589project

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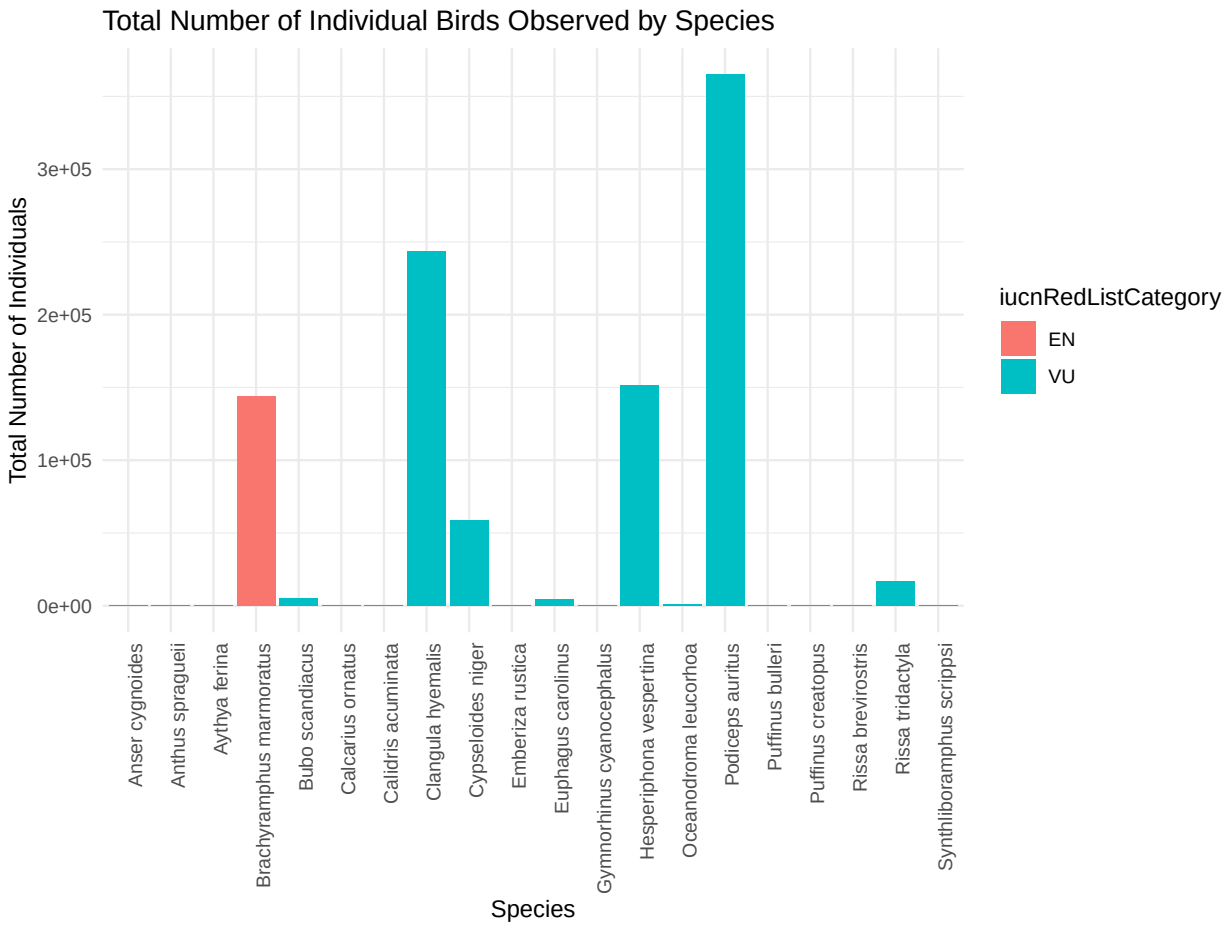
Load Package

```
library(sf)
library(spatstat)
library(sp)
library(maptools)
library(dplyr)
library(readr)
library(ggplot2)
library(lubridate)
```

Load Full Data

Species Distribution

```
ggplot(data = bird_bc, aes(x = species, weight = individualCount, fill = iucnRedListCategory)) +
  geom_bar() +
  labs(title = "Total Number of Individual Birds Observed by Species",
       x = "Species",
       y = "Total Number of Individuals") +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 90, hjust = 1))
```




```
#rm(bird_bc)
```

Filter data

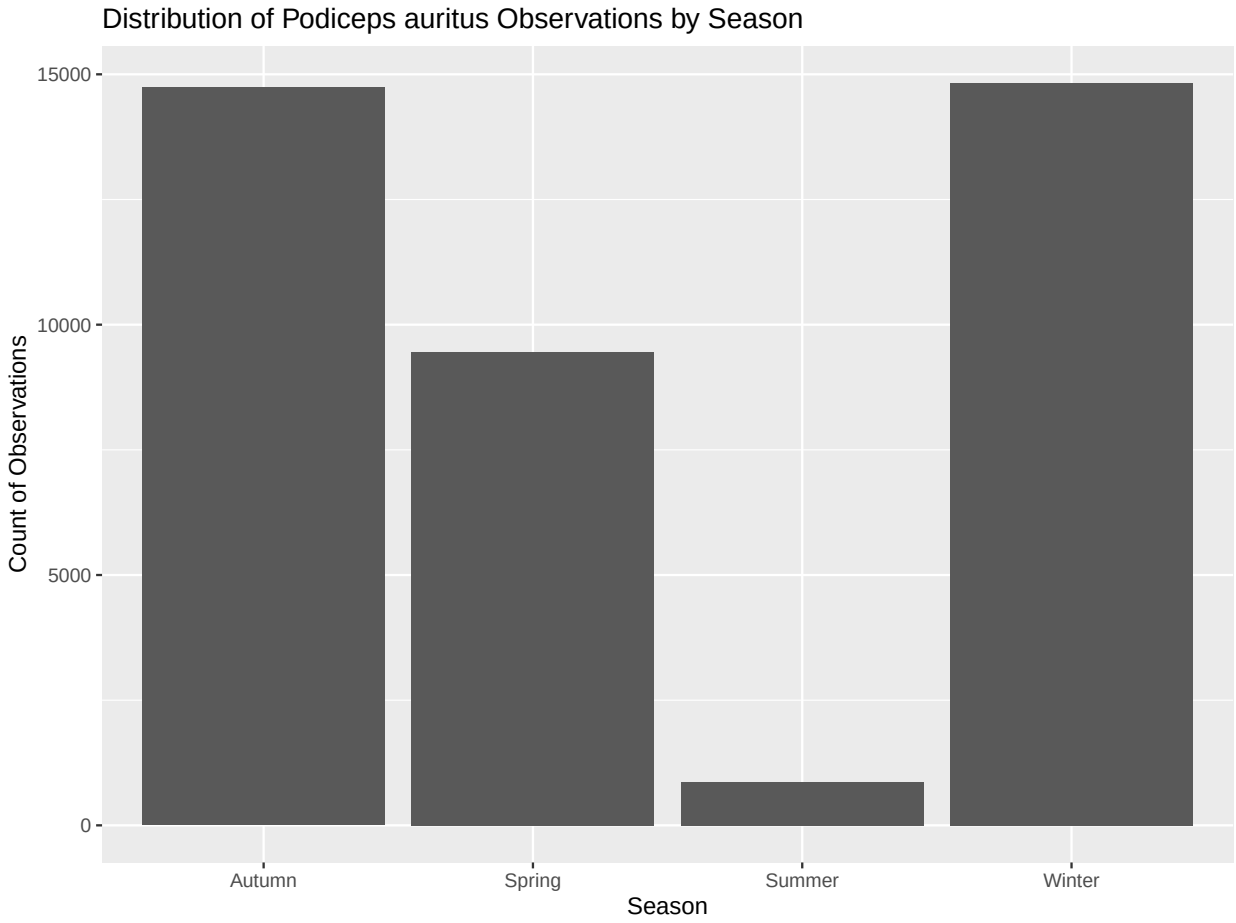
Load Data

```
bird_data <- read_csv('bird_data.csv')
load('BC_Covariates.Rda')
window = DATA$Window
```

Podiceps auritus Observations by Season

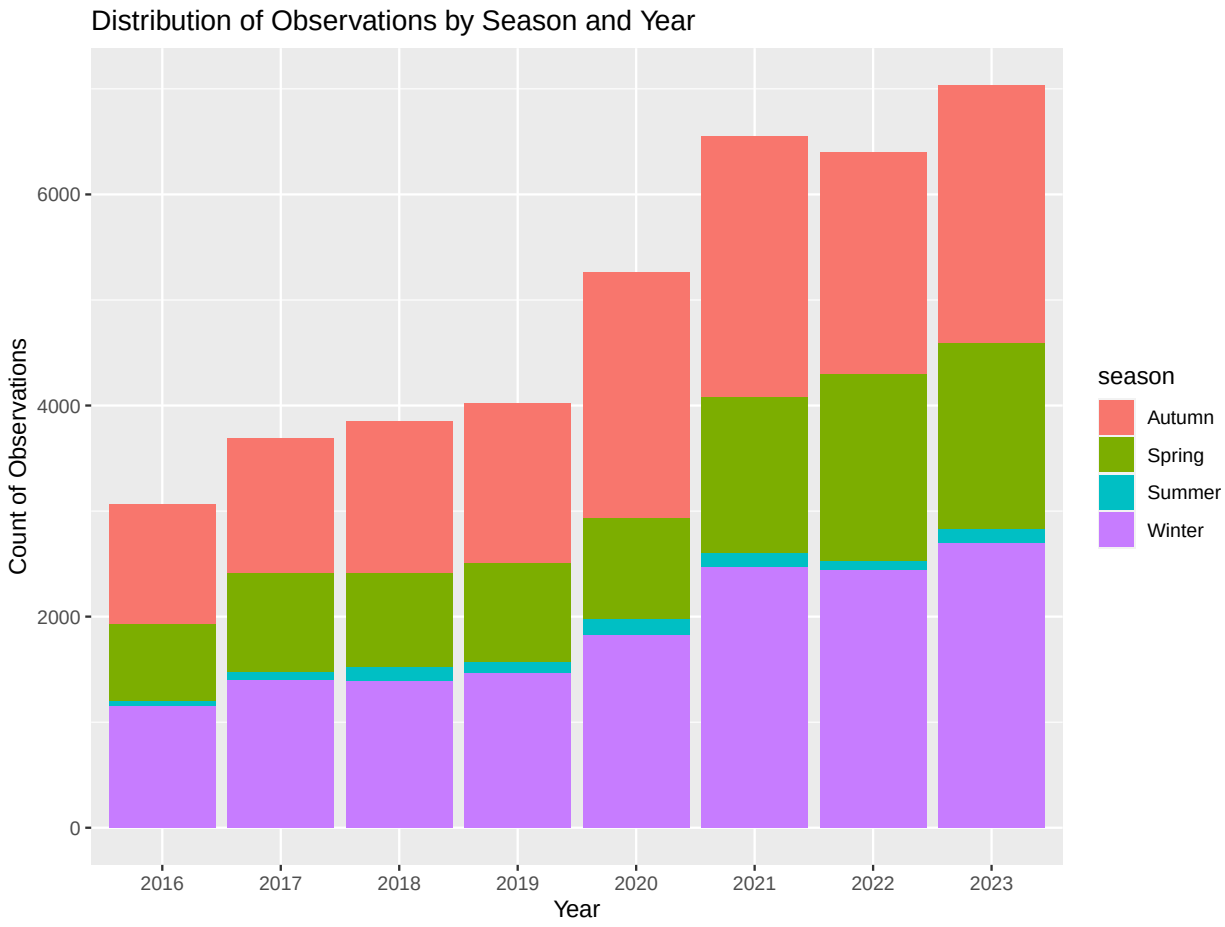
```
bird_data$eventDate <- as.Date(bird_data$eventDate, format = "%Y-%m-%d")
bird_data$season <- case_when(
  month(bird_data$eventDate) %in% 3:5   ~ "Spring",
  month(bird_data$eventDate) %in% 6:8   ~ "Summer",
  month(bird_data$eventDate) %in% 9:11  ~ "Autumn",
  month(bird_data$eventDate) %in% c(12, 1:2) ~ "Winter"
)
```

```r
ggplot(bird_data, aes(x = season)) +
  geom_bar() +
  labs(title = "Distribution of Podiceps auritus Observations by Season",
       x = "Season",
       y = "Count of Observations")
```



Podiceps auritus Observations by Year

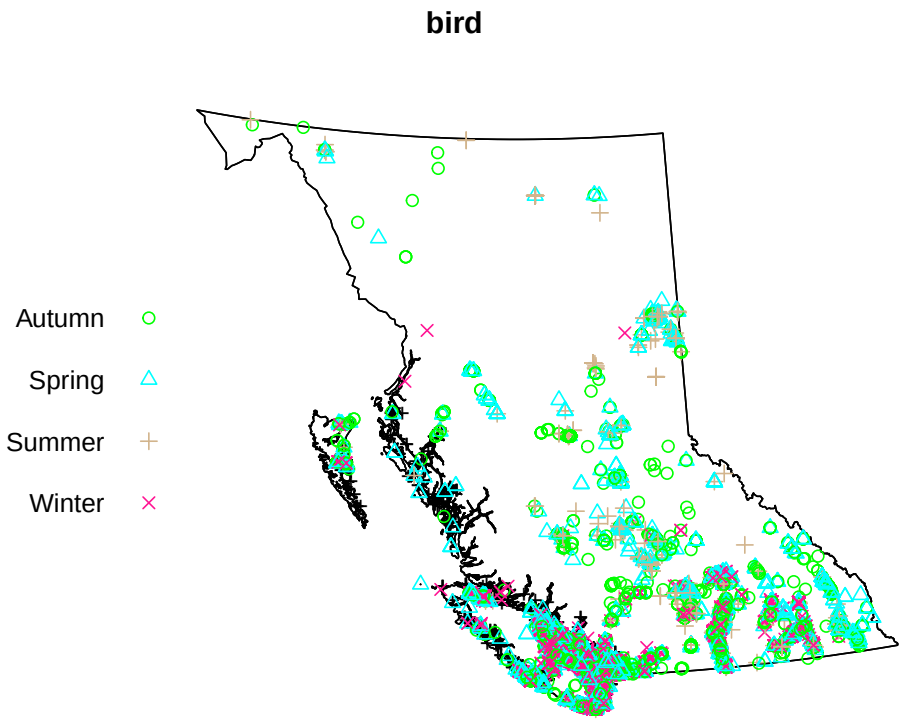
```r
bird_data$year <- as.integer(format(as.Date(bird_data$eventDate, "%Y-%m-%d"), "%Y"))

ggplot(bird_data, aes(x = factor(year))) +
  geom_bar(aes(fill = season)) +
  labs(title = "Distribution of Observations by Season and Year",
       x = "Year",
       y = "Count of Observations")
```



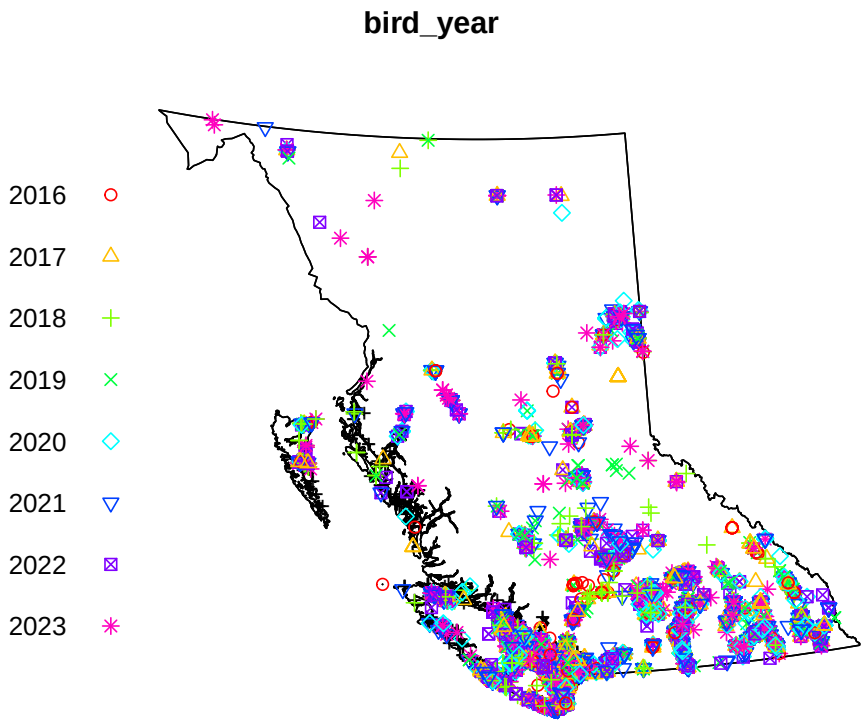
ppp Object

```
bird_sf <- st_as_sf(bird_data, coords = c("decimalLongitude", "decimalLatitude"), crs = 4326)
bc_albers_crs_string <- "+proj=aea +lat_0=45 +lon_0=-126 +lat_1=50 +lat_2=58.5 +x_0=1000000 +y_0=0 +datu
bird_albers <- st_transform(bird_sf, crs = bc_albers_crs_string)
```

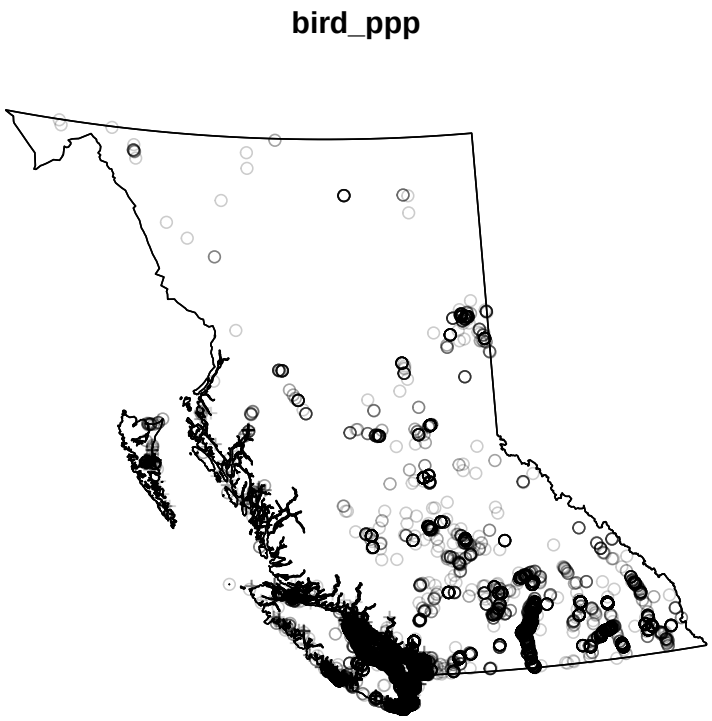
```
bird <- ppp(x = st_coordinates(bird_albers)[, 1],
            y = st_coordinates(bird_albers)[, 2],
            window = as.owin(window),
            marks = as.factor(bird_albers$season))
plot(bird, cols = c("green", "cyan", "tan", "deeppink"))
```




```
bird_year <- ppp(x = st_coordinates(bird_albers)[, 1],
                 y = st_coordinates(bird_albers)[, 2],
                 window = as.owin(window),
                 marks = as.factor(bird_albers$year))
plot(bird_year, cols = rainbow(length(unique(bird_albers$year))))
```

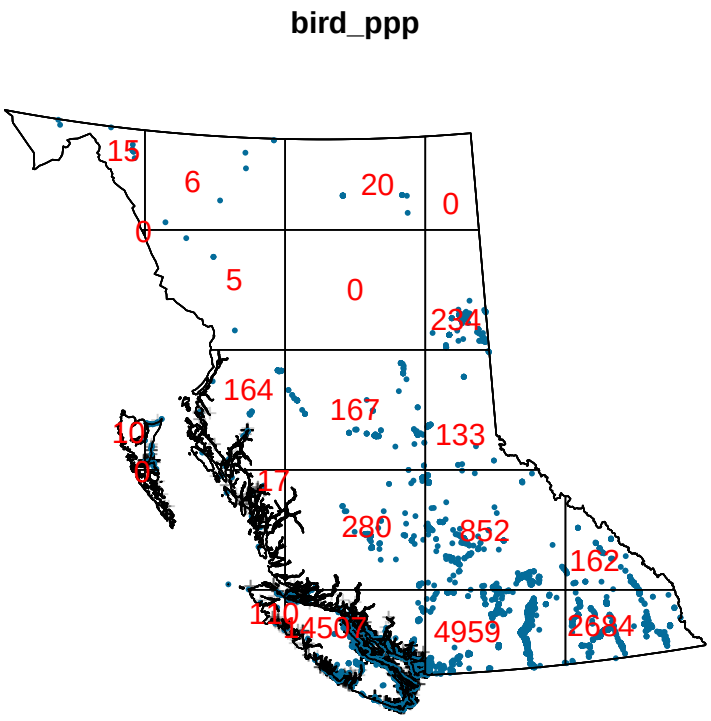



```
bird_ppp <- ppp(x = st_coordinates(bird_albers)[, 1],
                y = st_coordinates(bird_albers)[, 2],
                window = as.owin(window))
plot(bird_ppp)
```



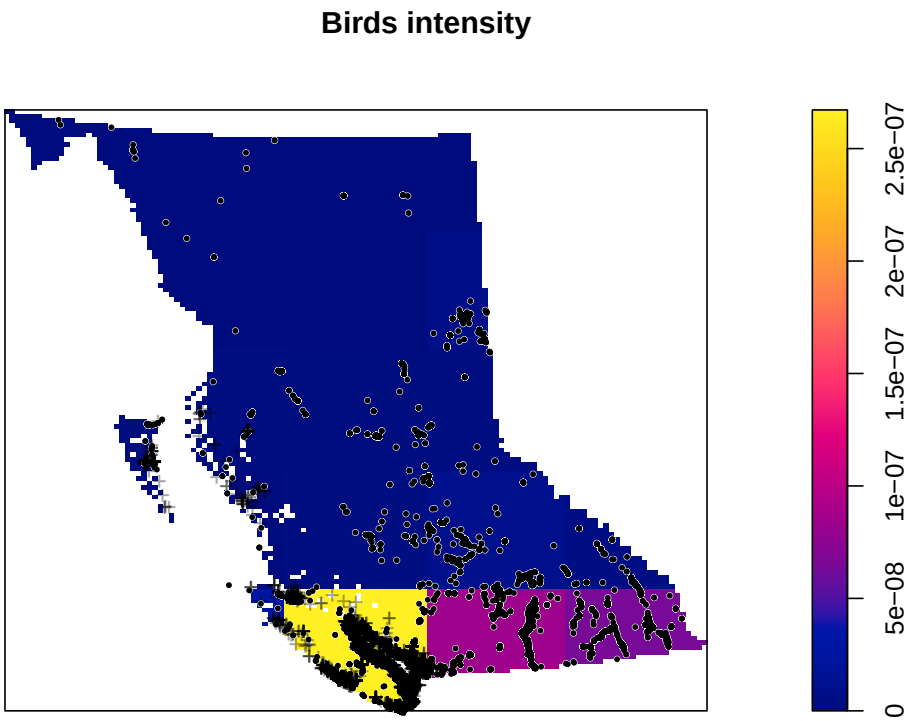
Spatially inhomogeneous λ

```
Q <- quadratcount(bird_ppp,
                  nx = 5,
                  ny = 5)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "#046C9A")

plot(Q, cex = 1.2, col = "red", add = T)
```



Intensity

```
plot(intensity(Q, image = T),
     main = "Birds intensity")

plot(bird_ppp,
     pch = 16,
     cex = 0.6,
     cols = "white",
     add = T)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "black",
     add = T)
```




```
quadrat.test(Q)
```

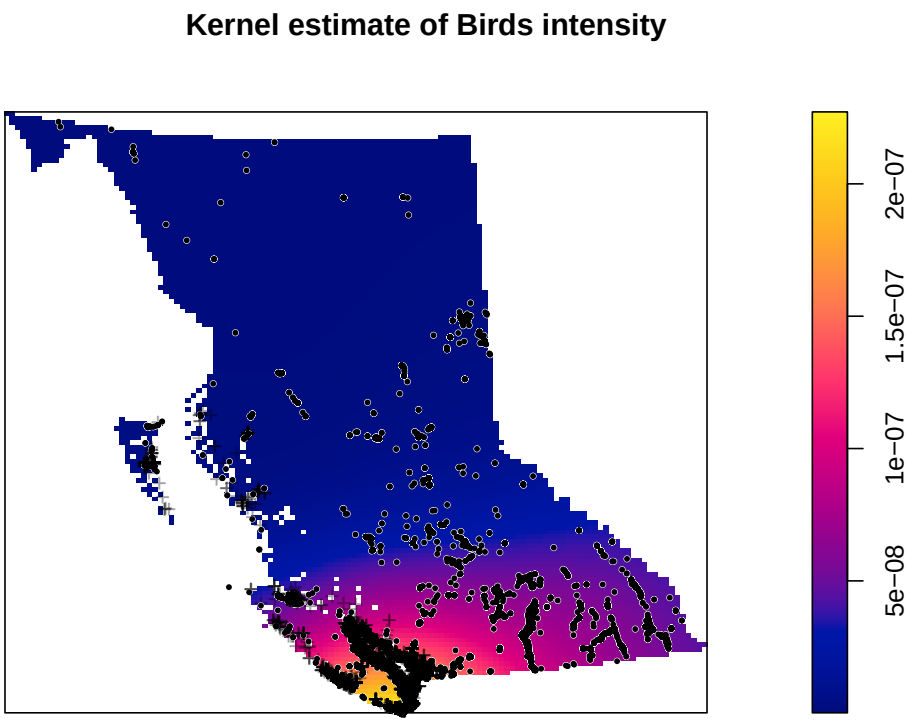
```
##
##  Chi-squared test of CSR using quadrat counts
##
## data:
## X2 = 150412, df = 20, p-value < 2.2e-16
## alternative hypothesis: two.sided
##
## Quadrats: 21 tiles (irregular windows)
```

The small p-value suggests that there is a significant deviation from homogeneity.

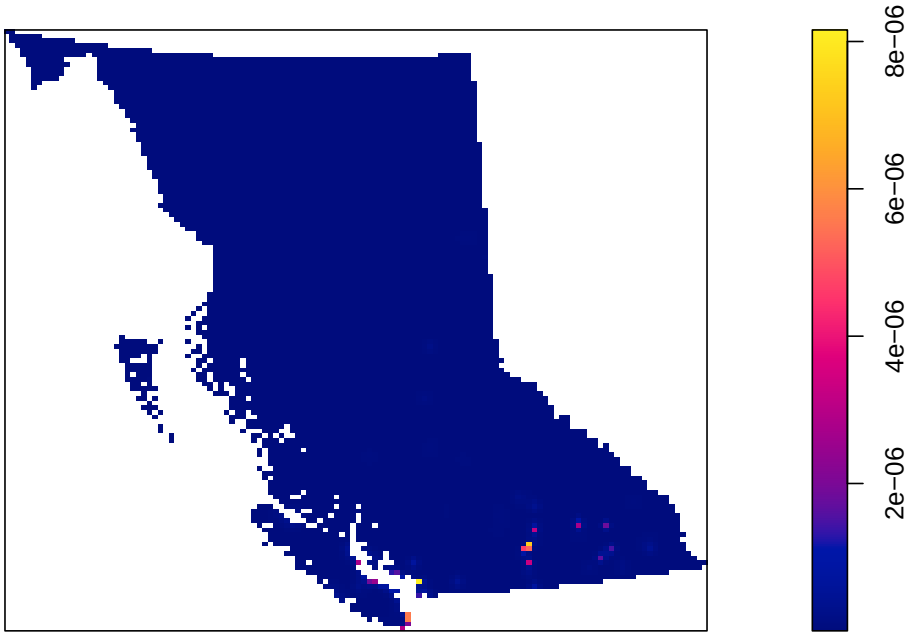
Kernel estimation

```
#Density estimation of lambda(u)
lambda_u_hat <- density(bird_ppp)

#Plot the output Note the use of image = TRUE
plot(lambda_u_hat,
```

```
     main = "Kernel estimate of Birds intensity")

plot(bird_ppp,
     pch = 16,
     cex = 0.6,
     cols = "white",
     add = T)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "black",
     add = T)
```

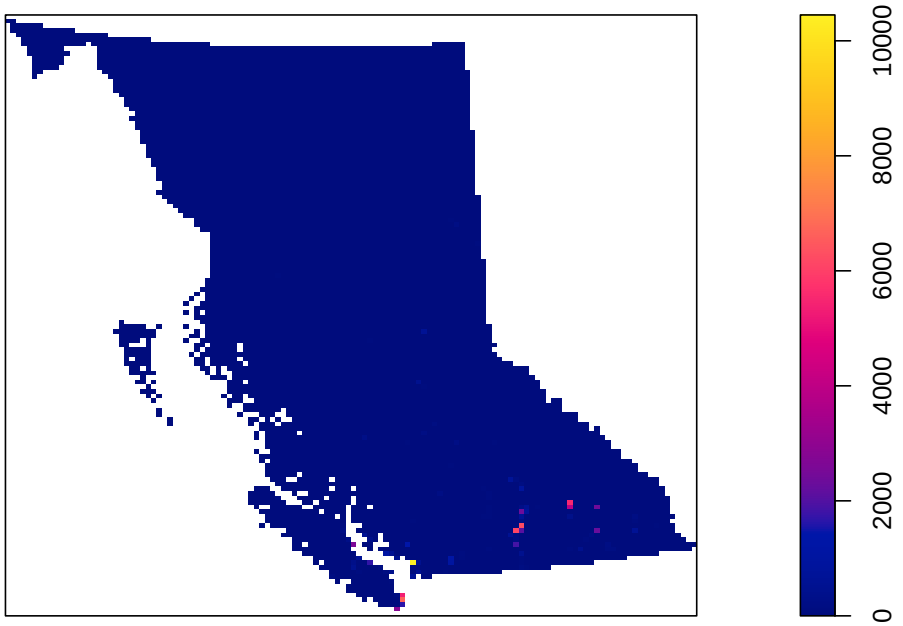



```
#Density estimation of lambda(u)
lambda_u_hat_adaptive <- adaptive.density(bird_ppp, method = "kernel")

#Plot the output Note the use of image = TRUE
plot(lambda_u_hat_adaptive,
     main = "Adaptive kernel estimate of intensity")
```

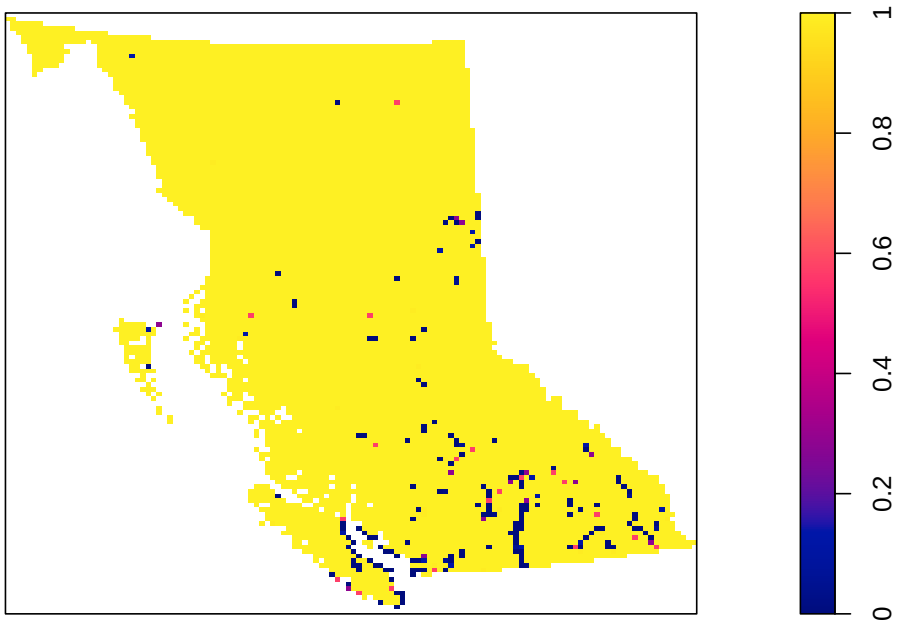


Hot spot analysis

```
# Estimate R
R <- bw.ppl(bird_ppp)
#Calculate test statistic
LR <- scanLRTS(bird_ppp, r = R)

plot(LR)
```




```
#Compute local p-values
pvals <- eval.im(pchisq(LR,
                        df = 1,
                        lower.tail = FALSE))

plot(pvals, main = "Local p-values")
```

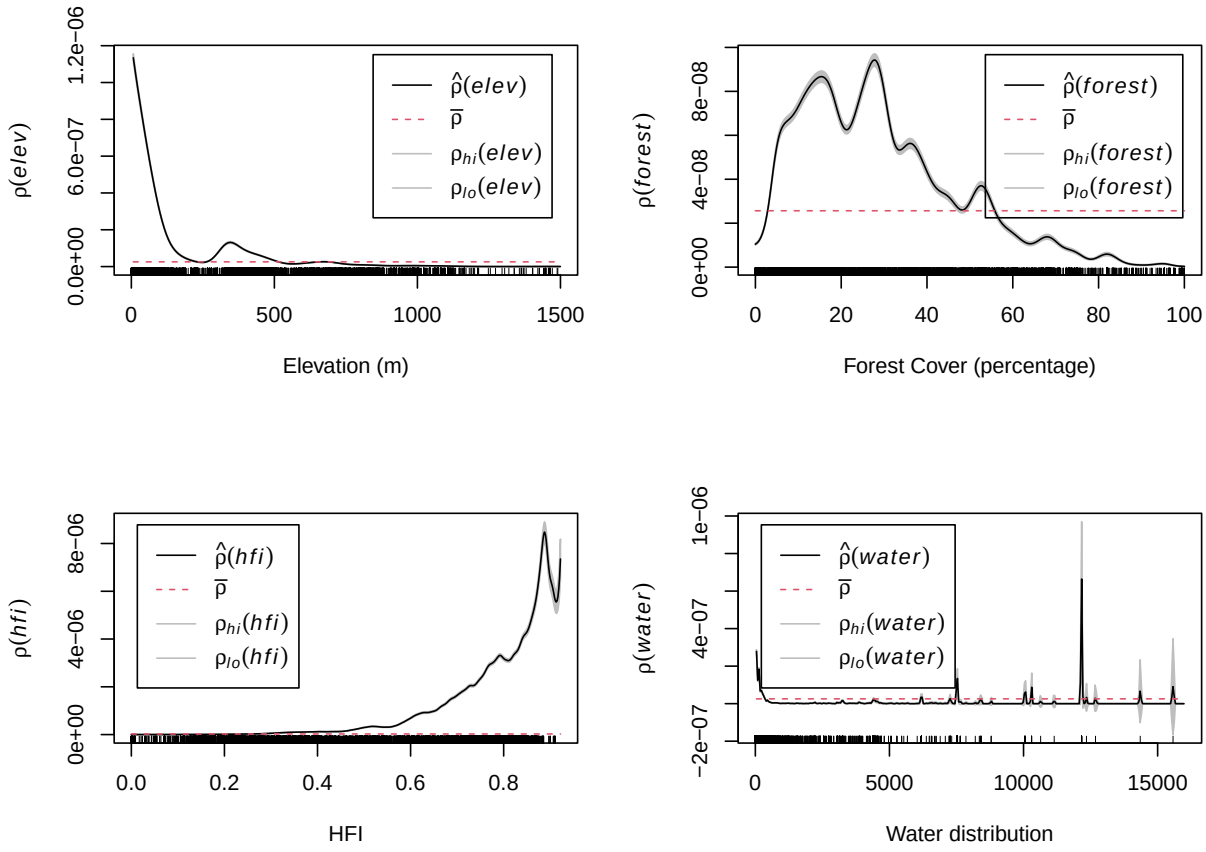


Relationships with covariates

```
elev <- DATA$Elevation
forest <- DATA$Forest
hfi <- DATA$HFI
water <- DATA$Dist_Water
rho_elev <- rhohat(bird_ppp, elev)
rho_forest <- rhohat(bird_ppp, forest)
rho_hfi <- rhohat(bird_ppp, hfi)
rho_water <- rhohat(bird_ppp, water)
```

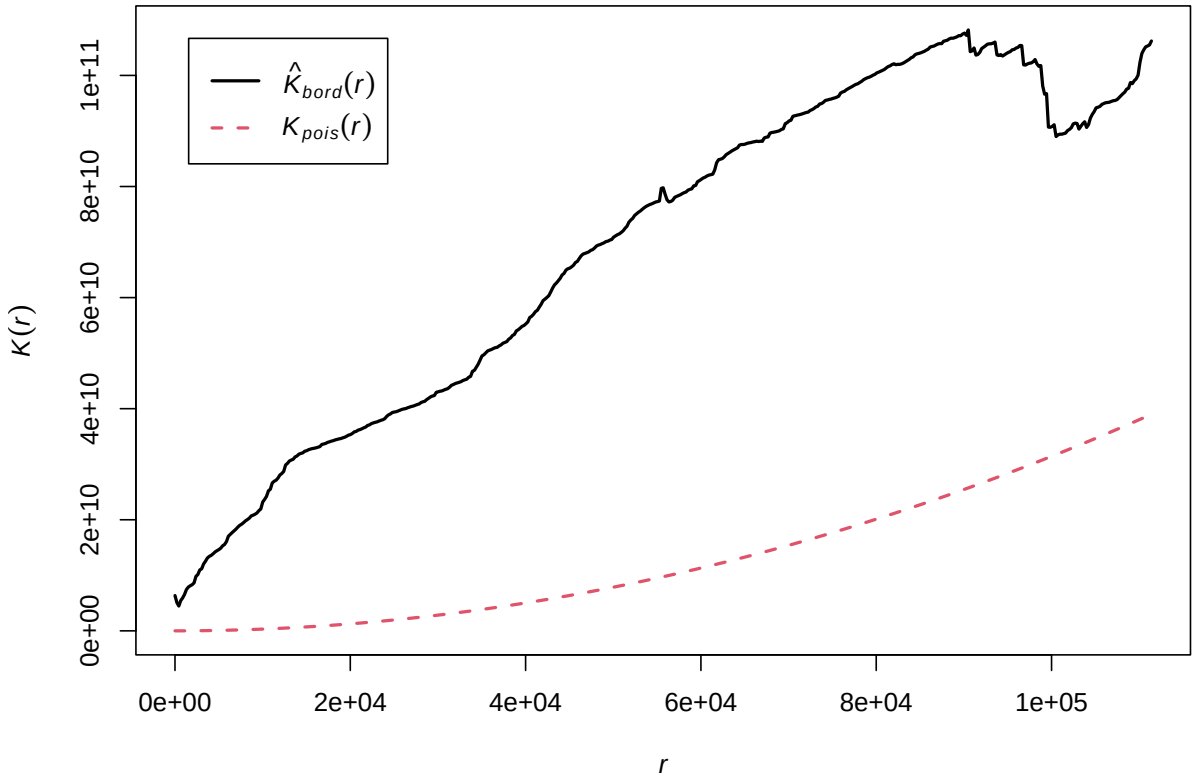
```
par(mfrow = c(2,2))
plot(rho_elev, xlim=c(0, 1500),
     main = "",
     xlab = "Elevation (m)")
plot(rho_forest,
     main = "",
     xlab = "Forest Cover (percentage)")
plot(rho_hfi,
     main = "",
     xlab = "HFI")
```

```
plot(rho_water, xlim=c(0, 16000),
     main = "",
     xlab = "Water distribution")
```



K-function

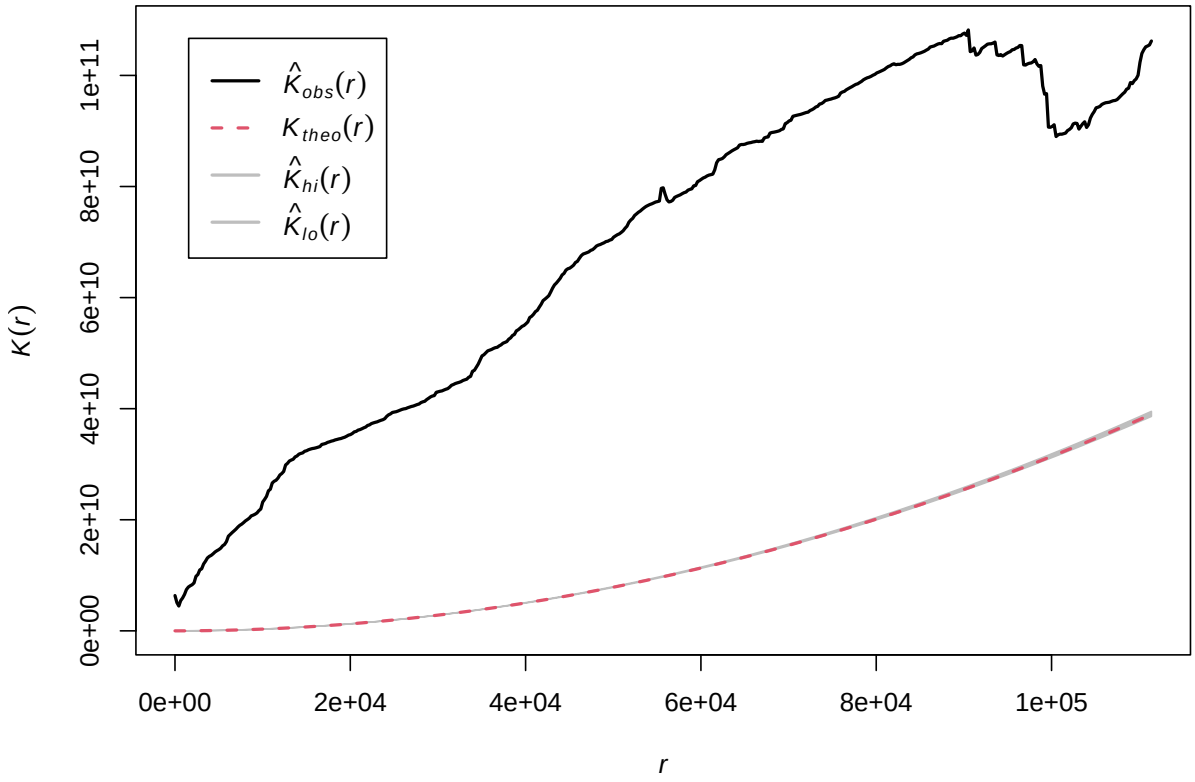
```
k_bird <- Kest(bird_ppp)
#visualise the results
plot(k_bird,
     main = "",
     lwd = 2)
```




```
E_bird <- envelope(bird_ppp,
                   Kest,
                   correction="border",
                   rank = 1,
                   nsim = 19,
                   fix.n = T)
```

```
## Generating 19 simulations of CSR with fixed number of points  ...
## 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,
## 19.
##
## Done.
```

```
plot(E_bird,
     main = "",
     lwd = 2)
```

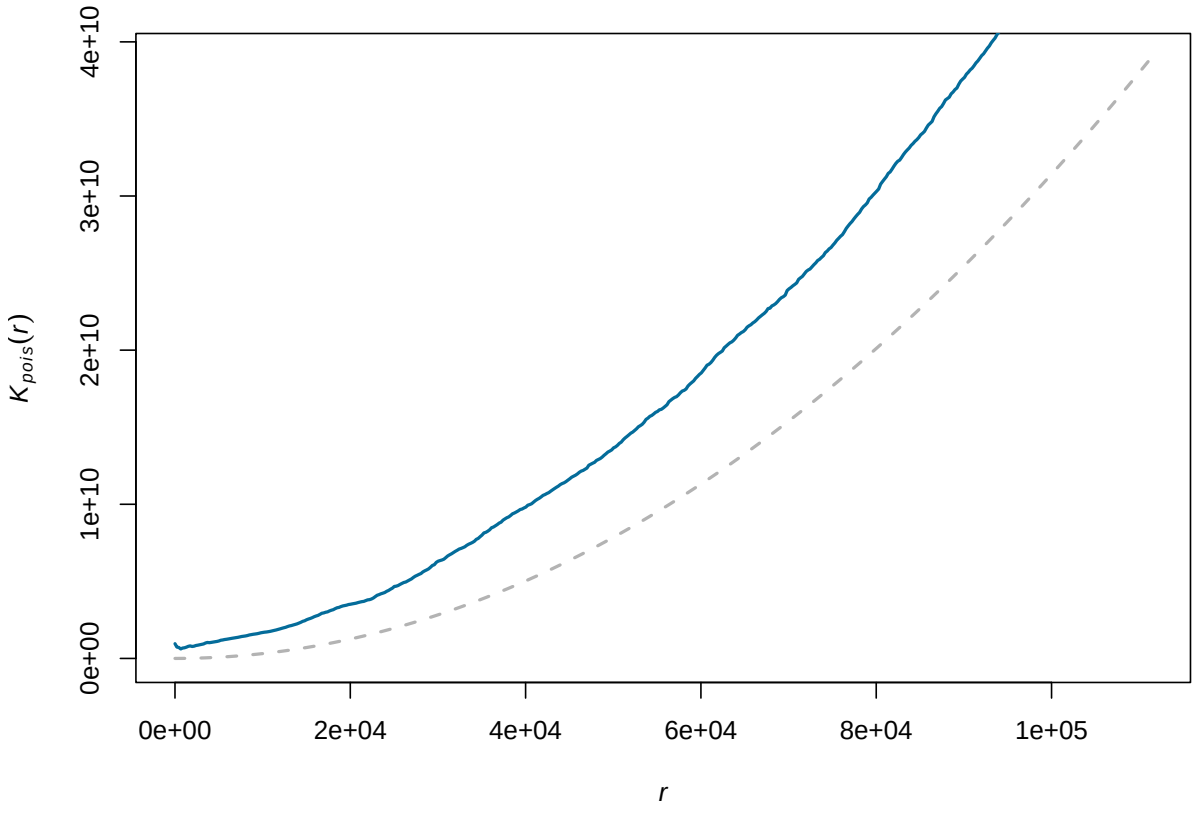



```
#Estimate intensity
lambda_bird <- density(bird_ppp, bw.ppl)

Kinhom_bird <- Kinhom(bird, lambda_bird)

Kinhom_bird
```

```
## Function value object (class 'fv')
## for the function r -> K[inhom](r)
## ..................................................................................
##             Math.label
## r           r
## theo        K[pois](r)
## border      {hat(K)[inhom]^{bord}}(r)
## bord.modif {hat(K)[inhom]^{bordm}}(r)
##             Description
## r           distance argument r
## theo        theoretical Poisson K[inhom](r)
## border      border-corrected estimate of K[inhom](r)
## bord.modif modified border-corrected estimate of K[inhom](r)
## ..................................................................................
## Default plot formula:  .~r
## where "." stands for 'bord.modif', 'border', 'theo'
```

```
## Recommended range of argument r: [0, 111390]
## Available range of argument r: [0, 111390]
```

```r
# visualise the results
plot(Kinhom_bird,
     theo ~ r,
     main = "",
     col = "grey70",
     lty = "dashed",
     lwd = 2)

plot(Kinhom_bird,
     border ~ r,
     col = c("#046C9A"),
     lwd = 2,
     add = T)
```

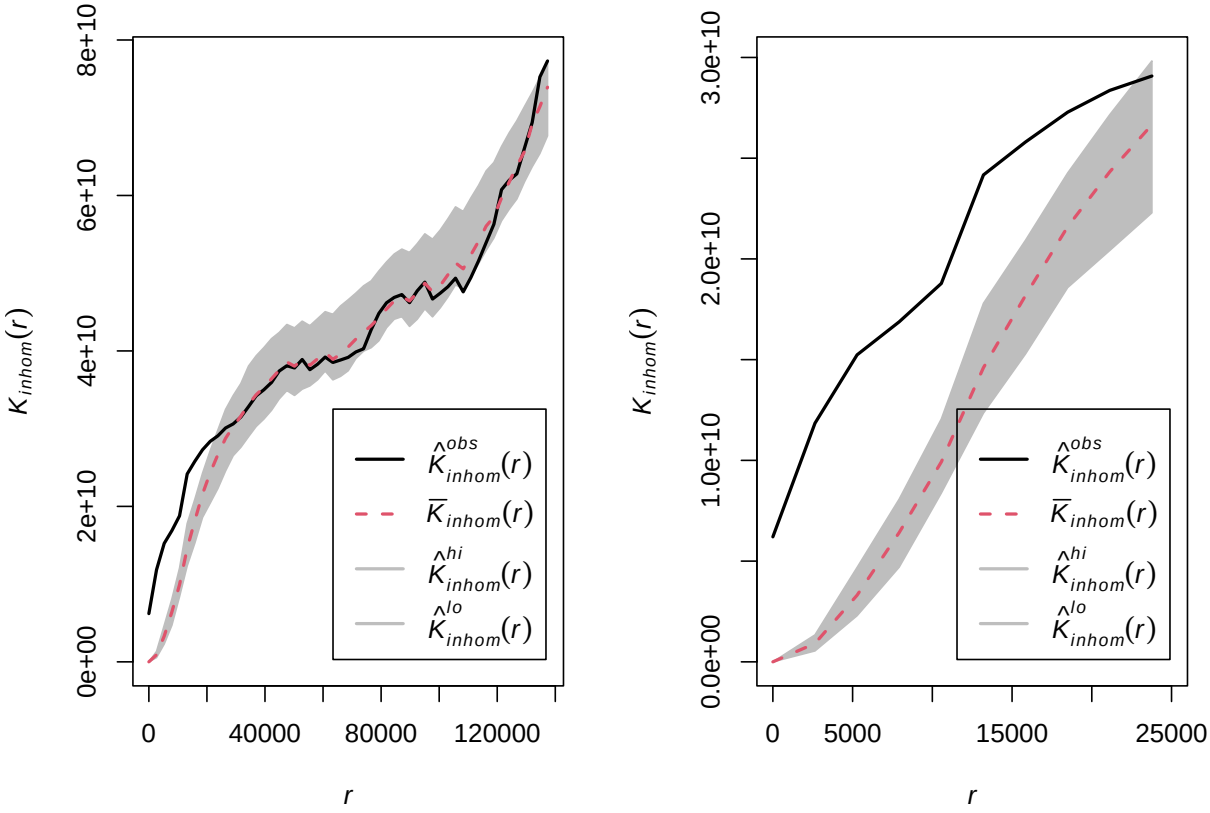



```r
#Estimate a strictly positive density
lambda_bird_pos <- density(bird_ppp,
                           sigma=bw.ppl,
                           positive=TRUE)

#Simulation envelope (with points drawn from the estimated intensity)
```

```r
E_bird_inhom <- envelope(bird_ppp,
                         Kinhom,
                         simulate = expression(rpoispp(lambda_bird_pos)),
                         correction="border",
                         rank = 1,
                         nsim = 19,
                         fix.n = TRUE)
```

```
## Generating 19 simulations by evaluating expression  ...
## 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,
## 19.
##
## Done.
```

```r
# visualise the results
par(mfrow = c(1,2))
plot(E_bird_inhom,
     main = "",
     lwd = 2)
# Zoom in on range where significant deviations appear
plot(E_bird_inhom,
     xlim = c(0,25000),
     main = "",
     lwd = 2)
```



When corrected for inhomogeneity, significant clustering only appears to exist in and around 0-20000 units.

PCF

```
pcf_bird_hom <- envelope(bird_ppp,
                         pcf,
                         simulate = expression(rpoispp(density.ppp(bird_ppp))),
                         rank = 1,
                         nsim = 19)
```

```
## Generating 19 simulations by evaluating expression  ...
## 1, 2,  [3:38 remaining] 3,
##  [3:31 remaining] 4,  [3:13 remaining] 5,  [3:03 remaining] 6,
##  [2:48 remaining] 7,  [2:34 remaining] 8,  [2:21 remaining] 9,
##  [2:08 remaining] 10,  [1:55 remaining] 11,  [1:42 remaining] 12,
##  [1:28 remaining] 13,  [1:16 remaining] 14,  [1:03 remaining] 15,
##  [50 sec remaining] 16,  [38 sec remaining] 17,  [25 sec remaining] 18,
##  [12 sec remaining]
## 19.
##
## Done.
```

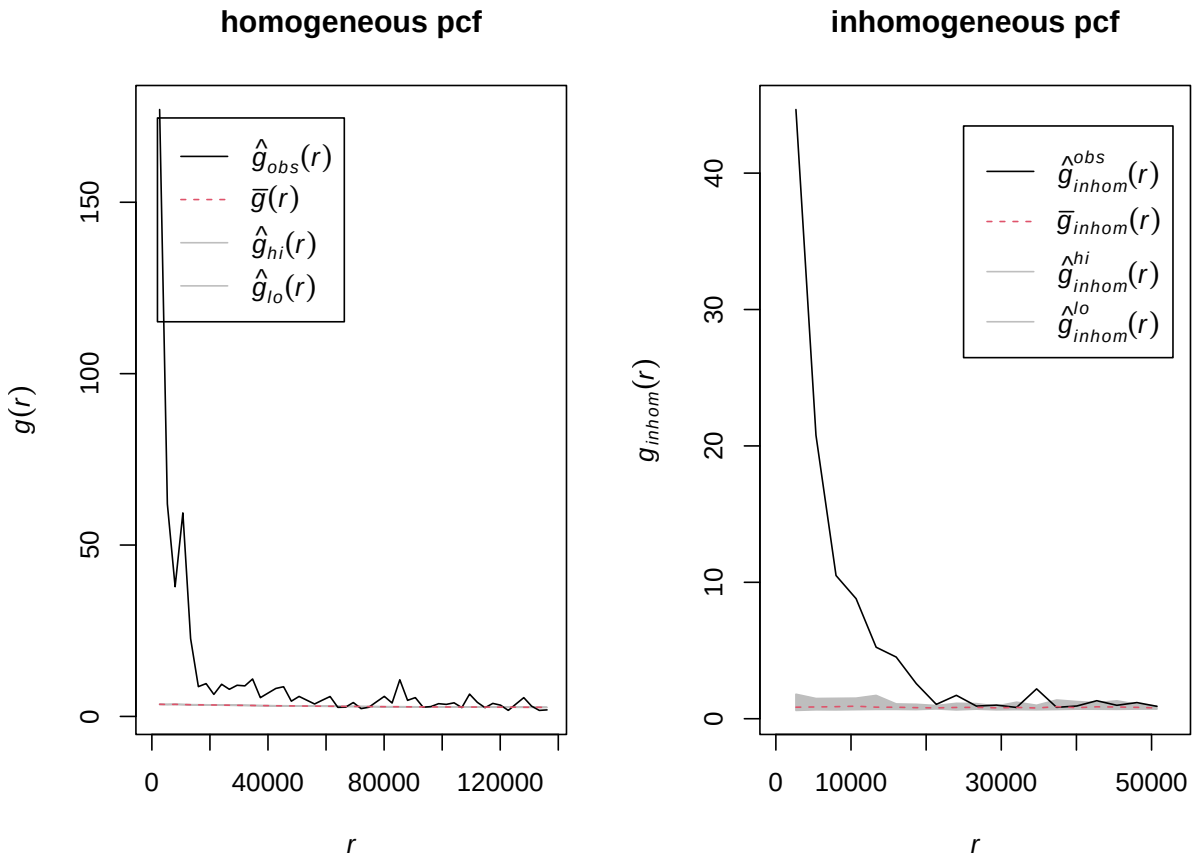
```
pcf_bird_inhom <- envelope(bird_ppp,
                           pcfinhom,
                           simulate = expression(rpoispp(density.ppp(bird_ppp))),
                           rank = 1,
                           nsim = 19)
```

```
## Generating 19 simulations by evaluating expression  ...
## 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,
## 19.
##
## Done.
```

```
par(mfrow = c(1,2))
plot(pcf_bird_hom, main = 'homogeneous pcf')
```

```
## Error in UseMethod("distmap") :
##   no applicable method for 'distmap' applied to an object of class "im"
```

```
plot(pcf_bird_inhom,  main = 'inhomogeneous pcf')
```



Collinearity

```
cor.im(elev, forest, hfi, water, use = 'complete.obs')
```

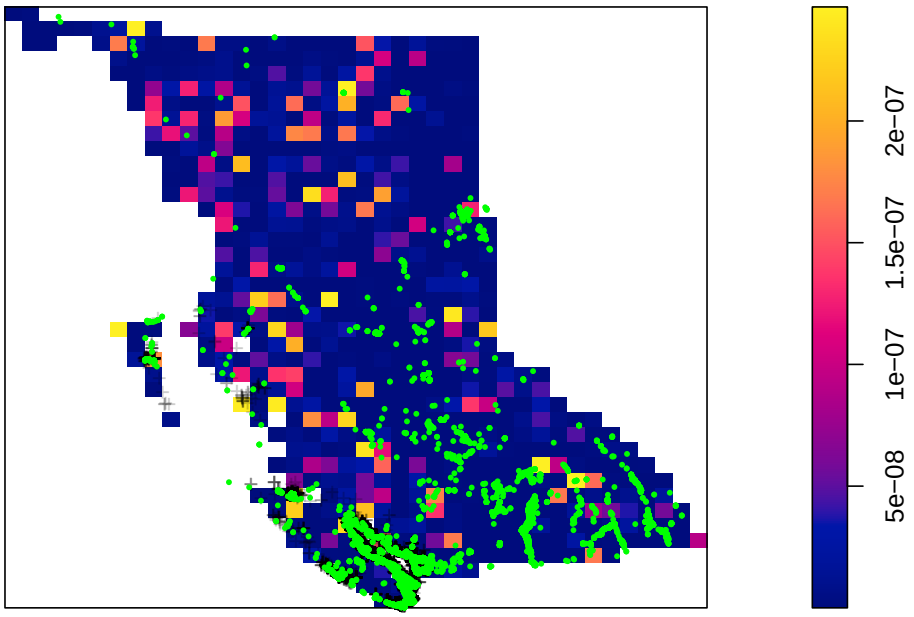
```
##             ..1         ..2         ..3         ..4
## ..1  1.00000000 -0.26225376 -0.26625626 -0.03493453
## ..2 -0.26225376  1.00000000  0.06618592  0.04818598
## ..3 -0.26625626  0.06618592  1.00000000  0.13246899
## ..4 -0.03493453  0.04818598  0.13246899  1.00000000
```

Model fitting

```
fit1 <- ppm(bird_ppp ~ forest + I(forest^2) + water)
fit1
```

```
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~forest + I(forest^2) + water
##
## Fitted trend coefficients:
##   (Intercept)        forest   I(forest^2)         water
## -1.560362e+01  3.537356e-02 -7.973387e-04 -2.951399e-03
##
##                  Estimate         S.E.       CI95.lo       CI95.hi Ztest
## (Intercept) -1.560362e+01 1.456965e-02 -1.563217e+01 -1.557506e+01   ***
## forest       3.537356e-02 9.346370e-04  3.354170e-02  3.720541e-02   ***
## I(forest^2) -7.973387e-04 1.343798e-05 -8.236767e-04 -7.710007e-04   ***
## water       -2.951399e-03 2.305444e-05 -2.996585e-03 -2.906213e-03   ***
##                    Zval
## (Intercept) -1070.96714
## forest         37.84737
## I(forest^2)   -59.33472
## water        -128.01871
## Problem:
##  Values of the covariate 'forest' were NA or undefined at 0.09% (65 out of
## 68828) of the quadrature points
```

```
plot(fit1,
     se = FALSE,
     superimpose = FALSE)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```

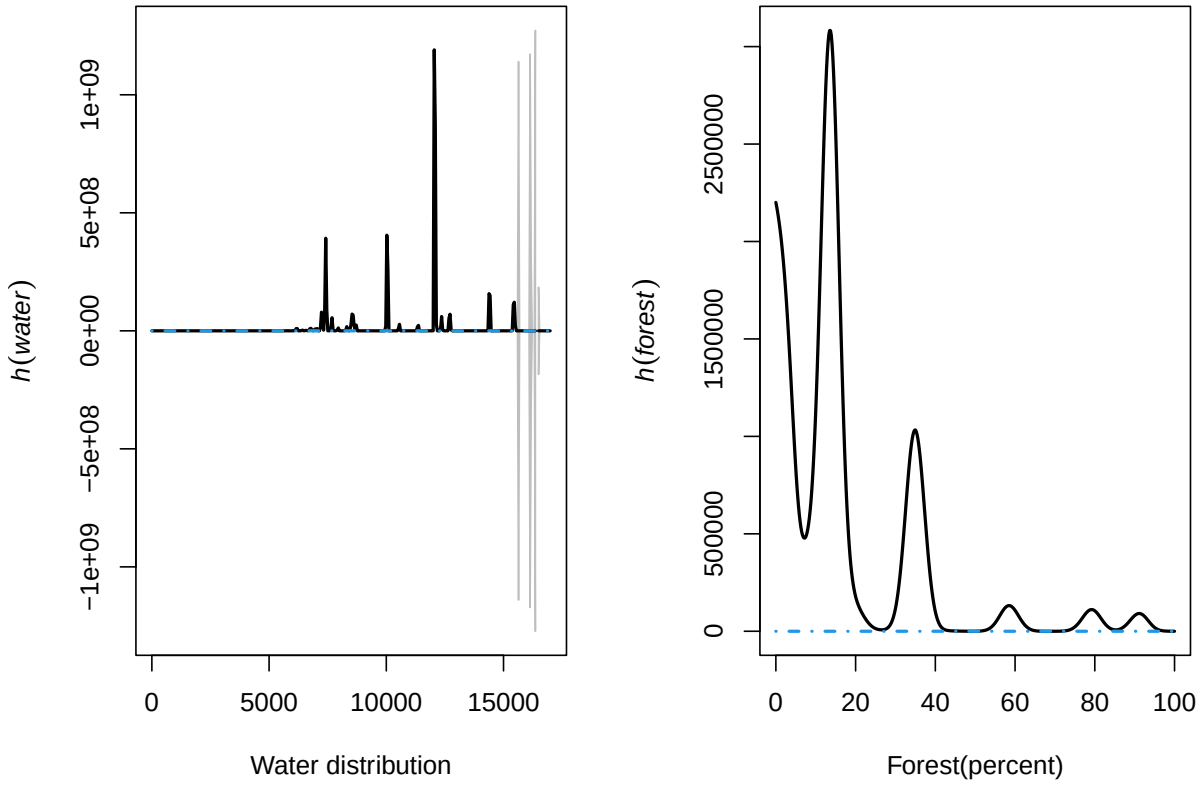



```
quadrat.test(fit1, nx = 4, ny = 2)
```

```
##
##  Chi-squared test of fitted Poisson model 'fit1' using quadrat counts
##
## data:  data from fit1
## X2 = 62147, df = 3, p-value < 2.2e-16
## alternative hypothesis: two.sided
##
## Quadrats: 7 tiles (irregular windows)
```

```
par_res_water <- parres(fit1, "water")
par_res_forest <- parres(fit1, "forest")

par(mfrow = c(1,2))
plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
plot(par_res_forest,
     legend = FALSE,
     lwd = 2,
```

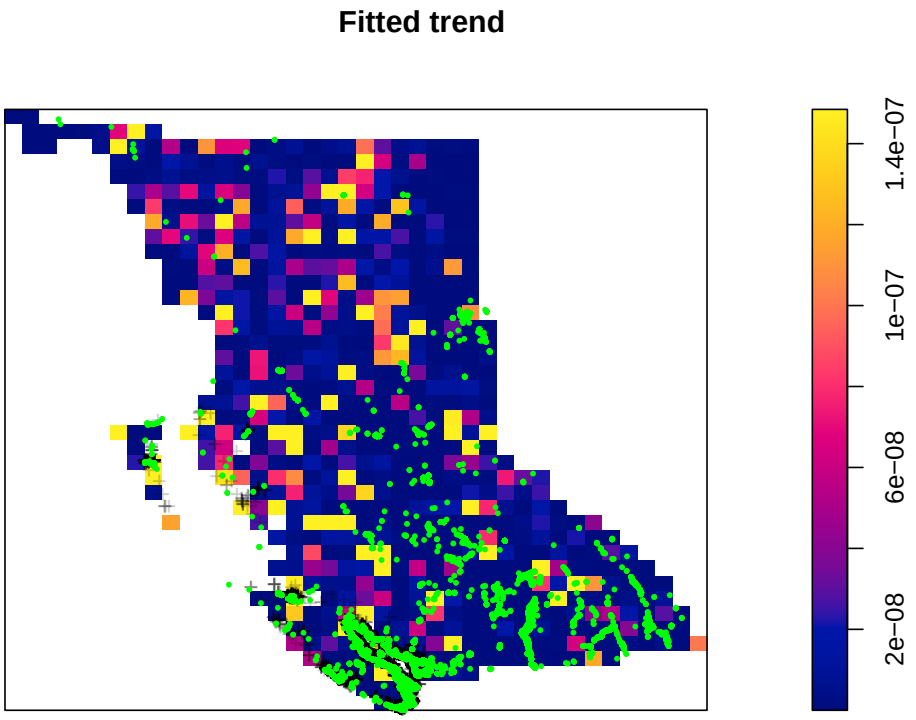
```
     main = "",
     xlab = "Forest(percent)")
```



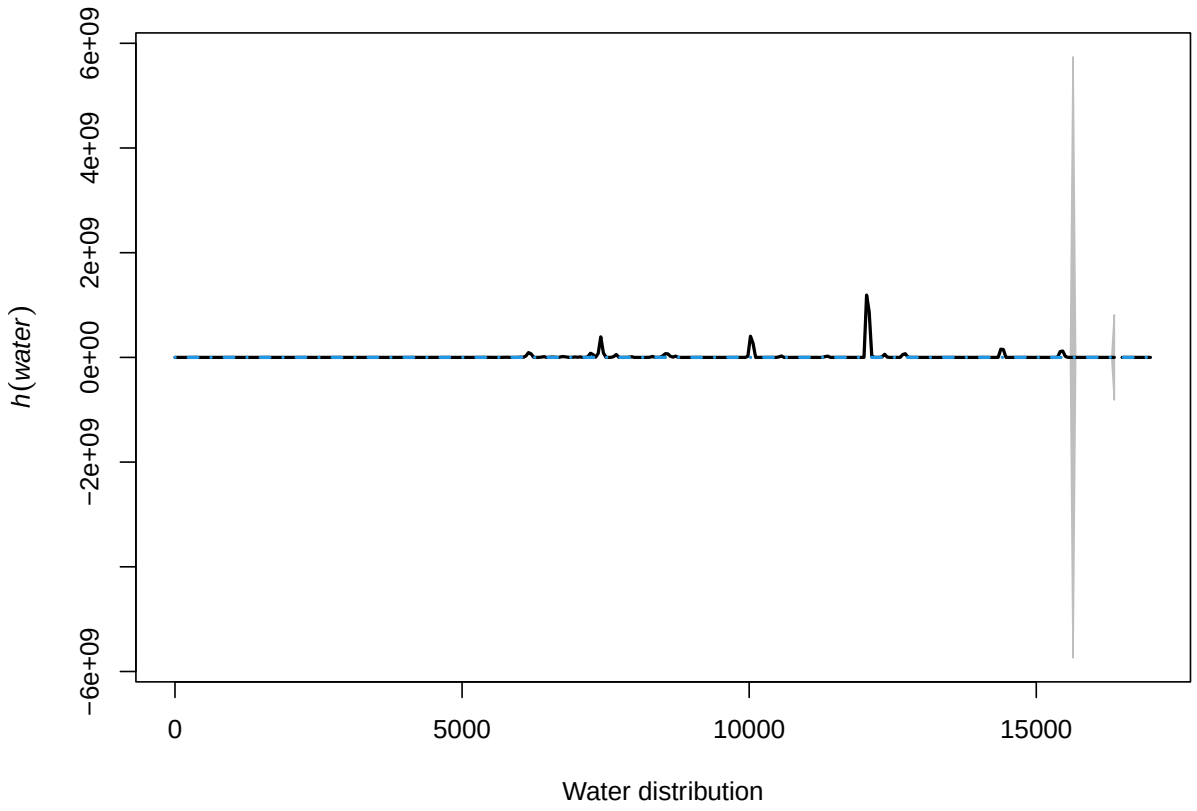

```
fit2 <- ppm(bird_ppp, ~ water)
fit2
```

```
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~water
##
## Fitted trend coefficients:
## (Intercept)       water
## -15.7229186  -0.0033746
##
##                Estimate         S.E.       CI95.lo       CI95.hi Ztest
## (Intercept) -15.7229186 7.893681e-03 -15.738389902 -15.707447242   ***
## water        -0.0033746 2.425101e-05  -0.003422131  -0.003327069   ***
##                   Zval
## (Intercept) -1991.836
## water        -139.153
```

```
plot(fit2,
     se = FALSE,
     superimpose = FALSE)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```




```
par_res_water <- parres(fit2, "water")

plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
```

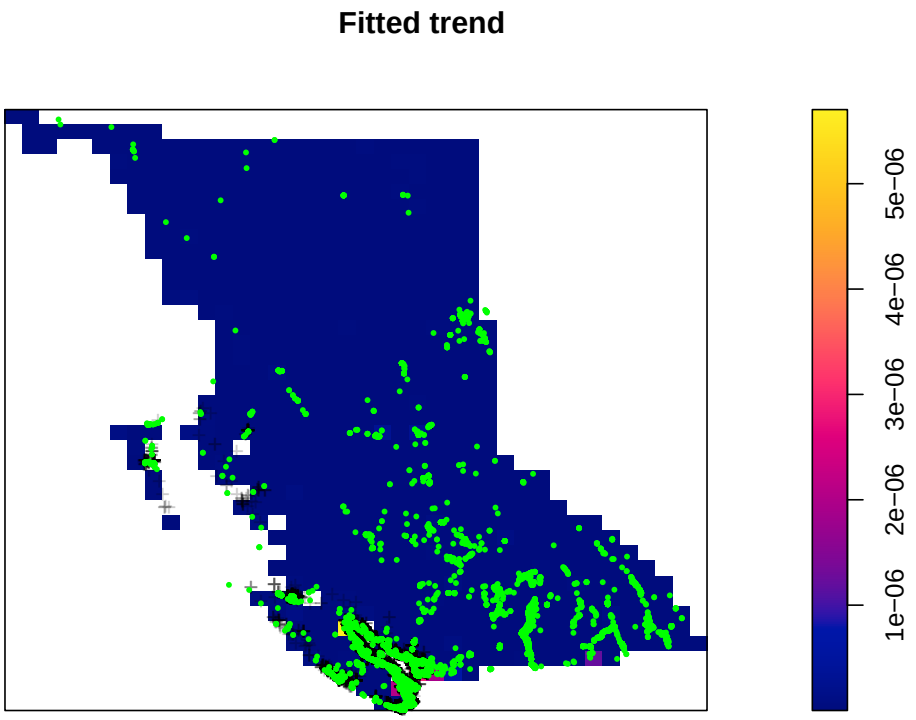



```
fit3 <- ppm(bird_ppp, ~ forest + I(forest^2) + elev + hfi)
fit3
```

```
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~forest + I(forest^2) + elev + hfi
##
## Fitted trend coefficients:
##   (Intercept)        forest   I(forest^2)          elev           hfi
## -1.736741e+01  3.538133e-02 -5.367716e-04 -2.920751e-03  6.043144e+00
##
##                  Estimate         S.E.       CI95.lo       CI95.hi Ztest
## (Intercept) -1.736741e+01 2.988399e-02 -1.742598e+01 -1.730884e+01   ***
## forest       3.538133e-02 8.753478e-04  3.366568e-02  3.709698e-02   ***
## I(forest^2) -5.367716e-04 1.139484e-05 -5.591051e-04 -5.144381e-04   ***
## elev        -2.920751e-03 2.600330e-05 -2.971717e-03 -2.869786e-03   ***
## hfi          6.043144e+00 3.275634e-02  5.978942e+00  6.107345e+00   ***
##                     Zval
## (Intercept) -581.16118
## forest        40.41974
## I(forest^2)  -47.10654
## elev        -112.32235
```

```
## hfi          184.48777
## Problem:
##  Values of the covariates 'forest', 'elev', 'hfi' were NA or undefined at 0.77%
## (528 out of 68828) of the quadrature points
```

```
plot(fit3,
     se = FALSE,
     superimpose = FALSE)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```




```
print(AIC(fit1))
```

```
## [1] 828613.2
```

```
print(AIC(fit2))
```

```
## [1] 842327.1
```

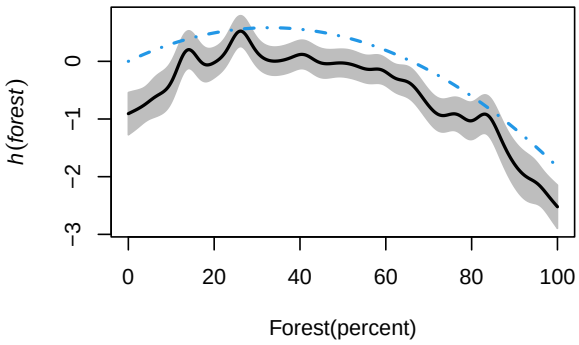
```r
print(AIC(fit3))
```

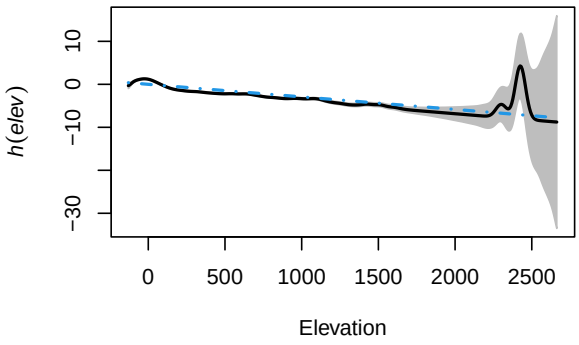
```
## [1] 719736
```

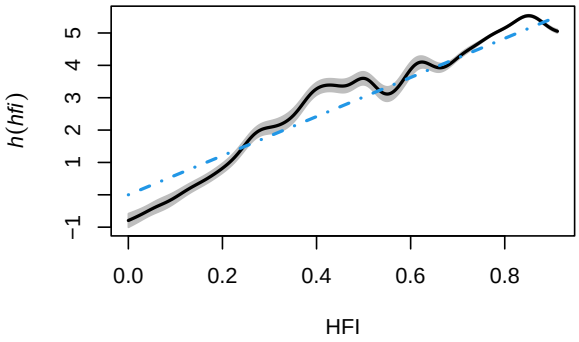
```r
print(anova(fit1, fit2, fit3, test="LRT"))
```

```
## Analysis of Deviance Table
##
## Model 1: ~forest + I(forest^2) + water    Poisson
## Model 2: ~water   Poisson
## Model 3: ~forest + I(forest^2) + elev + hfi   Poisson
##   Npar Df Deviance  Pr(>Chi)
## 1  467
## 2  465 -2   -11680 < 2.2e-16 ***
## 3  468  3   109661 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```r
par_res_forest <- parres(fit3, "forest")
par_res_elev <- parres(fit3, "elev")
par_res_hfi <- parres(fit3, "hfi")

par(mfrow = c(2,2))
plot(par_res_forest,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Forest(percent)")
plot(par_res_elev,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Elevation")
plot(par_res_hfi,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "HFI")
```

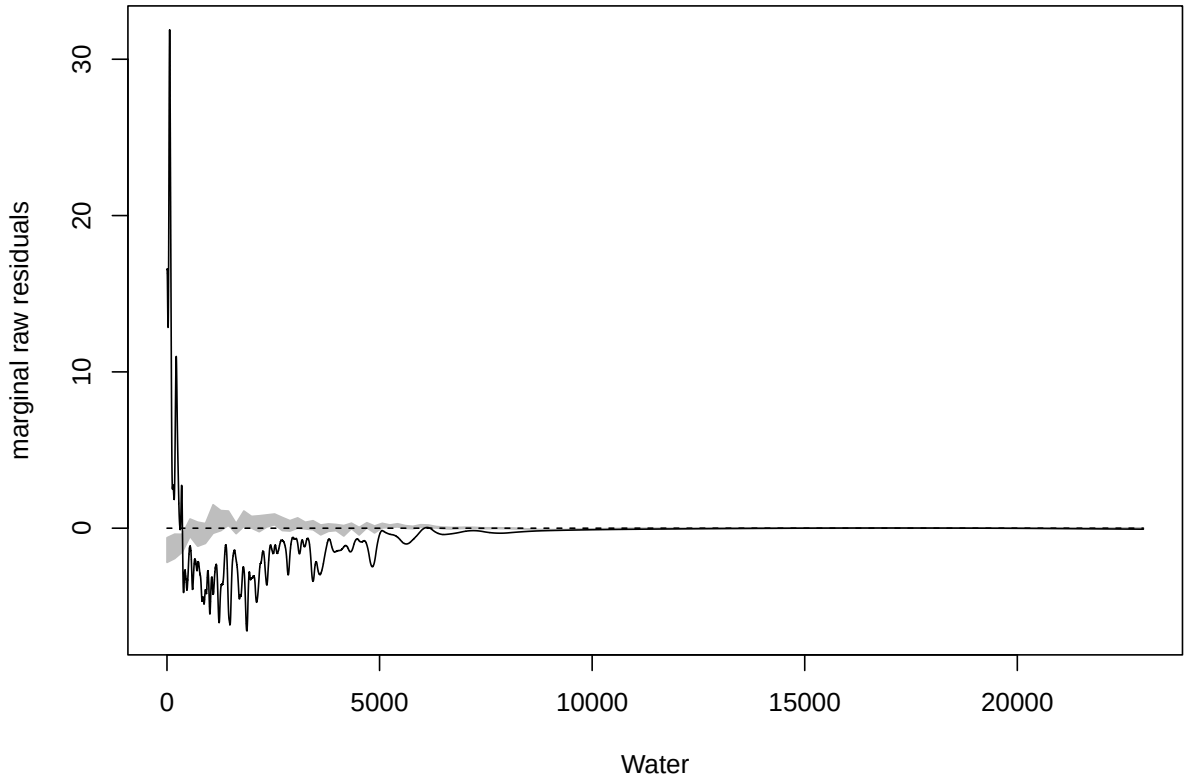







```
lurking(fit3, water,
        type = "raw", cumulative = F, envelope = T,
        xlab = "Water")
```

```
## Generating 39 simulated patterns ...1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19
## 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38,
## 39.
## Processing.. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20,
## 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38,
## 39.
## Done.
```

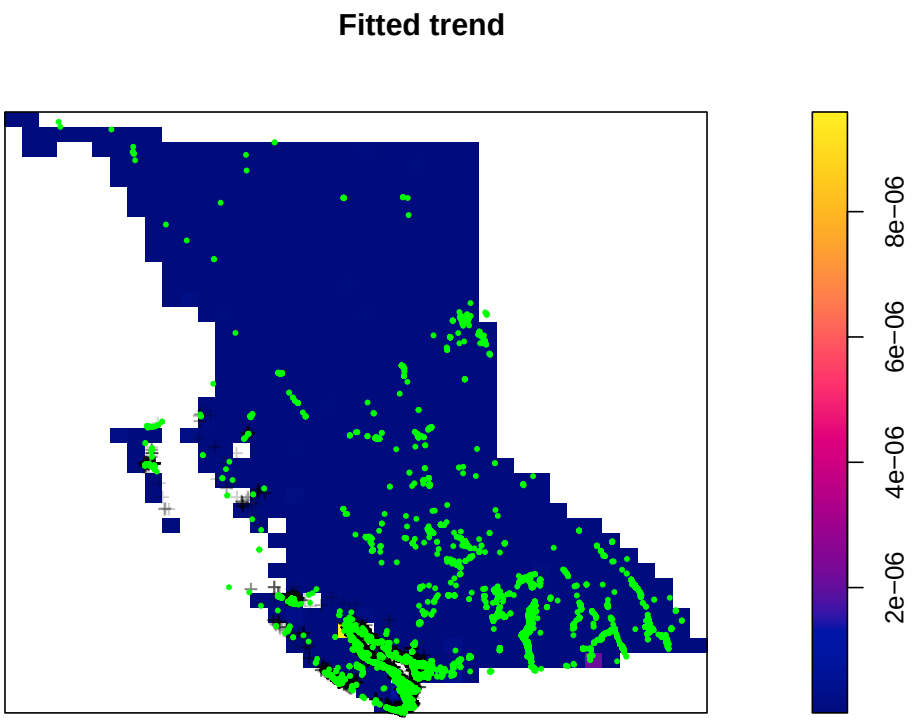



```
fit4 <- ppm(bird_ppp, ~ forest + I(forest^2) + elev + hfi + water)
fit4
```

```
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~forest + I(forest^2) + elev + hfi + water
##
## Fitted trend coefficients:
##   (Intercept)        forest   I(forest^2)          elev           hfi
## -1.609201e+01  7.201047e-03 -2.323025e-04 -2.575927e-03  5.806896e+00
##         water
## -1.503770e-03
##
##                   Estimate         S.E.       CI95.lo       CI95.hi Ztest
## (Intercept) -1.609201e+01 2.912923e-02 -1.614911e+01 -1.603492e+01   ***
## forest       7.201047e-03 9.181537e-04  5.401499e-03  9.000595e-03   ***
## I(forest^2) -2.323025e-04 1.194929e-05 -2.557227e-04 -2.088823e-04   ***
## elev        -2.575927e-03 2.444987e-05 -2.623848e-03 -2.528006e-03   ***
## hfi          5.806896e+00 3.111368e-02  5.745914e+00  5.867877e+00   ***
## water       -1.503770e-03 1.687063e-05 -1.536836e-03 -1.470704e-03   ***
##                     Zval
## (Intercept) -552.435237
```

```
## forest         7.842965
## I(forest^2)  -19.440691
## elev        -105.355429
## hfi          186.634792
## water        -89.135380
## Problem:
##  Values of the covariates 'forest', 'elev', 'hfi' were NA or undefined at 0.77%
## (528 out of 68828) of the quadrature points
```

```
plot(fit4,
     se = FALSE,
     superimpose = FALSE)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```




```
AIC(fit3); AIC(fit4)
```

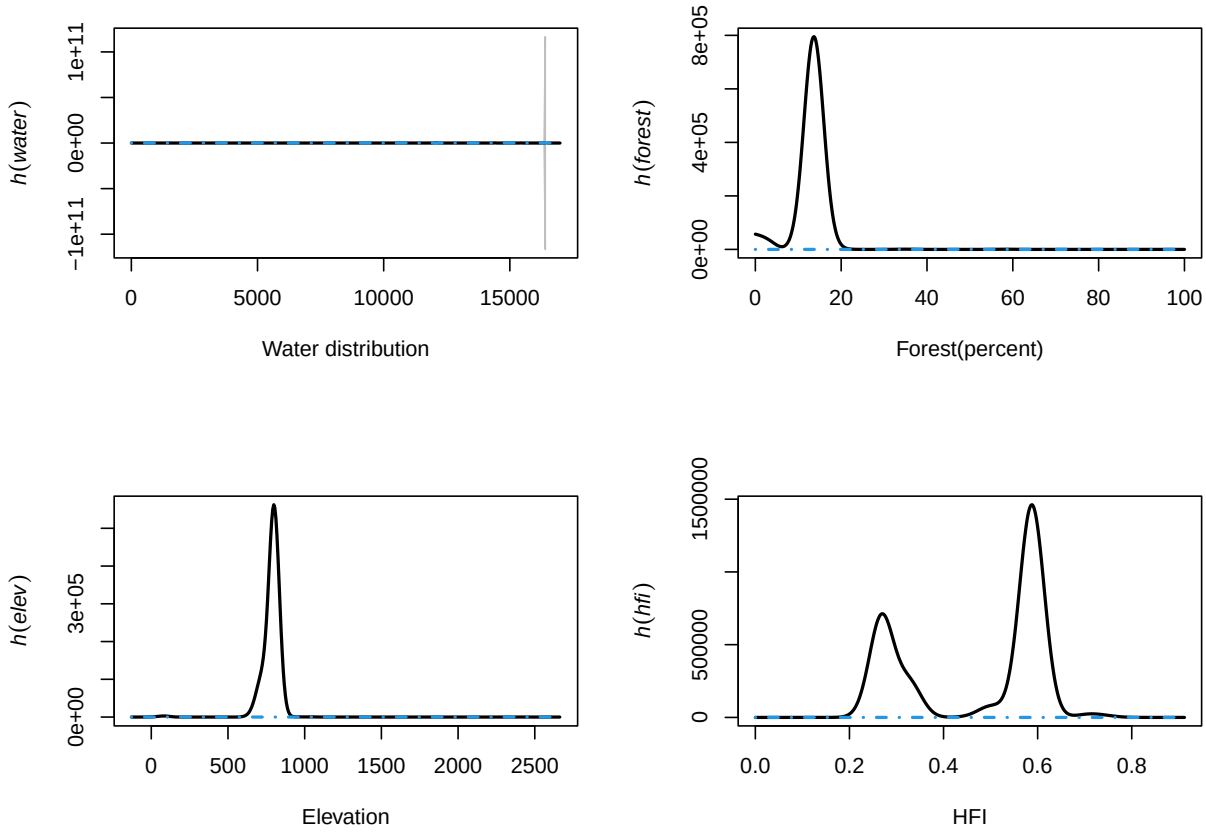
```
## [1] 719736
```

```
## [1] 695016.8
```

```
anova(fit3, fit4, test = "LRT")
```

```
## Analysis of Deviance Table
##
## Model 1: ~forest + I(forest^2) + elev + hfi   Poisson
## Model 2: ~forest + I(forest^2) + elev + hfi + water   Poisson
##   Npar Df Deviance  Pr(>Chi)
## 1    5
## 2    6  1    24721 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

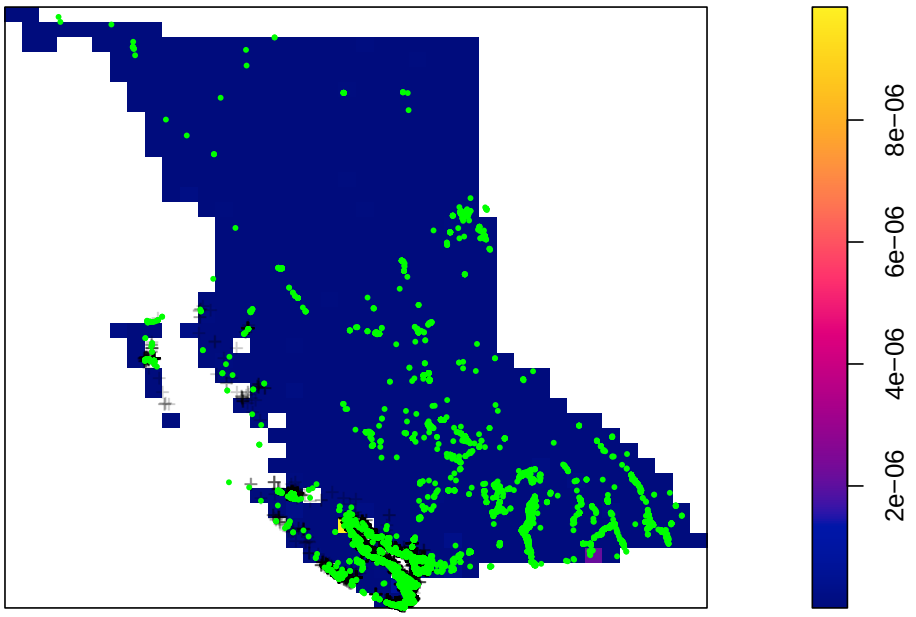
```
par_res_water <- parres(fit4, "water")
par_res_forest <- parres(fit4, "forest")
par_res_elev <- parres(fit4, "elev")
par_res_hfi <- parres(fit4, "hfi")

par(mfrow = c(2,2))
plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
plot(par_res_forest,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Forest(percent)")
plot(par_res_elev,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Elevation")
plot(par_res_hfi,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "HFI")
```




```
fit5 <- ppm(bird_ppp ~ forest + I(forest^2) + elev + hfi + water + I(water^2))
fit5
```

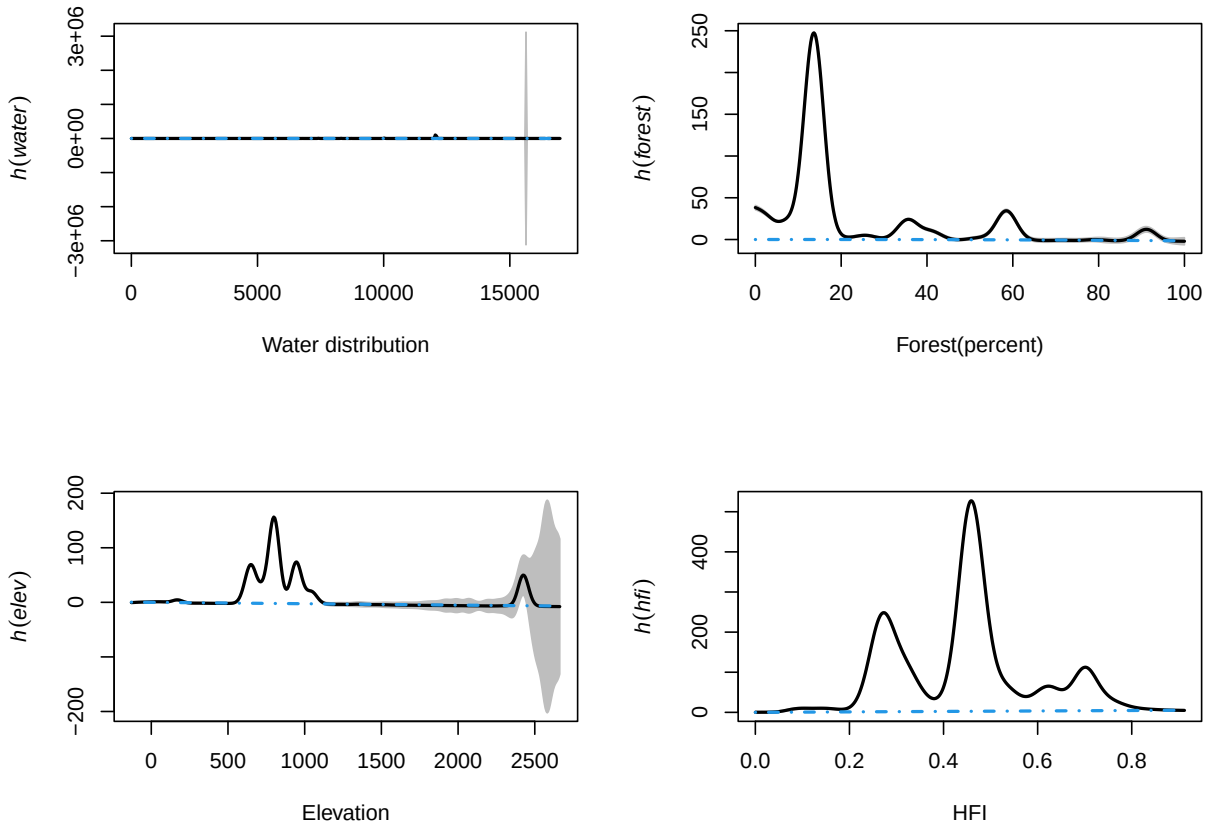
```
## Error in solve.default(M) :
##   system is computationally singular: reciprocal condition number = 7.91152e-17
## Error in solve.default(M) :
##   system is computationally singular: reciprocal condition number = 7.91152e-17
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~forest + I(forest^2) + elev + hfi + water + I(water^2)
##
## Fitted trend coefficients:
##   (Intercept)        forest   I(forest^2)          elev           hfi
## -1.602669e+01  6.151803e-03 -2.163719e-04 -2.550862e-03  5.778963e+00
##         water    I(water^2)
## -1.835384e-03  8.241579e-08
##
## Standard errors unavailable; Fisher information matrix is singular
## Problem:
##  Values of the covariates 'forest', 'elev', 'hfi' were NA or undefined at 0.77%
## (528 out of 68828) of the quadrature points
```

```
plot(fit5,
     se = FALSE,
     superimpose = FALSE)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```




```
par_res_water <- parres(fit5, "water")
par_res_forest <- parres(fit5, "forest")
par_res_elev <- parres(fit5, "elev")
par_res_hfi <- parres(fit5, "hfi")

par(mfrow = c(2,2))
plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
plot(par_res_forest,
     legend = FALSE,
```

```
     lwd = 2,
     main = "",
     xlab = "Forest(percent)")
plot(par_res_elev,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Elevation")
plot(par_res_hfi,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "HFI")
```




```
AIC(fit4); AIC(fit5)
```

```
## [1] 695016.8
```

```
## [1] 693035.7
```

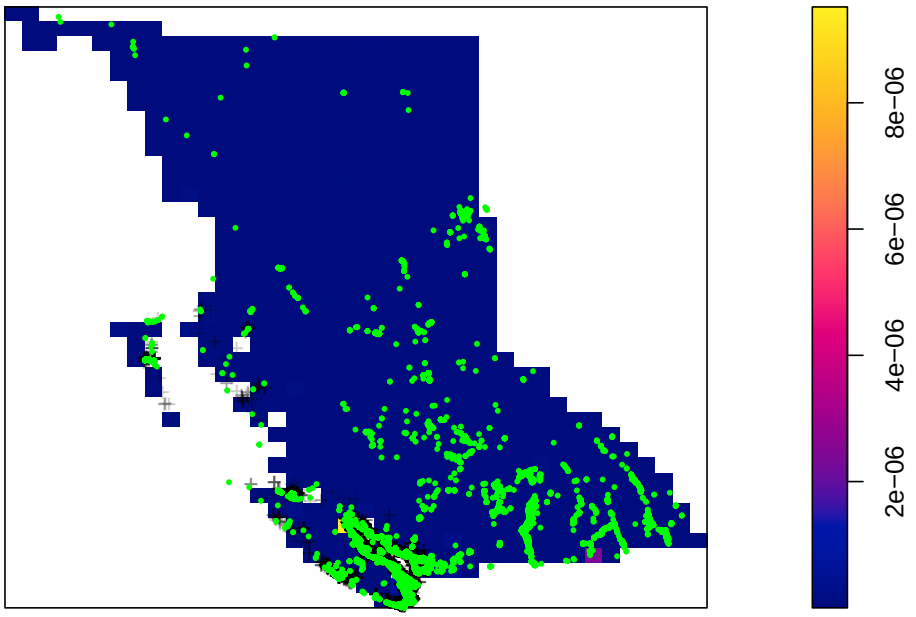
```r
anova(fit4, fit5, test = "LRT")
```

```
## Analysis of Deviance Table
##
## Model 1: ~forest + I(forest^2) + elev + hfi + water   Poisson
## Model 2: ~forest + I(forest^2) + elev + hfi + water + I(water^2)      Poisson
##   Npar Df Deviance  Pr(>Chi)
## 1    6
## 2    7  1   1983.1 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```r
fit6 <- ppm(bird_ppp ~ forest + I(forest^2) + elev + I(elev^2) + hfi + water + I(water^2))
fit6
```

```
## Error in solve.default(M) :
##   system is computationally singular: reciprocal condition number = 8.11593e-17
## Error in solve.default(M) :
##   system is computationally singular: reciprocal condition number = 8.11593e-17
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~forest + I(forest^2) + elev + I(elev^2) + hfi + water +
## I(water^2)
##
## Fitted trend coefficients:
##   (Intercept)        forest   I(forest^2)          elev     I(elev^2)
## -1.608612e+01  5.776975e-03 -2.143370e-04 -1.706166e-03 -9.083512e-07
##          hfi         water    I(water^2)
##  5.770464e+00 -1.827034e-03  8.191155e-08
##
## Standard errors unavailable; Fisher information matrix is singular
## Problem:
##  Values of the covariates 'forest', 'elev', 'hfi' were NA or undefined at 0.77%
## (528 out of 68828) of the quadrature points
```

```r
plot(fit6,
     se = FALSE,
     superimpose = FALSE)

plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```




```
AIC(fit4); AIC(fit5)
```

```
## [1] 695016.8
```

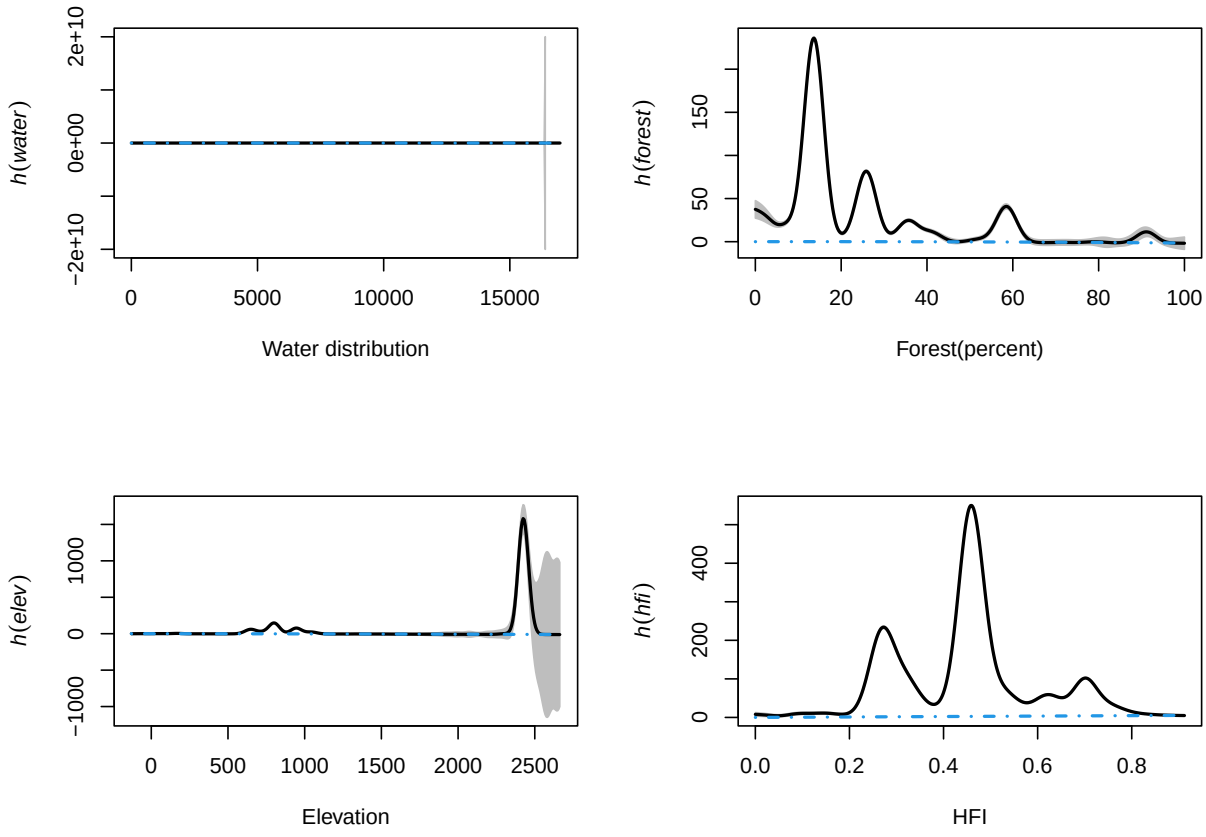
```
## [1] 693035.7
```

```
anova(fit5, fit6, test = "LRT")
```

```
## Analysis of Deviance Table
##
## Model 1: ~forest + I(forest^2) + elev + hfi + water + I(water^2)      Poisson
## Model 2: ~forest + I(forest^2) + elev + I(elev^2) + hfi + water + I(water^2)      Poisson
##   Npar Df Deviance  Pr(>Chi)
## 1    7
## 2    8  1   277.76 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
par_res_water <- parres(fit6, "water")
par_res_forest <- parres(fit6, "forest")
par_res_elev <- parres(fit6, "elev")
```

```r
par_res_hfi <- parres(fit6, "hfi")

par(mfrow = c(2,2))
plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
plot(par_res_forest,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Forest(percent)")
plot(par_res_elev,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Elevation")
plot(par_res_hfi,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "HFI")
```



```r
# Fit a point process model with selected covariates, considering potential interactions
fit7 <- ppm(bird_ppp ~ hfi + I(hfi^2) + forest + I(forest^2) + water + I(water^2)+ elev + I(elev^2))

# Check the summary of the model
summary(fit7)
```

```
## Error in solve.default(M) :
##   system is computationally singular: reciprocal condition number = 2.83187e-18
## Error in solve.default(M) :
##   system is computationally singular: reciprocal condition number = 2.83187e-18
```

```
## Point process model
## Fitted to data: bird_ppp
## Fitting method: maximum likelihood (Berman-Turner approximation)
## Model was fitted using glm()
## Algorithm converged
## Call:
## ppm.formula(Q = bird_ppp ~ hfi + I(hfi^2) + forest + I(forest^2) +
##     water + I(water^2) + elev + I(elev^2))
## Edge correction: "border"
##  [border correction distance r = 0 ]
## --------------------------------------------------------------------------------
## Quadrature scheme (Berman-Turner) = data + dummy + weights
##
## Data pattern:
## Planar point pattern:  24325 points
## Average intensity 2.57e-08 points per square unit
## Window: polygonal boundary
## 379 separate polygons (2 holes)
##                   vertices         area relative.area
## polygon 1             5454 889865000000      9.38e-01
## polygon 2             2129  31902300000      3.36e-02
## polygon 3 (hole)        55    -49871200     -5.26e-05
## polygon 4 (hole)        21    -15073400     -1.59e-05
## polygon 5              751   6476610000      6.83e-03
## polygon 6              764   2633530000      2.78e-03
## polygon 7              379   2286840000      2.41e-03
## polygon 8              281   1397560000      1.47e-03
## polygon 9              155   1020880000      1.08e-03
## polygon 10             178    822976000      8.68e-04
## polygon 11             189    531172000      5.60e-04
## polygon 12             135    523600000      5.52e-04
## polygon 13              93    429077000      4.52e-04
## polygon 14              59    375017000      3.95e-04
## polygon 15              80    366555000      3.87e-04
## polygon 16             130    389457000      4.11e-04
## polygon 17             129    361761000      3.81e-04
## polygon 18              73    325642000      3.43e-04
## polygon 19              72    284295000      3.00e-04
## polygon 20              98    291606000      3.08e-04
## polygon 21              87    301693000      3.18e-04
## polygon 22              60    271131000      2.86e-04
## polygon 23             105    273020000      2.88e-04
```

```
## polygon 24            67    238816000      2.52e-04
## polygon 25            72    240998000      2.54e-04
## polygon 26            51    207196000      2.19e-04
## polygon 27            81    175770000      1.85e-04
## polygon 28            72    186213000      1.96e-04
## polygon 29            60    170593000      1.80e-04
## polygon 30            52    171879000      1.81e-04
## polygon 31            62    174668000      1.84e-04
## polygon 32            55    163246000      1.72e-04
## polygon 33            63    151745000      1.60e-04
## polygon 34            62    164385000      1.73e-04
## polygon 35            70    155140000      1.64e-04
## polygon 36            63    152920000      1.61e-04
## polygon 37            72    134301000      1.42e-04
## polygon 38            88    135277000      1.43e-04
## polygon 39            93    128722000      1.36e-04
## polygon 40            45    127343000      1.34e-04
## polygon 41            84    130472000      1.38e-04
## polygon 42            49    114370000      1.21e-04
## polygon 43            44    106635000      1.12e-04
## polygon 44            53    102951000      1.09e-04
## polygon 45            52    100309000      1.06e-04
## polygon 46            45     95770200      1.01e-04
## polygon 47            43     95377600      1.01e-04
## polygon 48            39     92824200      9.79e-05
## polygon 49            47     81225900      8.57e-05
## polygon 50            40     80617200      8.50e-05
## polygon 51            64     83219400      8.78e-05
## polygon 52            33     76223000      8.04e-05
## polygon 53            34     67360500      7.10e-05
## polygon 54            54     68347400      7.21e-05
## polygon 55            44     64136400      6.76e-05
## polygon 56            42     66265500      6.99e-05
## polygon 57            29     62988400      6.64e-05
## polygon 58            31     59626500      6.29e-05
## polygon 59            25     54751800      5.77e-05
## polygon 60            31     55352900      5.84e-05
## polygon 61            30     53162300      5.61e-05
## polygon 62            44     57621600      6.08e-05
## polygon 63            26     56707500      5.98e-05
## polygon 64            36     56979200      6.01e-05
## polygon 65            32     55472500      5.85e-05
## polygon 66            21     50455600      5.32e-05
## polygon 67            40     51039400      5.38e-05
## polygon 68            26     53043500      5.59e-05
## polygon 69            29     51938100      5.48e-05
## polygon 70            27     50295800      5.30e-05
## polygon 71            33     47938300      5.06e-05
## polygon 72            18     44300200      4.67e-05
## polygon 73            25     45691800      4.82e-05
## polygon 74            29     43313200      4.57e-05
## polygon 75            36     46561100      4.91e-05
## polygon 76            31     46220100      4.87e-05
## polygon 77            26     40401700      4.26e-05
```

```
## polygon 78            30     43204000      4.56e-05
## polygon 79            26     41430100      4.37e-05
## polygon 80            25     36988000      3.90e-05
## polygon 81            28     37700100      3.98e-05
## polygon 82            20     35892800      3.79e-05
## polygon 83            34     38217700      4.03e-05
## polygon 84            21     34874700      3.68e-05
## polygon 85            25     33536100      3.54e-05
## polygon 86            30     36738900      3.87e-05
## polygon 87            30     35393400      3.73e-05
## polygon 88            23     32140100      3.39e-05
## polygon 89            28     31469400      3.32e-05
## polygon 90            23     32736900      3.45e-05
## polygon 91            28     34117200      3.60e-05
## polygon 92            20     31802600      3.35e-05
## polygon 93            26     30659000      3.23e-05
## polygon 94            24     29572700      3.12e-05
## polygon 95            27     27289800      2.88e-05
## polygon 96            16     23094400      2.44e-05
## polygon 97            23     24218600      2.55e-05
## polygon 98            18     21846600      2.30e-05
## polygon 99            14     23702300      2.50e-05
## polygon 100           21     24325800      2.57e-05
## polygon 101           23     22590100      2.38e-05
## polygon 102           24     19177800      2.02e-05
## polygon 103           22     18657800      1.97e-05
## polygon 104           15     17454800      1.84e-05
## polygon 105           14     16276800      1.72e-05
## polygon 106           13     15792300      1.67e-05
## polygon 107           17     16117900      1.70e-05
## polygon 108           12     16217100      1.71e-05
## polygon 109           19     16610700      1.75e-05
## polygon 110           18     16809400      1.77e-05
## polygon 111           15     15096400      1.59e-05
## polygon 112           14     14571400      1.54e-05
## polygon 113           11     13567300      1.43e-05
## polygon 114           16     13623600      1.44e-05
## polygon 115           15     13657400      1.44e-05
## polygon 116           18     14346200      1.51e-05
## polygon 117           15     12418500      1.31e-05
## polygon 118           22     13085700      1.38e-05
## polygon 119           11     13446800      1.42e-05
## polygon 120           14     13234700      1.40e-05
## polygon 121           15     13532800      1.43e-05
## polygon 122           16     12575800      1.33e-05
## polygon 123           15     13060700      1.38e-05
## polygon 124           15     11766100      1.24e-05
## polygon 125           18     11038100      1.16e-05
## polygon 126           12     12863200      1.36e-05
## polygon 127           19     11135700      1.17e-05
## polygon 128           11     10881600      1.15e-05
## polygon 129           14     12500500      1.32e-05
## polygon 130           12     10733900      1.13e-05
## polygon 131           15     11201200      1.18e-05
```

```
## polygon 132          13     10674100      1.13e-05
## polygon 133          13      9776920      1.03e-05
## polygon 134          14     10503500      1.11e-05
## polygon 135          12      9391460      9.90e-06
## polygon 136          10      9402110      9.92e-06
## polygon 137           9      9160880      9.66e-06
## polygon 138          11      8674110      9.15e-06
## polygon 139          12      9159420      9.66e-06
## polygon 140          14      8676590      9.15e-06
## polygon 141          12      9527540      1.00e-05
## polygon 142          12      8797870      9.28e-06
## polygon 143          11      8837670      9.32e-06
## polygon 144          13      9067690      9.56e-06
## polygon 145          12      7950440      8.38e-06
## polygon 146           9      8727650      9.20e-06
## polygon 147           8      8565660      9.03e-06
## polygon 148           8      6790020      7.16e-06
## polygon 149          11      6780640      7.15e-06
## polygon 150          11      7326980      7.73e-06
## polygon 151          10      6152880      6.49e-06
## polygon 152          13      6721370      7.09e-06
## polygon 153           8      6343870      6.69e-06
## polygon 154          11      6807170      7.18e-06
## polygon 155          10      6927150      7.31e-06
## polygon 156           9      6352310      6.70e-06
## polygon 157          13      6217600      6.56e-06
## polygon 158          15      6263440      6.61e-06
## polygon 159          11      5769240      6.08e-06
## polygon 160           8      5965270      6.29e-06
## polygon 161          10      6826030      7.20e-06
## polygon 162          10      5749960      6.06e-06
## polygon 163          15      5352810      5.64e-06
## polygon 164           9      5781470      6.10e-06
## polygon 165          13      5358790      5.65e-06
## polygon 166          10      6016930      6.35e-06
## polygon 167           9      5928820      6.25e-06
## polygon 168           8      5424110      5.72e-06
## polygon 169           9      5468680      5.77e-06
## polygon 170          11      5209670      5.49e-06
## polygon 171           9      4705250      4.96e-06
## polygon 172           9      4891810      5.16e-06
## polygon 173          11      5295110      5.58e-06
## polygon 174           7      4839440      5.10e-06
## polygon 175           7      4322930      4.56e-06
## polygon 176           7      4514530      4.76e-06
## polygon 177           7      4573450      4.82e-06
## polygon 178           9      5080950      5.36e-06
## polygon 179          12      4492120      4.74e-06
## polygon 180           8      4783060      5.04e-06
## polygon 181           8      3800770      4.01e-06
## polygon 182           5      4657790      4.91e-06
## polygon 183          11      4323150      4.56e-06
## polygon 184           9      3549270      3.74e-06
## polygon 185           6      4103470      4.33e-06
```

```
## polygon 186            8      3898980      4.11e-06
## polygon 187            8      4009440      4.23e-06
## polygon 188            9      3672080      3.87e-06
## polygon 189           11      3540120      3.73e-06
## polygon 190            6      3790670      4.00e-06
## polygon 191            8      3695580      3.90e-06
## polygon 192            7      3708650      3.91e-06
## polygon 193            7      3843670      4.05e-06
## polygon 194            7      3157020      3.33e-06
## polygon 195            9      2913680      3.07e-06
## polygon 196            9      3368170      3.55e-06
## polygon 197            7      3190600      3.36e-06
## polygon 198            6      3073660      3.24e-06
## polygon 199            9      3016490      3.18e-06
## polygon 200            8      3129780      3.30e-06
## polygon 201            6      3101410      3.27e-06
## polygon 202            7      2895440      3.05e-06
## polygon 203            8      2998870      3.16e-06
## polygon 204            7      2619570      2.76e-06
## polygon 205           10      3007320      3.17e-06
## polygon 206            7      2324090      2.45e-06
## polygon 207           10      2935450      3.10e-06
## polygon 208           10      2523640      2.66e-06
## polygon 209            6      2232050      2.35e-06
## polygon 210            6      2131190      2.25e-06
## polygon 211            6      1679950      1.77e-06
## polygon 212            6      2226470      2.35e-06
## polygon 213            8      2267800      2.39e-06
## polygon 214            6      2584690      2.73e-06
## polygon 215            5      2151150      2.27e-06
## polygon 216            6      1536960      1.62e-06
## polygon 217            6      2616700      2.76e-06
## polygon 218            7      2205520      2.33e-06
## polygon 219            8      2008210      2.12e-06
## polygon 220            5      2181540      2.30e-06
## polygon 221            7      2700450      2.85e-06
## polygon 222            7      2493440      2.63e-06
## polygon 223            7      2752380      2.90e-06
## polygon 224            5      2036350      2.15e-06
## polygon 225            5      2344480      2.47e-06
## polygon 226            5      1786340      1.88e-06
## polygon 227            8      2269610      2.39e-06
## polygon 228            6      1857450      1.96e-06
## polygon 229            5      1978280      2.09e-06
## polygon 230            5      1944240      2.05e-06
## polygon 231            6      2728340      2.88e-06
## polygon 232            8      1905200      2.01e-06
## polygon 233            7      2258780      2.38e-06
## polygon 234            5      1891180      1.99e-06
## polygon 235            5      1957860      2.06e-06
## polygon 236            7      2335470      2.46e-06
## polygon 237            4      2055120      2.17e-06
## polygon 238            6      1829730      1.93e-06
## polygon 239            5      1807400      1.91e-06
```

```
## polygon 240            5      2014070      2.12e-06
## polygon 241            5      1882630      1.99e-06
## polygon 242            5      1928800      2.03e-06
## polygon 243            5      2010320      2.12e-06
## polygon 244            5      1521870      1.60e-06
## polygon 245            6      1935590      2.04e-06
## polygon 246            5      1647440      1.74e-06
## polygon 247            4      1518380      1.60e-06
## polygon 248            6      1623490      1.71e-06
## polygon 249            5      1654240      1.74e-06
## polygon 250            5      1691180      1.78e-06
## polygon 251            3       765559      8.07e-07
## polygon 252            6      1792550      1.89e-06
## polygon 253            5      1428170      1.51e-06
## polygon 254            5      1356230      1.43e-06
## polygon 255            5      1536990      1.62e-06
## polygon 256            5      1188700      1.25e-06
## polygon 257            4       846360      8.93e-07
## polygon 258            5      1449400      1.53e-06
## polygon 259            4      1654610      1.74e-06
## polygon 260            6      1472190      1.55e-06
## polygon 261            4      1163890      1.23e-06
## polygon 262            7      1548860      1.63e-06
## polygon 263            6      1317820      1.39e-06
## polygon 264            5      1220870      1.29e-06
## polygon 265            4      1251210      1.32e-06
## polygon 266            6      1443280      1.52e-06
## polygon 267            5      1430870      1.51e-06
## polygon 268            5      1201830      1.27e-06
## polygon 269            7      1083120      1.14e-06
## polygon 270            5      1315200      1.39e-06
## polygon 271            5      1173590      1.24e-06
## polygon 272            5      1283640      1.35e-06
## polygon 273            5      1243830      1.31e-06
## polygon 274            5      1418840      1.50e-06
## polygon 275            6      1194150      1.26e-06
## polygon 276            3       732692      7.73e-07
## polygon 277            4       724047      7.64e-07
## polygon 278            4      1110880      1.17e-06
## polygon 279            4      1068690      1.13e-06
## polygon 280            5      1080070      1.14e-06
## polygon 281            5      1105010      1.17e-06
## polygon 282            4      1101910      1.16e-06
## polygon 283            5      1202270      1.27e-06
## polygon 284            5      1193280      1.26e-06
## polygon 285            5      1104420      1.16e-06
## polygon 286            5      1337410      1.41e-06
## polygon 287            6      1293100      1.36e-06
## polygon 288            4       715019      7.54e-07
## polygon 289            3       772725      8.15e-07
## polygon 290            4       856683      9.03e-07
## polygon 291            4       986692      1.04e-06
## polygon 292            4       808047      8.52e-07
## polygon 293            4       740351      7.81e-07
```

```
## polygon 294            4       839774      8.86e-07
## polygon 295            5       997422      1.05e-06
## polygon 296            4       841098      8.87e-07
## polygon 297            7      1180430      1.24e-06
## polygon 298            4      1072900      1.13e-06
## polygon 299            5      1071650      1.13e-06
## polygon 300            4       937949      9.89e-07
## polygon 301            4       714701      7.54e-07
## polygon 302            4       854803      9.01e-07
## polygon 303            4       965776      1.02e-06
## polygon 304            4       875646      9.23e-07
## polygon 305            4       682625      7.20e-07
## polygon 306            4       799391      8.43e-07
## polygon 307            4       915082      9.65e-07
## polygon 308            4       647125      6.82e-07
## polygon 309            5       850200      8.97e-07
## polygon 310            4       856777      9.04e-07
## polygon 311            5       926662      9.77e-07
## polygon 312            4       702365      7.41e-07
## polygon 313            4       877724      9.26e-07
## polygon 314            4       625455      6.60e-07
## polygon 315            4       604921      6.38e-07
## polygon 316            4       564256      5.95e-07
## polygon 317            5       943607      9.95e-07
## polygon 318            4       725841      7.65e-07
## polygon 319            4       838391      8.84e-07
## polygon 320            4       725920      7.66e-07
## polygon 321            4       607726      6.41e-07
## polygon 322            3       377075      3.98e-07
## polygon 323            4       801044      8.45e-07
## polygon 324            4       707601      7.46e-07
## polygon 325            4       701275      7.40e-07
## polygon 326            3       567574      5.99e-07
## polygon 327            4       656976      6.93e-07
## polygon 328            4       697610      7.36e-07
## polygon 329            3       429629      4.53e-07
## polygon 330            4       692723      7.31e-07
## polygon 331            5      1123680      1.18e-06
## polygon 332            4       638721      6.74e-07
## polygon 333            4       649515      6.85e-07
## polygon 334            5       885457      9.34e-07
## polygon 335            3       397429      4.19e-07
## polygon 336            3       311243      3.28e-07
## polygon 337            4       692962      7.31e-07
## polygon 338            4       637359      6.72e-07
## polygon 339            3       347030      3.66e-07
## polygon 340            4       545022      5.75e-07
## polygon 341            4       630075      6.64e-07
## polygon 342            4       682861      7.20e-07
## polygon 343            4       582135      6.14e-07
## polygon 344            4       685738      7.23e-07
## polygon 345            3       666827      7.03e-07
## polygon 346            4       638063      6.73e-07
## polygon 347            3       415934      4.39e-07
```

```
## polygon 348             3       496699      5.24e-07
## polygon 349             4       523038      5.52e-07
## polygon 350             4       629200      6.64e-07
## polygon 351             4       545075      5.75e-07
## polygon 352             4       523200      5.52e-07
## polygon 353             4       534278      5.63e-07
## polygon 354             4       617265      6.51e-07
## polygon 355             4       554460      5.85e-07
## polygon 356             3       422197      4.45e-07
## polygon 357             4       450587      4.75e-07
## polygon 358             3       506804      5.34e-07
## polygon 359             4       666360      7.03e-07
## polygon 360             4       648581      6.84e-07
## polygon 361             3       453422      4.78e-07
## polygon 362             4       572761      6.04e-07
## polygon 363             4       515850      5.44e-07
## polygon 364             4       501575      5.29e-07
## polygon 365             4       501226      5.29e-07
## polygon 366             4       601941      6.35e-07
## polygon 367             4       593073      6.25e-07
## polygon 368             3       427855      4.51e-07
## polygon 369             3       295928      3.12e-07
## polygon 370             4       640706      6.76e-07
## polygon 371             5       714352      7.53e-07
## polygon 372             4       494594      5.22e-07
## polygon 373             3       413224      4.36e-07
## polygon 374             3       254908      2.69e-07
## polygon 375             4       458639      4.84e-07
## polygon 376             3       374163      3.95e-07
## polygon 377             4       514470      5.43e-07
## polygon 378             4       419372      4.42e-07
## polygon 379             3       405491      4.28e-07
## enclosing rectangle: [273874.9, 1870573.4] x [369042.8, 1735666.4] units
##                      (1597000 x 1367000 units)
## Window area = 9.48262e+11 square units
## Fraction of frame area: 0.435
##
## Dummy quadrature points:
##      320 x 320 grid of dummy points, plus 4 corner points
##      dummy spacing: 4989.683 x 4270.699 units
##
## Original dummy parameters: =
## Planar point pattern:  44503 points
## Average intensity 4.69e-08 points per square unit
## Window: polygonal boundary
## 379 separate polygons (2 holes)
##                  vertices         area relative.area
## polygon 1            5454 889865000000      9.38e-01
## polygon 2            2129  31902300000      3.36e-02
## polygon 3 (hole)       55    -49871200     -5.26e-05
## polygon 4 (hole)       21    -15073400     -1.59e-05
## polygon 5             751   6476610000      6.83e-03
## polygon 6             764   2633530000      2.78e-03
## polygon 7             379   2286840000      2.41e-03
```

```
## polygon 8            281   1397560000      1.47e-03
## polygon 9            155   1020880000      1.08e-03
## polygon 10           178    822976000      8.68e-04
## polygon 11           189    531172000      5.60e-04
## polygon 12           135    523600000      5.52e-04
## polygon 13            93    429077000      4.52e-04
## polygon 14            59    375017000      3.95e-04
## polygon 15            80    366555000      3.87e-04
## polygon 16           130    389457000      4.11e-04
## polygon 17           129    361761000      3.81e-04
## polygon 18            73    325642000      3.43e-04
## polygon 19            72    284295000      3.00e-04
## polygon 20            98    291606000      3.08e-04
## polygon 21            87    301693000      3.18e-04
## polygon 22            60    271131000      2.86e-04
## polygon 23           105    273020000      2.88e-04
## polygon 24            67    238816000      2.52e-04
## polygon 25            72    240998000      2.54e-04
## polygon 26            51    207196000      2.19e-04
## polygon 27            81    175770000      1.85e-04
## polygon 28            72    186213000      1.96e-04
## polygon 29            60    170593000      1.80e-04
## polygon 30            52    171879000      1.81e-04
## polygon 31            62    174668000      1.84e-04
## polygon 32            55    163246000      1.72e-04
## polygon 33            63    151745000      1.60e-04
## polygon 34            62    164385000      1.73e-04
## polygon 35            70    155140000      1.64e-04
## polygon 36            63    152920000      1.61e-04
## polygon 37            72    134301000      1.42e-04
## polygon 38            88    135277000      1.43e-04
## polygon 39            93    128722000      1.36e-04
## polygon 40            45    127343000      1.34e-04
## polygon 41            84    130472000      1.38e-04
## polygon 42            49    114370000      1.21e-04
## polygon 43            44    106635000      1.12e-04
## polygon 44            53    102951000      1.09e-04
## polygon 45            52    100309000      1.06e-04
## polygon 46            45     95770200      1.01e-04
## polygon 47            43     95377600      1.01e-04
## polygon 48            39     92824200      9.79e-05
## polygon 49            47     81225900      8.57e-05
## polygon 50            40     80617200      8.50e-05
## polygon 51            64     83219400      8.78e-05
## polygon 52            33     76223000      8.04e-05
## polygon 53            34     67360500      7.10e-05
## polygon 54            54     68347400      7.21e-05
## polygon 55            44     64136400      6.76e-05
## polygon 56            42     66265500      6.99e-05
## polygon 57            29     62988400      6.64e-05
## polygon 58            31     59626500      6.29e-05
## polygon 59            25     54751800      5.77e-05
## polygon 60            31     55352900      5.84e-05
## polygon 61            30     53162300      5.61e-05
```

```
## polygon 62            44     57621600      6.08e-05
## polygon 63            26     56707500      5.98e-05
## polygon 64            36     56979200      6.01e-05
## polygon 65            32     55472500      5.85e-05
## polygon 66            21     50455600      5.32e-05
## polygon 67            40     51039400      5.38e-05
## polygon 68            26     53043500      5.59e-05
## polygon 69            29     51938100      5.48e-05
## polygon 70            27     50295800      5.30e-05
## polygon 71            33     47938300      5.06e-05
## polygon 72            18     44300200      4.67e-05
## polygon 73            25     45691800      4.82e-05
## polygon 74            29     43313200      4.57e-05
## polygon 75            36     46561100      4.91e-05
## polygon 76            31     46220100      4.87e-05
## polygon 77            26     40401700      4.26e-05
## polygon 78            30     43204000      4.56e-05
## polygon 79            26     41430100      4.37e-05
## polygon 80            25     36988000      3.90e-05
## polygon 81            28     37700100      3.98e-05
## polygon 82            20     35892800      3.79e-05
## polygon 83            34     38217700      4.03e-05
## polygon 84            21     34874700      3.68e-05
## polygon 85            25     33536100      3.54e-05
## polygon 86            30     36738900      3.87e-05
## polygon 87            30     35393400      3.73e-05
## polygon 88            23     32140100      3.39e-05
## polygon 89            28     31469400      3.32e-05
## polygon 90            23     32736900      3.45e-05
## polygon 91            28     34117200      3.60e-05
## polygon 92            20     31802600      3.35e-05
## polygon 93            26     30659000      3.23e-05
## polygon 94            24     29572700      3.12e-05
## polygon 95            27     27289800      2.88e-05
## polygon 96            16     23094400      2.44e-05
## polygon 97            23     24218600      2.55e-05
## polygon 98            18     21846600      2.30e-05
## polygon 99            14     23702300      2.50e-05
## polygon 100           21     24325800      2.57e-05
## polygon 101           23     22590100      2.38e-05
## polygon 102           24     19177800      2.02e-05
## polygon 103           22     18657800      1.97e-05
## polygon 104           15     17454800      1.84e-05
## polygon 105           14     16276800      1.72e-05
## polygon 106           13     15792300      1.67e-05
## polygon 107           17     16117900      1.70e-05
## polygon 108           12     16217100      1.71e-05
## polygon 109           19     16610700      1.75e-05
## polygon 110           18     16809400      1.77e-05
## polygon 111           15     15096400      1.59e-05
## polygon 112           14     14571400      1.54e-05
## polygon 113           11     13567300      1.43e-05
## polygon 114           16     13623600      1.44e-05
## polygon 115           15     13657400      1.44e-05
```

```
## polygon 116          18     14346200      1.51e-05
## polygon 117          15     12418500      1.31e-05
## polygon 118          22     13085700      1.38e-05
## polygon 119          11     13446800      1.42e-05
## polygon 120          14     13234700      1.40e-05
## polygon 121          15     13532800      1.43e-05
## polygon 122          16     12575800      1.33e-05
## polygon 123          15     13060700      1.38e-05
## polygon 124          15     11766100      1.24e-05
## polygon 125          18     11038100      1.16e-05
## polygon 126          12     12863200      1.36e-05
## polygon 127          19     11135700      1.17e-05
## polygon 128          11     10881600      1.15e-05
## polygon 129          14     12500500      1.32e-05
## polygon 130          12     10733900      1.13e-05
## polygon 131          15     11201200      1.18e-05
## polygon 132          13     10674100      1.13e-05
## polygon 133          13      9776920      1.03e-05
## polygon 134          14     10503500      1.11e-05
## polygon 135          12      9391460      9.90e-06
## polygon 136          10      9402110      9.92e-06
## polygon 137           9      9160880      9.66e-06
## polygon 138          11      8674110      9.15e-06
## polygon 139          12      9159420      9.66e-06
## polygon 140          14      8676590      9.15e-06
## polygon 141          12      9527540      1.00e-05
## polygon 142          12      8797870      9.28e-06
## polygon 143          11      8837670      9.32e-06
## polygon 144          13      9067690      9.56e-06
## polygon 145          12      7950440      8.38e-06
## polygon 146           9      8727650      9.20e-06
## polygon 147           8      8565660      9.03e-06
## polygon 148           8      6790020      7.16e-06
## polygon 149          11      6780640      7.15e-06
## polygon 150          11      7326980      7.73e-06
## polygon 151          10      6152880      6.49e-06
## polygon 152          13      6721370      7.09e-06
## polygon 153           8      6343870      6.69e-06
## polygon 154          11      6807170      7.18e-06
## polygon 155          10      6927150      7.31e-06
## polygon 156           9      6352310      6.70e-06
## polygon 157          13      6217600      6.56e-06
## polygon 158          15      6263440      6.61e-06
## polygon 159          11      5769240      6.08e-06
## polygon 160           8      5965270      6.29e-06
## polygon 161          10      6826030      7.20e-06
## polygon 162          10      5749960      6.06e-06
## polygon 163          15      5352810      5.64e-06
## polygon 164           9      5781470      6.10e-06
## polygon 165          13      5358790      5.65e-06
## polygon 166          10      6016930      6.35e-06
## polygon 167           9      5928820      6.25e-06
## polygon 168           8      5424110      5.72e-06
## polygon 169           9      5468680      5.77e-06
```

```
## polygon 170           11      5209670      5.49e-06
## polygon 171            9      4705250      4.96e-06
## polygon 172            9      4891810      5.16e-06
## polygon 173           11      5295110      5.58e-06
## polygon 174            7      4839440      5.10e-06
## polygon 175            7      4322930      4.56e-06
## polygon 176            7      4514530      4.76e-06
## polygon 177            7      4573450      4.82e-06
## polygon 178            9      5080950      5.36e-06
## polygon 179           12      4492120      4.74e-06
## polygon 180            8      4783060      5.04e-06
## polygon 181            8      3800770      4.01e-06
## polygon 182            5      4657790      4.91e-06
## polygon 183           11      4323150      4.56e-06
## polygon 184            9      3549270      3.74e-06
## polygon 185            6      4103470      4.33e-06
## polygon 186            8      3898980      4.11e-06
## polygon 187            8      4009440      4.23e-06
## polygon 188            9      3672080      3.87e-06
## polygon 189           11      3540120      3.73e-06
## polygon 190            6      3790670      4.00e-06
## polygon 191            8      3695580      3.90e-06
## polygon 192            7      3708650      3.91e-06
## polygon 193            7      3843670      4.05e-06
## polygon 194            7      3157020      3.33e-06
## polygon 195            9      2913680      3.07e-06
## polygon 196            9      3368170      3.55e-06
## polygon 197            7      3190600      3.36e-06
## polygon 198            6      3073660      3.24e-06
## polygon 199            9      3016490      3.18e-06
## polygon 200            8      3129780      3.30e-06
## polygon 201            6      3101410      3.27e-06
## polygon 202            7      2895440      3.05e-06
## polygon 203            8      2998870      3.16e-06
## polygon 204            7      2619570      2.76e-06
## polygon 205           10      3007320      3.17e-06
## polygon 206            7      2324090      2.45e-06
## polygon 207           10      2935450      3.10e-06
## polygon 208           10      2523640      2.66e-06
## polygon 209            6      2232050      2.35e-06
## polygon 210            6      2131190      2.25e-06
## polygon 211            6      1679950      1.77e-06
## polygon 212            6      2226470      2.35e-06
## polygon 213            8      2267800      2.39e-06
## polygon 214            6      2584690      2.73e-06
## polygon 215            5      2151150      2.27e-06
## polygon 216            6      1536960      1.62e-06
## polygon 217            6      2616700      2.76e-06
## polygon 218            7      2205520      2.33e-06
## polygon 219            8      2008210      2.12e-06
## polygon 220            5      2181540      2.30e-06
## polygon 221            7      2700450      2.85e-06
## polygon 222            7      2493440      2.63e-06
## polygon 223            7      2752380      2.90e-06
```

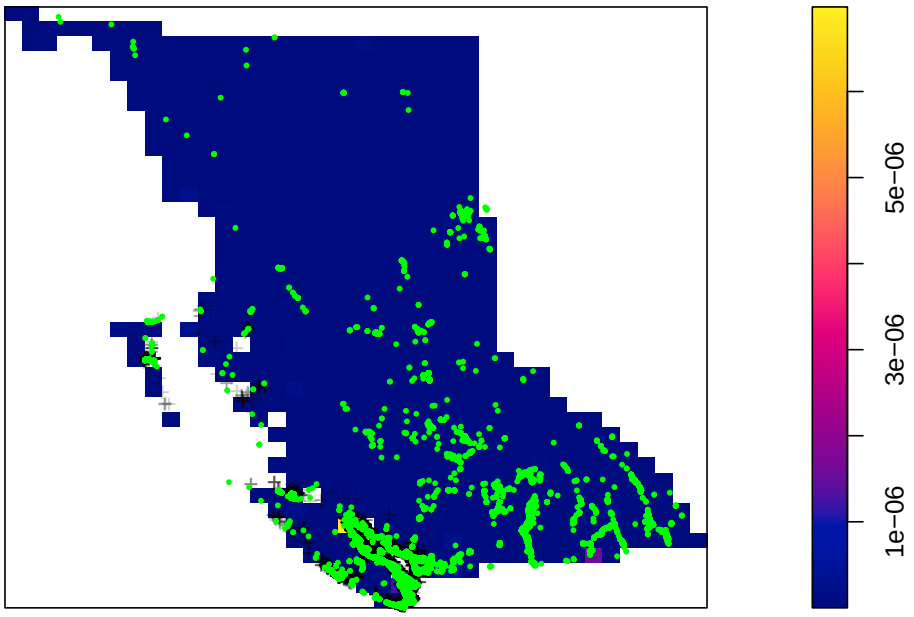
```
## polygon 224            5      2036350      2.15e-06
## polygon 225            5      2344480      2.47e-06
## polygon 226            5      1786340      1.88e-06
## polygon 227            8      2269610      2.39e-06
## polygon 228            6      1857450      1.96e-06
## polygon 229            5      1978280      2.09e-06
## polygon 230            5      1944240      2.05e-06
## polygon 231            6      2728340      2.88e-06
## polygon 232            8      1905200      2.01e-06
## polygon 233            7      2258780      2.38e-06
## polygon 234            5      1891180      1.99e-06
## polygon 235            5      1957860      2.06e-06
## polygon 236            7      2335470      2.46e-06
## polygon 237            4      2055120      2.17e-06
## polygon 238            6      1829730      1.93e-06
## polygon 239            5      1807400      1.91e-06
## polygon 240            5      2014070      2.12e-06
## polygon 241            5      1882630      1.99e-06
## polygon 242            5      1928800      2.03e-06
## polygon 243            5      2010320      2.12e-06
## polygon 244            5      1521870      1.60e-06
## polygon 245            6      1935590      2.04e-06
## polygon 246            5      1647440      1.74e-06
## polygon 247            4      1518380      1.60e-06
## polygon 248            6      1623490      1.71e-06
## polygon 249            5      1654240      1.74e-06
## polygon 250            5      1691180      1.78e-06
## polygon 251            3       765559      8.07e-07
## polygon 252            6      1792550      1.89e-06
## polygon 253            5      1428170      1.51e-06
## polygon 254            5      1356230      1.43e-06
## polygon 255            5      1536990      1.62e-06
## polygon 256            5      1188700      1.25e-06
## polygon 257            4       846360      8.93e-07
## polygon 258            5      1449400      1.53e-06
## polygon 259            4      1654610      1.74e-06
## polygon 260            6      1472190      1.55e-06
## polygon 261            4      1163890      1.23e-06
## polygon 262            7      1548860      1.63e-06
## polygon 263            6      1317820      1.39e-06
## polygon 264            5      1220870      1.29e-06
## polygon 265            4      1251210      1.32e-06
## polygon 266            6      1443280      1.52e-06
## polygon 267            5      1430870      1.51e-06
## polygon 268            5      1201830      1.27e-06
## polygon 269            7      1083120      1.14e-06
## polygon 270            5      1315200      1.39e-06
## polygon 271            5      1173590      1.24e-06
## polygon 272            5      1283640      1.35e-06
## polygon 273            5      1243830      1.31e-06
## polygon 274            5      1418840      1.50e-06
## polygon 275            6      1194150      1.26e-06
## polygon 276            3       732692      7.73e-07
## polygon 277            4       724047      7.64e-07
```

```
## polygon 278            4      1110880      1.17e-06
## polygon 279            4      1068690      1.13e-06
## polygon 280            5      1080070      1.14e-06
## polygon 281            5      1105010      1.17e-06
## polygon 282            4      1101910      1.16e-06
## polygon 283            5      1202270      1.27e-06
## polygon 284            5      1193280      1.26e-06
## polygon 285            5      1104420      1.16e-06
## polygon 286            5      1337410      1.41e-06
## polygon 287            6      1293100      1.36e-06
## polygon 288            4       715019      7.54e-07
## polygon 289            3       772725      8.15e-07
## polygon 290            4       856683      9.03e-07
## polygon 291            4       986692      1.04e-06
## polygon 292            4       808047      8.52e-07
## polygon 293            4       740351      7.81e-07
## polygon 294            4       839774      8.86e-07
## polygon 295            5       997422      1.05e-06
## polygon 296            4       841098      8.87e-07
## polygon 297            7      1180430      1.24e-06
## polygon 298            4      1072900      1.13e-06
## polygon 299            5      1071650      1.13e-06
## polygon 300            4       937949      9.89e-07
## polygon 301            4       714701      7.54e-07
## polygon 302            4       854803      9.01e-07
## polygon 303            4       965776      1.02e-06
## polygon 304            4       875646      9.23e-07
## polygon 305            4       682625      7.20e-07
## polygon 306            4       799391      8.43e-07
## polygon 307            4       915082      9.65e-07
## polygon 308            4       647125      6.82e-07
## polygon 309            5       850200      8.97e-07
## polygon 310            4       856777      9.04e-07
## polygon 311            5       926662      9.77e-07
## polygon 312            4       702365      7.41e-07
## polygon 313            4       877724      9.26e-07
## polygon 314            4       625455      6.60e-07
## polygon 315            4       604921      6.38e-07
## polygon 316            4       564256      5.95e-07
## polygon 317            5       943607      9.95e-07
## polygon 318            4       725841      7.65e-07
## polygon 319            4       838391      8.84e-07
## polygon 320            4       725920      7.66e-07
## polygon 321            4       607726      6.41e-07
## polygon 322            3       377075      3.98e-07
## polygon 323            4       801044      8.45e-07
## polygon 324            4       707601      7.46e-07
## polygon 325            4       701275      7.40e-07
## polygon 326            3       567574      5.99e-07
## polygon 327            4       656976      6.93e-07
## polygon 328            4       697610      7.36e-07
## polygon 329            3       429629      4.53e-07
## polygon 330            4       692723      7.31e-07
## polygon 331            5      1123680      1.18e-06
```

```
## polygon 332             4       638721      6.74e-07
## polygon 333             4       649515      6.85e-07
## polygon 334             5       885457      9.34e-07
## polygon 335             3       397429      4.19e-07
## polygon 336             3       311243      3.28e-07
## polygon 337             4       692962      7.31e-07
## polygon 338             4       637359      6.72e-07
## polygon 339             3       347030      3.66e-07
## polygon 340             4       545022      5.75e-07
## polygon 341             4       630075      6.64e-07
## polygon 342             4       682861      7.20e-07
## polygon 343             4       582135      6.14e-07
## polygon 344             4       685738      7.23e-07
## polygon 345             3       666827      7.03e-07
## polygon 346             4       638063      6.73e-07
## polygon 347             3       415934      4.39e-07
## polygon 348             3       496699      5.24e-07
## polygon 349             4       523038      5.52e-07
## polygon 350             4       629200      6.64e-07
## polygon 351             4       545075      5.75e-07
## polygon 352             4       523200      5.52e-07
## polygon 353             4       534278      5.63e-07
## polygon 354             4       617265      6.51e-07
## polygon 355             4       554460      5.85e-07
## polygon 356             3       422197      4.45e-07
## polygon 357             4       450587      4.75e-07
## polygon 358             3       506804      5.34e-07
## polygon 359             4       666360      7.03e-07
## polygon 360             4       648581      6.84e-07
## polygon 361             3       453422      4.78e-07
## polygon 362             4       572761      6.04e-07
## polygon 363             4       515850      5.44e-07
## polygon 364             4       501575      5.29e-07
## polygon 365             4       501226      5.29e-07
## polygon 366             4       601941      6.35e-07
## polygon 367             4       593073      6.25e-07
## polygon 368             3       427855      4.51e-07
## polygon 369             3       295928      3.12e-07
## polygon 370             4       640706      6.76e-07
## polygon 371             5       714352      7.53e-07
## polygon 372             4       494594      5.22e-07
## polygon 373             3       413224      4.36e-07
## polygon 374             3       254908      2.69e-07
## polygon 375             4       458639      4.84e-07
## polygon 376             3       374163      3.95e-07
## polygon 377             4       514470      5.43e-07
## polygon 378             4       419372      4.42e-07
## polygon 379             3       405491      4.28e-07
## enclosing rectangle: [273874.9, 1870573.4] x [369042.8, 1735666.4] units
##                      (1597000 x 1367000 units)
## Window area = 9.48262e+11 square units
## Fraction of frame area: 0.435
## Quadrature weights:
##      (counting weights based on 320 x 320 array of rectangular tiles)
```

```
## All weights:
##  range: [3120, 21300000] total: 9.39e+11
## Weights on data points:
##  range: [3120, 14500000] total: 1.3e+10
## Weights on dummy points:
##  range: [16000, 21300000]    total: 9.26e+11
## --------------------------------------------------------------------------------
## FITTED :
##
## Nonstationary Poisson process
##
## ---- Intensity: ----
##
## Log intensity: ~hfi + I(hfi^2) + forest + I(forest^2) + water + I(water^2) +
## elev + I(elev^2)
## Model depends on external covariates 'hfi', 'forest', 'water' and 'elev'
## Covariates provided:
##  hfi: im
##  forest: im
##  water: im
##  elev: im
##
## Fitted trend coefficients:
##   (Intercept)           hfi      I(hfi^2)        forest   I(forest^2)
## -1.737796e+01  1.447282e+01 -8.888066e+00 -7.481589e-03 -4.582808e-05
##         water    I(water^2)          elev     I(elev^2)
## -1.801111e-03  7.942545e-08 -2.012736e-03 -6.000812e-07
##
## ----------- gory details -----
##
## Fitted regular parameters (theta):
##   (Intercept)           hfi      I(hfi^2)        forest   I(forest^2)
## -1.737796e+01  1.447282e+01 -8.888066e+00 -7.481589e-03 -4.582808e-05
##         water    I(water^2)          elev     I(elev^2)
## -1.801111e-03  7.942545e-08 -2.012736e-03 -6.000812e-07
##
## Fitted exp(theta):
##  (Intercept)          hfi     I(hfi^2)       forest  I(forest^2)        water
## 2.836911e-08 1.929593e+06 1.380264e-04 9.925463e-01 9.999542e-01 9.982005e-01
##   I(water^2)         elev    I(elev^2)
## 1.000000e+00 9.979893e-01 9.999994e-01
## Problem:
##  Values of the covariates 'hfi', 'forest', 'elev' were NA or undefined at 0.77% (528 out of 68828) o
```

```
# Visualize the fitted model against observed data
plot(fit7, se = FALSE, superimpose = FALSE)
plot(bird_ppp,
     pch = 16,
     cex = 0.5,
     cols = "green",
     add = TRUE)
```




```
AIC(fit6); AIC(fit7)
```

```
## [1] 692760
```

```
## [1] 688681
```

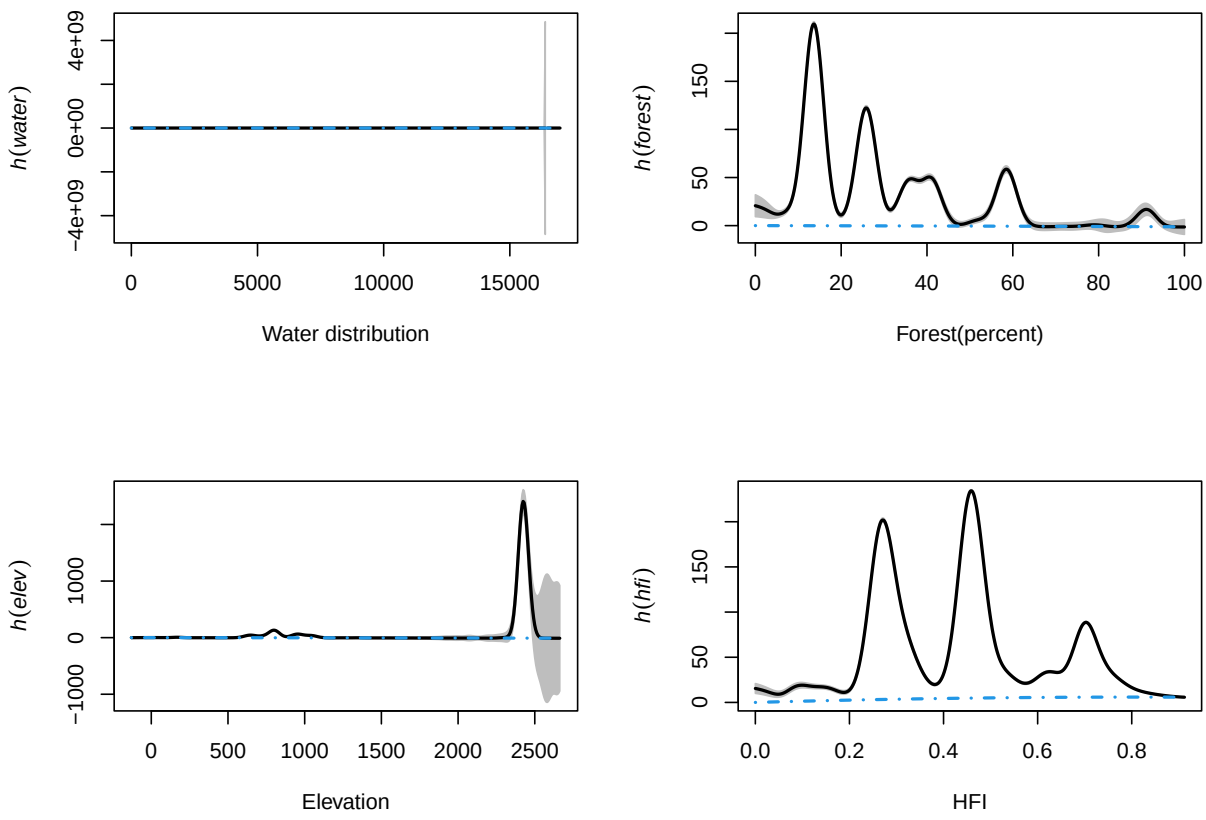
```
anova(fit6, fit7, test = "LRT")
```

```
## Analysis of Deviance Table
##
## Model 1: ~forest + I(forest^2) + elev + I(elev^2) + hfi + water + I(water^2)      Poisson
## Model 2: ~hfi + I(hfi^2) + forest + I(forest^2) + water + I(water^2) + elev + I(elev^2)   Poisson
##   Npar Df Deviance  Pr(>Chi)
## 1    8
## 2    9  1   4080.9 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
#Run the quadrat test for fit7
quadrat.test(fit7, nx = 5, ny = 6)
```

```
##
##  Chi-squared test of fitted Poisson model 'fit7' using quadrat counts
##
## data:  data from fit7
## X2 = 9777.6, df = 15, p-value < 2.2e-16
## alternative hypothesis: two.sided
##
## Quadrats: 24 tiles (irregular windows)
```

```r
par_res_water <- parres(fit7, "water")
par_res_forest <- parres(fit7, "forest")
par_res_elev <- parres(fit7, "elev")
par_res_hfi <- parres(fit7, "hfi")

par(mfrow = c(2,2))
plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
plot(par_res_forest,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Forest(percent)")
plot(par_res_elev,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Elevation")
plot(par_res_hfi,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "HFI")
```




```
## smooth model
library(splines)

#Fit the PPP model
fit_smooth <- ppm(bird_ppp ~ bs(elev,7) + bs(forest, 8) + bs(water, 8) + bs(hfi, 7), use.gam = TRUE, na

fit_smooth
```

```
## Nonstationary Poisson process
## Fitted to point pattern dataset 'bird_ppp'
##
## Log intensity:  ~bs(elev, 7) + bs(forest, 8) + bs(water, 8) + bs(hfi, 7)
##
## Fitted trend coefficients:
##    (Intercept)   bs(elev, 7)1   bs(elev, 7)2   bs(elev, 7)3   bs(elev, 7)4
##   -14.48980264    -3.51431820    -3.37659638    -4.97792436    -5.29046223
##   bs(elev, 7)5   bs(elev, 7)6   bs(elev, 7)7 bs(forest, 8)1 bs(forest, 8)2
##   -10.09293266   -17.67829689    -3.16236691    -0.49589816    -0.62643611
## bs(forest, 8)3 bs(forest, 8)4 bs(forest, 8)5 bs(forest, 8)6 bs(forest, 8)7
##    -0.01306355    -1.04201842    -0.43904502    -1.15815516    -1.68473960
## bs(forest, 8)8  bs(water, 8)1  bs(water, 8)2  bs(water, 8)3  bs(water, 8)4
##    -0.62394785    -0.31632648    -0.16567559    -0.34526231    -2.06818122
##  bs(water, 8)5  bs(water, 8)6  bs(water, 8)7  bs(water, 8)8    bs(hfi, 7)1
```

```
##    -4.25265977    -2.71386306    -5.16563355    -5.48413092     0.18082051
##    bs(hfi, 7)2    bs(hfi, 7)3    bs(hfi, 7)4    bs(hfi, 7)5    bs(hfi, 7)6
##     2.30714075     1.46607954     6.39160747     5.21248012     7.53188406
##    bs(hfi, 7)7
##     6.12080730
##
## For standard errors, type coef(summary(x))
## Problem:
##  Values of the covariates 'elev', 'forest', 'hfi' were NA or undefined at 0.77%
## (528 out of 68828) of the quadrature points
```

```
AIC(fit7); AIC(fit_smooth)
```

```
## [1] 688681
```

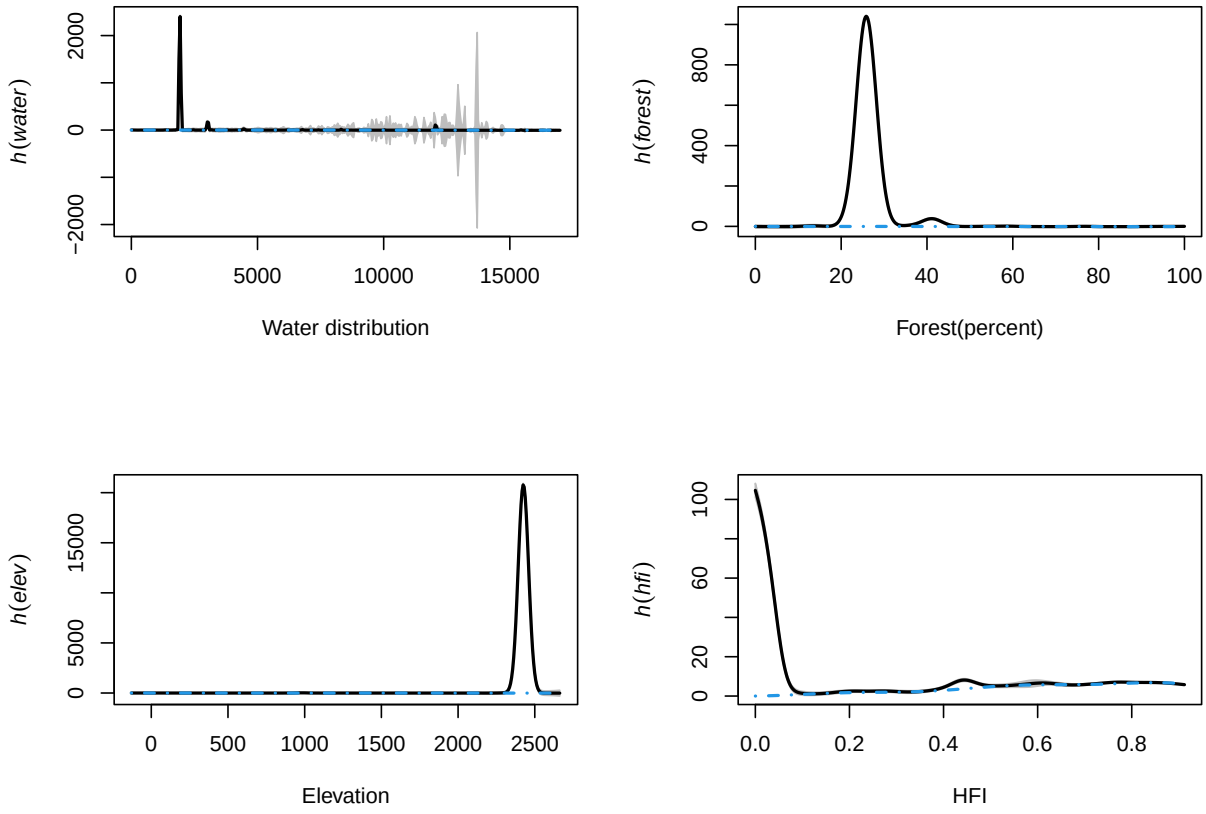
```
## [1] 683118.2
```

```
anova(fit7, fit_smooth, test = "LRT")
```

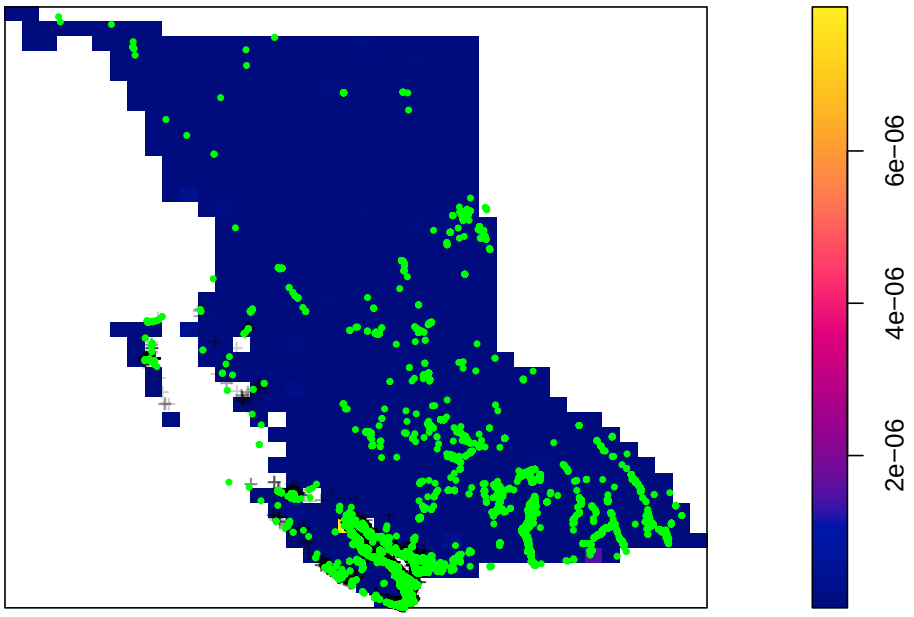
```
## Analysis of Deviance Table
##
## Model 1: ~hfi + I(hfi^2) + forest + I(forest^2) + water + I(water^2) + elev + I(elev^2)   Poisson
## Model 2: ~bs(elev, 7) + bs(forest, 8) + bs(water, 8) + bs(hfi, 7)     Poisson
##   Npar Df Deviance  Pr(>Chi)
## 1    9
## 2   31 22   5606.9 < 2.2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
par_res_water <- parres(fit_smooth, "water")
par_res_forest <- parres(fit_smooth, "forest")
par_res_elev <- parres(fit_smooth, "elev")
par_res_hfi <- parres(fit_smooth, "hfi")

par(mfrow = c(2,2))
plot(par_res_water,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Water distribution")
plot(par_res_forest,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Forest(percent)")
plot(par_res_elev,
     legend = FALSE,
     lwd = 2,
     main = "",
     xlab = "Elevation")
plot(par_res_hfi,
     legend = FALSE,
```

```
     lwd = 2,
     main = "",
     xlab = "HFI")
```




```
#Plot the model predictions
plot(fit_smooth,
     se = FALSE,
     superimpose = FALSE)

#Overlay the occurrence
plot(bird_ppp,
     pch = 16,
     cex = 0.6,
     cols = "green",
     add = TRUE)
```


Fitted trend
2e−06
4e−06
6e−06