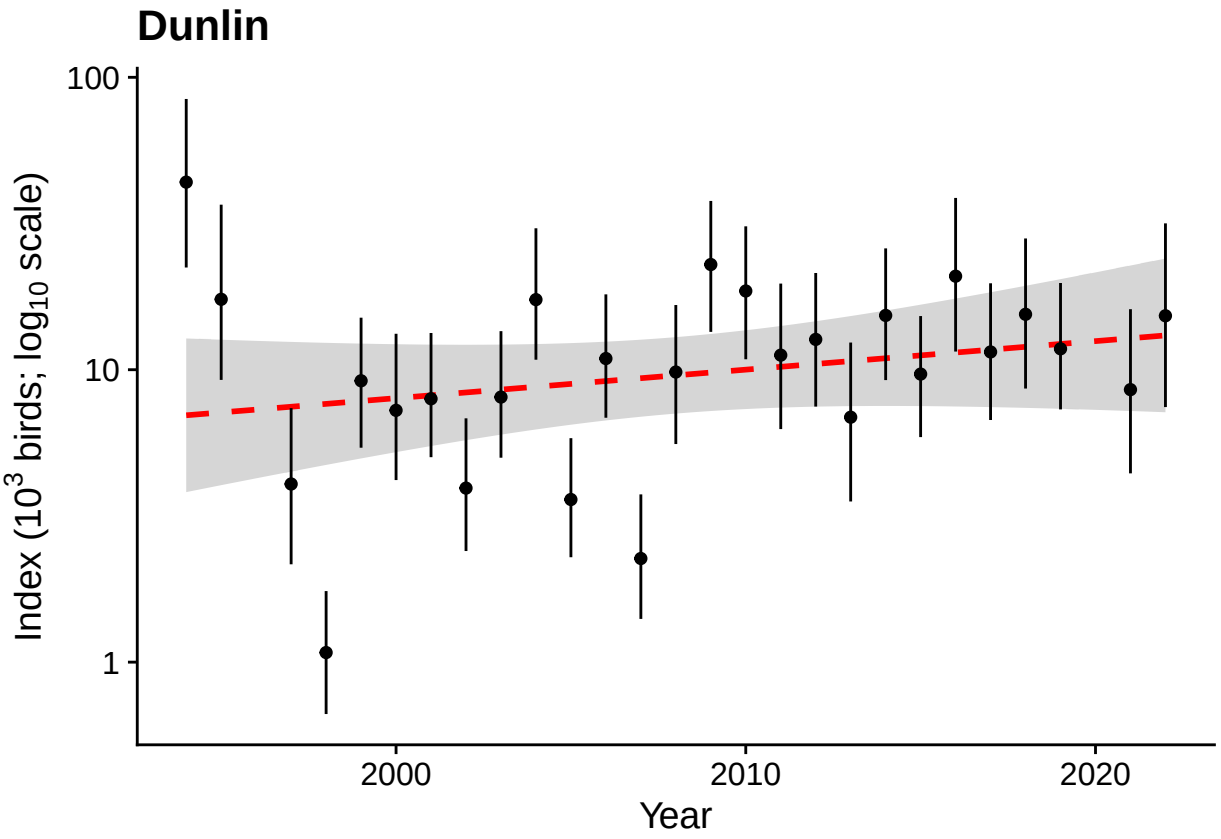
```
## scale(flow)        -0.17804    0.09479 113.24428  -1.878  0.06292 .
## scale(u)            0.05764    0.03774 411.61758   1.527  0.12748
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) year_c dos    I(d^2) scl(_) scl(f)
## year_c      -0.061
## dos          0.204 -0.038
## I(dos^2)    -0.382 -0.001  0.106
## scl(lv_rng) -0.018 -0.005 -0.060  0.008
## scale(flow) -0.089  0.072 -0.431  0.043  0.066
## scale(u)    -0.011 -0.006  0.005  0.007 -0.090  0.064
```

7.1.2 DUNL

```
## 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: 1225.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -6.0878 -0.4109  0.0403  0.4687  2.8480
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  year     (Intercept) 0.3737   0.6113
##           dos         0.4504   0.6711   -0.04
##           I(dos^2)    0.4265   0.6531   -0.66  0.25
##  Residual             0.5115   0.7152
## Number of obs: 474, groups:  year, 26
##
## Fixed effects:
##                    Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)         9.21816    0.13010  21.48622  70.854  < 2e-16 ***
## year_c             -0.09842    0.09158  23.30418  -1.075  0.29351
## dos                -1.45448    0.15299  30.96880  -9.507 1.07e-10 ***
## I(dos^2)           -0.71386    0.13645  23.46328  -5.232 2.48e-05 ***
## scale(elev_range)  -0.11852    0.03902 426.10854  -3.037  0.00254 **
## scale(flow)        -0.22829    0.08945 105.32789  -2.552  0.01214 *
## scale(u)            0.04964    0.03637 416.86452   1.365  0.17302
## ---
## 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      -0.050
```

```
## dos           0.002 -0.037
## I(dos^2)     -0.653 -0.004  0.194
## scl(lv_rng) -0.019  0.010 -0.063  0.007
## scale(flow) -0.080  0.059 -0.405  0.038  0.077
## scale(u)    -0.010 -0.008  0.008  0.006 -0.089  0.057
```




Dunlin
100
10
1
Index (10^3 birds; $\log_{10}$ scale)
2000
2010
2020
Year