Supplementary information for 'Fire risk modulation by long-term in land cover and dominant forest type dynamics in Eastern and Central Europe

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Contents

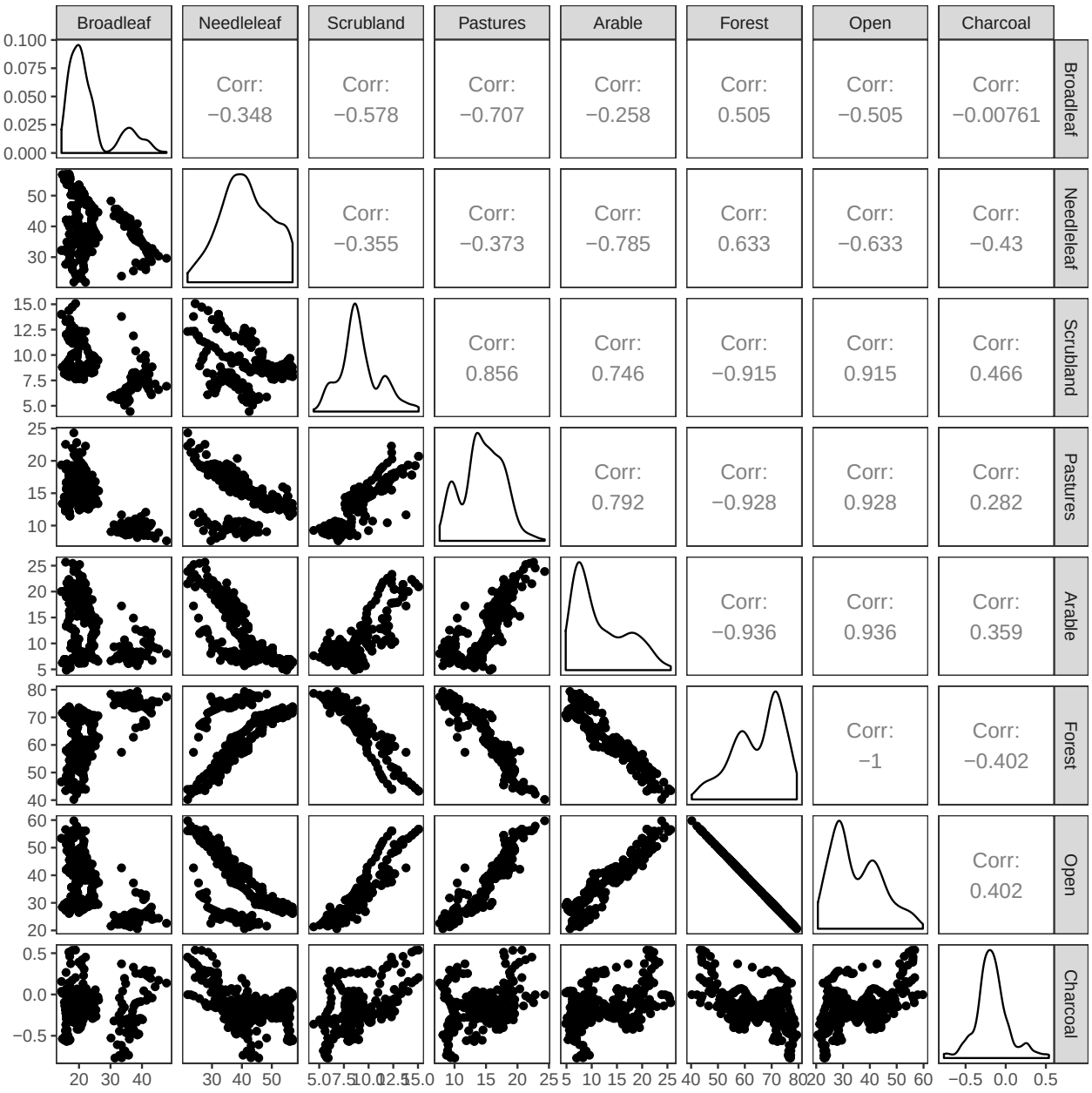
Loading in packages and data.

```
knitr::opts_chunk$set(echo = TRUE)
library(mgcv)
library(dplyr)
library(ggplot2)
library(GGally)
library(knitr)
library(qpcR)
library(voxel)
library(gridExtra)
library(grid)
setwd('~/Projects/Fire_Landcover_CentralEasternEurope/v2')
AllEurope<-read.csv('char_anom_allregions.csv')
region.cols <- c("Atlantic" = "dodgerblue", "Continental" = "green", "Boreo-nemoral" = "darkgreen" )
```

Predictor variable exploration

Here one can look at the predictors' distributions and the correlations between them.

```
ggpairs(AllEurope[,2:9], columnLabels = c("Broadleaf", "Needleleaf", "Scrubland", "Pastures", "Arable",
```



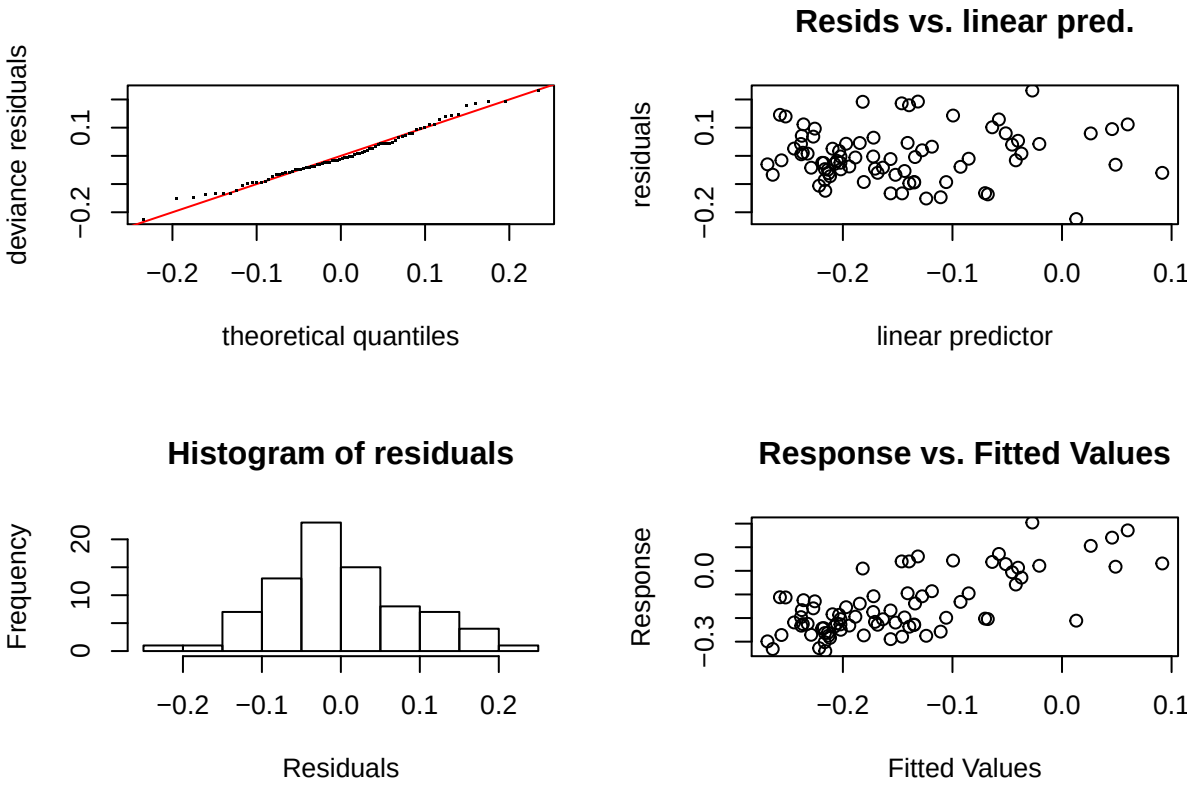
GAMs

Here we made GAMs for each predictor set and each region. We have used thin plate splines with a Gaussian error distribution, and restricted maximum likelihood to choose smoother complexity and eliminate model terms. Rather than dredge for combinations of land cover predictors that build the best possible model, we built one model that contains climate alone and then a separate model for each land cover variable and climate. We chose this approach because our goal is to look at the relative explanatory power of each variable over climate. Given that several of these land cover variables are somewhat correlated (see plot above), we decided that this approach more directly answered our research question.

Climate only, full time period

Climate only, Continental ecoregion

```
climate.continental <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = AllEurope[AllEurope$Region ==
# Checking climate.continental
gam.check(climate.continental)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-3.678624e-05,3.37166e-05]
## (score -67.52538 & scale 0.008806763).
## Hessian positive definite, eigenvalue range [6.594764e-07,39.55671].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                   k'   edf k-index p-value
## s(Temperature) 9.000 2.806    0.99    0.43
## s(P.PET)       9.000 0.924    1.26    0.98
```

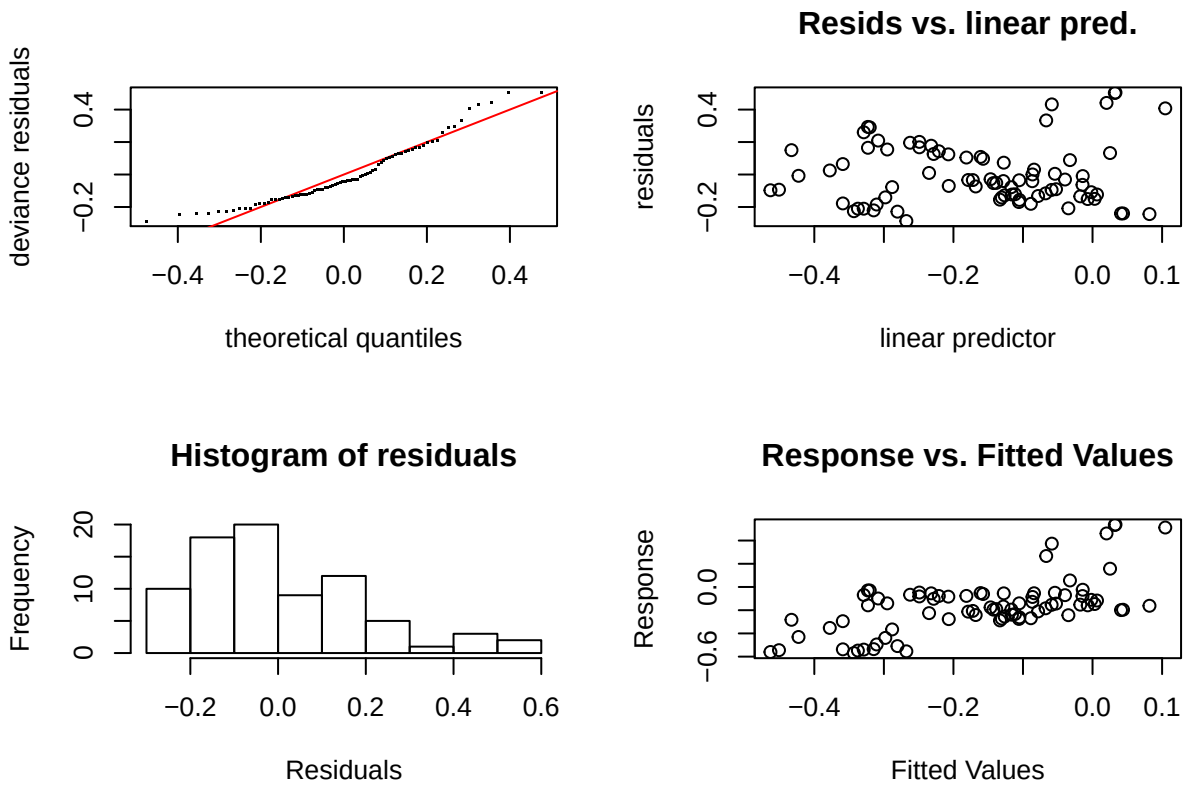
```
summary(climate.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
```

```
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.14942    0.01049  -14.24   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 2.8058      9 4.233 3.49e-08 ***
## s(P.PET)       0.9236      9 1.340 0.000339 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.467   Deviance explained = 49.2%
## -REML = -67.525  Scale est. = 0.0088068  n = 80
```

Climate only, Atlantic ecoregion

```
climate.atlantic <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = AllEurope[AllEurope$Region == "Atl
# Checking climate.atlantic
gam.check(climate.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 13 iterations.
```

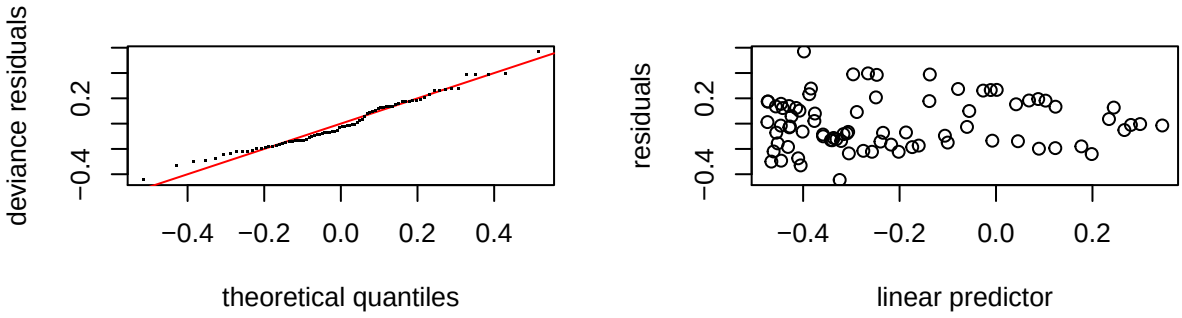
```
## Gradient range [-4.524082e-06,8.62491e-06]
## (score -13.82682 & scale 0.03624344).
## Hessian positive definite, eigenvalue range [3.40692e-07,39.51739].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                   k'   edf k-index p-value
## s(Temperature) 9.000 0.971    0.85    0.06 .
## s(P.PET)       9.000 1.336    0.96    0.27
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

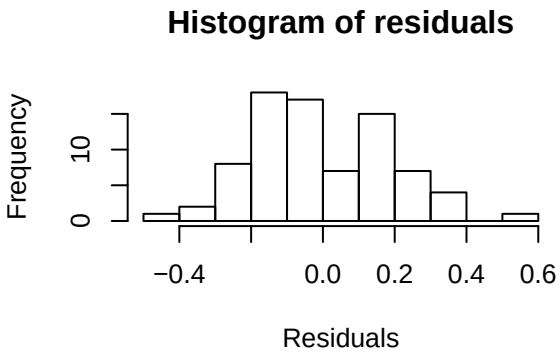
```
summary(climate.atlantic)
```

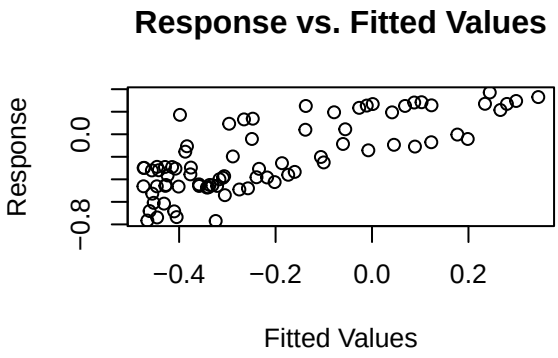
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.02128  -7.592 6.31e-11 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 0.9711      9 3.734 4.38e-08 ***
## s(P.PET)       1.3365      9 0.267    0.161
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.359   Deviance explained = 37.8%
## -REML = -13.827  Scale est. = 0.036243  n = 80
```

Climate only, Boreo-Nemoral ecoregion

```
climate.boreonemoral <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = AllEurope[AllEurope$Region ==
# Checking climate.boreonemoral
gam.check(climate.boreonemoral)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 10 iterations.
## Gradient range [-1.036606e-06,1.653724e-06]
## (score -3.844071 & scale 0.04253241).
## Hessian positive definite, eigenvalue range [6.457457e-07,39.59389].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                  k'  edf k-index p-value
## s(Temperature) 9.00 3.13    0.92    0.23
## s(P.PET)       9.00 2.17    1.14    0.86
```

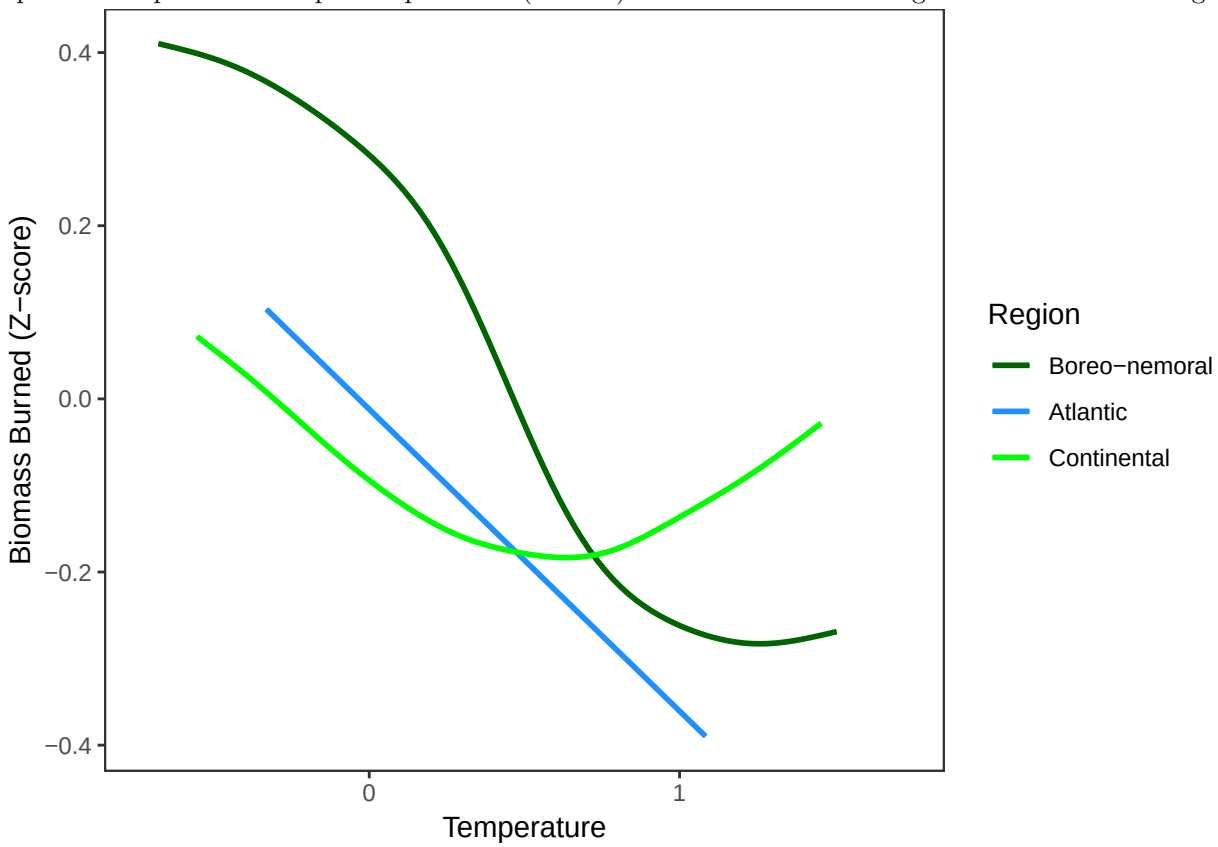
```
summary(climate.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.02306  -9.124 1.01e-13 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
```

```
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 3.135      9 4.260 2.48e-08 ***
## s(P.PET)       2.165      9 1.495 0.000835 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.571   Deviance explained =   60%
## -REML = -3.8441  Scale est. = 0.042532  n = 80
```

Temperature plot

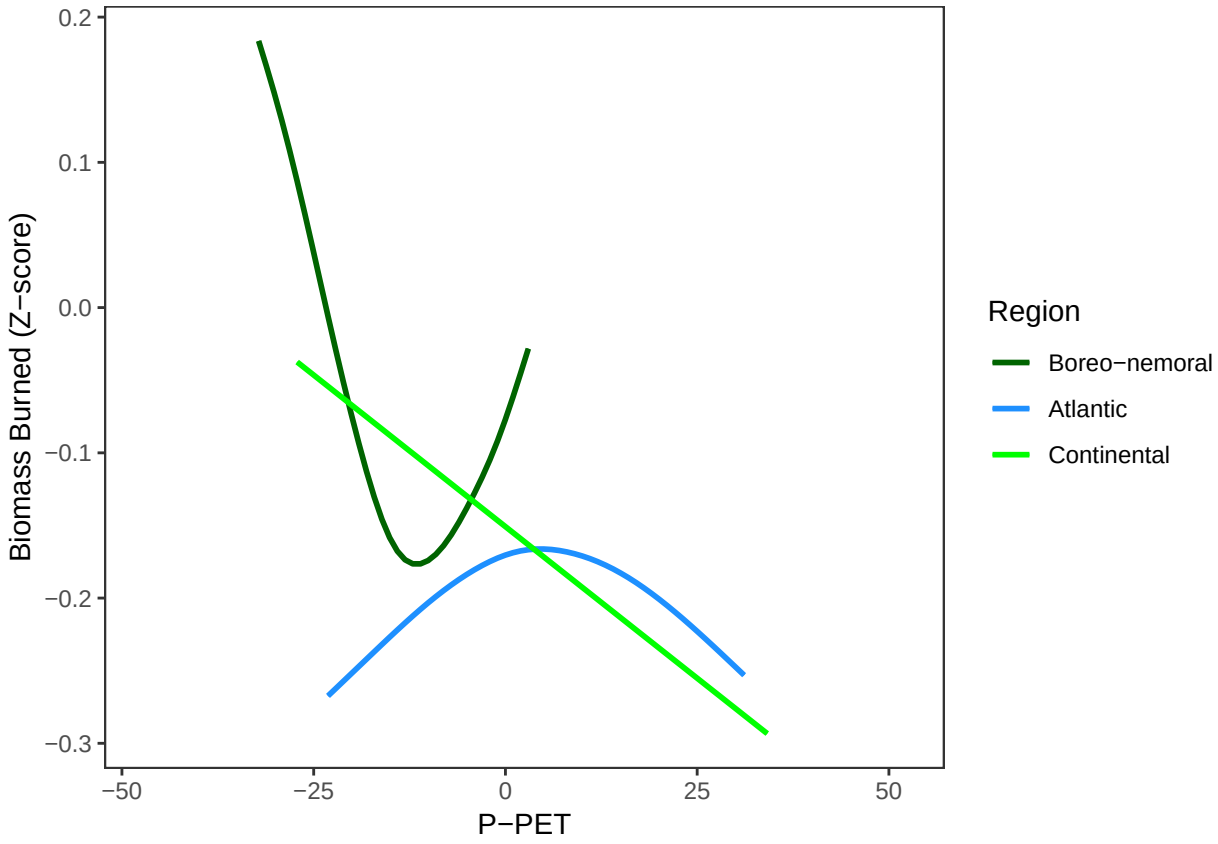
Here we show the marginal response of biomass burned to temperature in each region, holding precipitation - potential evapotransporation (P-PET) constant at its average value over each region.




```
## pdf
##   2
```

P-PET plot

Here we show the marginal response of biomass burned to P-PET in each region, holding the temperature constant at its average value over each region.




```
## pdf
##   2
```

Conclusion

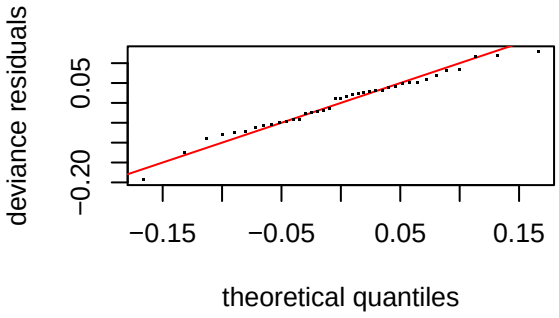
GAMs produced with climate only over the entire period do not produce relationships that consistent across ecoregions or as we might expect.

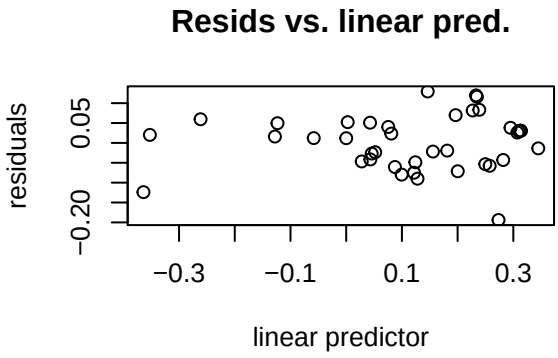
Climate only GAMs before and after 8ka BP

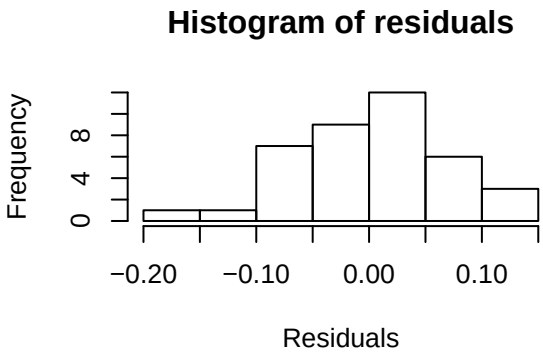
8 ka BP-12 ka BP, climate only

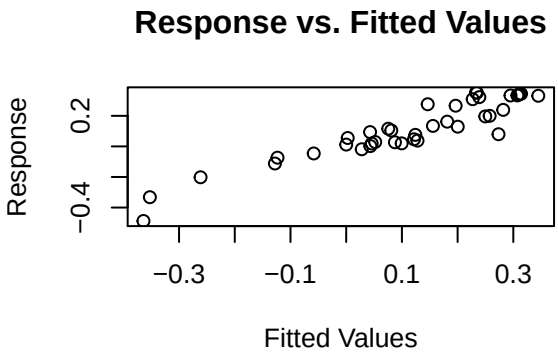
8 ka BP-12 ka BP climate data, Continental ecoregion

```
full.climate <- read.csv('climate_anom_12k.csv')

early.climate <- full.climate[full.climate$Age > 8000,]

early.climate.continental <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = early.climate[early.clima
# Checking early.climate.continental
gam.check(early.climate.continental)
```










```
##
## Method: REML   Optimizer: outer newton
## full convergence after 7 iterations.
## Gradient range [-1.199105e-05,1.070345e-05]
## (score -35.48881 & scale 0.005544089).
## Hessian positive definite, eigenvalue range [1.893156e-06,19.20561].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                  k'  edf k-index p-value
## s(Temperature) 9.00 2.94    1.01    0.40
## s(P.PET)       9.00 2.47    1.23    0.92
```

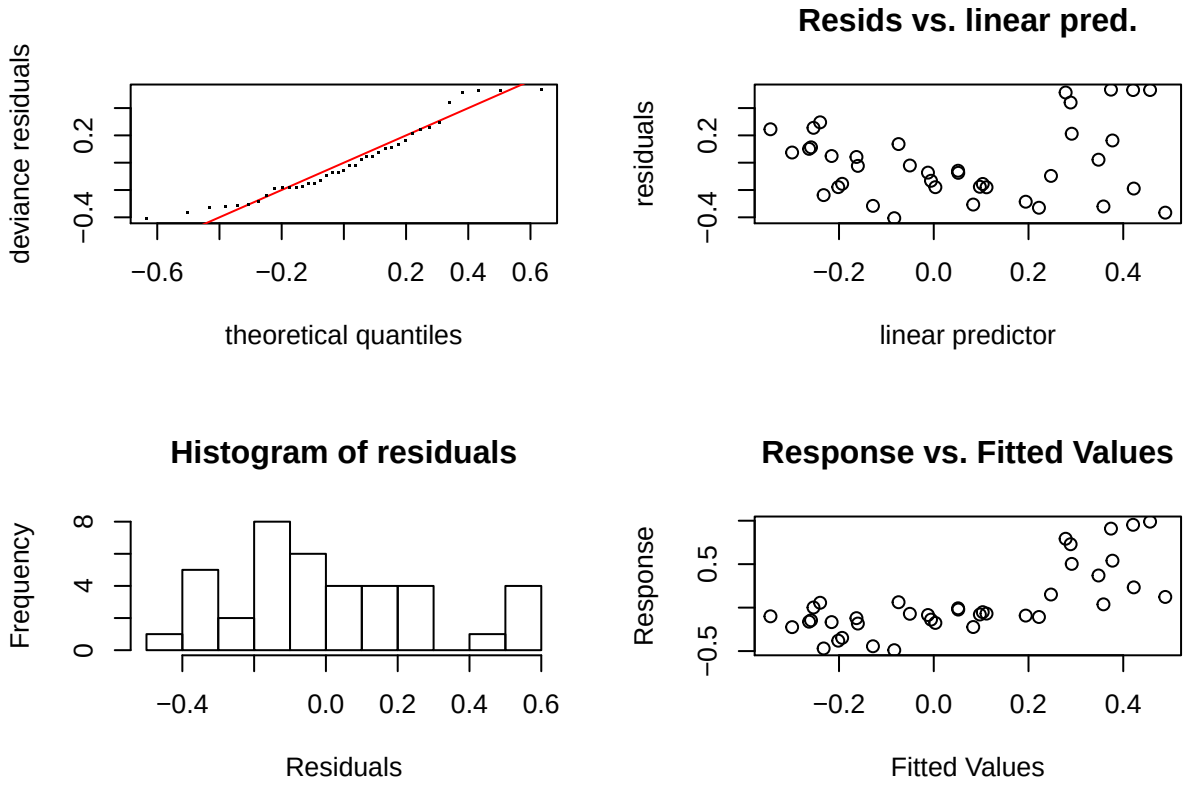
```
summary(early.climate.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  0.11295    0.01192   9.473 6.97e-11 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
```

```
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 2.938      9 14.99  < 2e-16 ***
## s(P.PET)       2.467      9  4.68 1.73e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.854   Deviance explained = 87.4%
## -REML = -35.489  Scale est. = 0.0055441  n = 39
```

8 ka BP-12 ka BP climate data, Atlantic ecoregion

```
early.climate.atlantic <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = early.climate[early.climate$
# Checking early.climate.atlantic
gam.check(early.climate.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 8 iterations.
## Gradient range [-3.578941e-06,2.76732e-06]
## (score 13.38783 & scale 0.08089621).
## Hessian positive definite, eigenvalue range [3.578872e-06,19.11939].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                  k'  edf k-index p-value
## s(Temperature) 9.00 2.85    0.76   0.045 *
```

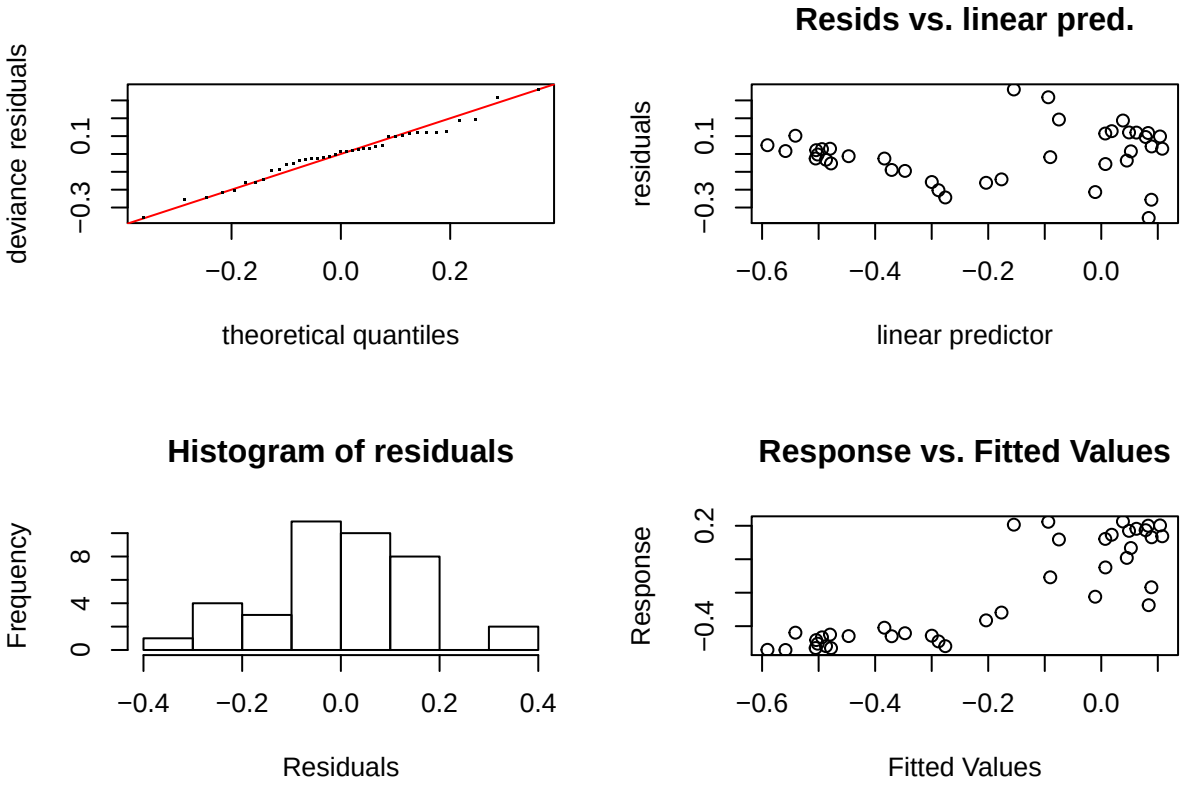
```
## s(P.PET)       9.00 1.25    1.01   0.410
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
summary(early.climate.atlantic)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  0.05358    0.04554   1.177    0.248
##
## Approximate significance of smooth terms:
##                  edf Ref.df     F  p-value
## s(Temperature) 2.849      9 1.798 0.001678 **
## s(P.PET)       1.252      9 1.333 0.000962 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =   0.47   Deviance explained = 52.7%
## -REML = 13.388  Scale est. = 0.080896  n = 39
```

8 ka BP-12 ka BP climate data, Boreo-Nemoral ecoregion

```
early.climate.boreonemoral <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = early.climate[early.cli
# Checking early.climate.boreonemoral
gam.check(early.climate.boreonemoral)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 9 iterations.
## Gradient range [-2.868178e-06,4.43397e-06]
## (score -5.755863 & scale 0.02618218).
## Hessian positive definite, eigenvalue range [8.680564e-08,19.21605].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                  k'  edf k-index p-value
## s(Temperature) 9.00 3.45    0.94    0.30
## s(P.PET)       9.00 2.05    0.88    0.18
```

```
summary(early.climate.boreonemoral)
```

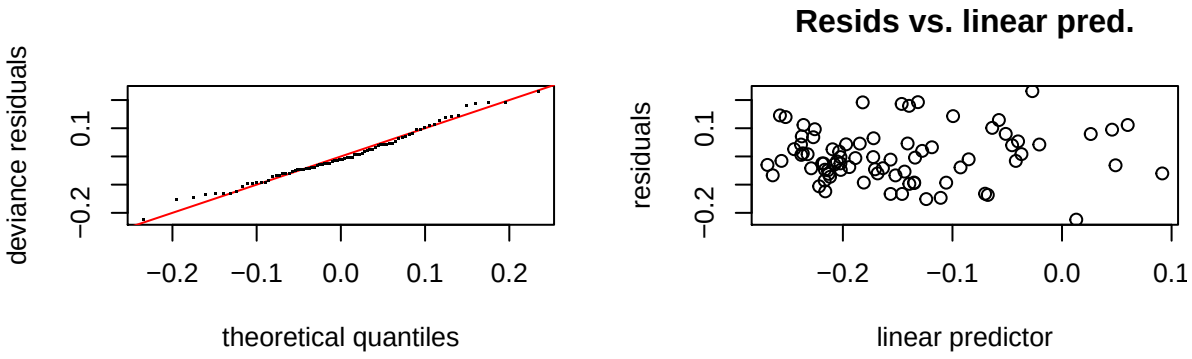
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.19081    0.02591  -7.364 2.04e-08 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
```

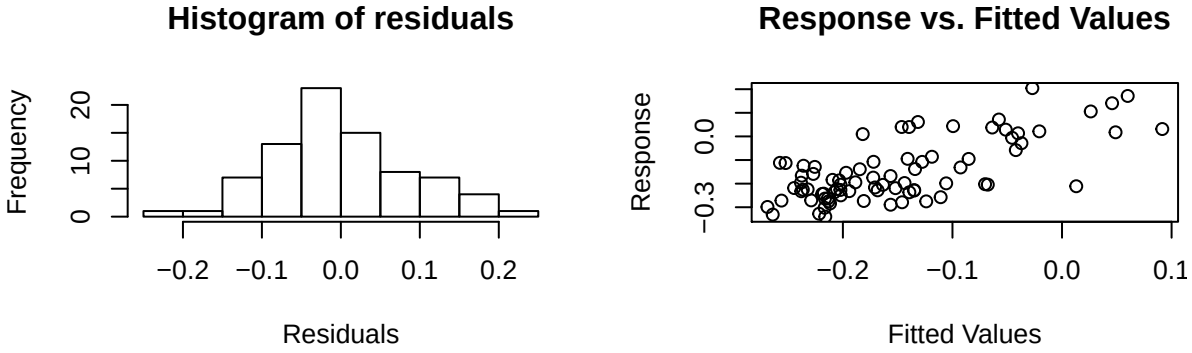
```
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 3.447      9 8.947 5.76e-12 ***
## s(P.PET)       2.049      9 1.133  0.00574 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.709   Deviance explained = 75.1%
## -REML = -5.7559  Scale est. = 0.026182  n = 39
```

0 ka BP-8 ka BP, climate only

0 ka BP-8 ka BP climate data, Continental ecoregion

```
late.climate <- full.climate[full.climate$Age <= 8000,]


late.climate.continental <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = late.climate[late.climate
# Checking late.climate.continental
gam.check(late.climate.continental)
```






```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-3.678624e-05,3.37166e-05]
## (score -67.52538 & scale 0.008806763).
## Hessian positive definite, eigenvalue range [6.594764e-07,39.55671].
## Model rank =  19 / 19
##
```

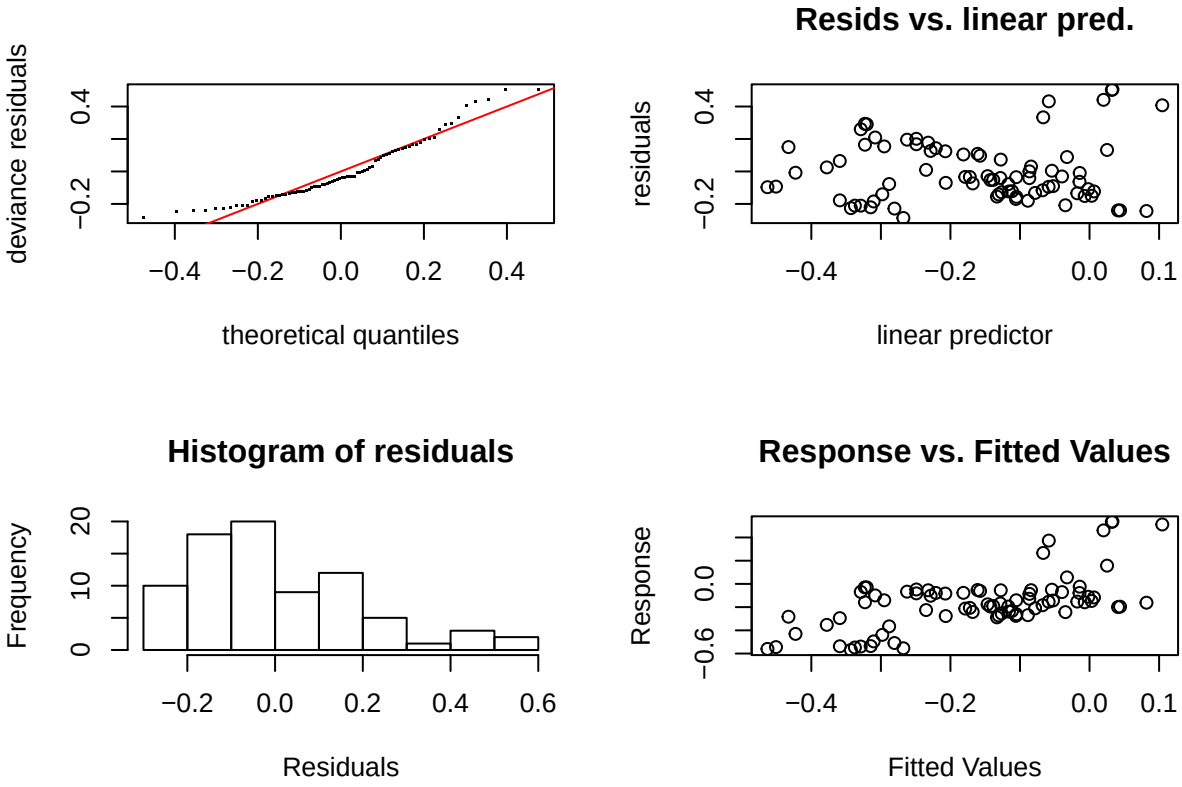
```
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                   k'   edf k-index p-value
## s(Temperature) 9.000 2.806    0.99    0.45
## s(P.PET)       9.000 0.924    1.26    0.97
```

```
summary(late.climate.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.14942    0.01049  -14.24   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 2.8058      9 4.233 3.49e-08 ***
## s(P.PET)       0.9236      9 1.340 0.000339 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.467   Deviance explained = 49.2%
## -REML = -67.525  Scale est. = 0.0088068  n = 80
```

0 ka BP-8 ka BP climate data, Atlantic ecoregion

```
late.climate.atlantic <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = late.climate[late.climate$Re
# Checking late.climate.atlantic
gam.check(late.climate.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 13 iterations.
## Gradient range [-4.524082e-06,8.62491e-06]
## (score -13.82682 & scale 0.03624344).
## Hessian positive definite, eigenvalue range [3.40692e-07,39.51739].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                   k'   edf k-index p-value
## s(Temperature) 9.000 0.971    0.85   0.055 .
## s(P.PET)       9.000 1.336    0.96   0.335
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

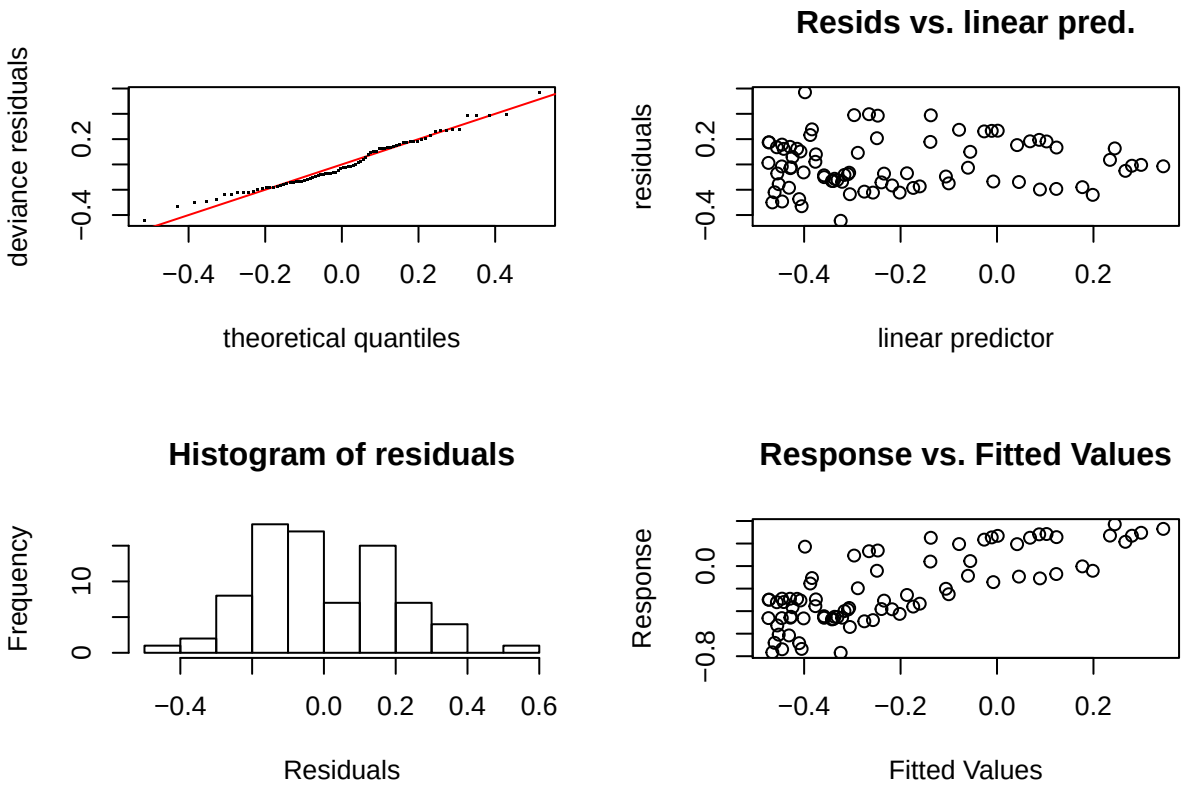
```
summary(late.climate.atlantic)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.02128  -7.592 6.31e-11 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                   edf Ref.df     F  p-value
## s(Temperature) 0.9711      9 3.734 4.38e-08 ***
## s(P.PET)       1.3365      9 0.267    0.161
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.359   Deviance explained = 37.8%
## -REML = -13.827  Scale est. = 0.036243  n = 80
```

0 ka BP-8 ka BP climate data, Boreo-Nemoral ecoregion

```
late.climate.boreonemoral <- gam(Charcoal ~ s(Temperature)  + s(P.PET), data = late.climate[late.climat
# Checking late.climate.boreonemoral
gam.check(late.climate.boreonemoral)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 10 iterations.
## Gradient range [-1.036606e-06,1.653724e-06]
## (score -3.844071 & scale 0.04253241).
## Hessian positive definite, eigenvalue range [6.457457e-07,39.59389].
## Model rank =  19 / 19
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
```

```
##                   k'  edf k-index p-value
## s(Temperature) 9.00 3.13    0.92    0.23
## s(P.PET)       9.00 2.17    1.14    0.90
```

```
summary(late.climate.boreonemoral)
```

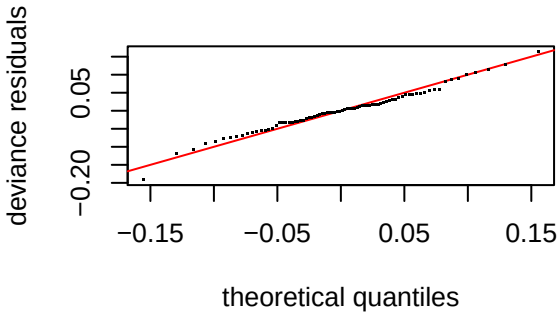
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.02306  -9.124 1.01e-13 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                  edf Ref.df     F  p-value
## s(Temperature) 3.135      9 4.260 2.48e-08 ***
## s(P.PET)       2.165      9 1.495 0.000835 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.571   Deviance explained =   60%
## -REML = -3.8441  Scale est. = 0.042532  n = 80
```

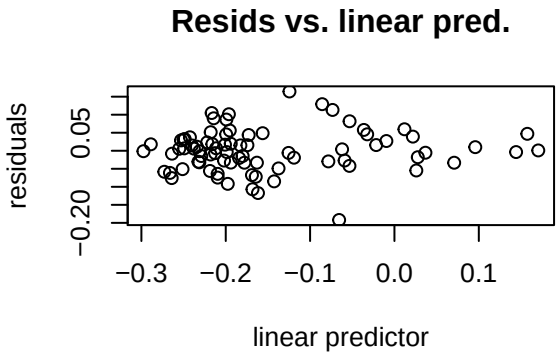
Climate and some land cover GAMs, after 8ka BP

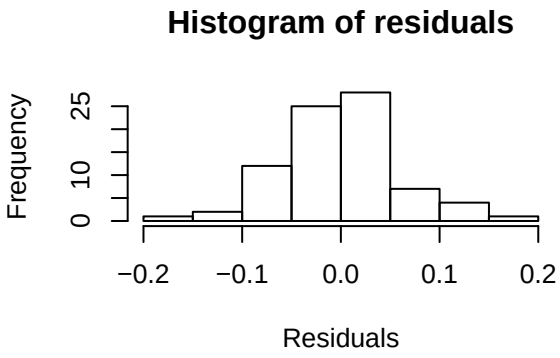
0 ka BP-8 ka BP, climate plus land cover

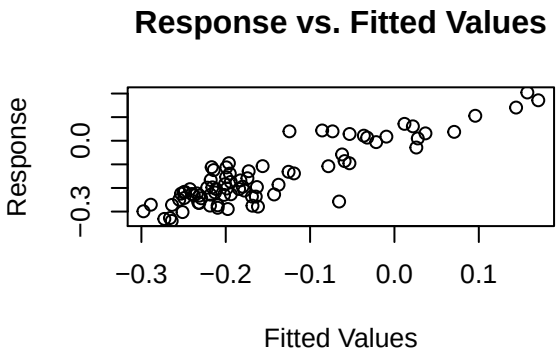
0 ka BP-8 ka BP climate plus total tree and arable cover, Continental ecoregion

```
late.climate.cover.continental <- gam(Charcoal ~ s(Temperature)  + s(P.PET) + s(Sumoftotalforestclosedt
# Checking late.climate.cover.continental
gam.check(late.climate.cover.continental)
```










```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-3.787913e-05,4.118093e-05]
## (score -90.10825 & scale 0.003874367).
## Hessian positive definite, eigenvalue range [3.547143e-08,39.74207].
## Model rank =  37 / 37
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                   k'   edf k-index p-value
## s(Temperature)                 9.000 5.275    1.04    0.63
## s(P.PET)                       9.000 1.335    1.05    0.66
## s(SumoftotalforestclosedtoLCCs) 9.000 2.937    0.85    0.06 .
## s(Arabledisturbedlandin)       9.000 0.683    0.72  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

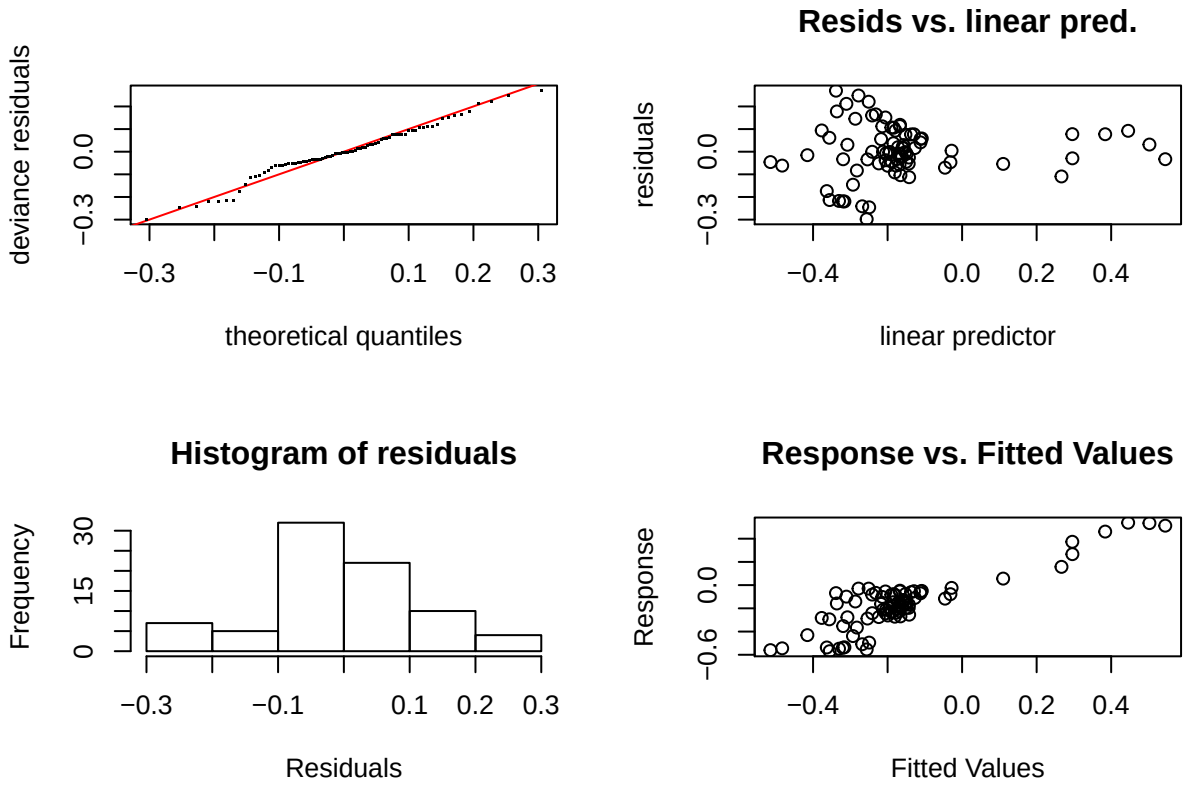
```
summary(late.climate.cover.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET) + s(SumoftotalforestclosedtoLCCs) +
##     s(Arabledisturbedlandin)
##
## Parametric coefficients:
```

```
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.149423   0.006959  -21.47   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                    edf Ref.df     F  p-value
## s(Temperature)                  5.2752      9 3.119 3.68e-05 ***
## s(P.PET)                        1.3347      9 0.622   0.0181 *
## s(SumoftotalforestclosedtoLCCs) 2.9374      9 4.468 1.49e-09 ***
## s(Arabledisturbedlandin)        0.6834      9 0.240   0.0297 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.765   Deviance explained = 79.6%
## -REML = -90.108  Scale est. = 0.0038744  n = 80
```

0 ka BP-8 ka BP climate plus total tree and arable cover, Atlantic ecoregion

```
late.climate.cover.atlantic <- gam(Charcoal ~ s(Temperature)  + s(P.PET) + s(SumoftotalforestclosedtoLC
# Checking late.climate.cover.atlantic
gam.check(late.climate.cover.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 17 iterations.
## Gradient range [-9.453484e-06,5.542208e-06]
## (score -39.1279 & scale 0.01488095).
## Hessian positive definite, eigenvalue range [9.453359e-06,39.64709].
```

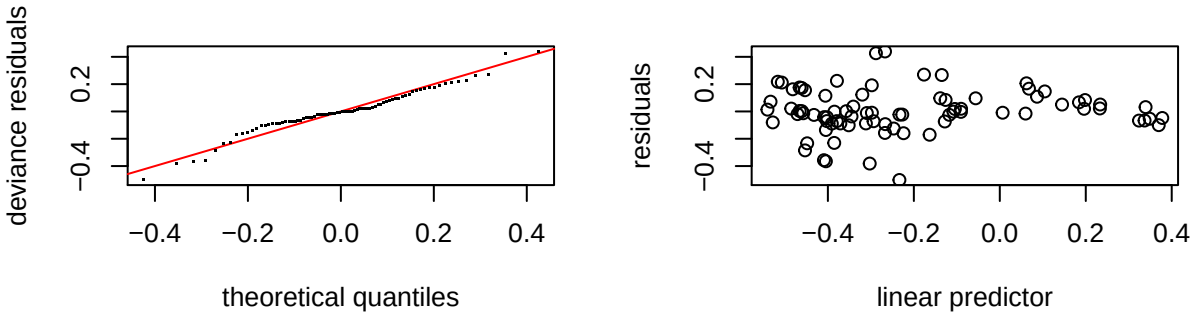
```
## Model rank =  37 / 37
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                    k'   edf k-index p-value
## s(Temperature)                  9.000 2.366    1.33   1.000
## s(P.PET)                        9.000 1.436    1.09   0.715
## s(SumoftotalforestclosedtoLCCs) 9.000 0.784    1.29   0.995
## s(Arabledisturbedlandin)        9.000 4.621    0.70   0.005 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

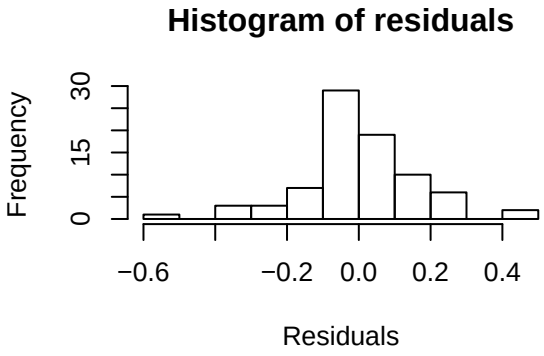
```
summary(late.climate.cover.atlantic)
```

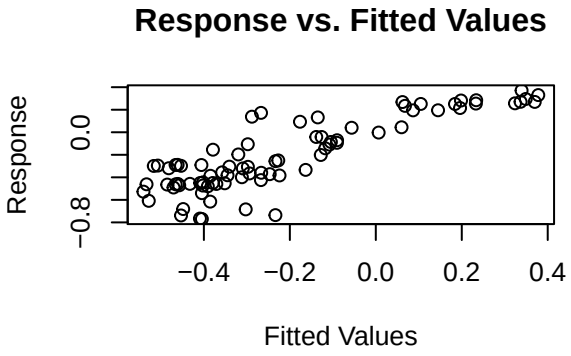
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET) + s(SumoftotalforestclosedtoLCCs) +
##     s(Arabledisturbedlandin)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.01364  -11.85   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                    edf Ref.df     F  p-value
## s(Temperature)                  2.3662      9 1.395 0.000888 ***
## s(P.PET)                        1.4358      9 0.469 0.044000 *
## s(SumoftotalforestclosedtoLCCs) 0.7841      9 0.404 0.018360 *
## s(Arabledisturbedlandin)        4.6207      9 5.708 6.39e-10 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.737   Deviance explained = 76.7%
## -REML = -39.128  Scale est. = 0.014881  n = 80
```

0 ka BP-8 ka BP climate plus total tree and arable cover, Boreo-Nemoral ecoregion

```
late.climate.cover.boreonemoral <- gam(Charcoal ~ s(Temperature)  + s(P.PET) + s(Sumoftotalforestclosed
# Checking late.climate.cover.boreonemoral
gam.check(late.climate.cover.boreonemoral)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-6.582047e-06,1.31808e-05]
## (score -16.27728 & scale 0.0289127).
## Hessian positive definite, eigenvalue range [4.742891e-07,39.6105].
## Model rank =  37 / 37
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                   k'   edf k-index p-value
## s(Temperature)                 9.000 2.351    0.98    0.34
## s(P.PET)                       9.000 2.477    1.11    0.79
## s(SumoftotalforestclosedtoLCCs) 9.000 0.853    0.90    0.14
## s(Arabledisturbedlandin)       9.000 2.269    1.06    0.66
```

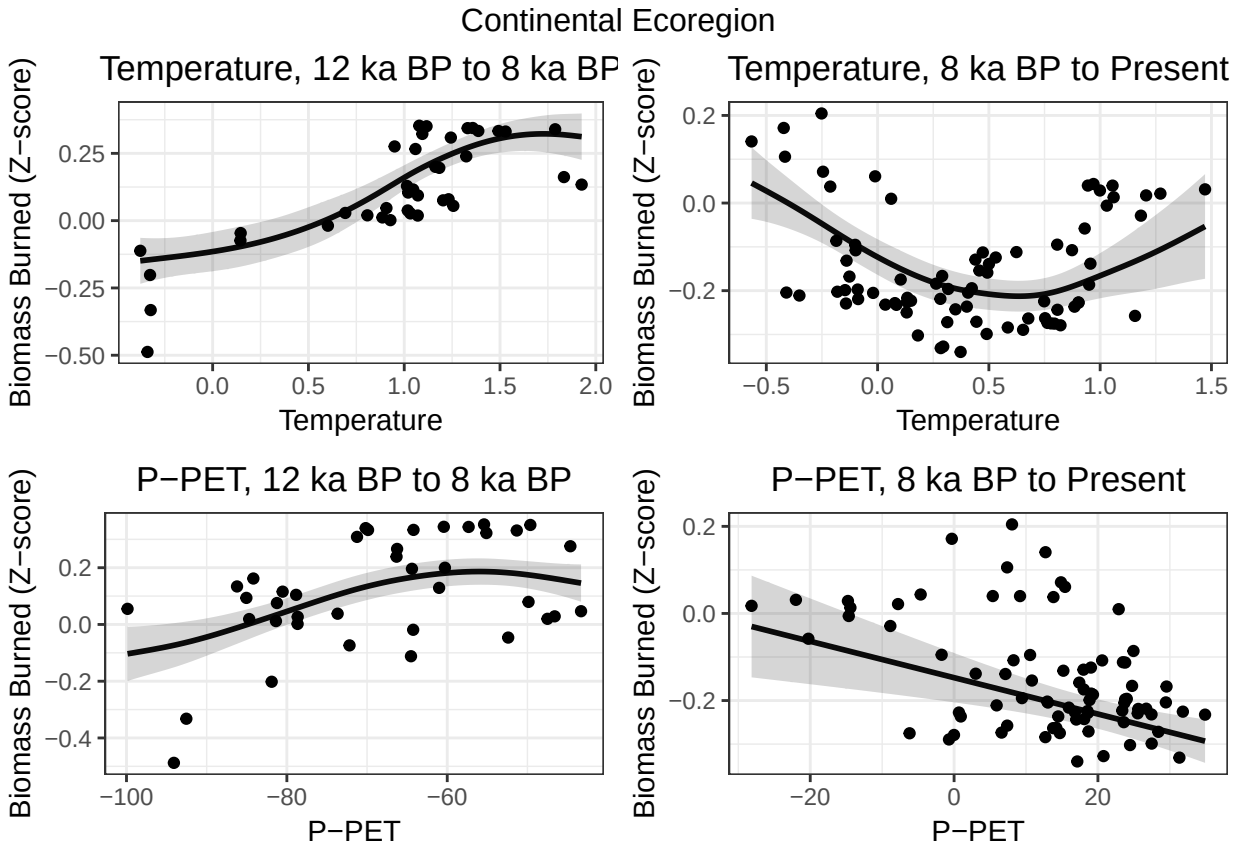
```
summary(late.climate.cover.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Temperature) + s(P.PET) + s(SumoftotalforestclosedtoLCCs) +
##     s(Arabledisturbedlandin)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.01901  -11.07   <2e-16 ***
```

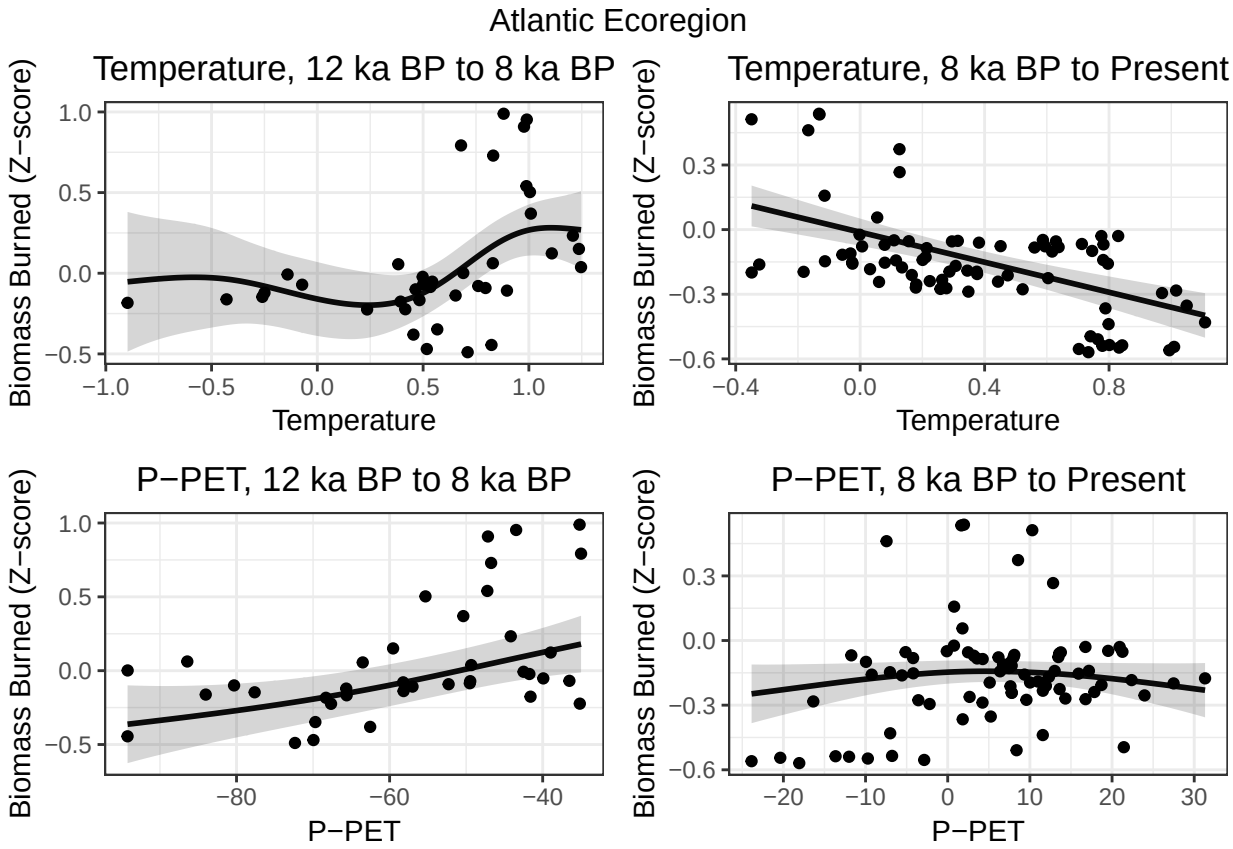
```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                    edf Ref.df     F  p-value
## s(Temperature)                   2.3514      9 1.624 0.000362 ***
## s(P.PET)                         2.4771      9 1.506 0.001094 **
## s(SumoftotalforestclosedtoLCCs) 0.8534      9 0.217 0.059901 .
## s(Arabledisturbedlandin)         2.2694      9 1.905  1.7e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.708   Deviance explained = 73.8%
## -REML = -16.277  Scale est. = 0.028913  n = 80
```

Plots

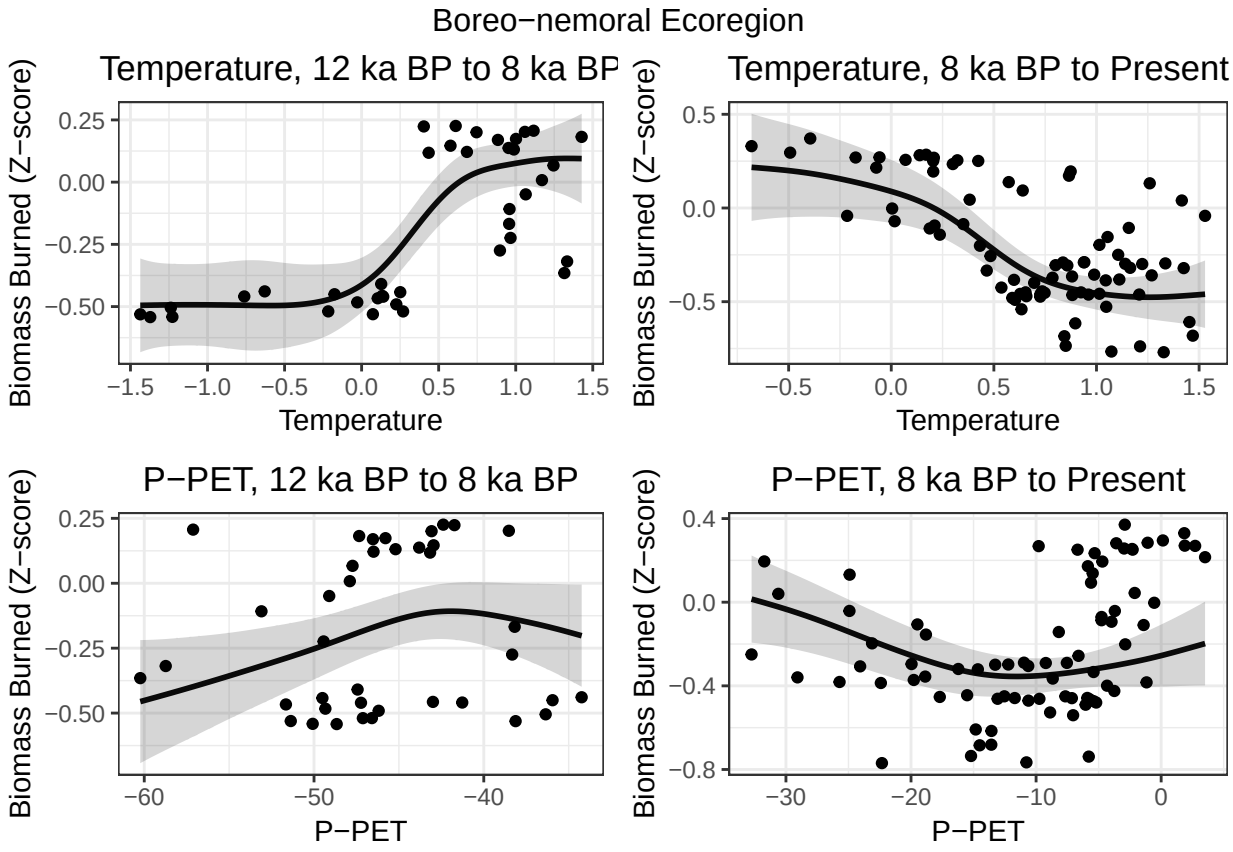
Continental ecoregion, pre- and post-8 ka BP, climate only



Atlantic ecoregion, pre- and post-8 ka BP, climate only



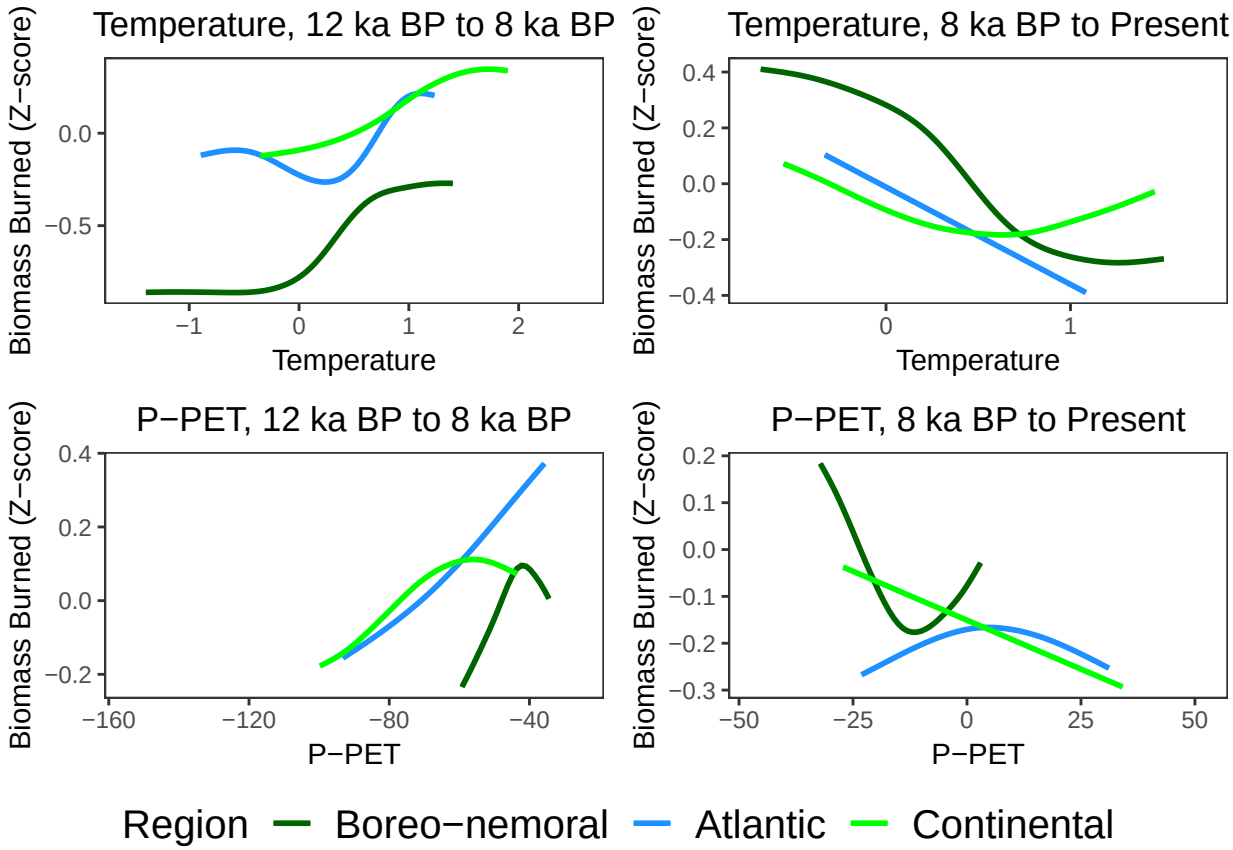
Boreo-nemoral ecoregion, pre- and post-8 ka BP, climate only



Summary Table - Deviance Explained

region	climate.12k.to.8ky	climate.8ky.to.0ky	climate.plus.cover.8ky.to.0ky
Continental	0.8744627	0.4920065	0.7958207
Atlantic	0.5268266	0.3776453	0.7674590
Boreo-nemoral	0.7510058	0.5995821	0.7375969
Mean of Regions	0.7174317	0.4897446	0.7669589

Summary Plot - All climate only GAMs, pre- and post-8 ka BP




```
## pdf
##   2
```

Summary for climate GAMs

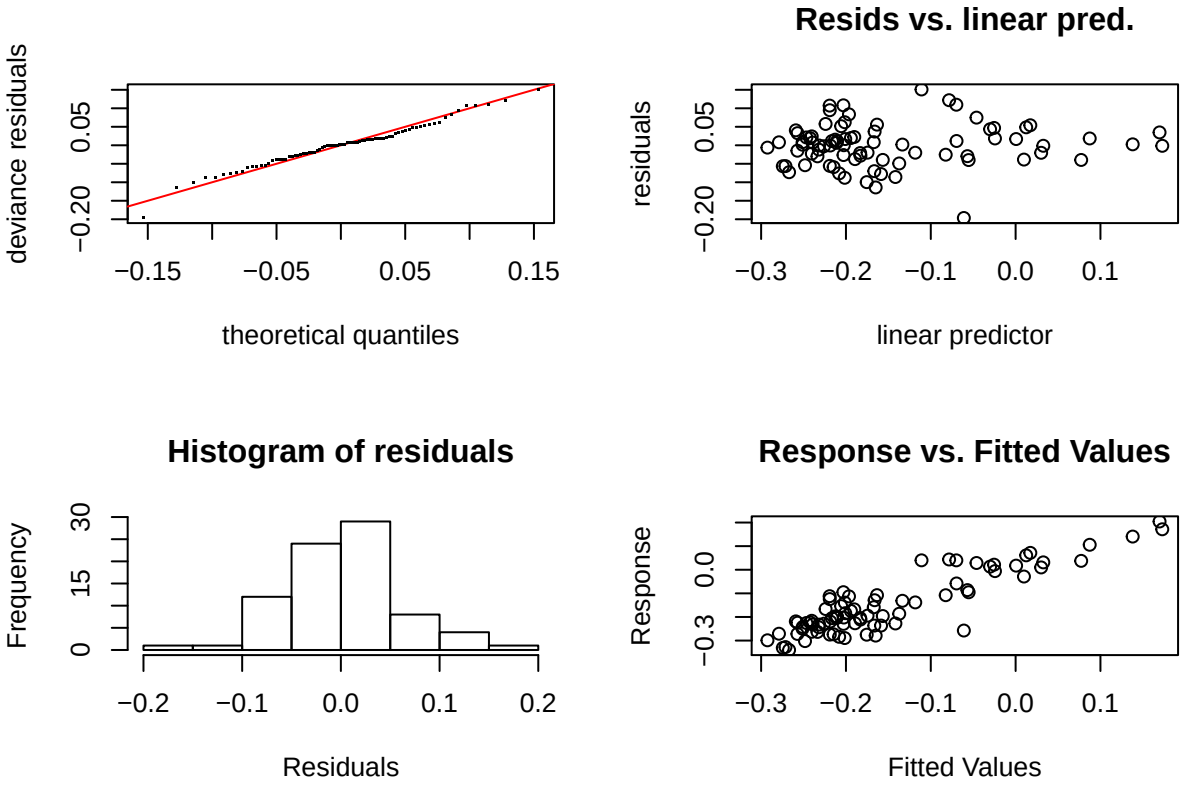
GAMs made before 8 ka BP with climate alone are both consistent and sensible and explain, on average, 70% of the deviance. After 8 ka BP, GAMs made with climate only explain much less of the deviance, on average 45%, and produce results that are inconsistent across ecoregions and have unexpected trends (fire increases at lower temperatures). However, including two land cover types in the GAMs increases the deviance explain to 75%.

GAMs After 8ka BP with full land cover analysis

Total tree cover

Total tree cover, Continental ecoregion

```
totaltree.continental <- gam(Charcoal ~ s(SumoftotalforestclosedtoLCCs) + s(Temperature)  + s(P.PET), da
# Checking totaltree.continental
gam.check(totaltree.continental)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 9 iterations.
## Gradient range [-1.504697e-05,6.536313e-06]
## (score -89.80714 & scale 0.003770801).
## Hessian positive definite, eigenvalue range [1.50464e-05,39.78544].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                  k'  edf k-index p-value
## s(SumoftotalforestclosedtoLCCs) 9.00 3.60    0.85    0.05 *
## s(Temperature)                  9.00 5.80    1.07    0.64
## s(P.PET)                        9.00 1.29    1.03    0.53
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

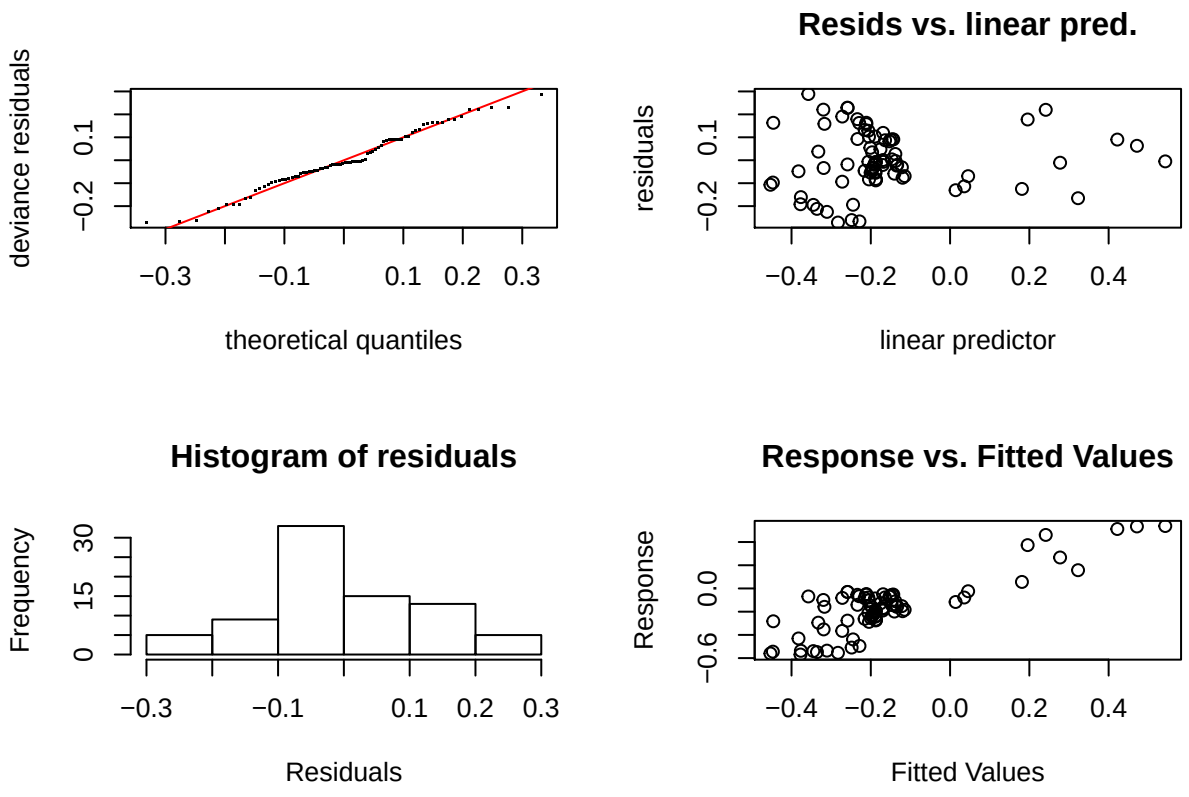
```
summary(totaltree.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(SumoftotalforestclosedtoLCCs) + s(Temperature) +
##     s(P.PET)
##
## Parametric coefficients:
##              Estimate Std. Error t value Pr(>|t|)
```

```
## (Intercept) -0.149423   0.006865  -21.76   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                   edf Ref.df      F  p-value
## s(SumoftotalforestclosedtoLCCs) 3.597      9 10.053  < 2e-16 ***
## s(Temperature)                  5.797      9  3.432 2.59e-05 ***
## s(P.PET)                        1.289      9  0.538   0.0269 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.772   Deviance explained = 80.3%
## -REML = -89.807  Scale est. = 0.0037708  n = 80
```

Total tree cover, Atlantic ecoregion

```
totaltree.atlantic <- gam(Charcoal ~ s(SumoftotalforestclosedtoLCCs) + s(Temperature)  + s(P.PET), data
# Checking totaltree.atlantic
gam.check(totaltree.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-4.628882e-06,5.950208e-06]
## (score -35.74327 & scale 0.01766711).
## Hessian positive definite, eigenvalue range [0.0258906,39.58458].
## Model rank =  28 / 28
```

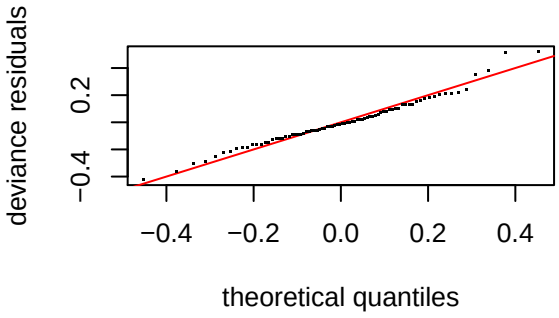
```
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                   k'  edf k-index p-value
## s(SumoftotalforestclosedtoLCCs) 9.00 3.74    1.25    0.99
## s(Temperature)                  9.00 1.51    1.28    1.00
## s(P.PET)                        9.00 1.80    1.02    0.52
```

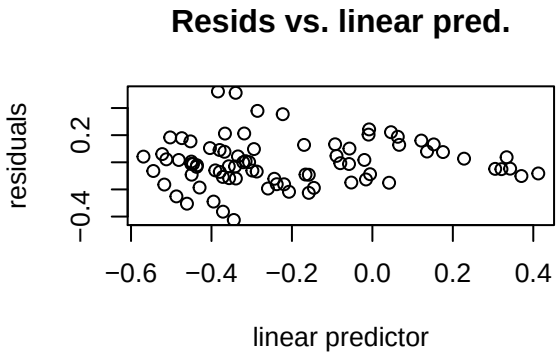
```
summary(totaltree.atlantic)
```

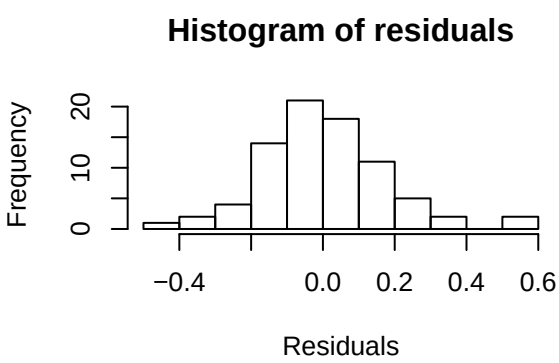
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(SumoftotalforestclosedtoLCCs) + s(Temperature) +
##     s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.01486  -10.88   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                   edf Ref.df     F  p-value
## s(SumoftotalforestclosedtoLCCs) 3.744      9 9.166 5.24e-16 ***
## s(Temperature)                  1.508      9 0.527   0.0290 *
## s(P.PET)                        1.797      9 0.835   0.0101 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.688   Deviance explained = 71.5%
## -REML = -35.743  Scale est. = 0.017667  n = 80
```

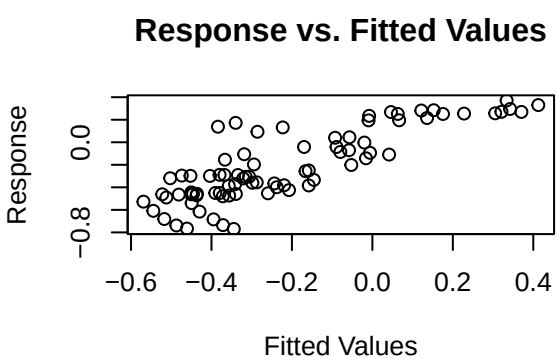
Total tree cover, Boreo-Nemoral ecoregion

```
totaltree.boreonemoral <- gam(Charcoal ~ s(SumoftotalforestclosedtoLCCs) + s(Temperature)  + s(P.PET), d
# Checking totaltree.boreonemoral
gam.check(totaltree.boreonemoral)
```










```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-2.082303e-05,3.009454e-05]
## (score -12.50301 & scale 0.03283606).
## Hessian positive definite, eigenvalue range [1.496118e-06,39.58805].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                  k'  edf k-index p-value
## s(SumoftotalforestclosedtoLCCs) 9.00 2.55    0.94    0.21
## s(Temperature)                  9.00 2.02    1.00    0.41
## s(P.PET)                        9.00 2.35    1.08    0.69
```

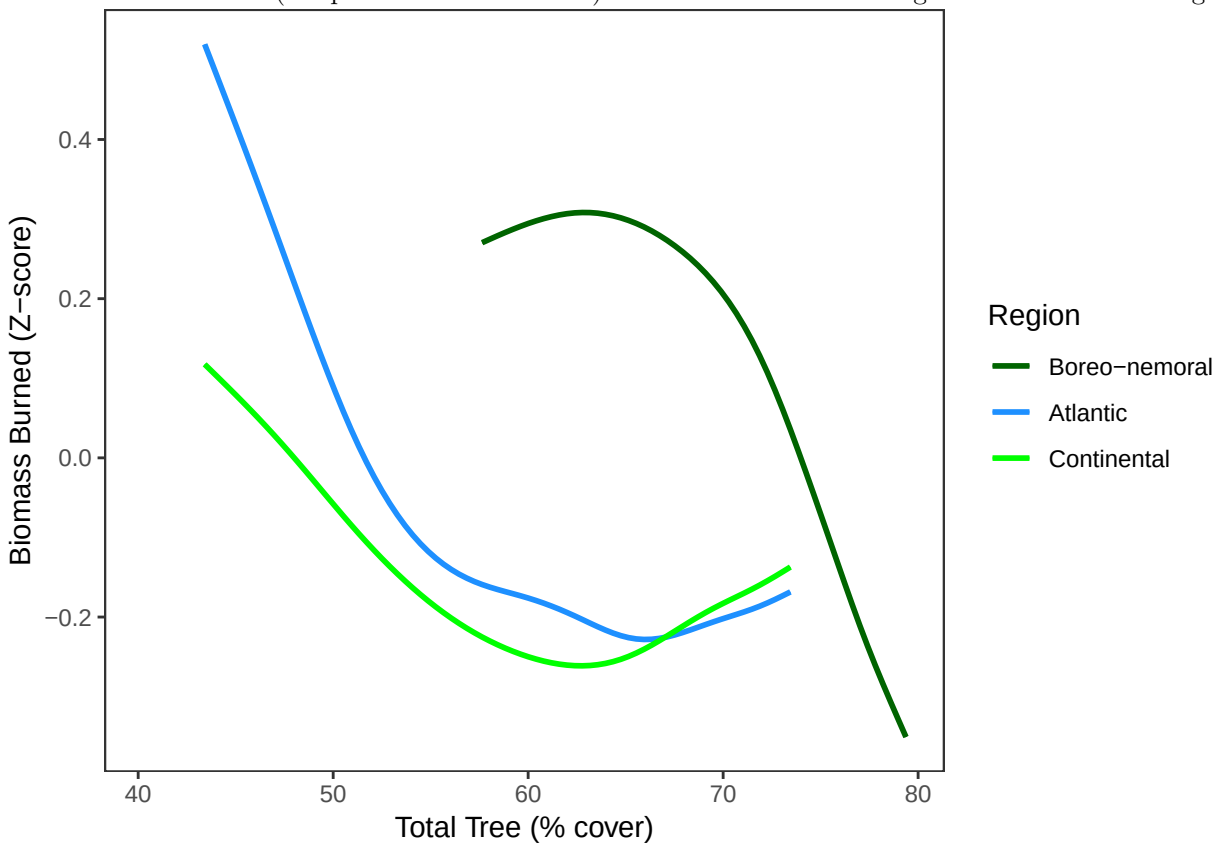
```
summary(totaltree.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(SumoftotalforestclosedtoLCCs) + s(Temperature) +
##     s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.02026  -10.38 5.78e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                   edf Ref.df     F  p-value
## s(SumoftotalforestclosedtoLCCs) 2.547      9 3.234 6.42e-07 ***
## s(Temperature)                  2.024      9 1.025 0.004113 **
## s(P.PET)                        2.346      9 1.909 0.000148 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.669   Deviance explained = 69.8%
## -REML = -12.503  Scale est. = 0.032836  n = 80
```

Total tree cover plot

Here we show the marginal response of biomass burned to total tree cover in each region, holding the climate variables (temperature and P-PET) constant at their average value over each region.

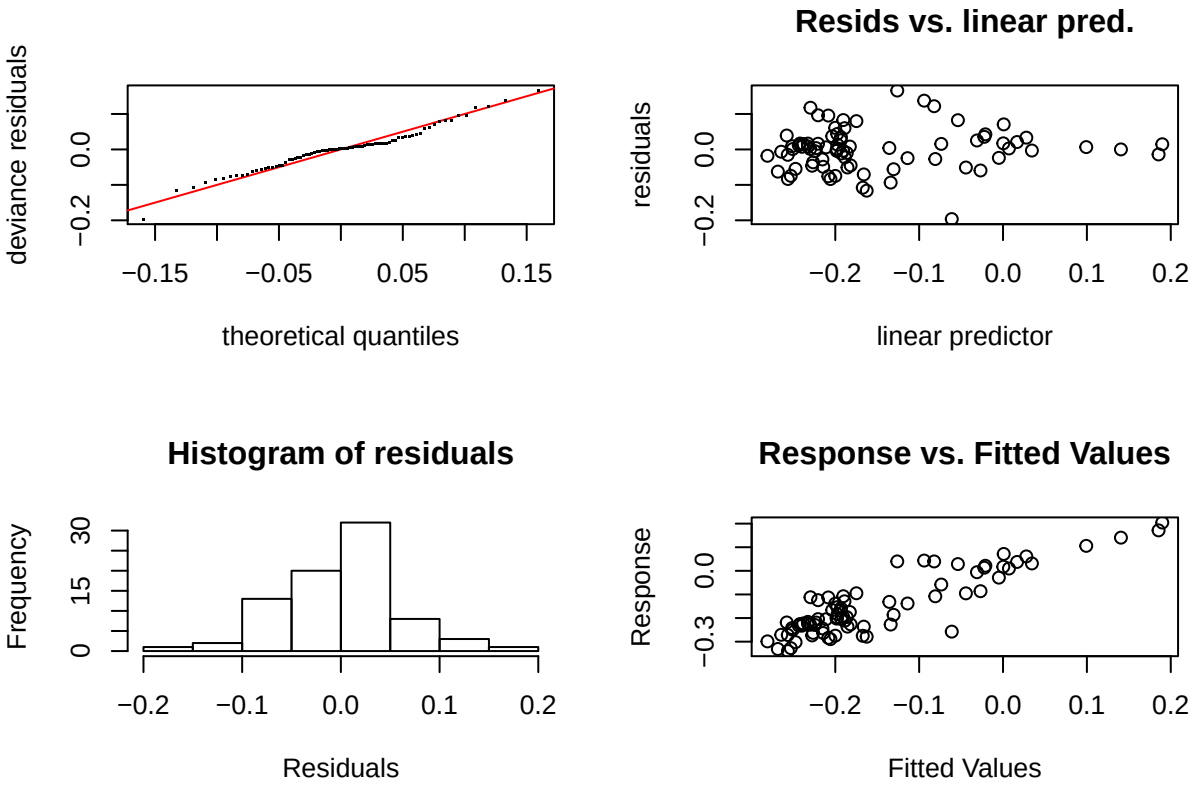



```
## pdf
##   2
```

Broadleaf tree cover

Broadleaf tree cover, Continental ecoregion

```
broad.continental <- gam(Charcoal ~ s(Broadleafforestin) + s(Temperature)  + s(P.PET), data = AllEurope
# Checking broad.continental
gam.check(broad.continental)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 8 iterations.
## Gradient range [-2.18593e-05,9.138687e-06]
## (score -87.9711 & scale 0.004071206).
## Hessian positive definite, eigenvalue range [4.691582e-07,39.76897].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                         k'  edf k-index p-value
## s(Broadleafforestin) 9.00 4.14    1.21    0.97
## s(Temperature)       9.00 4.92    1.05    0.65
## s(P.PET)             9.00 1.25    1.00    0.38
```

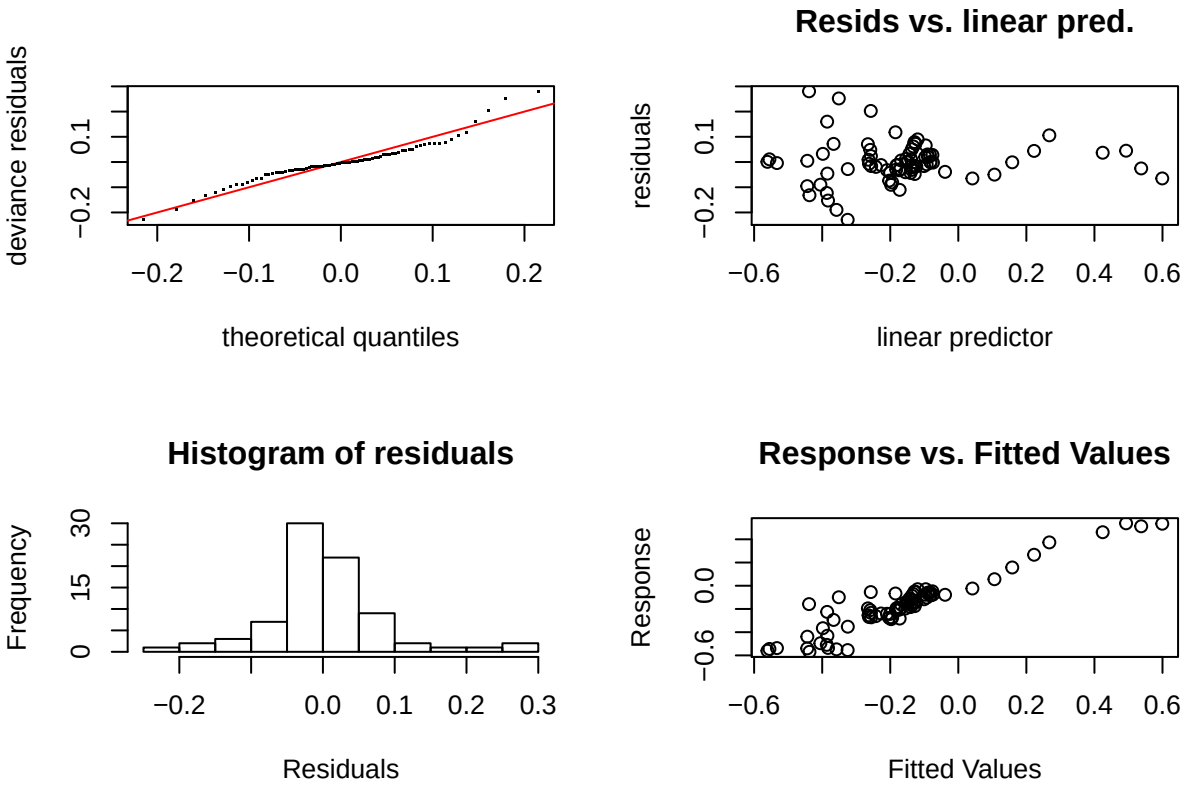
```
summary(broad.continental)
```

```
##
## Family: gaussian
## Link function: identity
```

```
##
## Formula:
## Charcoal ~ s(Broadleafforestin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.149423   0.007134  -20.95   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                          edf Ref.df     F  p-value
## s(Broadleafforestin) 4.142      9 9.222 6.54e-15 ***
## s(Temperature)       4.923      9 2.271 0.000542 ***
## s(P.PET)             1.248      9 0.416 0.049588 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.754   Deviance explained = 78.6%
## -REML = -87.971  Scale est. = 0.0040712  n = 80
```

Broadleaf tree cover, Atlantic ecoregion

```
broad.atlantic <- gam(Charcoal ~ s(Broadleafforestin) + s(Temperature)  + s(P.PET), data = AllEurope[Al
# Checking broad.atlantic
gam.check(broad.atlantic)
```




```
##
```

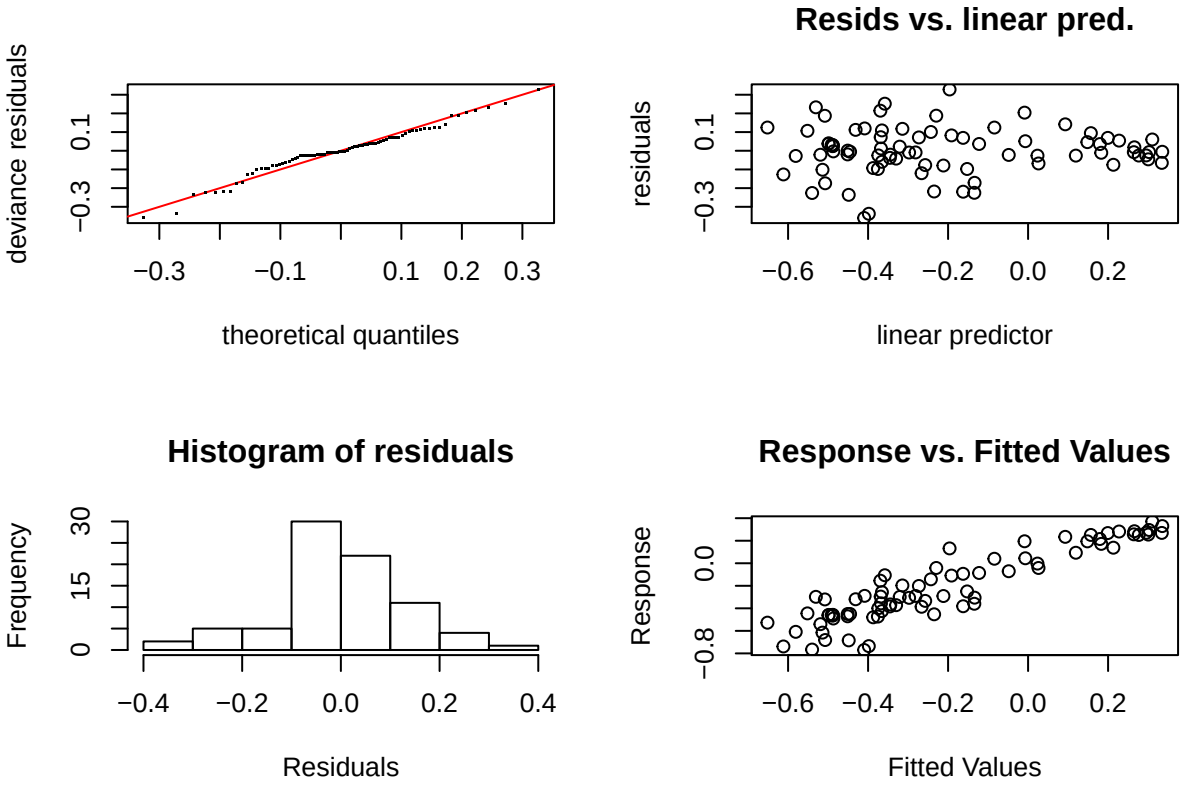
```
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-2.114109e-05,2.745618e-05]
## (score -61.12791 & scale 0.00741223).
## Hessian positive definite, eigenvalue range [4.647857e-07,39.8619].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                            k'      edf k-index p-value
## s(Broadleafforestin) 9.000000 7.813265    1.16    0.91
## s(Temperature)       9.000000 1.147403    1.24    0.98
## s(P.PET)             9.000000 0.000102    1.17    0.92
```

```
summary(broad.atlantic)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Broadleafforestin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.161603   0.009626  -16.79   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                            edf Ref.df      F p-value
## s(Broadleafforestin) 7.8132646      9 38.200  <2e-16 ***
## s(Temperature)       1.1474031      9  0.243   0.137
## s(P.PET)             0.0001023      9  0.000   0.509
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.869   Deviance explained = 88.4%
## -REML = -61.128  Scale est. = 0.0074122  n = 80
```

Broadleaf tree cover, Boreo-Nemoral ecoregion

```
broad.boreonemoral <- gam(Charcoal ~ s(Broadleafforestin) + s(Temperature)  + s(P.PET), data = AllEurop
# Checking broad.boreonemoral
gam.check(broad.boreonemoral)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-1.643455e-05,2.894894e-05]
## (score -36.93374 & scale 0.01706061).
## Hessian positive definite, eigenvalue range [6.704241e-07,39.64722].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                            k'      edf k-index p-value
## s(Broadleafforestin) 9.00e+00 4.12e+00    1.14    0.82
## s(Temperature)       9.00e+00 9.05e-05    0.87    0.07 .
## s(P.PET)             9.00e+00 2.74e+00    1.05    0.63
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

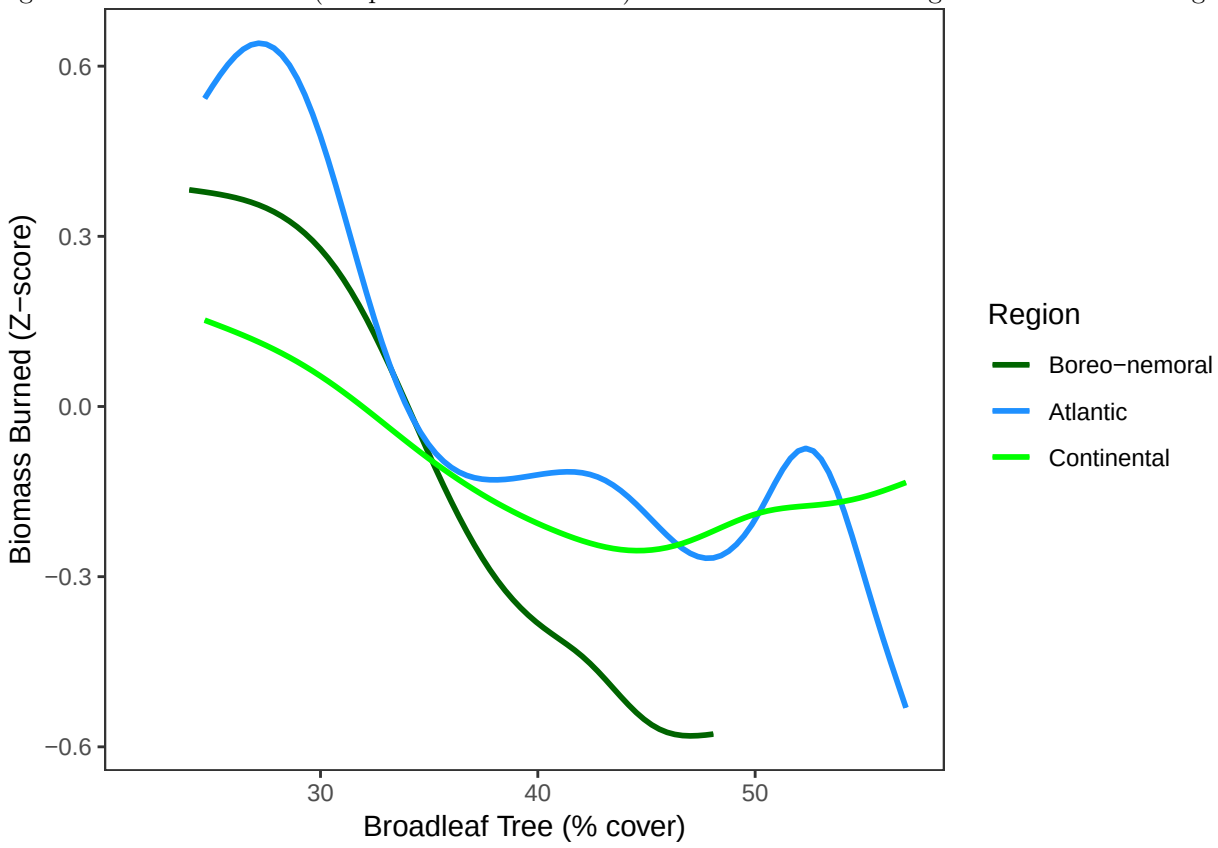
```
summary(broad.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Broadleafforestin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -0.2104     0.0146  -14.41   <2e-16 ***
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                             edf Ref.df      F  p-value
## s(Broadleafforestin) 4.123e+00      9 22.479  < 2e-16 ***
## s(Temperature)       9.049e-05      9  0.000    0.515
## s(P.PET)             2.740e+00      9  5.693 1.97e-10 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.828   Deviance explained = 84.3%
## -REML = -36.934  Scale est. = 0.017061  n = 80
```

Broadleaf tree cover plot

Here we show the marginal response of biomass burned to broadleaf forest cover in each region, holding the climate variables (temperature and P-PET) constant at their average value over each region.

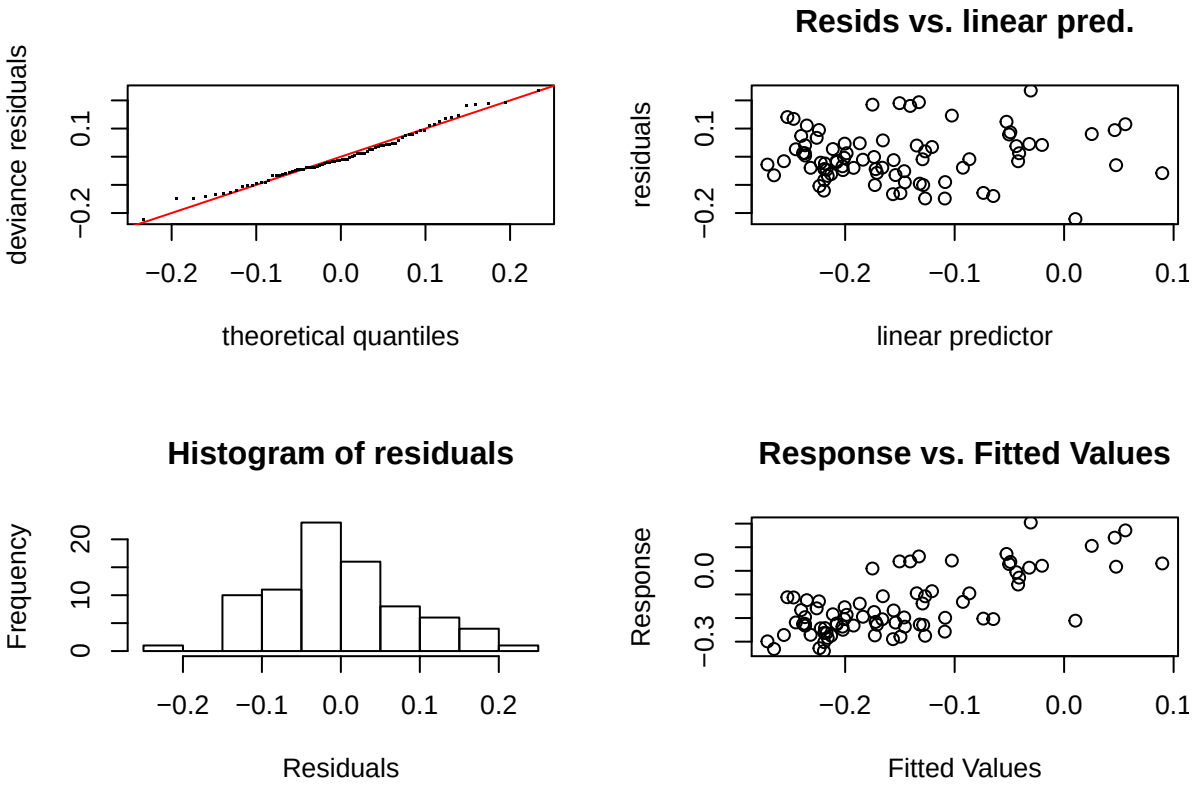



```
## pdf
##   2
```

Needleleaf tree cover

Needleleaf tree cover, Continental ecoregion

```
needle.continental <- gam(Charcoal ~ s(Needleleafforestin) + s(Temperature)  + s(P.PET), data = AllEuro
# Checking needle.continental
gam.check(needle.continental)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-3.671855e-05,3.482512e-05]
## (score -67.52341 & scale 0.008724176).
## Hessian positive definite, eigenvalue range [5.017568e-07,39.55758].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                          k'   edf k-index p-value
## s(Needleleafforestin) 9.000 0.607    1.12    0.84
## s(Temperature)        9.000 2.767    0.99    0.42
## s(P.PET)              9.000 0.922    1.26    0.99
```

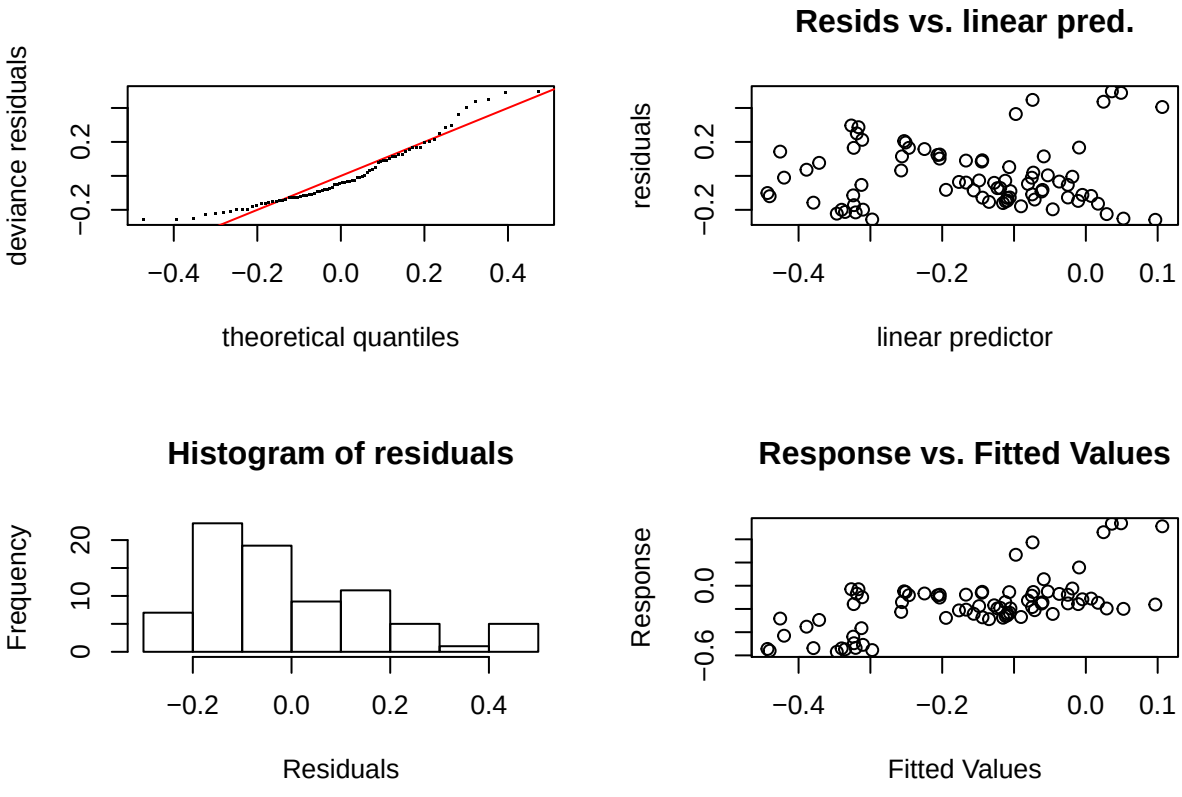
```
summary(needle.continental)
```

```
##
## Family: gaussian
## Link function: identity
```

```
##
## Formula:
## Charcoal ~ s(Needleleafforestin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.14942    0.01044  -14.31   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                           edf Ref.df     F  p-value
## s(Needleleafforestin) 0.6073      9 0.082  0.26172
## s(Temperature)        2.7671      9 3.920 5.58e-08 ***
## s(P.PET)              0.9223      9 1.316  0.00038 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.472   Deviance explained = 50.1%
## -REML = -67.523  Scale est. = 0.0087242  n = 80
```

Needleleaf tree cover, Atlantic ecoregion

```
needle.atlantic <- gam(Charcoal ~ s(Needleleafforestin) + s(Temperature)  + s(P.PET), data = AllEurope[A
# Checking needle.atlantic
gam.check(needle.atlantic)
```




```
##
```

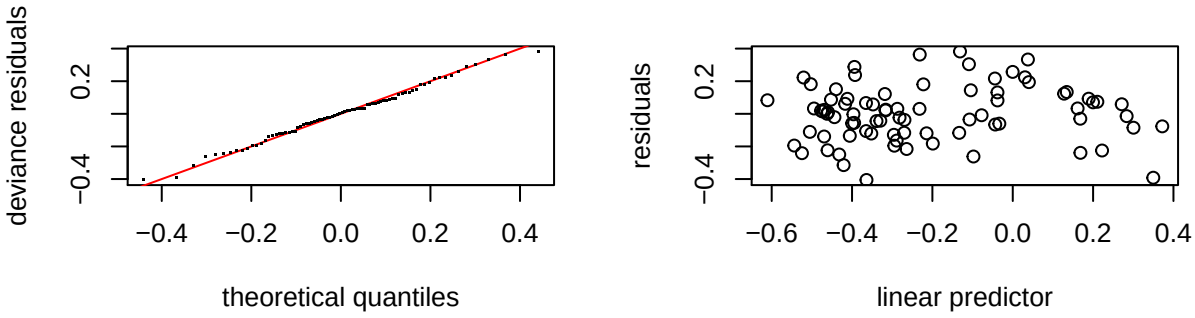
```
## Method: REML   Optimizer: outer newton
## full convergence after 14 iterations.
## Gradient range [-5.809434e-06,4.591029e-06]
## (score -13.90265 & scale 0.03579219).
## Hessian positive definite, eigenvalue range [1.275032e-07,39.51623].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                           k'   edf k-index p-value
## s(Needleleafforestin) 9.000 0.539    0.86    0.12
## s(Temperature)        9.000 1.305    0.82    0.03 *
## s(P.PET)              9.000 1.122    0.94    0.29
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

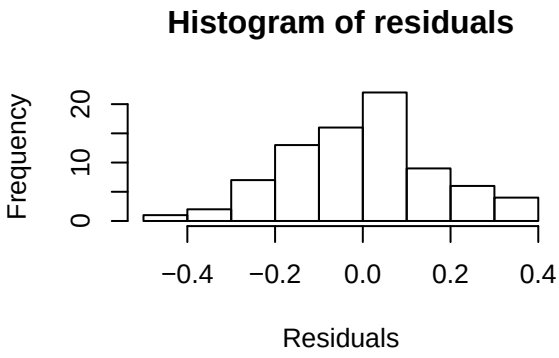
```
summary(needle.atlantic)
```

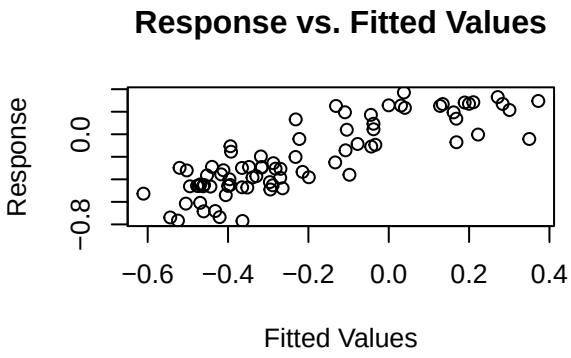
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Needleleafforestin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.02115   -7.64 5.35e-11 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                           edf Ref.df     F  p-value
## s(Needleleafforestin) 0.5387      9 0.130    0.126
## s(Temperature)        1.3051      9 3.911 2.15e-08 ***
## s(P.PET)              1.1223      9 0.191    0.199
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.367   Deviance explained = 39.1%
## -REML = -13.903  Scale est. = 0.035792  n = 80
```

Needleleaf tree cover, Boreo-Nemoral ecoregion

```
needle.boreonemoral <- gam(Charcoal ~ s(Needleleafforestin) + s(Temperature)  + s(P.PET), data = AllEur
# Checking needle.boreonemoral
gam.check(needle.boreonemoral)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 8 iterations.
## Gradient range [-4.91621e-06,4.841804e-06]
## (score -13.52827 & scale 0.03114691).
## Hessian positive definite, eigenvalue range [4.916201e-06,39.60288].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                         k'  edf k-index p-value
## s(Needleleafforestin) 9.00 1.85    0.99    0.47
## s(Temperature)        9.00 3.22    0.92    0.24
## s(P.PET)              9.00 2.26    0.99    0.43
```

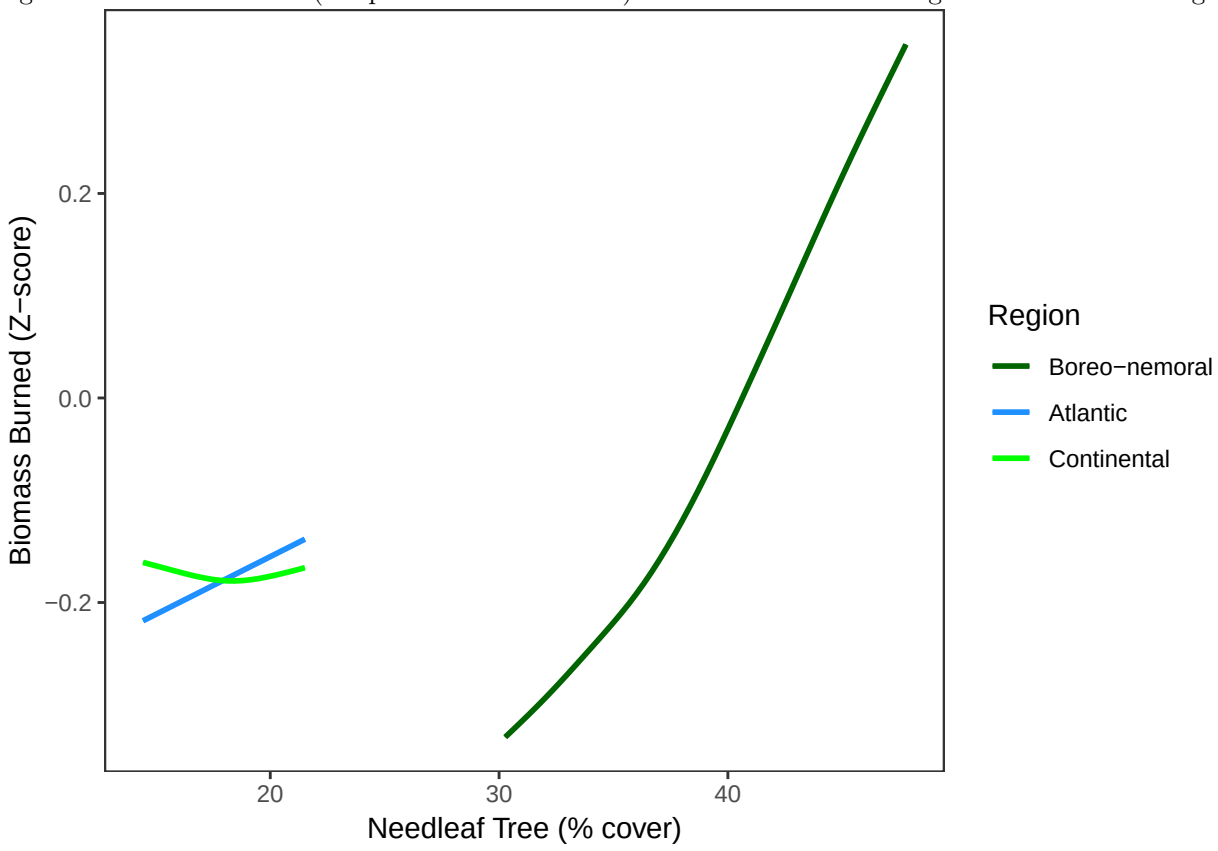
```
summary(needle.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Needleleafforestin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.01973  -10.66   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## Approximate significance of smooth terms:
##                           edf Ref.df     F  p-value
## s(Needleleafforestin) 1.849      9 3.114 5.79e-07 ***
## s(Temperature)        3.218      9 3.761 1.73e-07 ***
## s(P.PET)              2.261      9 2.384 1.94e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.686   Deviance explained = 71.5%
## -REML = -13.528  Scale est. = 0.031147  n = 80
```

Needleleaf tree cover plot

Here we show the marginal response of biomass burned to needleleaf forest cover in each region, holding the climate variables (temperature and P-PET) constant at their average value over each region.

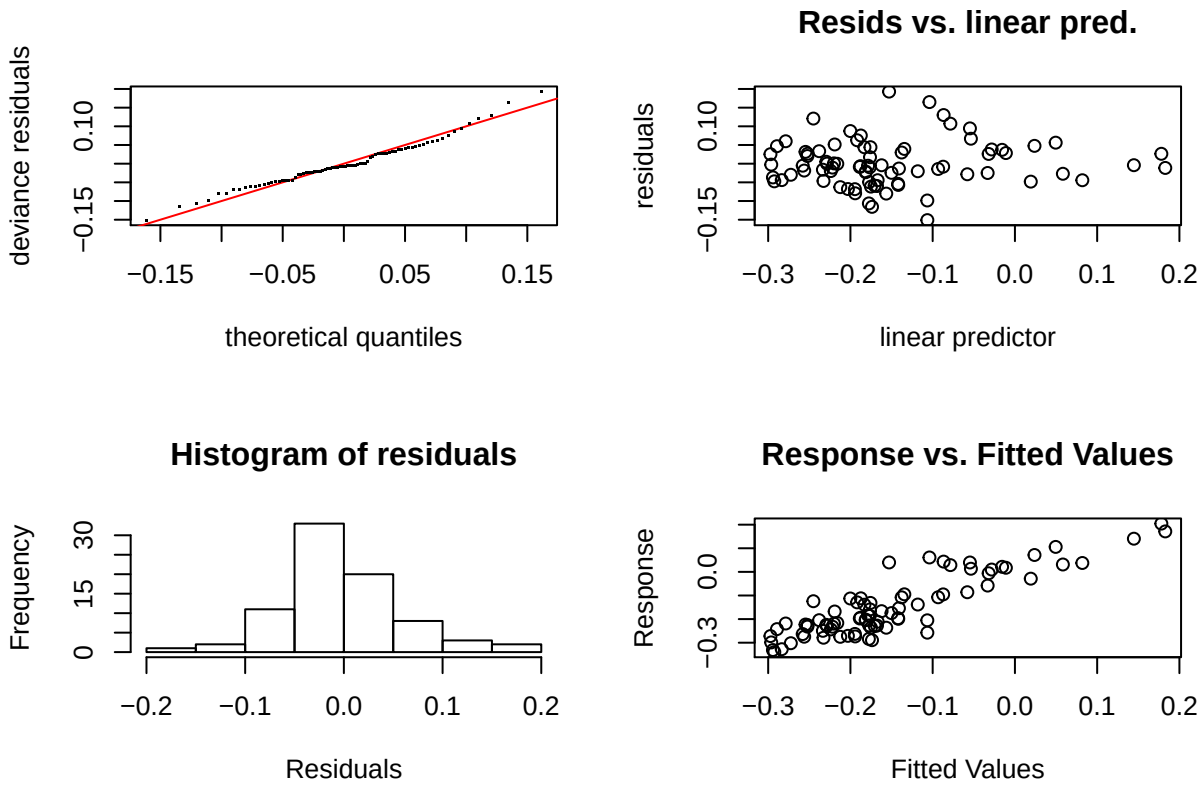



```
## pdf
##   2
```

Heath/Scrubland

Heath/Scrubland, Continental ecoregion

```r
scrub.continental <- gam(Charcoal ~ s(Heathscrublandin) + s(Temperature)  + s(P.PET), data = AllEurope[
# Checking scrub.continental
gam.check(scrub.continental)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 9 iterations.
## Gradient range [-1.181102e-05,6.144709e-06]
## (score -89.14724 & scale 0.0041755).
## Hessian positive definite, eigenvalue range [2.749896e-06,39.70913].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                       k'  edf k-index p-value
## s(Heathscrublandin) 9.00 3.80    0.99    0.38
## s(Temperature)      9.00 4.11    1.08    0.74
## s(P.PET)            9.00 1.39    1.07    0.69
```

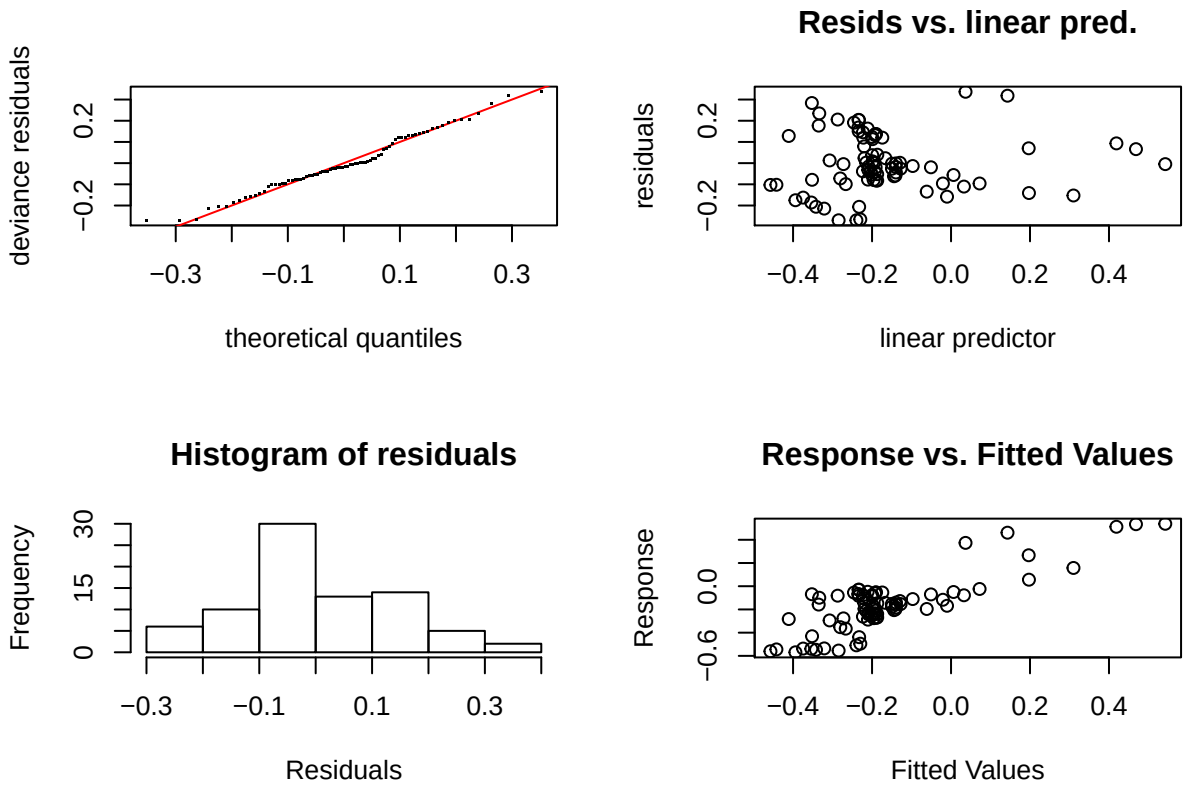
```r
summary(scrub.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Heathscrublandin) + s(Temperature) + s(P.PET)
##
```

```
## Parametric coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.149423   0.007225  -20.68   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                        edf Ref.df     F  p-value
## s(Heathscrublandin) 3.798      9 9.096  4.4e-15 ***
## s(Temperature)      4.115      9 2.478 0.000104 ***
## s(P.PET)            1.395      9 0.580 0.022575 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.747   Deviance explained = 77.7%
## -REML = -89.147  Scale est. = 0.0041755  n = 80
```

Heath/Scrubland, Atlantic ecoregion

```
scrub.atlantic <- gam(Charcoal ~ s(Heathscrublandin) + s(Temperature)  + s(P.PET), data = AllEurope[All
# Checking scrub.atlantic
gam.check(scrub.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-1.27329e-05,3.21502e-05]
## (score -32.60928 & scale 0.01988639).
```

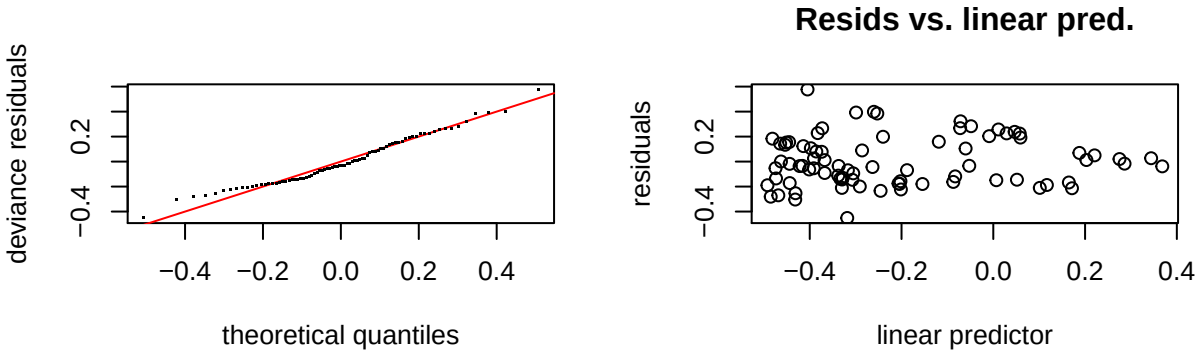
```
## Hessian positive definite, eigenvalue range [0.001578365,39.57095].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                         k'   edf k-index p-value
## s(Heathscrublandin) 9.000 3.333    1.23    0.96
## s(Temperature)      9.000 0.972    1.26    0.99
## s(P.PET)            9.000 1.850    1.02    0.51
```

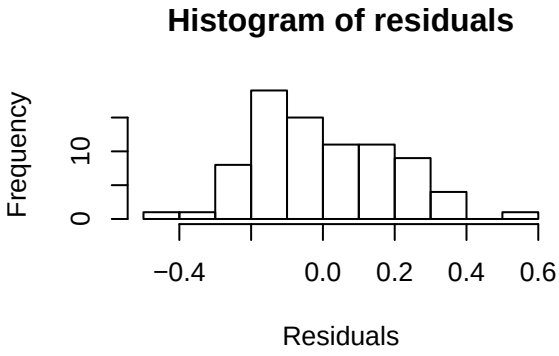
```
summary(scrub.atlantic)
```

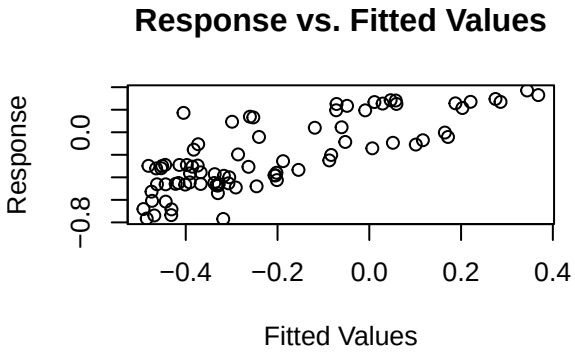
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Heathscrublandin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.01577  -10.25 9.03e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                         edf Ref.df     F  p-value
## s(Heathscrublandin) 3.3330      9 8.158 7.97e-15 ***
## s(Temperature)      0.9719      9 0.191  0.13929
## s(P.PET)            1.8497      9 1.009  0.00417 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.648   Deviance explained = 67.6%
## -REML = -32.609  Scale est. = 0.019886  n = 80
```

Heath/Scrubland, Boreo-Nemoral ecoregion

```
scrub.boreonemoral <- gam(Charcoal ~ s(Heathscrublandin) + s(Temperature)  + s(P.PET), data = AllEurope
# Checking scrub.boreonemoral
gam.check(scrub.boreonemoral)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 15 iterations.
## Gradient range [-1.919209e-06,1.541329e-06]
## (score -4.275707 & scale 0.04116738).
## Hessian positive definite, eigenvalue range [5.868978e-08,39.60019].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                        k'   edf k-index p-value
## s(Heathscrublandin) 9.000 0.668    0.85   0.045 *
## s(Temperature)      9.000 3.190    0.91   0.205
## s(P.PET)            9.000 2.216    1.16   0.910
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

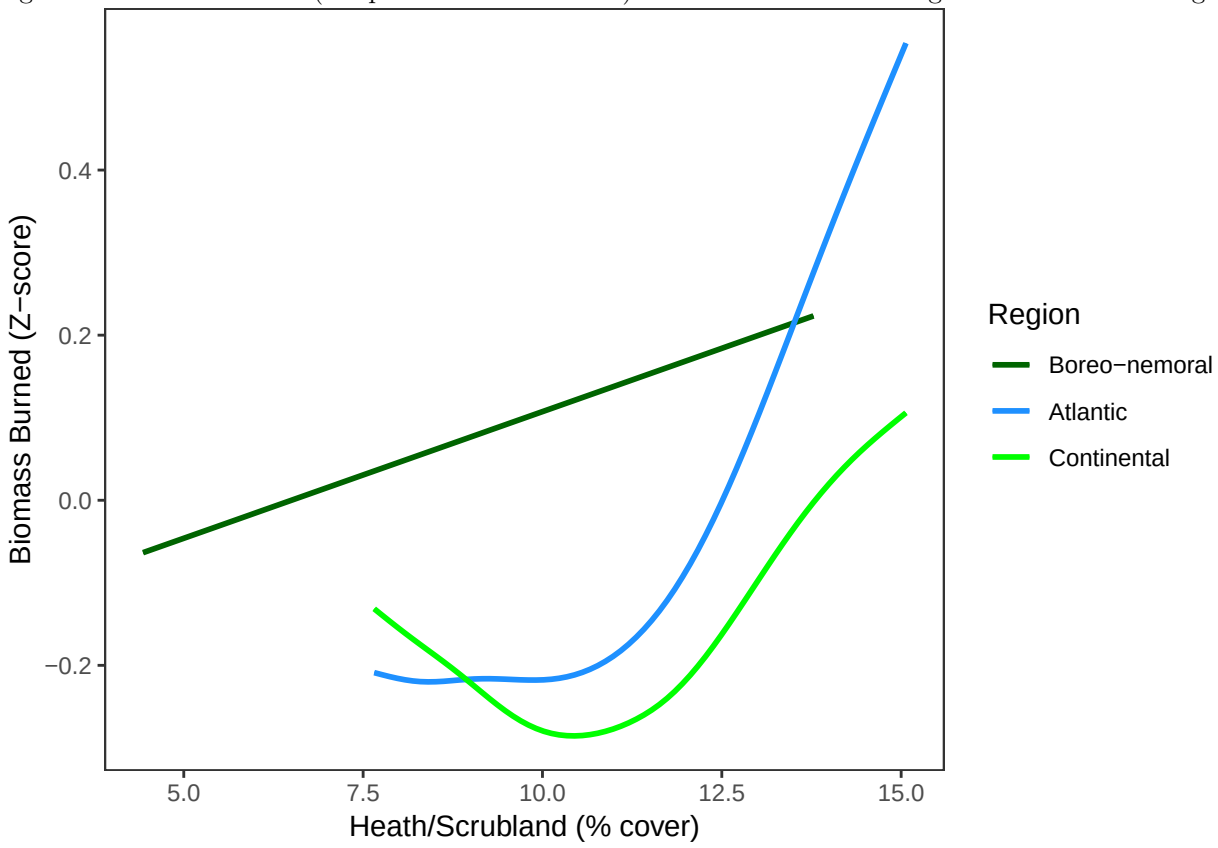
```
summary(scrub.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Heathscrublandin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.02268  -9.274 5.77e-14 ***
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                        edf Ref.df     F  p-value
## s(Heathscrublandin) 0.668      9 0.224 0.072065 .
## s(Temperature)      3.190      9 2.865 4.89e-06 ***
## s(P.PET)            2.216      9 1.728 0.000305 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.585   Deviance explained = 61.7%
## -REML = -4.2757  Scale est. = 0.041167  n = 80
```

Heath/Scrubland cover plot

Here we show the marginal response of biomass burned to Heath/Scrubland cover in each region, holding the climate variables (temperature and P-PET) constant at their average value over each region.

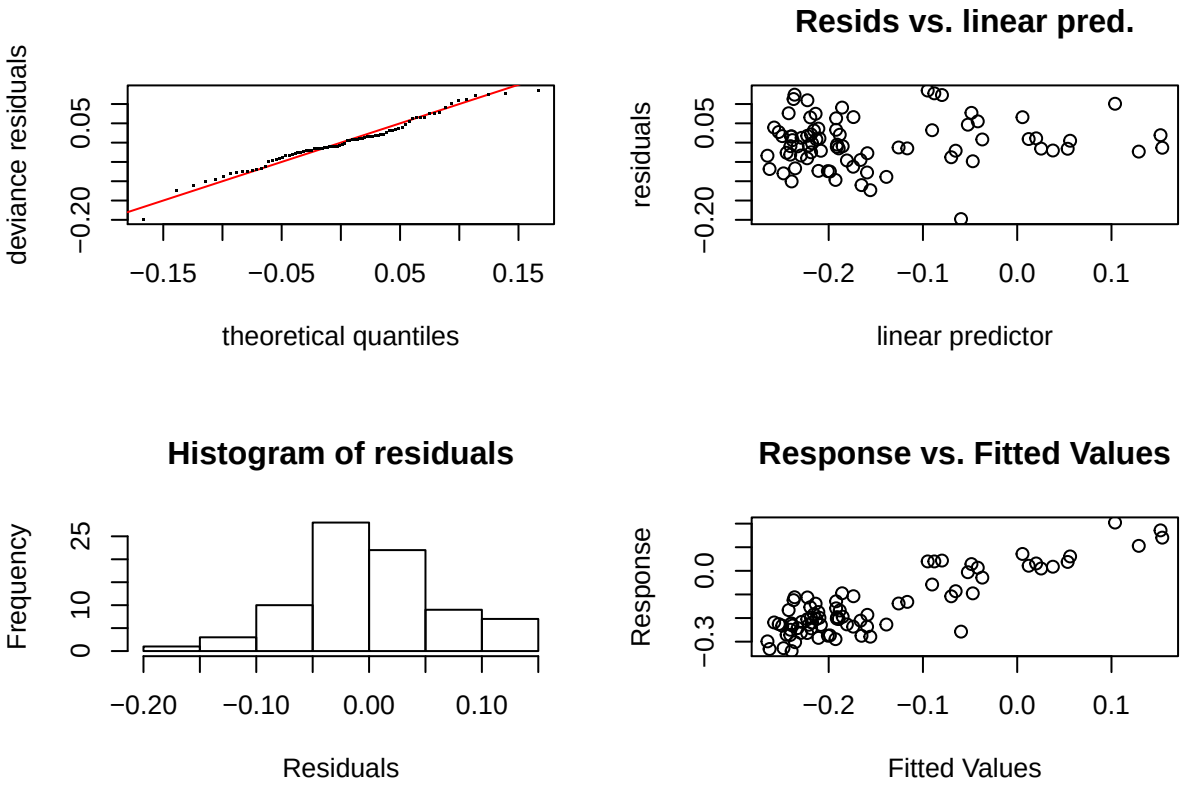



```
## pdf
##   2
```

Arable/disturbed land

Arable/disturbed land, Continental ecoregion

```
arable.continental <- gam(Charcoal ~ s(Arabledisturbedlandin) + s(Temperature)  + s(P.PET), data = AllEu
# Checking arable.continental
gam.check(arable.continental)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 15 iterations.
## Gradient range [-4.11805e-05,0.0002885247]
## (score -86.15972 & scale 0.004454921).
## Hessian positive definite, eigenvalue range [1.627516e-06,39.73204].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                              k'   edf k-index p-value
## s(Arabledisturbedlandin) 9.000 3.115    0.73   0.005 **
## s(Temperature)           9.000 5.106    1.05   0.620
## s(P.PET)                 9.000 0.821    1.01   0.535
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

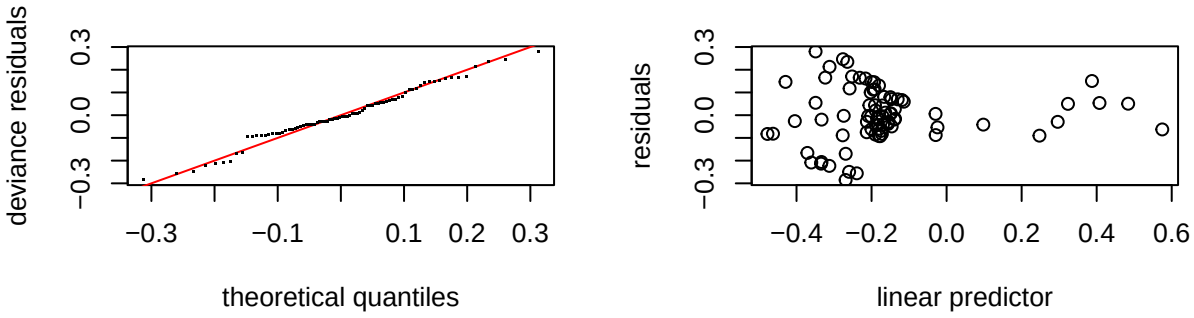
```
summary(arable.continental)
```

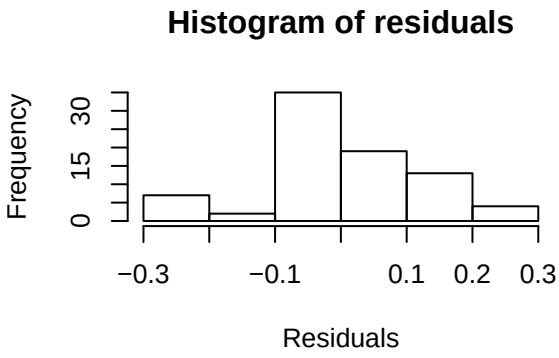
```
##
```

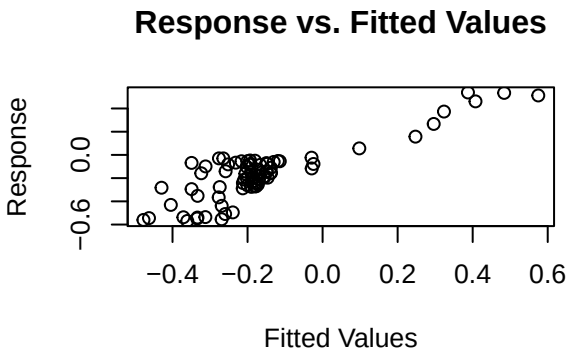
```
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Arabledisturbedlandin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.149423   0.007462  -20.02   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                              edf Ref.df     F  p-value
## s(Arabledisturbedlandin) 3.1148      9 7.578 3.23e-13 ***
## s(Temperature)           5.1063      9 2.177 0.000973 ***
## s(P.PET)                 0.8213      9 0.509 0.019546 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =   0.73   Deviance explained = 76.1%
## -REML = -86.16  Scale est. = 0.0044549  n = 80
```

Arable/disturbed land, Atlantic ecoregion

```
arable.atlantic <- gam(Charcoal ~ s(Arabledisturbedlandin) + s(Temperature)  + s(P.PET), data = AllEurop
# Checking arable.atlantic
gam.check(arable.atlantic)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 14 iterations.
## Gradient range [-8.165404e-06,1.135047e-05]
## (score -38.26363 & scale 0.01565882).
## Hessian positive definite, eigenvalue range [0.0254846,39.6302].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                            k'  edf k-index p-value
## s(Arabledisturbedlandin) 9.00 4.64    0.68  <2e-16 ***
## s(Temperature)           9.00 1.99    1.31    1.00
## s(P.PET)                 9.00 1.65    1.05    0.66
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

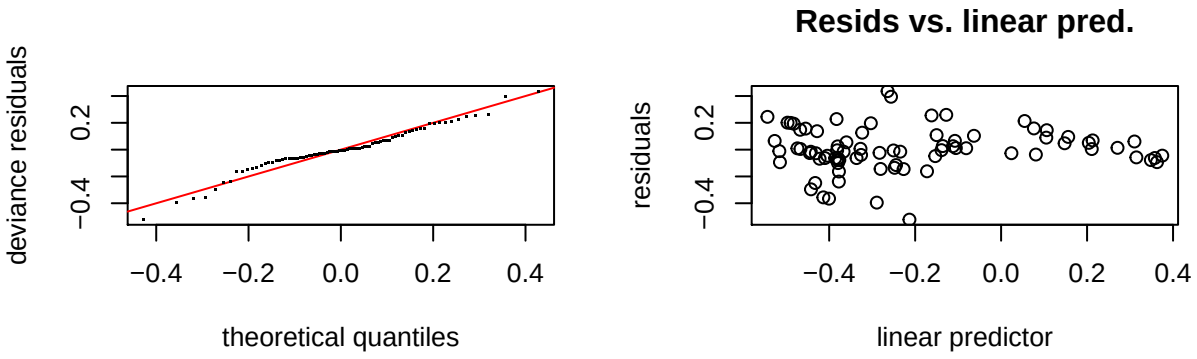
```
summary(arable.atlantic)
```

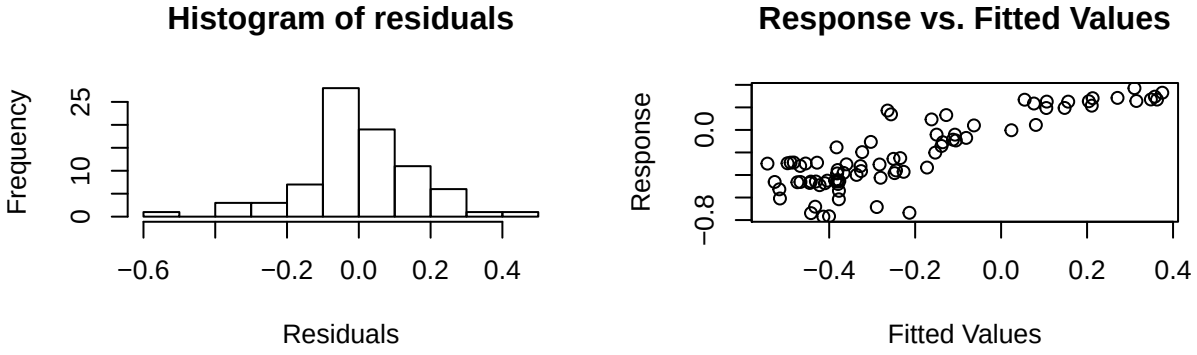
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Arabledisturbedlandin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.01399  -11.55   <2e-16 ***
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                              edf Ref.df      F p-value
## s(Arabledisturbedlandin) 4.641      9 11.208 < 2e-16 ***
## s(Temperature)           1.992      9  0.938 0.00519 **
## s(P.PET)                 1.647      9  0.618 0.02552 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.723   Deviance explained = 75.2%
## -REML = -38.264  Scale est. = 0.015659  n = 80
```

Arable/disturbed land, Boreo-Nemoral ecoregion

```
arable.boreonemoral <- gam(Charcoal ~ s(Arabledisturbedlandin) + s(Temperature)  + s(P.PET), data = All
# Checking arable.boreonemoral
gam.check(arable.boreonemoral)
```






```
##
## Method: REML   Optimizer: outer newton
## full convergence after 8 iterations.
## Gradient range [-1.065331e-05,2.773487e-05]
## (score -15.94575 & scale 0.02931754).
## Hessian positive definite, eigenvalue range [5.096656e-07,39.62093].
## Model rank =  28 / 28
##
```

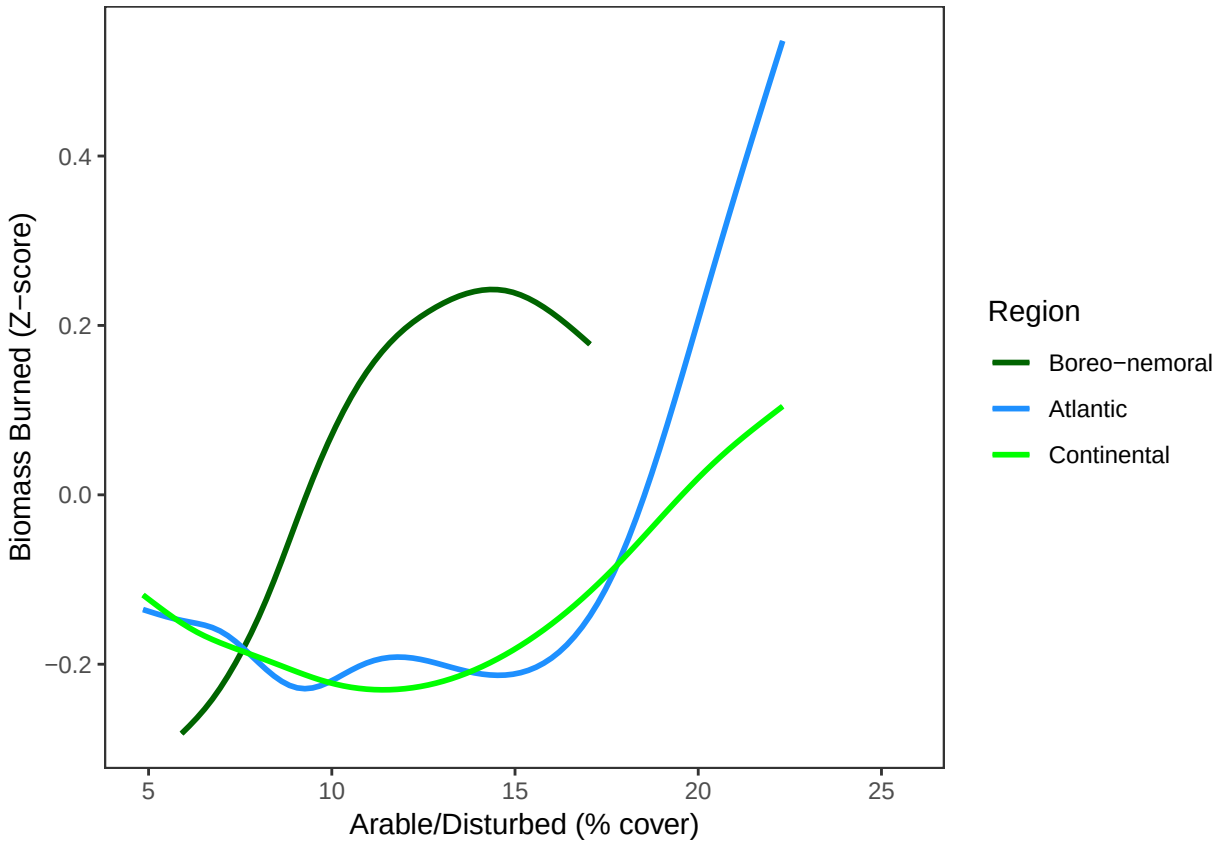
```
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                             k'  edf k-index p-value
## s(Arabledisturbedlandin) 9.00 2.53    1.06    0.67
## s(Temperature)           9.00 2.55    0.97    0.43
## s(P.PET)                 9.00 2.47    1.11    0.83
```

```
summary(arable.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Arabledisturbedlandin) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.01914  -10.99   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                             edf Ref.df     F  p-value
## s(Arabledisturbedlandin) 2.527      9 4.116 2.15e-08 ***
## s(Temperature)           2.545      9 2.087 6.59e-05 ***
## s(P.PET)                 2.469      9 1.382  0.00201 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.704   Deviance explained = 73.2%
## -REML = -15.946  Scale est. = 0.029318  n = 80
```

Arable/disturbed land cover plot

Here we show the marginal response of biomass burned to arable and arable cover in each region, holding the climate variables (temperature and P-PET) constant at their average value over each region.

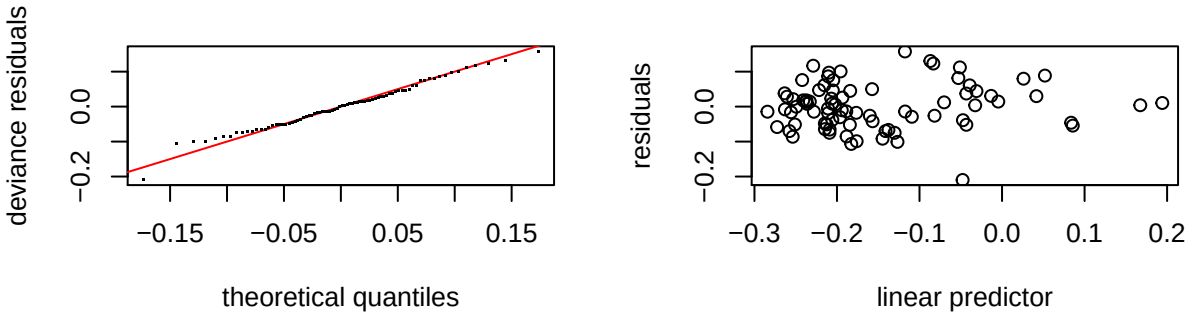


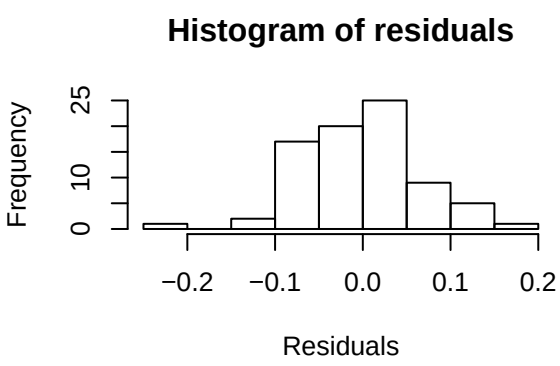

```
## pdf
##   2
```

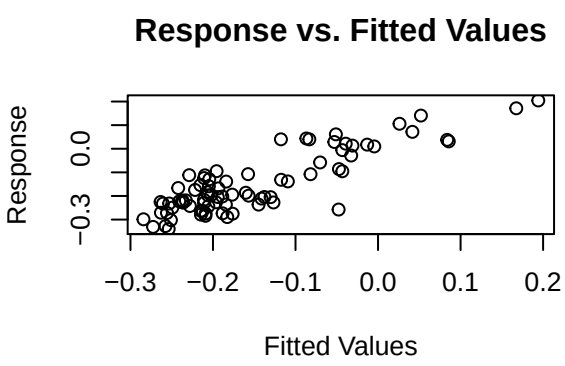
Grassland/pasture

Grassland/pasture cover, Continental ecoregion

```
pasture.continental <- gam(Charcoal ~ s(Pasturenaturalgrassla) + s(Temperature)  + s(P.PET), data = All
# Checking pasture.continental
gam.check(pasture.continental)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 12 iterations.
## Gradient range [-2.939047e-05,0.0001116154]
## (score -81.80595 & scale 0.004819602).
## Hessian positive definite, eigenvalue range [1.936251e-06,39.72786].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                              k'   edf k-index p-value
## s(Pasturenaturalgrassla) 9.000 4.567    1.14    0.84
## s(Temperature)           9.000 4.456    1.05    0.56
## s(P.PET)                 9.000 0.842    1.09    0.81
```

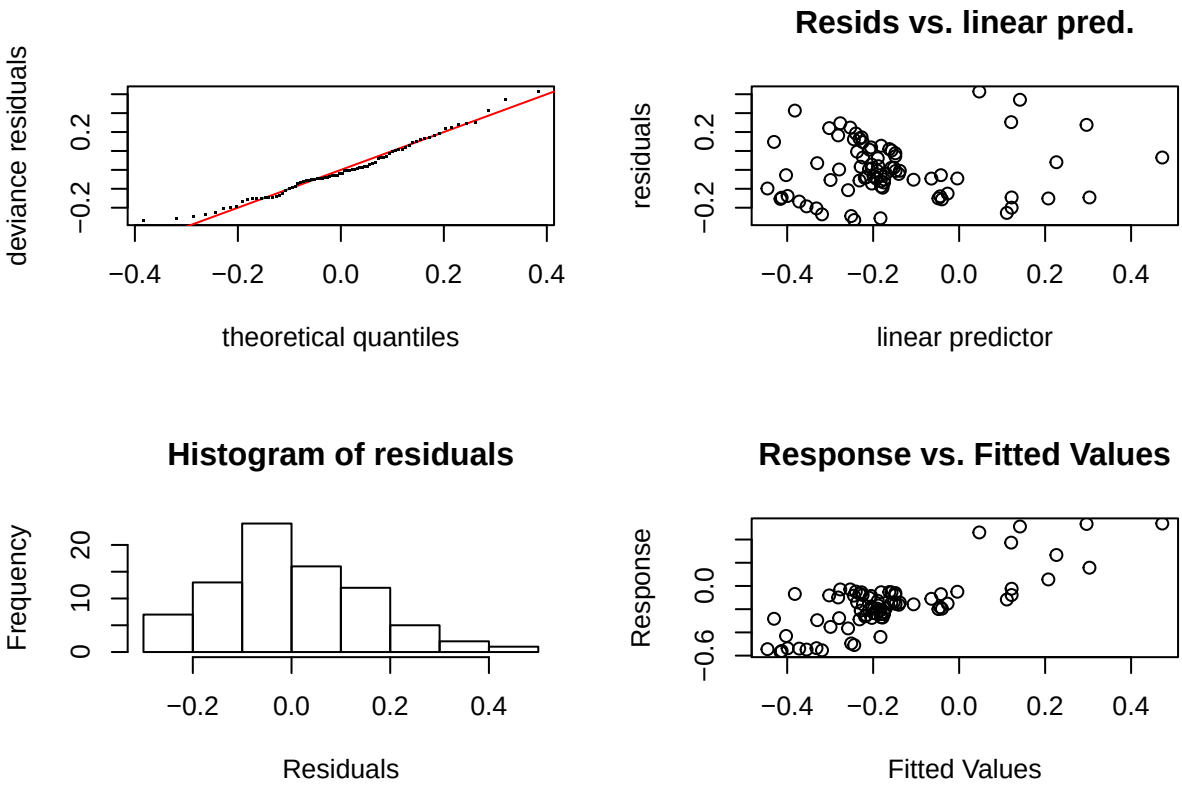
```
summary(pasture.continental)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Pasturenaturalgrassla) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.149423   0.007762  -19.25   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## Approximate significance of smooth terms:
##                               edf Ref.df     F  p-value
## s(Pasturenaturalgrassla) 4.5668      9 6.567 1.34e-10 ***
## s(Temperature)           4.4562      9 2.981 3.00e-05 ***
## s(P.PET)                 0.8424      9 0.593   0.0132 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.708   Deviance explained = 74.5%
## -REML = -81.806  Scale est. = 0.0048196  n = 80
```

Grassland/pasture cover, Atlantic ecoregion

```
pasture.atlantic <- gam(Charcoal ~ s(Pasturenaturalgrassla) + s(Temperature)  + s(P.PET), data = AllEur
# Checking pasture.atlantic
gam.check(pasture.atlantic)
```




```
##
## Method: REML   Optimizer: outer newton
## full convergence after 14 iterations.
## Gradient range [-4.784535e-05,9.766556e-05]
## (score -26.69937 & scale 0.0235591).
## Hessian positive definite, eigenvalue range [7.398593e-06,39.5824].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
```

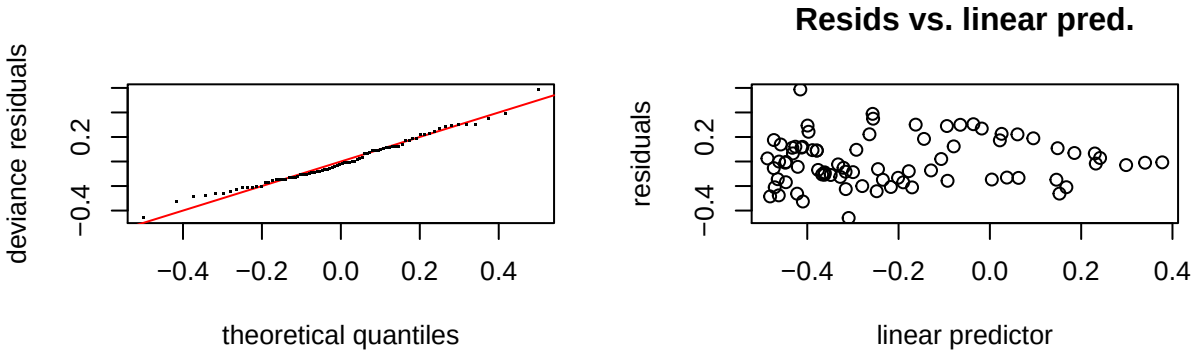
```
##
##                              k'   edf k-index p-value
## s(Pasturenaturalgrassla) 9.000 3.071    1.31    1.00
## s(Temperature)           9.000 0.779    1.10    0.82
## s(P.PET)                 9.000 1.931    1.01    0.48
```

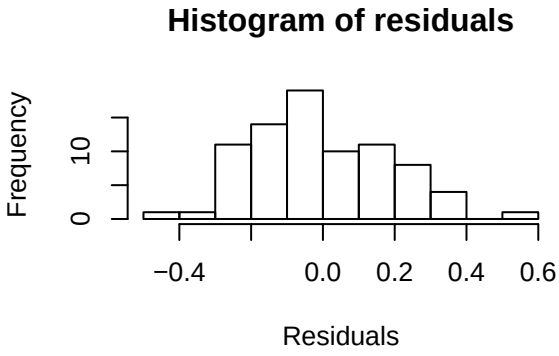
```
summary(pasture.atlantic)
```

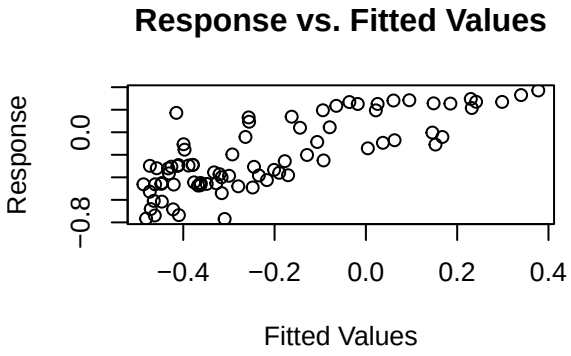
```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Pasturenaturalgrassla) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.16160    0.01716  -9.417    3e-14 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                              edf Ref.df     F  p-value
## s(Pasturenaturalgrassla) 3.0708      9 4.864 2.89e-09 ***
## s(Temperature)           0.7788      9 0.391  0.03113 *
## s(P.PET)                 1.9307      9 1.050  0.00455 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.583   Deviance explained = 61.4%
## -REML = -26.699  Scale est. = 0.023559  n = 80
```

Grassland/pasture cover, Boreo-Nemoral ecoregion

```
pasture.boreonemoral <- gam(Charcoal ~ s(Pasturenaturalgrassla) + s(Temperature)  + s(P.PET), data = Al
# Checking pasture.boreonemoral
gam.check(pasture.boreonemoral)
```








```
##
## Method: REML   Optimizer: outer newton
## full convergence after 10 iterations.
## Gradient range [-1.181911e-06,1.838096e-06]
## (score -4.663647 & scale 0.04010133).
## Hessian positive definite, eigenvalue range [9.603398e-07,39.60802].
## Model rank =  28 / 28
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                            k'  edf k-index p-value
## s(Pasturenaturalgrassla) 9.00 1.77    1.09    0.73
## s(Temperature)           9.00 2.98    0.90    0.15
## s(P.PET)                 9.00 2.17    1.15    0.91
```

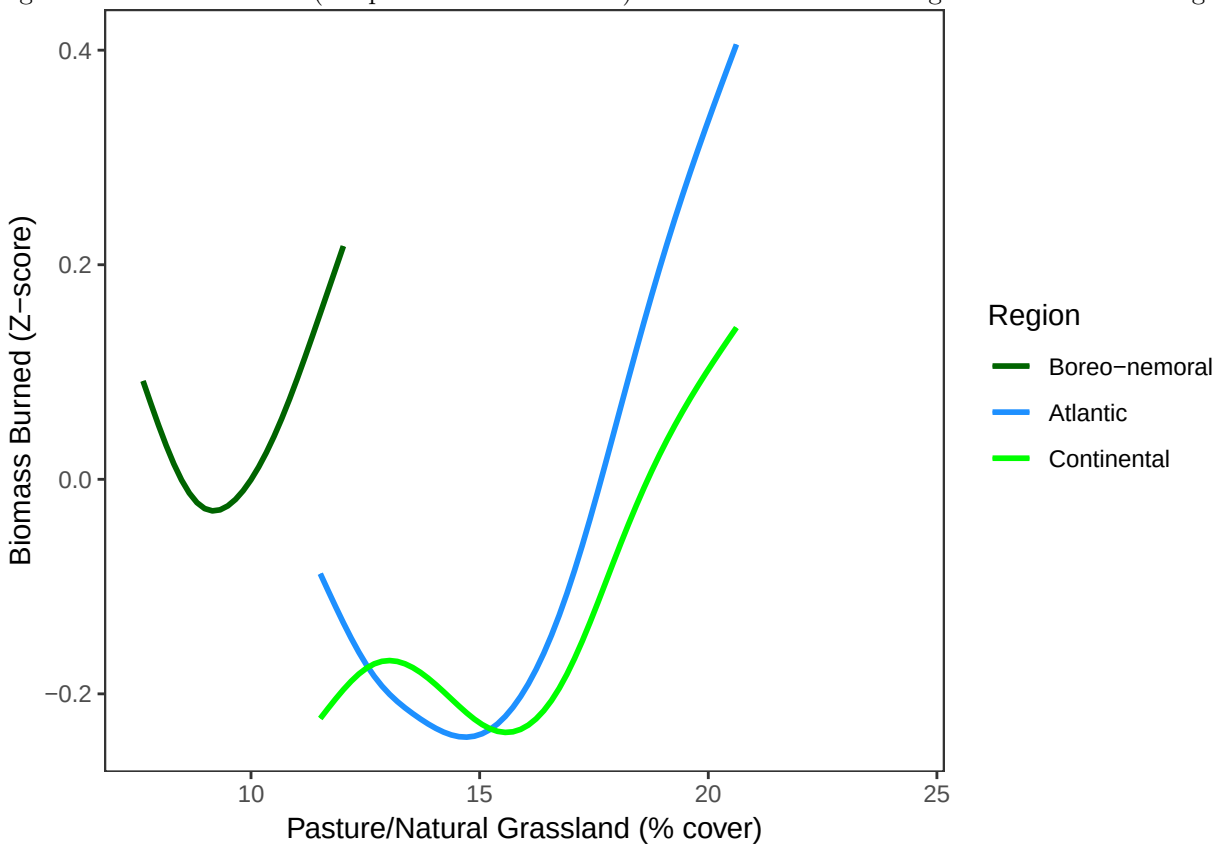
```
summary(pasture.boreonemoral)
```

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Charcoal ~ s(Pasturenaturalgrassla) + s(Temperature) + s(P.PET)
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.21038    0.02239  -9.396  3.8e-14 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
##
## Approximate significance of smooth terms:
##                              edf Ref.df     F  p-value
## s(Pasturenaturalgrassla) 1.769      9 0.580 0.042367 *
## s(Temperature)           2.983      9 3.632 2.32e-07 ***
## s(P.PET)                 2.171      9 1.573 0.000592 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.595   Deviance explained = 63.1%
## -REML = -4.6636  Scale est. = 0.040101  n = 80
```

Grassland/pasture cover plot

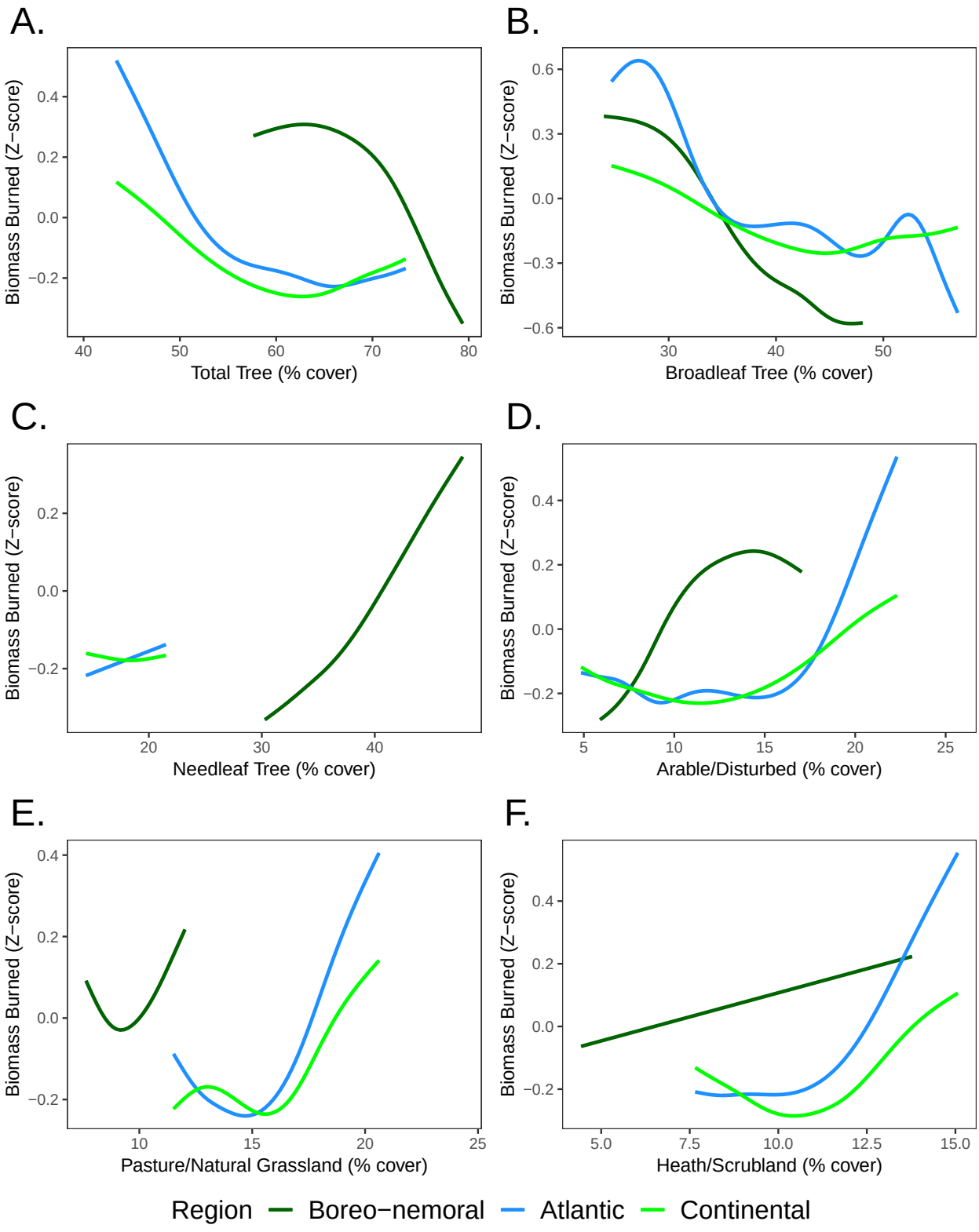
Here we show the marginal response of biomass burned to grassland/pasture cover in each region, holding the climate variables (temperature and P-PET) constant at their average value over each region.




```
## pdf
##   2
```

Plot the six landcover GAMs together (main manuscript figure)

```
## pdf
##   2
```


A.
B.
C.
D.
E.
F.
Biomass Burned (Z−score)
Total Tree (% cover)
Broadleaf Tree (% cover)
Needleaf Tree (% cover)
Arable/Disturbed (% cover)
Pasture/Natural Grassland (% cover)
Heath/Scrubland (% cover)
Region
Boreo−nemoral
Atlantic
Continental

```
## pdf
##   2
```

Model selection by region

First, we built some intercept-only GAMs to use in the AIC tables. These models basically represent a model with no explanatory variable, and are used as a baseline to indicate what we should expect about charcoal burned if our predictors were fundamentally uninformative.

```
intercept.continental <- gam(Charcoal ~ 1, data = AllEurope[AllEurope$Region == "Continental",], select

intercept.atlantic <- gam(Charcoal ~ 1, data = AllEurope[AllEurope$Region == "Atlantic",], select = TRU

intercept.boreonemoral <- gam(Charcoal ~1, data = AllEurope[AllEurope$Region == "Boreo-nemoral",], sele
```

Here we group models by region and get AIC values and AIC weights for each set of predictors over that region.

Atlantic ecoregion

```
atlantic.models <- list(climate.atlantic = climate.atlantic,
                        needleleaf.atlantic = needle.atlantic,
                        scrub.atlantic = scrub.atlantic,
                        broadleaf.atlantic = broad.atlantic,
                        totaltree.atlantic = totaltree.atlantic,
                        arable.atlantic = arable.atlantic,
                        pasture.atlantic = pasture.atlantic,
                        intercept.atlantic = intercept.atlantic)
atlantic.aic.df <- data.frame(Model = names(atlantic.models),
                              AIC = sapply(atlantic.models, function(x) x$aic),
                              akaike.weights(sapply(atlantic.models, function(x) x$aic)))

atlantic.aic.df <- atlantic.aic.df[order(atlantic.aic.df$AIC),]
atlantic.aic.df$Cumulative.Weight <- cumsum(atlantic.aic.df$weights)

kable(atlantic.aic.df, row.names = FALSE)
```

Model	AIC	deltaAIC	rel.LL	weights	Cumulative.Weight
broadleaf.atlantic	-154.0558978	0.00000	1	1	1
arable.atlantic	-94.8110940	59.24480	0	0	1
totaltree.atlantic	-86.2392459	67.81665	0	0	1
scrub.atlantic	-77.5731477	76.48275	0	0	1
pasture.atlantic	-64.3536747	89.70222	0	0	1
needleleaf.atlantic	-33.5075403	120.54836	0	0	1
climate.atlantic	-33.1322949	120.92360	0	0	1
intercept.atlantic	0.1920688	154.24797	0	0	1

```
write.csv(atlantic.aic.df, file = "atlantic.aic.csv")
```

Continental ecoregion

```
continental.models <- list(climate.continental = climate.continental,
                           needleleaf.continental = needle.continental,
```

```
                            scrub.continental = scrub.continental,
                            broadleaf.continental = broad.continental,
                            totaltree.continental = totaltree.continental,
                            arable.continental = arable.continental,
                            pasture.continental = pasture.continental,
                            intercept.continental = intercept.continental)
continental.aic.df <- data.frame(Model = names(continental.models),
                                 AIC = sapply(continental.models, function(x) x$aic),
                                 akaike.weights(sapply(continental.models, function(x) x$aic)))

continental.aic.df <- continental.aic.df[order(continental.aic.df$AIC),]
continental.aic.df$Cumulative.Weight <- cumsum(continental.aic.df$weights)

kable(continental.aic.df, row.names = FALSE)
```

Model	AIC	deltaAIC	rel.LL	weights	Cumulative.Weight
totaltree.continental	-206.67043	0.000000	1.0000000	0.9197937	0.9197937
broadleaf.continental	-200.84680	5.823633	0.0543769	0.0500155	0.9698092
scrub.continental	-199.67135	6.999087	0.0302112	0.0277881	0.9975973
arable.continental	-194.71565	11.954779	0.0025354	0.0023321	0.9999294
pasture.continental	-187.72188	18.948548	0.0000768	0.0000706	1.0000000
needleleaf.continental	-145.18921	61.481222	0.0000000	0.0000000	1.0000000
climate.continental	-144.96485	61.705585	0.0000000	0.0000000	1.0000000
intercept.continental	-98.24067	108.429762	0.0000000	0.0000000	1.0000000

```
write.csv(continental.aic.df, file = "continental.aic.csv")
```

Boreo-Nemoral ecoregion

```
boreonemoral.models <- list(climate.boreonemoral = climate.boreonemoral,
                            needleleaf.boreonemoral = needle.boreonemoral,
                            scrub.boreonemoral = scrub.boreonemoral,
                            broadleaf.boreonemoral = broad.boreonemoral,
                            totaltree.boreonemoral = totaltree.boreonemoral,
                            arable.boreonemoral = arable.boreonemoral,
                            pasture.boreonemoral = pasture.boreonemoral,
                            intercept.boreonemoral = intercept.boreonemoral)
boreonemoral.aic.df <- data.frame(Model = names(boreonemoral.models),
                                  AIC = sapply(boreonemoral.models, function(x) x$aic),
                                  akaike.weights(sapply(boreonemoral.models, function(x) x$aic)))
boreonemoral.aic.df <- boreonemoral.aic.df[order(boreonemoral.aic.df$AIC),]
boreonemoral.aic.df$Cumulative.Weight <- cumsum(boreonemoral.aic.df$weights)

kable(boreonemoral.aic.df, row.names = FALSE)
```

Model	AIC	deltaAIC	rel.LL	weights	Cumulative.Weight
broadleaf.boreonemoral	-89.19857	0.00000	1	1	1
arable.boreonemoral	-45.28533	43.91325	0	0	1
needleleaf.boreonemoral	-40.63121	48.56736	0	0	1
totaltree.boreonemoral	-36.77012	52.42845	0	0	1

Model	AIC	deltaAIC	rel.LL	weights	Cumulative.Weight
pasture.boreonemoral	-20.77414	68.42443	0	0	1
scrub.boreonemoral	-19.43688	69.76169	0	0	1
climate.boreonemoral	-17.53115	71.66743	0	0	1
intercept.boreonemoral	45.08921	134.28778	0	0	1

```
write.csv(boreonemoral.aic.df, file = "boreonemoral.aic.csv")
```

Summary

Although some of the land cover classes are highly correlated (arable and pastures vs. total tree cover and broadleaf tree vs. total tree cover) comparison of AIC scores shows differences in their explanatory power for patterns of biomass burning. Evaluation of the models using AIC scores and weights shows that broadleaf cover produces the best fitting model in determining biomass burning in all ecoregions: ATL, BNE, CON (Table 1). Most of the explanatory power (including > 0.99 of the total cumulative AIC weight) comes from models that include broadleaf cover alone for the BNE and ATL ecoregions and the joint effects of broadleaf, total tree and arable cover for the CON ecoregion (Table 1, Fig. SUPPLEMENT HTML FILE).

The contrast between models including land cover and climate vs. those including climate alone demonstrates that most of the explanatory power in these sets of candidate models is coming from the land cover variables, not from the climate variables.