

2013 Black Forest Fire (Colorado) burn severity impact on soil physical and soil hydraulic properties.

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1. Rationale and Research Questions

Wildfires are becoming more severe, and climate change is creating warmer and drier conditions in many places around the globe, making them more wildfire prone. Depending on their severity, wildfire can have significant and negative impacts on physical properties of soil, which directly relates to how much water an area can hold.

The 2013 Black Forest Fire in Colorado's El Paso County covered 14,280 acres and destroyed 489 homes. It is one of the most destructive forest fires in the state's history. Following the fire, researchers collected soil data at various sites with varying burn severity.

We seek to better understand how the wildfire and its different intensities impacted the soil's physical characteristics.

2. Dataset Information

Table 1: Dataset information

Item	Value
Data Source	Soil-physical and soil-hydraulic properties as a function of burn severity for 2013, 2015, and 2017 in the area affected by the 2013 Black Forest Fire, Colorado USA (ver. 2.0, June 2021)
Date range	2013-07-23 to 2017-06-19
Source	Retrieved from: https://www.sciencebase.gov/catalog/item/5b8452f5e4b05f6e321b629b
Variables used	Soil dry bulk density, soil particle size, soil-hydraulic properties

3. Exploration of raw data

4. Data wrangling

```
#filter each hp dataset for BF1 (high severity), BF3 (moderate severity), and
#BF5 (low severity)
hp_filtered_2013 <- soil_hp_2013_raw %>%
  filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
  rename(Kfs..mm.per.hr...DL = Kfs..mm.per.hr...DL.method) %>%
  rename(Sorptivity..mm.per.sqrt.hr...DL = Sorptivity..mm.per.sqrt.hr...DL.method) %>%
  mutate(Year = "2013")

hp_filtered_2015 <- soil_hp_2015_raw %>%
  filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
  select(SampleID,
         Site,
         Kfs..mm.per.hr...DL,
         Sorptivity..mm.per.sqrt.hr...DL) %>%
  na.omit() %>%
  mutate(Year = "2015")

hp_filtered_2017 <- soil_hp_2017_raw %>%
  filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
  select(SampleID,
         Site,
         Kfs..mm.per.hr...DL,
         Sorptivity..mm.per.sqrt.hr...DL) %>%
  na.omit() %>%
  mutate(Year = "2017")

all_hp <- rbind(hp_filtered_2013, hp_filtered_2015, hp_filtered_2017)
all_hp_new <- all_hp[all_hp$Kfs..mm.per.hr...DL != 682.7, ]
all_hp_new <- all_hp_new %>%
  mutate(log.kfs = log10(Kfs..mm.per.hr...DL))
```

```
#filter each ps dataset for BF1 (high severity), BF3 (moderate severity), and
#BF5 (low severity)
ps_filtered_2013 <- soil_ps_2013_raw %>%
  filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
  mutate(Year = "2013")

ps_filtered_2015 <- soil_ps_2015_raw %>%
  filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
  mutate(Year = "2015")

ps_filtered_2017 <- soil_ps_2017_raw %>%
  filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
  mutate(Year = "2017")

all_ps <- rbind(ps_filtered_2013, ps_filtered_2015, ps_filtered_2017)
```

```
#filter each bd dataset for BF1 (high severity), BF3 (moderate severity), and
#BF5 (low severity)
bd_filtered_2013 <- soil_bd_2013_raw %>%
```



```
filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
mutate(Year = "2013")

bd_filtered_2015 <- soil_bd_2015_raw %>%
filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
mutate(Year = "2015")

bd_filtered_2017 <- soil_bd_2017_raw %>%
filter(Site == "BF1" | Site == "BF3" | Site == "BF5") %>%
mutate(Year = "2017")

all_bd <- rbind(bd_filtered_2013, bd_filtered_2015, bd_filtered_2017)
```

5. Analysis

5.1 Question 1: Does wildfire severity influence soil hydraulic properties and recovery over time?

H0: There is no significant difference in soil hydraulic properties across sites or over time

HA: There is a significant difference in soil hydraulic properties across sites and over time

5.1.1 Model: two-way ANOVA for hydraulic properties

Next, we run our ANOVA tests

```
#kfs
kfs.anova.2way <- aov(data = all_hp_new,
                      log.kfs ~ Site * Year)
summary(kfs.anova.2way)

##              Df Sum Sq Mean Sq F value Pr(>F)
## Site          2  2.500   1.2500    4.090 0.0223 *
## Year          2  1.529   0.7647    2.502 0.0915 .
## Site:Year      4  0.456   0.1139    0.373 0.8270
## Residuals     53 16.198   0.3056
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(kfs.anova.2way)
```

```
##    Tukey multiple comparisons of means
##      95% family-wise confidence level
##
## Fit: aov(formula = log.kfs ~ Site * Year, data = all_hp_new)
##
## $Site
##              diff              lwr              upr              p adj
## BF3-BF1 0.3580158 -0.020228089 0.7362596 0.0670973
## BF5-BF1 0.4710122  0.008532723 0.9334917 0.0450467
## BF5-BF3 0.1129964 -0.361695812 0.5876887 0.8345280
##
## $Year
##              diff              lwr              upr              p adj
## 2015-2013 0.2793157 -0.13387029 0.6925018 0.2420983
## 2017-2013 0.4545763 -0.05054346 0.9596961 0.0858001
## 2017-2015 0.1752606 -0.25942022 0.6099414 0.5974858
##
## $'Site:Year'
##              diff              lwr              upr              p adj
## BF3:2013-BF1:2013 0.50642528 -0.58813575 1.6009863 0.8524209
## BF5:2013-BF1:2013 0.53237904 -0.67770371 1.7424618 0.8840558
## BF1:2015-BF1:2013 0.34048010 -0.45170502 1.1326652 0.8967710
## BF3:2015-BF1:2013 0.64142570 -0.14109825 1.4239497 0.1911575
## BF5:2015-BF1:2013 0.91935990 -0.09962096 1.9383408 0.1076564
```

```
## BF1:2017-BF1:2013 0.66847431 -0.35050655 1.6874552 0.4706371
## BF3:2017-BF1:2013 0.87375537 -0.22080566 1.9683164 0.2191682
## BF5:2017-BF1:2013 0.76556277 -0.32899826 1.8601238 0.3832878
## BF5:2013-BF3:2013 0.02595376 -1.33920369 1.3911112 1.0000000
## BF1:2015-BF3:2013 -0.16594518 -1.17931178 0.8474214 0.9998176
## BF3:2015-BF3:2013 0.13500042 -0.87083175 1.1408326 0.9999596
## BF5:2015-BF3:2013 0.41293462 -0.78609691 1.6119662 0.9695926
## BF1:2017-BF3:2013 0.16204903 -1.03698250 1.3610806 0.9999574
## BF3:2017-BF3:2013 0.36733009 -0.89656012 1.6312203 0.9894470
## BF5:2017-BF3:2013 0.25913749 -1.00475272 1.5230277 0.9990459
## BF1:2015-BF5:2013 -0.19189894 -1.32906572 0.9452678 0.9997717
## BF3:2015-BF5:2013 0.10904666 -1.02141111 1.2395044 0.9999969
## BF5:2015-BF5:2013 0.38698086 -0.91835934 1.6923211 0.9880028
## BF1:2017-BF5:2013 0.13609527 -1.16924492 1.4414355 0.9999943
## BF3:2017-BF5:2013 0.34137633 -1.02378112 1.7065338 0.9961353
## BF5:2017-BF5:2013 0.23318373 -1.13197373 1.5983412 0.9997501
## BF3:2015-BF1:2015 0.30094561 -0.36327707 0.9651683 0.8663090
## BF5:2015-BF1:2015 0.57887980 -0.35233984 1.5100994 0.5436455
## BF1:2017-BF1:2015 0.32799421 -0.60322543 1.2592139 0.9652667
## BF3:2017-BF1:2015 0.53327527 -0.48009133 1.5466419 0.7428957
## BF5:2017-BF1:2015 0.42508267 -0.58828393 1.4384493 0.9087843
## BF5:2015-BF3:2015 0.27793420 -0.64508071 1.2009491 0.9867418
## BF1:2017-BF3:2015 0.02704861 -0.89596630 0.9500635 1.0000000
## BF3:2017-BF3:2015 0.23232967 -0.77350250 1.2381618 0.9977716
## BF5:2017-BF3:2015 0.12413706 -0.88169511 1.1299692 0.9999788
## BF1:2017-BF5:2015 -0.25088559 -1.38134336 0.8795722 0.9983188
## BF3:2017-BF5:2015 -0.04560453 -1.24463606 1.1534270 1.0000000
## BF5:2017-BF5:2015 -0.15379713 -1.35282866 1.0452344 0.9999715
## BF3:2017-BF1:2017 0.20528106 -0.99375047 1.4043126 0.9997458
## BF5:2017-BF1:2017 0.09708846 -1.10194308 1.2961200 0.9999992
## BF5:2017-BF3:2017 -0.10819260 -1.37208281 1.1556976 0.9999988
```

```
kfs.interaction <- with(all_hp_new, interaction(Site, Year))
kfs.anova.2way2 <- aov(data = all_hp_new, log.kfs ~ kfs.interaction)
kfs.groups <- HSD.test(kfs.anova.2way2, "kfs.interaction", group = TRUE)
kfs.groups
```

```
## $statistics
##      MSerror Df      Mean      CV
##    0.3056157 53 1.837259 30.08967
##
## $parameters
##      test      name.t ntr StudentizedRange alpha
##    Tukey kfs.interaction 9      4.572477 0.05
##
## $means
##      log.kfs      std r      se      Min      Max      Q25      Q50
## BF1.2013 1.312946 0.4225423 8 0.1954532 0.5314789 1.698970 1.180658 1.449363
## BF1.2015 1.653426 0.7464377 14 0.1477488 -0.5228787 2.393751 1.566676 1.920532
## BF1.2017 1.981421 0.2473658 5 0.2472310 1.6354837 2.248954 1.891537 1.940516
## BF3.2013 1.819372 0.3338816 4 0.2764126 1.3424227 2.079181 1.714742 1.927941
## BF3.2015 1.954372 0.6000435 15 0.1427389 0.3010300 2.515741 1.939544 2.080266
## BF3.2017 2.186702 0.1152440 4 0.2764126 2.0161974 2.257439 2.166570 2.236585
## BF5.2013 1.845325 0.4921898 3 0.3191738 1.2787536 2.167317 1.684329 2.089905
```

```
## BF5.2015 2.232306 0.4409037 5 0.2472310 1.4578819 2.507991 2.321805 2.365862
## BF5.2017 2.078509 0.5108126 4 0.2764126 1.4361626 2.590619 1.799524 2.143627
##          Q75
## BF1.2013 1.608988
## BF1.2015 2.050992
## BF1.2017 2.190612
## BF3.2013 2.032570
## BF3.2015 2.316557
## BF3.2017 2.256718
## BF5.2013 2.128611
## BF5.2015 2.507991
## BF5.2017 2.422612
##
## $comparison
## NULL
##
## $groups
##      log.kfs groups
## BF5.2015 2.232306      a
## BF3.2017 2.186702      a
## BF5.2017 2.078509      a
## BF1.2017 1.981421      a
## BF3.2015 1.954372      a
## BF5.2013 1.845325      a
## BF3.2013 1.819372      a
## BF1.2015 1.653426      a
## BF1.2013 1.312946      a
##
## attr("class")
## [1] "group"
```

```
kfs.anova.plot <- ggplot(all_hp_new, aes(y = log.kfs, x = Site, color = Year)) +
  geom_boxplot()
```

```
#sorptivity
sorptivity.anova.2way <- aov(data = all_hp,
                             Sorptivity..mm.per.sqrt.hr....DL ~ Site * Year)
summary(sorptivity.anova.2way)
```

```
##           Df Sum Sq Mean Sq F value Pr(>F)
## Site        2    911   455.6    1.588 0.2136
## Year        2   1483   741.3    2.585 0.0847 .
## Site:Year    4   1530   382.6    1.334 0.2692
## Residuals   54  15488   286.8
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(sorptivity.anova.2way)
```

```
##      Tukey multiple comparisons of means
##      95% family-wise confidence level
##
```

```
## Fit: aov(formula = Sorptivity..mm.per.sqrt.hr....DL ~ Site * Year, data = all_hp)
##
## $Site
##           diff           lwr           upr           p adj
## BF3-BF1  8.564412  -3.016905  20.145729  0.1851916
## BF5-BF1  3.798860  -9.979425  17.577146  0.7849786
## BF5-BF3 -4.765552 -18.927872   9.396768  0.6979159
##
## $Year
##           diff           lwr           upr           p adj
## 2015-2013 10.9732089  -1.67799  23.62441  0.1013519
## 2017-2013 11.9637141  -3.20358  27.13101  0.1482056
## 2017-2015  0.9905052 -11.97042  13.95143  0.9814798
##
## $'Site:Year'
##           diff           lwr           upr           p adj
## BF3:2013-BF1:2013  7.21250000 -26.2935608  40.71856  0.9986582
## BF5:2013-BF1:2013 17.86250000 -19.1798439  54.90484  0.8225277
## BF1:2015-BF1:2013 17.94107143  -6.3088350  42.19098  0.3101471
## BF3:2015-BF1:2013 19.42250000  -4.5316648  43.37666  0.2027945
## BF5:2015-BF1:2013 12.28250000 -18.9099450  43.47495  0.9350756
## BF1:2017-BF1:2013  9.34250000 -21.8499450  40.53495  0.9872770
## BF3:2017-BF1:2013 32.63750000  -0.8685608  66.14356  0.0618166
## BF5:2017-BF1:2013 15.56250000 -15.6299450  46.75495  0.7941552
## BF5:2013-BF3:2013 10.65000000 -31.1393999  52.43940  0.9956346
## BF1:2015-BF3:2013 10.72857143 -20.2920131  41.74916  0.9690097
## BF3:2015-BF3:2013 12.21000000 -18.5799450  42.99995  0.9325396
## BF5:2015-BF3:2013  5.07000000 -31.6340506  41.77405  0.9999501
## BF1:2017-BF3:2013  2.13000000 -34.5740506  38.83405  0.9999999
## BF3:2017-BF3:2013 25.42500000 -13.2644664  64.11447  0.4691173
## BF5:2017-BF3:2013  8.35000000 -28.3540506  45.05405  0.9980139
## BF1:2015-BF5:2013  0.07857143 -34.7317115  34.88885  1.0000000
## BF3:2015-BF5:2013  1.56000000 -33.0449108  36.16491  1.0000000
## BF5:2015-BF5:2013 -5.58000000 -45.5383091  34.37831  0.9999458
## BF1:2017-BF5:2013 -8.52000000 -48.4783091  31.43831  0.9987464
## BF3:2017-BF5:2013 14.77500000 -27.0143999  56.56440  0.9647009
## BF5:2017-BF5:2013 -2.30000000 -42.2583091  37.65831  0.9999999
## BF3:2015-BF1:2015  1.48142857 -18.8513668  21.81422  0.9999997
## BF5:2015-BF1:2015 -5.65857143 -34.1645214  22.84738  0.9992515
## BF1:2017-BF1:2015 -8.59857143 -37.1045214  19.90738  0.9866867
## BF3:2017-BF1:2015 14.69642857 -16.3241560  45.71701  0.8360985
## BF5:2017-BF1:2015 -2.37857143 -30.8845214  26.12738  0.9999990
## BF5:2015-BF3:2015 -7.14000000 -35.3947913  21.11479  0.9958799
## BF1:2017-BF3:2015 -10.08000000 -38.3347913  18.17479  0.9627931
## BF3:2017-BF3:2015 13.21500000 -17.5749450  44.00495  0.8979844
## BF5:2017-BF3:2015 -3.86000000 -32.1147913  24.39479  0.9999542
## BF1:2017-BF5:2015 -2.94000000 -37.5449108  31.66491  0.9999989
## BF3:2017-BF5:2015 20.35500000 -16.3490506  57.05905  0.6872046
## BF5:2017-BF5:2015  3.28000000 -31.3249108  37.88491  0.9999973
## BF3:2017-BF1:2017 23.29500000 -13.4090506  59.99905  0.5166114
## BF5:2017-BF1:2017  6.22000000 -28.3849108  40.82491  0.9996384
## BF5:2017-BF3:2017 -17.07500000 -53.7790506  19.62905  0.8492601
```

```
sorptivity.interaction <- with(all_hp, interaction(Site, Year))
sorptivity.anova.2way2 <- aov(data = all_hp, Sorptivity..mm.per.sqrt.hr....DL ~ sorptivity.interaction)
sorptivity.groups <- HSD.test(sorptivity.anova.2way2, "sorptivity.interaction", group = TRUE)
sorptivity.groups
```

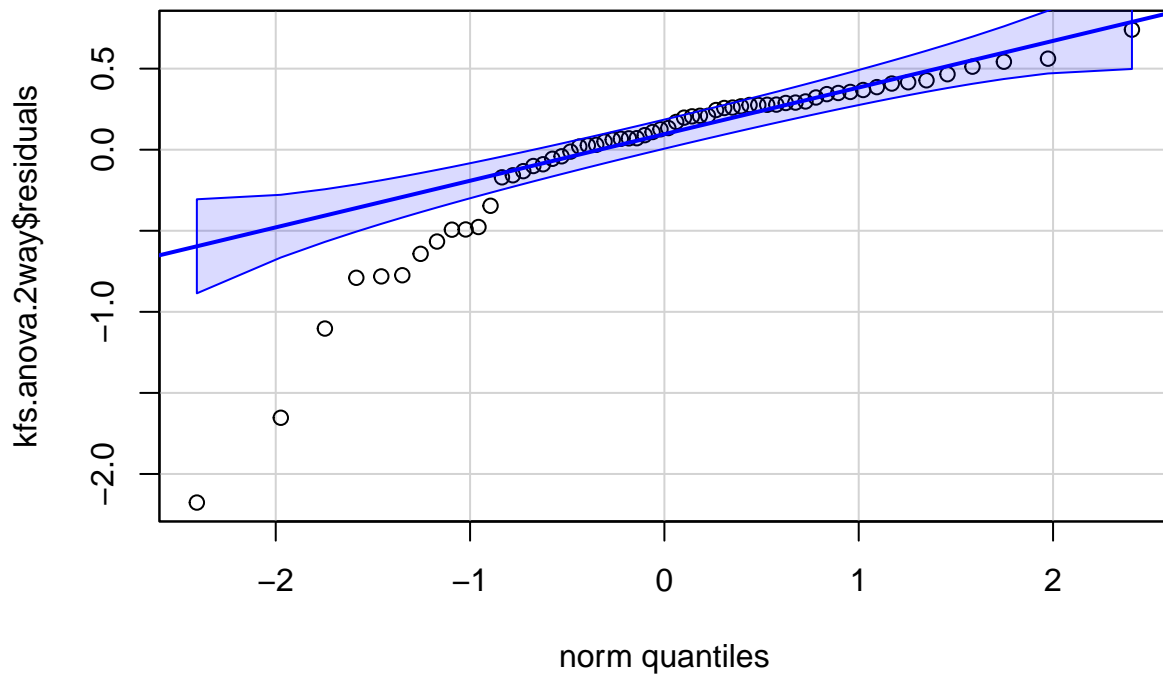
```
## $statistics
##      MSerror Df      Mean      CV
##  286.8198 54 16.48095 102.7596
##
## $parameters
##      test              name.t ntr StudentizedRange alpha
##  Tukey sorptivity.interaction  9          4.568968  0.05
##
## $means
##      Sorptivity..mm.per.sqrt.hr....DL      std  r      se Min  Max    Q25
## BF1.2013                1.53750  1.067624  8 5.987694 0.3  3.4  0.925
## BF1.2015                19.47857  20.057003 14 4.526271 1.3 63.6  4.425
## BF1.2017                10.88000   7.702078  5 7.573901 3.1 22.3  4.400
## BF3.2013                 8.75000  10.704049  4 8.467878 0.5 24.0  1.775
## BF3.2015                20.96000  17.280575 15 4.372794 3.0 71.4 10.650
## BF3.2017                34.17500  35.335947  4 8.467878 1.9 82.2 11.425
## BF5.2013                19.40000  18.537260  3 9.777864 8.3 40.8  8.700
## BF5.2015                13.82000  10.507711  5 7.573901 2.0 23.0  2.900
## BF5.2017                17.10000  12.390924  5 7.573901 2.4 34.0  8.500
##
##      Q50    Q75
## BF1.2013  1.30  1.775
## BF1.2015  9.90 28.675
## BF1.2017 11.90 12.700
## BF3.2013  5.25 12.225
## BF3.2015 17.80 22.800
## BF3.2017 26.30 49.050
## BF5.2013  9.10 24.950
## BF5.2015 18.80 22.400
## BF5.2017 17.30 23.300
##
## $comparison
## NULL
##
## $groups
##      Sorptivity..mm.per.sqrt.hr....DL groups
## BF3.2017                34.17500      a
## BF3.2015                20.96000      a
## BF1.2015                19.47857      a
## BF5.2013                19.40000      a
## BF5.2017                17.10000      a
## BF5.2015                13.82000      a
## BF1.2017                10.88000      a
## BF3.2013                 8.75000      a
## BF1.2013                 1.53750      a
##
## attr(,"class")
## [1] "group"
```

```
sorptivity.anova.plot <- ggplot(all_hp, aes(y = Sorptivity..mm.per.sqrt.hr....DL, x = Site, color = Year)) +
  geom_boxplot()
```

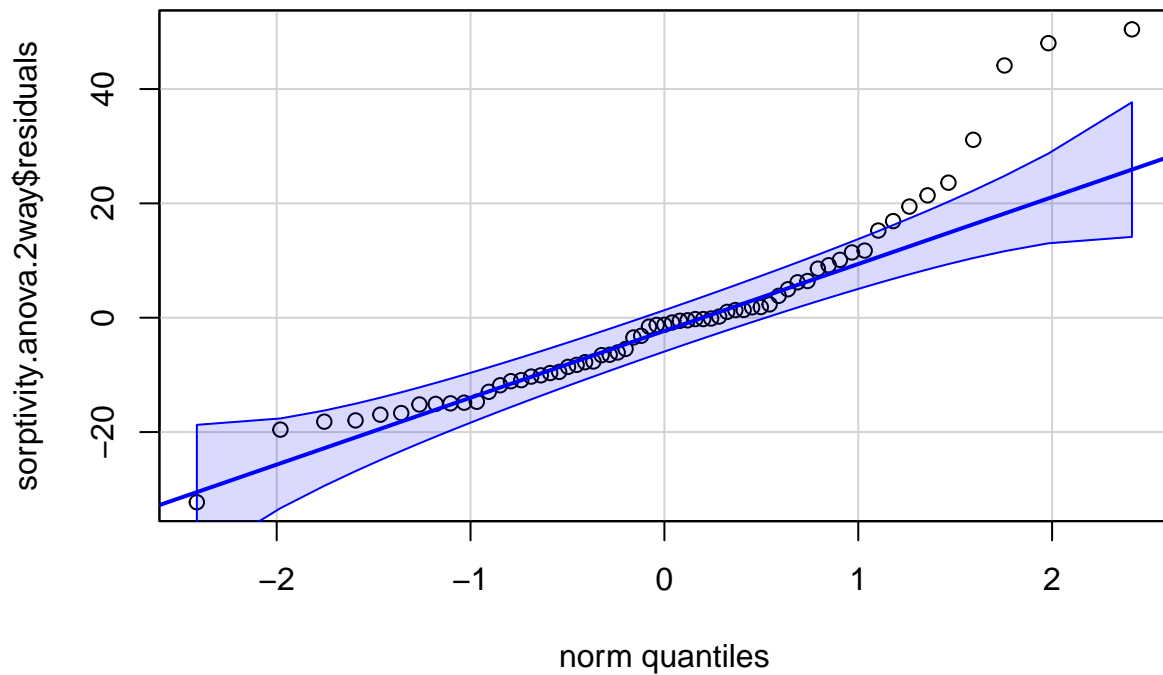
5.1.2 Assumptions

First, we test for normality and variance.

```
#normality
qqPlot(kfs.anova.2way$residuals, id = F)
```



```
qqPlot(sorptivity.anova.2way$residuals, id = F)
```



```
#homogeneity of variances
```

```
leveneTest(kfs.anova.2way) #original value after outlier removal p = 0.02207. data was then log transf
```

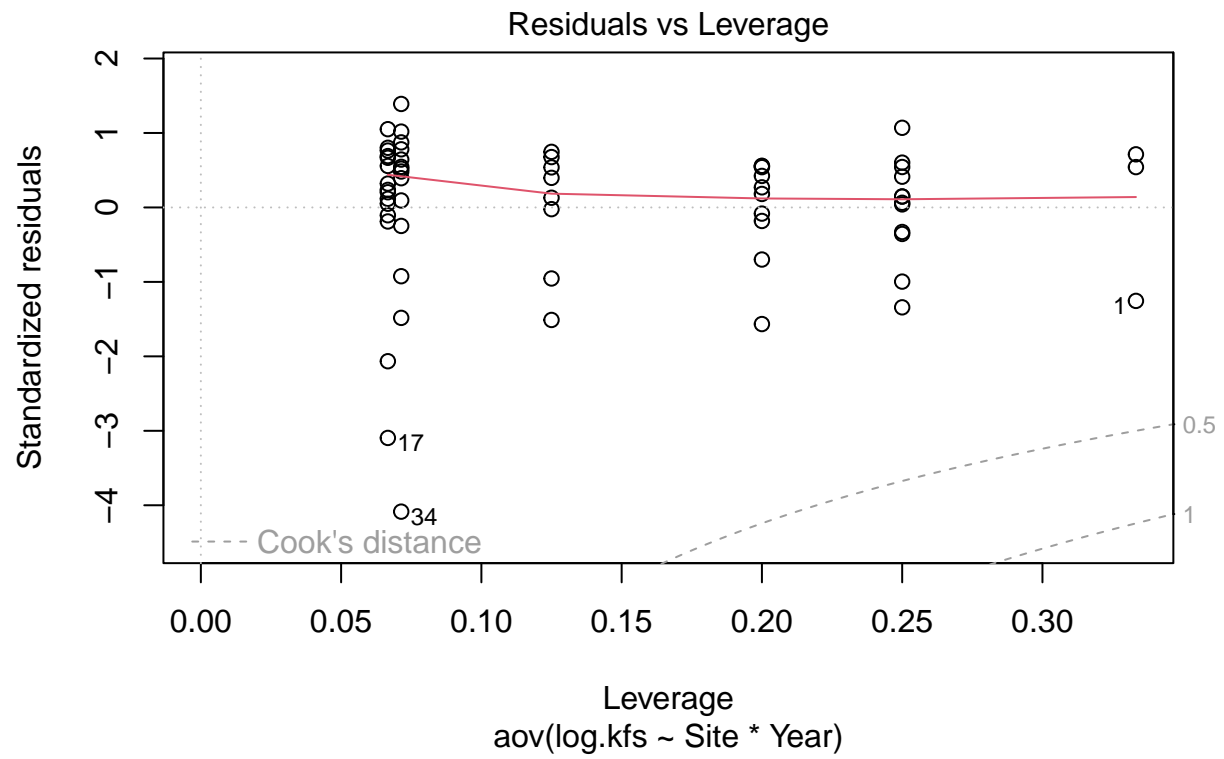
```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value Pr(>F)
## group 8  0.3904  0.921
##      53
```

```
leveneTest(sorpitivity.anova.2way)
```

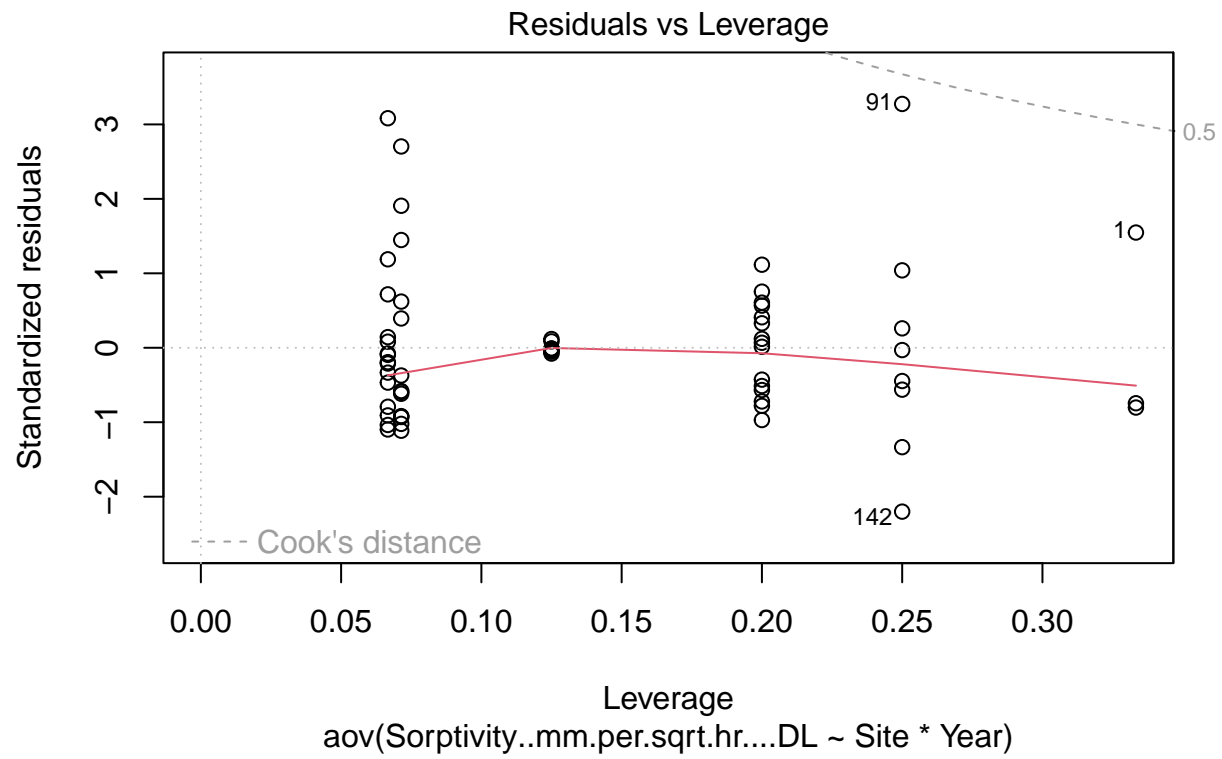
```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value Pr(>F)
## group 8  1.6037 0.1455
##      54
```

```
#outliers
```

```
plot(kfs.anova.2way, which = 5) #observation 310 was an outlier. it has been removed.
```

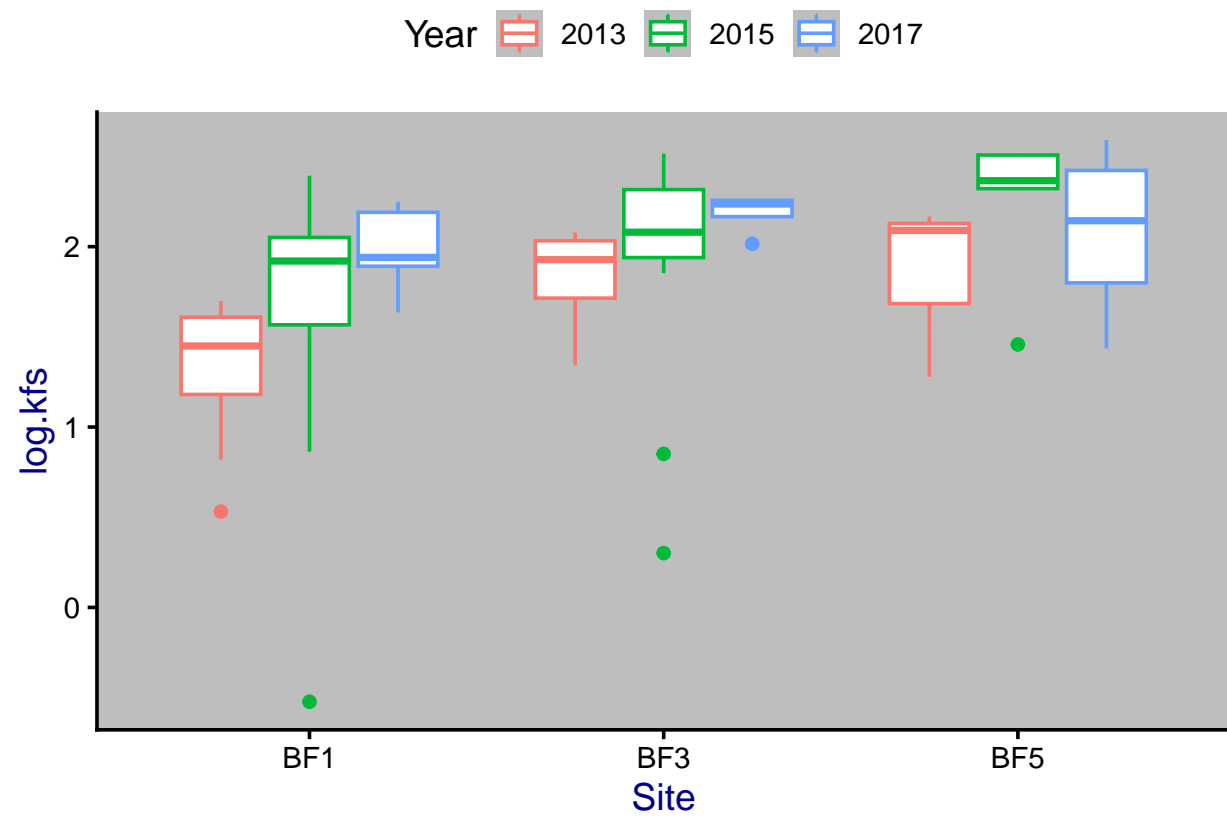
```
plot(sorptivity.anova.2way, which = 5)
```



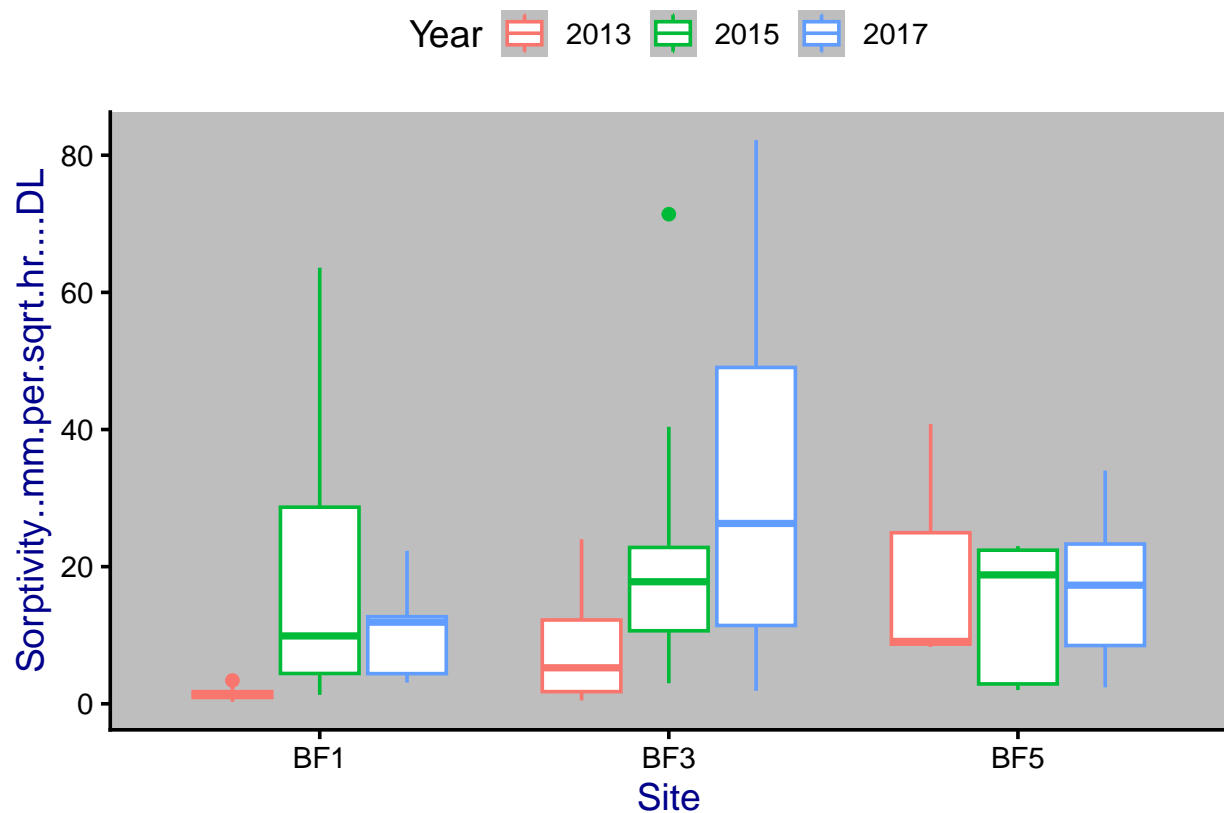
5.1.3 Residuals

5.1.4 Kfs and sorptivity by site and year

```
# plots
print(kfs.anova.plot)
```



```
print(sorptivity.anova.plot)
```



```
#sorptivity.anova.plot.alt <- ggplot(all_hp, aes(y = Sorptivity..mm.per.sqrt.hr....DL, x = Year, color = Year)) +
#   geom_boxplot()

#print(sorptivity.anova.plot.alt)
```

5.2 Question 2: Does wildfire severity influence particle size and recovery over time?

5.2.1 Model: two-way ANOVA for particle size

```
#gravel
ps.g.anova.2way <- aov(data = all_ps, Gravel.... ~ Site * Year)
summary(ps.g.anova.2way)
```

```
##              Df Sum Sq Mean Sq F value    Pr(>F)
## Site           2   1360    679.8  13.706 3.11e-06 ***
## Year           2    473    236.3   4.764 0.00974 **
## Site:Year       4   2592    648.0  13.064 2.89e-09 ***
## Residuals     165   8184     49.6
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(ps.g.anova.2way)
```

```
## Tukey multiple comparisons of means
## 95% family-wise confidence level
##
## Fit: aov(formula = Gravel.... ~ Site * Year, data = all_ps)
##
## $Site
##          diff          lwr          upr          p adj
## BF3-BF1  3.501724  0.4087691  6.5946792  0.0221306
## BF5-BF1 -3.344828 -6.4377827 -0.2518725  0.0305798
## BF5-BF3 -6.846552 -9.9395068 -3.7535966  0.0000015
##
## $Year
##          diff          lwr          upr          p adj
## 2015-2013 -4.9911111 -8.817580 -1.16464244  0.0067158
## 2017-2013 -4.0583333 -8.081157 -0.03550955  0.0474835
## 2017-2015  0.9327778 -1.843234  3.70878992  0.7068142
##
## $'Site:Year'
##          diff          lwr          upr          p adj
## BF3:2013-BF1:2013 23.8500000 12.7810993 34.9189007 0.0000000
## BF5:2013-BF1:2013 -1.5500000 -12.6189007  9.5189007 0.9999604
## BF1:2015-BF1:2013  3.5266667 -5.2822127 12.3355461 0.9416351
## BF3:2015-BF1:2013  5.0933333 -3.7155461 13.9022127 0.6705420
## BF5:2015-BF1:2013 -1.2933333 -10.1022127  7.5155461 0.9999431
## BF1:2017-BF1:2013  4.5700000 -4.6909067 13.8309067 0.8292802
## BF3:2017-BF1:2013  2.8350000 -6.4259067 12.0959067 0.9886554
## BF5:2017-BF1:2013  2.7200000 -6.5409067 11.9809067 0.9913629
## BF5:2013-BF3:2013 -25.4000000 -36.4689007 -14.3310993 0.0000000
## BF1:2015-BF3:2013 -20.3233333 -29.1322127 -11.5144539 0.0000000
## BF3:2015-BF3:2013 -18.7566667 -27.5655461 -9.9477873 0.0000000
## BF5:2015-BF3:2013 -25.1433333 -33.9522127 -16.3344539 0.0000000
## BF1:2017-BF3:2013 -19.2800000 -28.5409067 -10.0190933 0.0000000
## BF3:2017-BF3:2013 -21.0150000 -30.2759067 -11.7540933 0.0000000
## BF5:2017-BF3:2013 -21.1300000 -30.3909067 -11.8690933 0.0000000
## BF1:2015-BF5:2013  5.0766667 -3.7322127 13.8855461 0.6744909
## BF3:2015-BF5:2013  6.6433333 -2.1655461 15.4522127 0.3072109
## BF5:2015-BF5:2013  0.2566667 -8.5522127  9.0655461 1.0000000
## BF1:2017-BF5:2013  6.1200000 -3.1409067 15.3809067 0.4923832
## BF3:2017-BF5:2013  4.3850000 -4.8759067 13.6459067 0.8595174
## BF5:2017-BF5:2013  4.2700000 -4.9909067 13.5309067 0.8766551
## BF3:2015-BF1:2015  1.5666667 -4.1492891  7.2826224 0.9945738
## BF5:2015-BF1:2015 -4.8200000 -10.5359557  0.8959557 0.1742580
## BF1:2017-BF1:2015  1.0433333 -5.3472995  7.4339661 0.9998726
## BF3:2017-BF1:2015 -0.6916667 -7.0822995  5.6989661 0.9999946
## BF5:2017-BF1:2015 -0.8066667 -7.1972995  5.5839661 0.9999822
## BF5:2015-BF3:2015 -6.3866667 -12.1026224 -0.6707109 0.0163158
## BF1:2017-BF3:2015 -0.5233333 -6.9139661  5.8672995 0.9999994
## BF3:2017-BF3:2015 -2.2583333 -8.6489661  4.1322995 0.9719042
## BF5:2017-BF3:2015 -2.3733333 -8.7639661  4.0172995 0.9621499
## BF1:2017-BF5:2015  5.8633333 -0.5272995 12.2539661 0.1001841
## BF3:2017-BF5:2015  4.1283333 -2.2622995 10.5189661 0.5244334
```

```
## BF5:2017-BF5:2015 4.013333 -2.3772995 10.4039661 0.5635758
## BF3:2017-BF1:2017 -1.7350000 -8.7355875 5.2655875 0.9972939
## BF5:2017-BF1:2017 -1.8500000 -8.8505875 5.1505875 0.9957732
## BF5:2017-BF3:2017 -0.1150000 -7.1155875 6.8855875 1.0000000
```

```
ps.g.interaction <- with(all_ps, interaction(Site, Year))
ps.g.anova.2way2 <- aov(data = all_ps, Gravel.... ~ ps.g.interaction)
ps.g.groups <- HSD.test(ps.g.anova.2way2, "ps.g.interaction", group = TRUE)
ps.g.groups
```

```
## $statistics
##      MSerror Df      Mean      CV
## 49.59779 165 5.352299 131.5803
##
## $parameters
##      test      name.t ntr StudentizedRange alpha
## Tukey ps.g.interaction 9      4.445476 0.05
##
## $means
##      Gravel....      std r      se Min Max      Q25      Q50      Q75
## BF1.2013 1.9000000 2.564594 8 2.489924 0.0 6.7 0.000 0.65 3.050
## BF1.2015 5.4266667 7.678269 30 1.285791 0.0 26.8 0.575 3.10 5.550
## BF1.2017 6.4700000 6.463183 20 1.574767 0.0 23.7 1.325 3.85 9.700
## BF3.2013 25.7500000 21.767735 8 2.489924 0.8 57.7 10.325 24.40 34.950
## BF3.2015 6.9933333 7.034052 30 1.285791 0.0 29.2 0.850 5.10 12.000
## BF3.2017 4.7350000 4.672346 20 1.574767 0.0 15.1 0.400 2.45 8.850
## BF5.2013 0.3500000 0.600000 8 2.489924 0.0 1.5 0.000 0.00 0.425
## BF5.2015 0.6066667 1.220495 30 1.285791 0.0 4.3 0.000 0.00 0.275
## BF5.2017 4.6200000 4.712760 20 1.574767 0.0 14.1 0.575 2.60 8.625
##
## $comparison
## NULL
##
## $groups
##      Gravel.... groups
## BF3.2013 25.7500000 a
## BF3.2015 6.9933333 b
## BF1.2017 6.4700000 bc
## BF1.2015 5.4266667 bc
## BF3.2017 4.7350000 bc
## BF5.2017 4.6200000 bc
## BF1.2013 1.9000000 bc
## BF5.2015 0.6066667 c
## BF5.2013 0.3500000 c
##
## attr(,"class")
## [1] "group"
```

```
ps.g.anova.plot <- ggplot(all_ps, aes(y = Gravel...., x = Site, color = Year)) +
  geom_boxplot()
```

```
#sand
ps.s.anova.2way <- aov(data = all_ps, Sand.... ~ Site * Year)
summary(ps.s.anova.2way)

##              Df Sum Sq Mean Sq F value    Pr(>F)
## Site           2    5383     2692  26.711 8.92e-11 ***
## Year           2    6694     3347  33.212 7.56e-13 ***
## Site:Year       4     550      138   1.365  0.248
## Residuals     165   16627      101
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(ps.s.anova.2way)
```

```
##      Tukey multiple comparisons of means
##      95% family-wise confidence level
##
## Fit: aov(formula = Sand.... ~ Site * Year, data = all_ps)
##
## $Site
##              diff            lwr            upr            p adj
## BF3-BF1    2.912069   -1.496600    7.320737    0.2649932
## BF5-BF1   12.982759    8.574090   17.391427    0.0000000
## BF5-BF3   10.070690    5.662021   14.479358    0.0000007
##
## $Year
##              diff            lwr            upr            p adj
## 2015-2013  13.173056    7.718844   18.62727    0.0000002
## 2017-2013  19.707500   13.973406   25.44159    0.0000000
## 2017-2015    6.534444    2.577543   10.49135    0.0004005
##
## $'Site:Year'
##              diff            lwr            upr            p adj
## BF3:2013-BF1:2013 -2.0625000  -17.8400049   13.715005    0.9999767
## BF5:2013-BF1:2013  12.2875000   -3.4900049   28.065005    0.2655542
## BF1:2015-BF1:2013  11.6991667   -0.8569255   24.255259    0.0893615
## BF3:2015-BF1:2013  12.7858333    0.2297411   25.341926    0.0424024
## BF5:2015-BF1:2013  25.2591667   12.7030745   37.815259    0.0000001
## BF1:2017-BF1:2013  16.4375000    3.2370923   29.637908    0.0041136
## BF3:2017-BF1:2013  24.0775000   10.8770923   37.277908    0.0000016
## BF5:2017-BF1:2013  28.8325000   15.6320923   42.032908    0.0000000
## BF5:2013-BF3:2013  14.3500000   -1.4275049   30.127505    0.1066724
## BF1:2015-BF3:2013  13.7616667    1.2055745   26.317759    0.0202155
## BF3:2015-BF3:2013  14.8483333    2.2922411   27.404426    0.0082378
## BF5:2015-BF3:2013  27.3216667   14.7655745   39.877759    0.0000000
## BF1:2017-BF3:2013  18.5000000    5.2995923   31.700408    0.0006284
## BF3:2017-BF3:2013  26.1400000   12.9395923   39.340408    0.0000001
## BF5:2017-BF3:2013  30.8950000   17.6945923   44.095408    0.0000000
## BF1:2015-BF5:2013  -0.5883333  -13.1444255   11.967759    1.0000000
## BF3:2015-BF5:2013  0.4983333  -12.0577589   13.054426    1.0000000
## BF5:2015-BF5:2013  12.9716667    0.4155745   25.527759    0.0370089
## BF1:2017-BF5:2013  4.1500000   -9.0504077   17.350408    0.9865150
```

```
## BF3:2017-BF5:2013 11.7900000 -1.4104077 24.990408 0.1210520
## BF5:2017-BF5:2013 16.5450000 3.3445923 29.745408 0.0037489
## BF3:2015-BF1:2015 1.0866667 -7.0608018 9.234135 0.9999728
## BF5:2015-BF1:2015 13.5600000 5.4125315 21.707468 0.0000176
## BF1:2017-BF1:2015 4.7383333 -4.3708134 13.847480 0.7840575
## BF3:2017-BF1:2015 12.3783333 3.2691866 21.487480 0.0010696
## BF5:2017-BF1:2015 17.1333333 8.0241866 26.242480 0.0000007
## BF5:2015-BF3:2015 12.4733333 4.3258648 20.620802 0.0001147
## BF1:2017-BF3:2015 3.6516667 -5.4574800 12.760813 0.9412039
## BF3:2017-BF3:2015 11.2916667 2.1825200 20.400813 0.0043848
## BF5:2017-BF3:2015 16.0466667 6.9375200 25.155813 0.0000042
## BF1:2017-BF5:2015 -8.8216667 -17.9308134 0.287480 0.0658473
## BF3:2017-BF5:2015 -1.1816667 -10.2908134 7.927480 0.9999780
## BF5:2017-BF5:2015 3.5733333 -5.5358134 12.682480 0.9479869
## BF3:2017-BF1:2017 7.6400000 -2.3385702 17.618570 0.2873561
## BF5:2017-BF1:2017 12.3950000 2.4164298 22.373570 0.0042592
## BF5:2017-BF3:2017 4.7550000 -5.2235702 14.733570 0.8551468
```

```
ps.s.interaction <- with(all_ps, interaction(Site, Year))
ps.s.anova.2way2 <- aov(data = all_ps, Sand.... ~ ps.s.interaction)
ps.s.groups <- HSD.test(ps.s.anova.2way2, "ps.s.interaction", group = TRUE)
ps.s.groups
```

```
## $statistics
##      MSerror Df      Mean      CV
##    100.7697 165 70.20517 14.29868
##
## $parameters
##      test      name.t ntr StudentizedRange alpha
##    Tukey ps.s.interaction 9      4.445476 0.05
##
## $means
##      Sand....      std r      se Min Max      Q25      Q50      Q75
## BF1.2013 53.18750 9.313498 8 3.549114 40.8 67.3 45.875 53.75 57.900
## BF1.2015 64.88667 9.365702 30 1.832755 48.1 89.3 58.225 64.80 71.350
## BF1.2017 69.62500 7.258307 20 2.244657 54.8 83.7 66.775 70.05 72.050
## BF3.2013 51.12500 11.730150 8 3.549114 35.9 70.3 43.100 52.45 55.725
## BF3.2015 65.97333 11.776450 30 1.832755 43.3 98.3 59.550 65.45 71.575
## BF3.2017 77.26500 4.358811 20 2.244657 71.5 87.1 73.350 77.45 79.575
## BF5.2013 65.47500 14.151300 8 3.549114 46.8 85.2 52.425 69.05 74.400
## BF5.2015 78.44667 13.479480 30 1.832755 49.4 98.8 70.175 76.55 90.925
## BF5.2017 82.02000 4.909883 20 2.244657 73.7 93.2 78.850 81.50 85.075
##
## $comparison
## NULL
##
## $groups
##      Sand.... groups
## BF5.2017 82.02000 a
## BF5.2015 78.44667 ab
## BF3.2017 77.26500 ab
## BF1.2017 69.62500 bc
## BF3.2015 65.97333 c
## BF5.2013 65.47500 cd
```



```
## BF1.2015 64.88667      cd
## BF1.2013 53.18750      d
## BF3.2013 51.12500      d
##
## attr(,"class")
## [1] "group"
```

```
ps.s.anova.plot <- ggplot(all_ps, aes(y = Sand..., x = Site, color = Year)) +
  geom_boxplot()
```

```
#silt/clay
```

```
ps.sc.anova.2way <- aov(data = all_ps, Silt...Clay.... ~ Site * Year)
summary(ps.sc.anova.2way)
```

```
##              Df Sum Sq Mean Sq F value    Pr(>F)
## Site           2   2783   1391.5   15.730 5.59e-07 ***
## Year           2   4600   2299.8   25.999 1.53e-10 ***
## Site:Year      4   1429    357.3    4.039 0.00376 **
## Residuals    165  14595     88.5
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(ps.sc.anova.2way)
```

```
##      Tukey multiple comparisons of means
##      95% family-wise confidence level
##
## Fit: aov(formula = Silt...Clay.... ~ Site * Year, data = all_ps)
##
## $Site
##              diff              lwr              upr              p adj
## BF3-BF1 -6.408621 -10.539183 -2.2780582 0.0009519
## BF5-BF1 -9.620690 -13.751252 -5.4901272 0.0000004
## BF5-BF3 -3.212069  -7.342631  0.9184935 0.1601348
##
## $Year
##              diff              lwr              upr              p adj
## 2015-2013  -8.186667 -13.29682   -3.076516 0.0006175
## 2017-2013 -15.666667 -21.03905  -10.294288 0.0000000
## 2017-2015  -7.480000 -11.18729   -3.772707 0.0000119
##
## $'Site:Year'
##              diff              lwr              upr              p adj
## BF3:2013-BF1:2013 -21.787500 -36.569734  -7.0052659 0.0002464
## BF5:2013-BF1:2013 -10.737500 -25.519734   4.0447341 0.3583112
## BF1:2015-BF1:2013 -15.248333 -27.012367  -3.4843000 0.0022793
## BF3:2015-BF1:2013 -17.888333 -29.652367  -6.1243000 0.0001320
## BF5:2015-BF1:2013 -23.948333 -35.712367 -12.1843000 0.0000001
## BF1:2017-BF1:2013 -21.020000 -33.387704  -8.6522957 0.0000106
## BF3:2017-BF1:2013 -26.930000 -39.297704 -14.5622957 0.0000000
## BF5:2017-BF1:2013 -31.575000 -43.942704 -19.2072957 0.0000000
## BF5:2013-BF3:2013  11.050000  -3.732234  25.8322341 0.3190499
```

```
## BF1:2015-BF3:2013    6.539167  -5.224867  18.3032000  0.7162754
## BF3:2015-BF3:2013    3.899167  -7.864867  15.6632000  0.9811091
## BF5:2015-BF3:2013   -2.160833 -13.924867   9.6032000  0.9996914
## BF1:2017-BF3:2013    0.767500 -11.600204  13.1352043  0.9999999
## BF3:2017-BF3:2013   -5.142500 -17.510204   7.2252043  0.9280346
## BF5:2017-BF3:2013   -9.787500 -22.155204   2.5802043  0.2457013
## BF1:2015-BF5:2013   -4.510833 -16.274867   7.2532000  0.9543661
## BF3:2015-BF5:2013   -7.150833 -18.914867   4.6132000  0.6073436
## BF5:2015-BF5:2013  -13.210833 -24.974867  -1.4468000  0.0154041
## BF1:2017-BF5:2013  -10.282500 -22.650204   2.0852043  0.1890986
## BF3:2017-BF5:2013  -16.192500 -28.560204  -3.8247957  0.0019519
## BF5:2017-BF5:2013  -20.837500 -33.205204  -8.4697957  0.0000131
## BF3:2015-BF1:2015   -2.640000 -10.273513   4.9935128  0.9753801
## BF5:2015-BF1:2015   -8.700000 -16.333513  -1.0664872  0.0129669
## BF1:2017-BF1:2015   -5.771667 -14.306193   2.7628601  0.4595241
## BF3:2017-BF1:2015  -11.681667 -20.216193  -3.1471399  0.0009468
## BF5:2017-BF1:2015  -16.326667 -24.861193  -7.7921399  0.0000004
## BF5:2015-BF3:2015   -6.060000 -13.693513   1.5735128  0.2418836
## BF1:2017-BF3:2015   -3.131667 -11.666193   5.4028601  0.9647541
## BF3:2017-BF3:2015   -9.041667 -17.576193  -0.5071399  0.0288834
## BF5:2017-BF3:2015  -13.686667 -22.221193  -5.1521399  0.0000419
## BF1:2017-BF5:2015    2.928333  -5.606193  11.4628601  0.9765546
## BF3:2017-BF5:2015   -2.981667 -11.516193   5.5528601  0.9737988
## BF5:2017-BF5:2015   -7.626667 -16.161193   0.9078601  0.1206182
## BF3:2017-BF1:2017   -5.910000 -15.259106   3.4391057  0.5545519
## BF5:2017-BF1:2017  -10.555000 -19.904106  -1.2058943  0.0144858
## BF5:2017-BF3:2017   -4.645000 -13.994106   4.7041057  0.8238710
```

```
ps.sc.interaction <- with(all_ps, interaction(Site, Year))
ps.sc.anova.2way2 <- aov(data = all_ps, Silt...Clay... ~ ps.sc.interaction)
ps.sc.groups <- HSD.test(ps.sc.anova.2way2, "ps.sc.interaction", group = TRUE)
ps.sc.groups
```

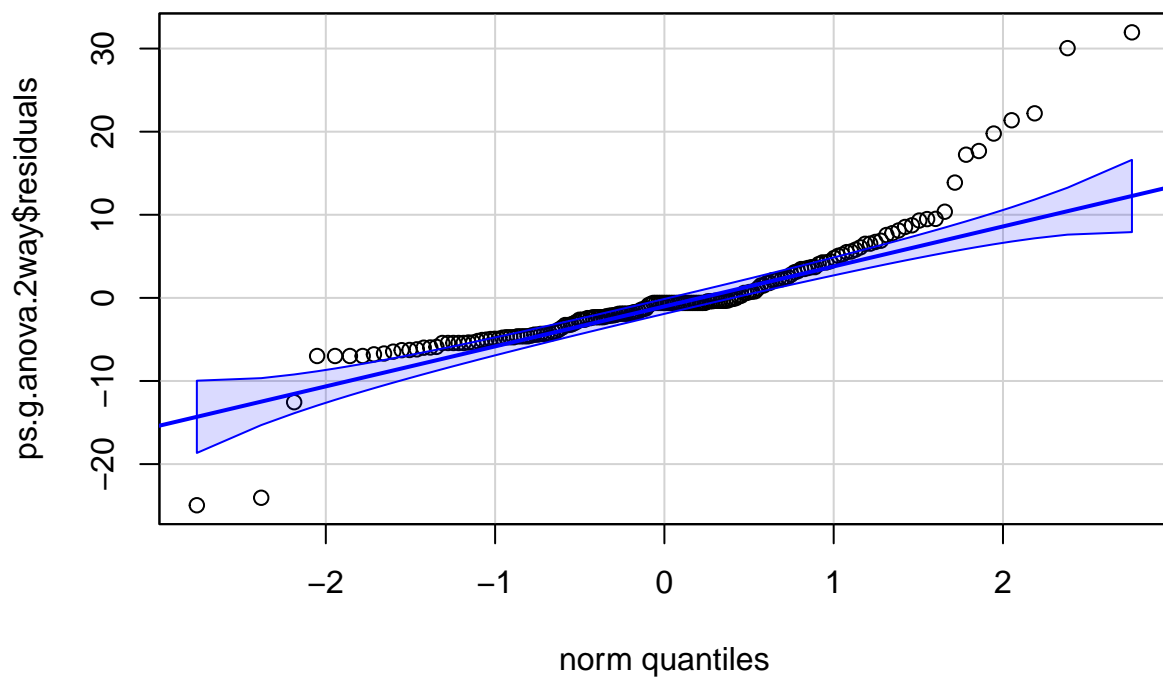
```
## $statistics
##      MSerror Df      Mean      CV
##    88.45726 165 24.44655 38.47239
##
## $parameters
##      test          name.t ntr StudentizedRange alpha
##    Tukey ps.sc.interaction    9         4.445476  0.05
##
## $means
##      Silt...Clay...      std  r      se Min Max   Q25   Q50   Q75
## BF1.2013      44.92500 10.231569  8 3.325231 28.0 59.2 40.525 45.35 49.850
## BF1.2015      29.67667  8.921948 30 1.717142  9.6 44.1 23.425 29.00 37.800
## BF1.2017      23.90500  5.928741 20 2.103060 14.2 34.0 18.300 23.80 28.025
## BF3.2013      23.13750 11.925595  8 3.325231  5.2 36.2 16.325 24.50 33.500
## BF3.2015      27.03667  9.622799 30 1.717142  1.7 44.2 23.075 26.55 33.400
## BF3.2017      17.99500  3.951346 20 2.103060 10.4 24.5 16.125 18.25 20.500
## BF5.2013      34.18750 14.102425  8 3.325231 14.8 53.0 24.550 30.95 46.750
## BF5.2015      20.97667 13.382662 30 1.717142  1.2 50.6  8.200 22.75 29.350
## BF5.2017      13.35000  4.122531 20 2.103060  6.8 21.9 10.125 13.40 15.625
##
## $comparison
```

```
## NULL
##
## $groups
##      Silt...Clay.... groups
## BF1.2013      44.92500      a
## BF5.2013      34.18750      ab
## BF1.2015      29.67667      b
## BF3.2015      27.03667      bc
## BF1.2017      23.90500      bcd
## BF3.2013      23.13750      bcde
## BF5.2015      20.97667      cde
## BF3.2017      17.99500      de
## BF5.2017      13.35000      e
##
## attr("class")
## [1] "group"
```

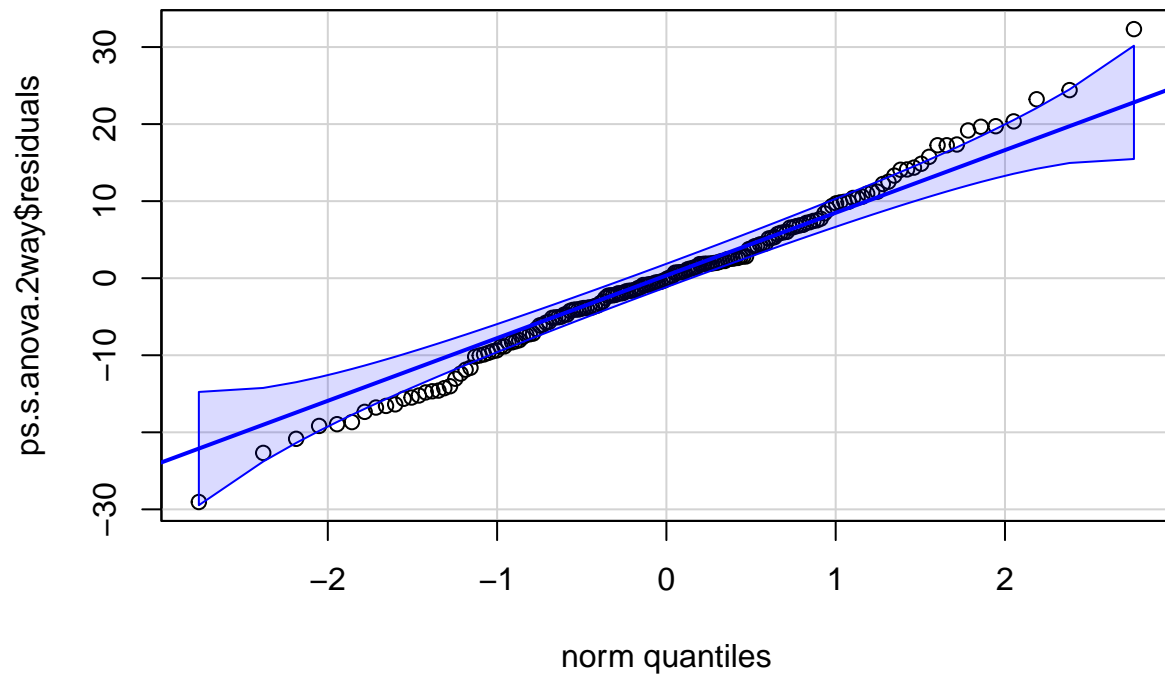
```
ps.sc.anova.plot <- ggplot(all_ps, aes(y = Silt...Clay..., x = Site, color = Year)) +
  geom_boxplot()
```

5.2.1 Assumptions

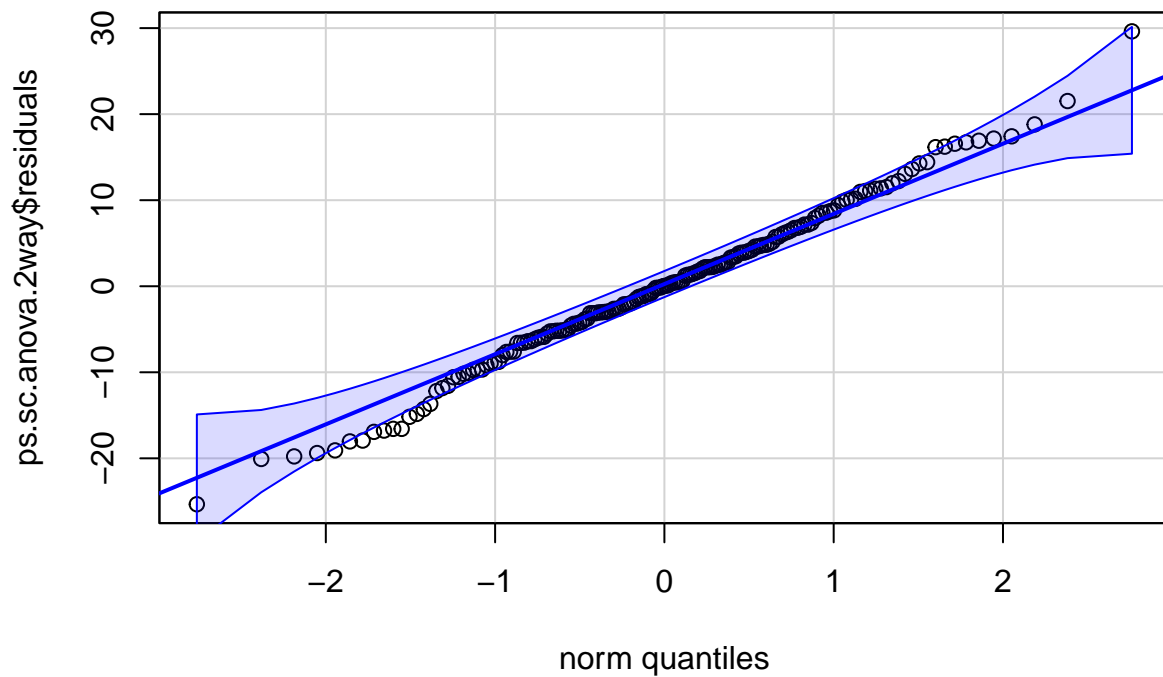
```
#normality
qqPlot(ps.g.anova.2way$residuals, id = F)
```



```
qqPlot(ps.s.anova.2way$residuals, id = F)
```



```
qqPlot(ps.sc.anova.2way$residuals, id = F)
```



#homogeneity of variances

`leveneTest(ps.g.anova.2way)` *#p-value = 7.0882×10^{-11} . transformations did not work. using original, un*

```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value    Pr(>F)
## group  8  9.5992 7.082e-11 ***
##      165
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

`leveneTest(ps.s.anova.2way)` *#p-value = 0.0002052. transformations did not work. using original, untransn*

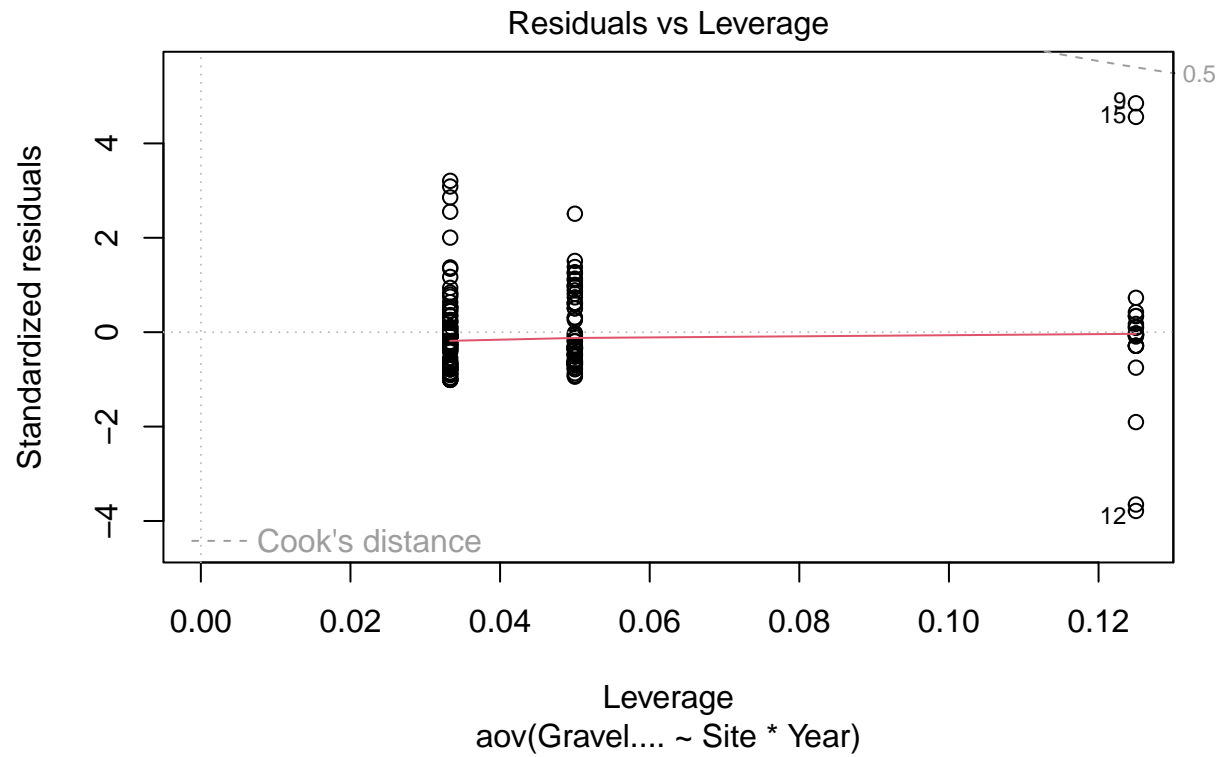
```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value    Pr(>F)
## group  8  4.0447 0.0002052 ***
##      165
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

`leveneTest(ps.sc.anova.2way)` *#p-value = 7.027×10^{-7} . transformations did not work. using original, un*

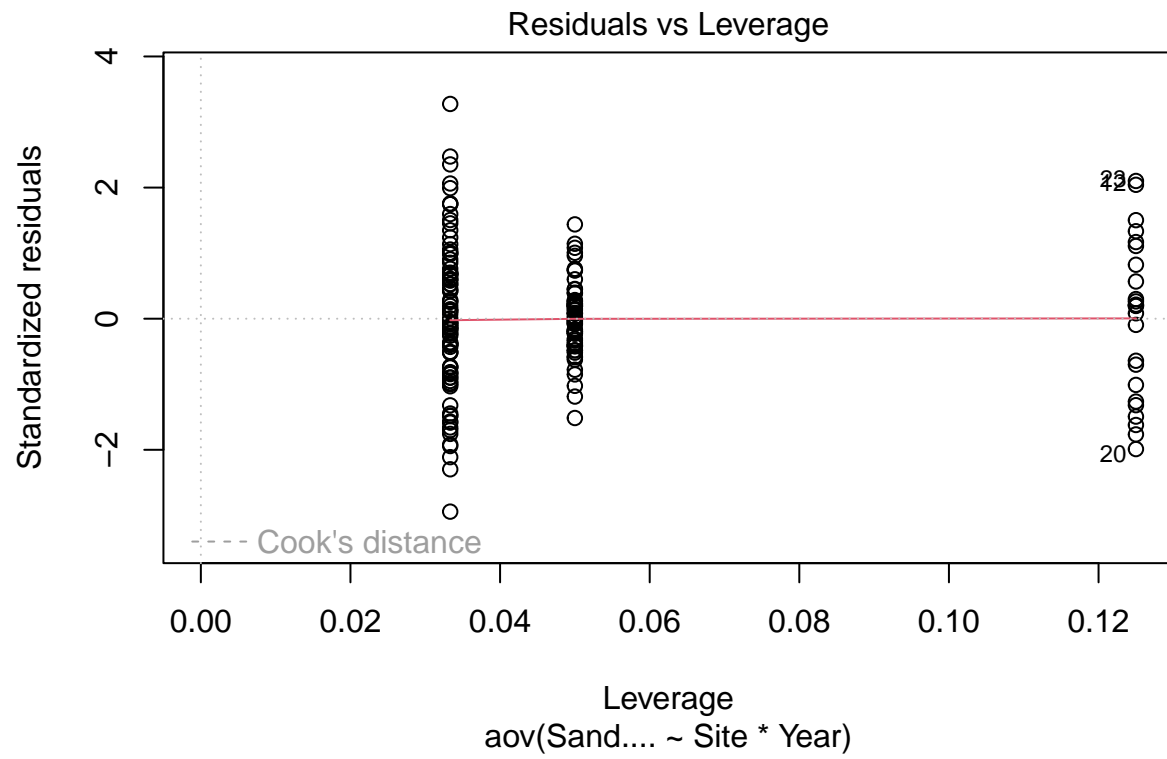
```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value    Pr(>F)
## group  8  6.1011 7.027e-07 ***
```

```
##          165
## ----
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

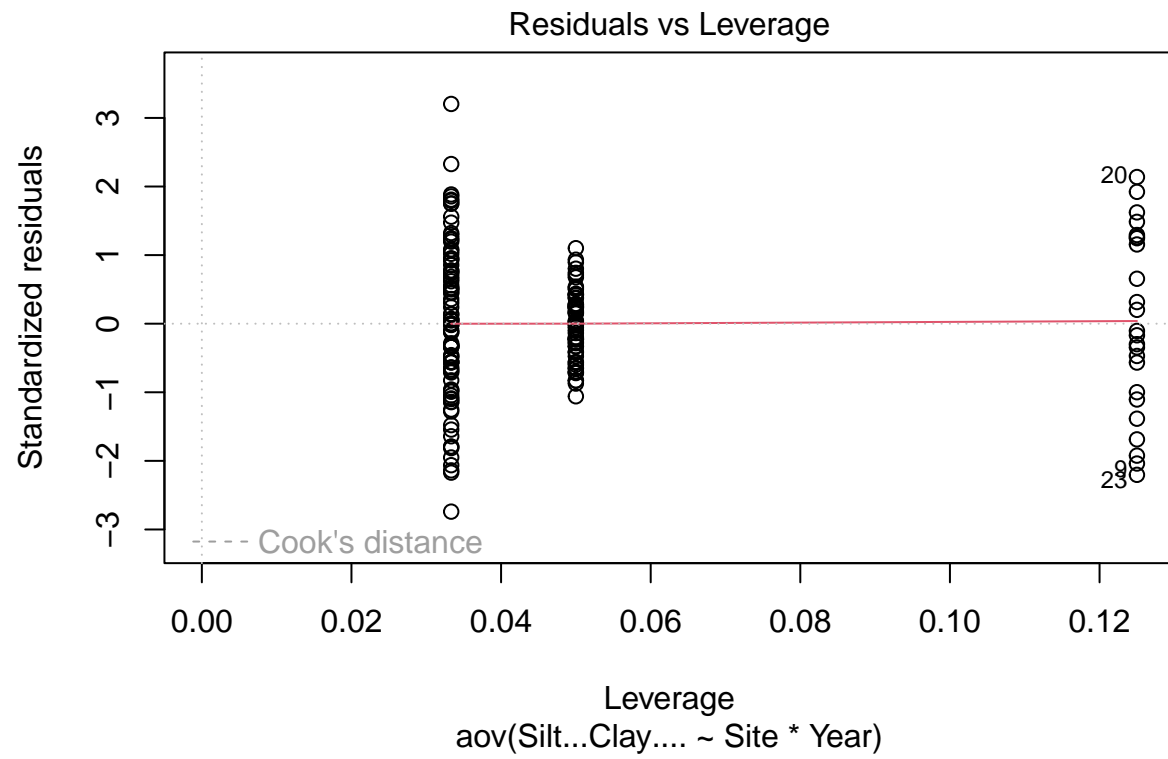
```
#outliers
plot(ps.g.anova.2way, which = 5)
```



```
plot(ps.s.anova.2way, which = 5)
```



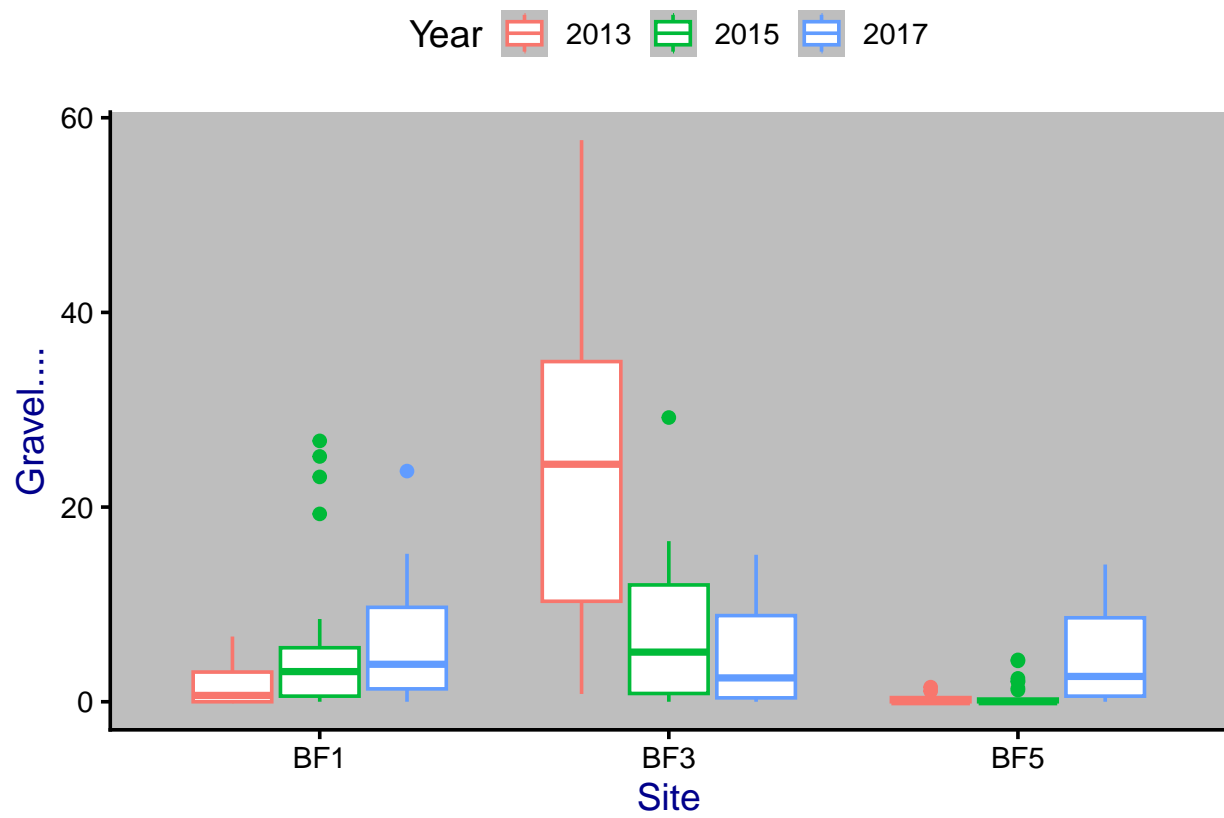
```
plot(ps.sc.anova.2way, which = 5)
```



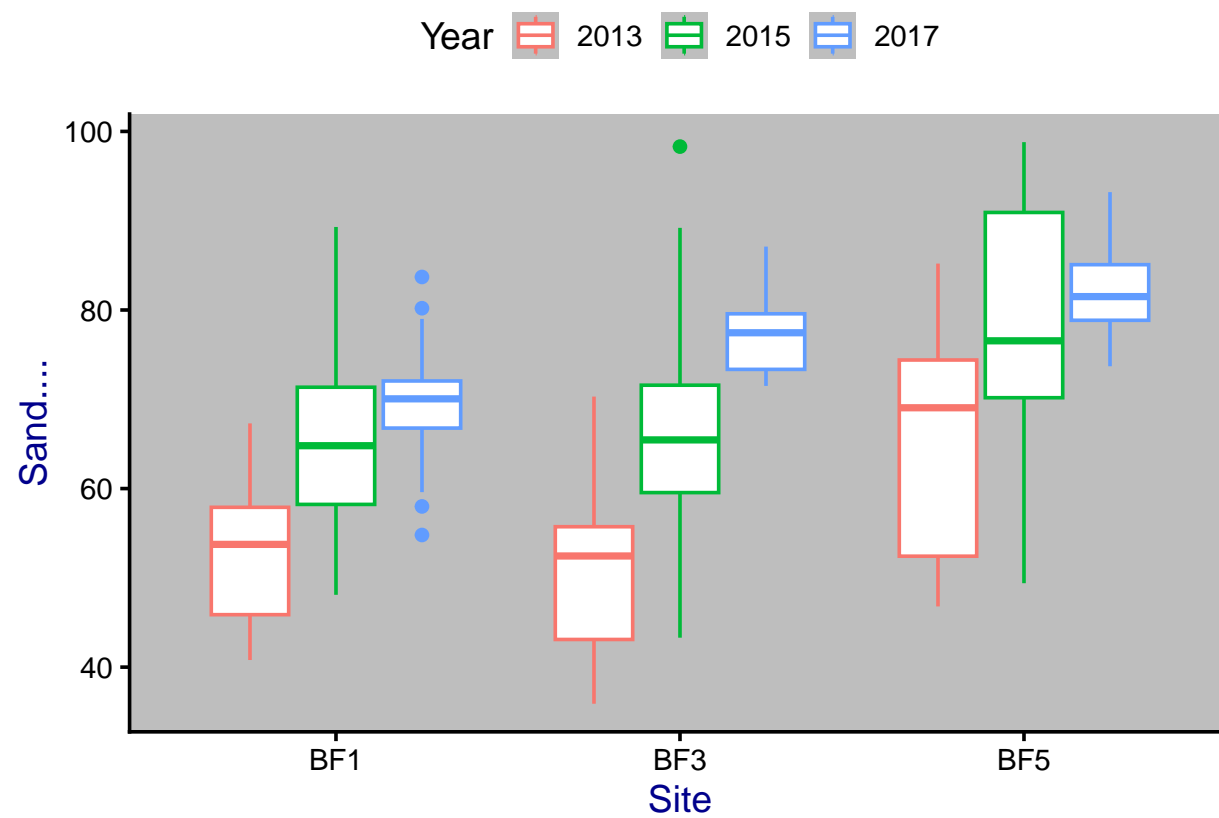
5.2.3 Residuals

5.2.4 Plots

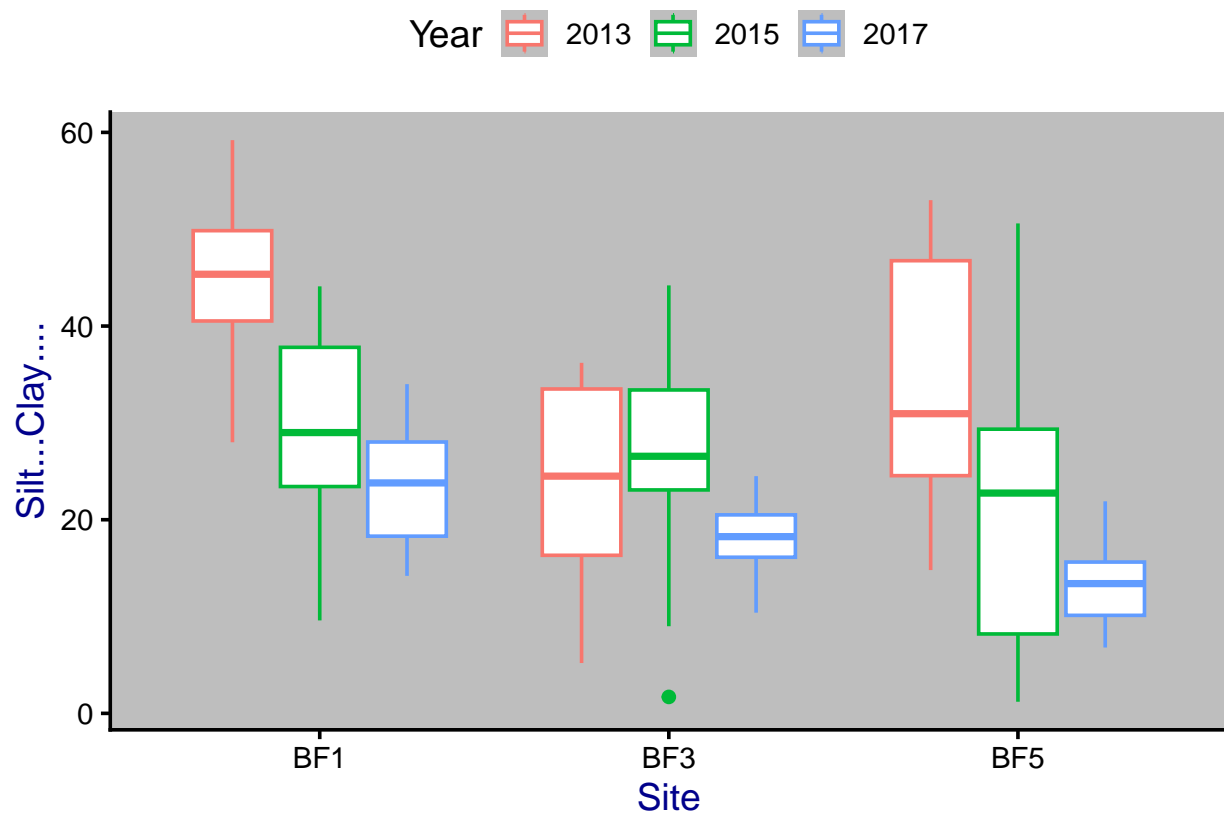
```
print(ps.g.anova.plot)
```

```
print(ps.s.anova.plot)
```



```
print(ps.sc.anova.plot)
```



5.3 Question 3: How does wildfire severity influence bulk density and recovery over time?

5.3.1 Model: two-way ANOVA for bulk density

```
#0-1 cm
bdA.anova.2way <- aov(data = all_bd,
                      X0.1.0.cm ~ Site * Year)
summary(bdA.anova.2way)
```

```
##           Df Sum Sq Mean Sq F value    Pr(>F)
## Site         2  5.136   2.5680  29.229 1.22e-10 ***
## Year         2  0.370   0.1852   2.108  0.12701
## Site:Year     4  1.297   0.3242   3.690  0.00772 **
## Residuals    96  8.434   0.0879
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(bdA.anova.2way)
```

```
## Tukey multiple comparisons of means
## 95% family-wise confidence level
```

```
##
## Fit: aov(formula = X0.1.0.cm ~ Site * Year, data = all_bd)
##
## $Site
##           diff           lwr           upr           p adj
## BF3-BF1 -0.3420000 -0.5106782 -0.17332180 0.0000155
## BF5-BF1 -0.5348571 -0.7035353 -0.36617894 0.0000000
## BF5-BF3 -0.1928571 -0.3615353 -0.02417894 0.0208682
##
## $Year
##           diff           lwr           upr           p adj
## 2015-2013 0.10200000 -0.06431895 0.2683190 0.3147391
## 2017-2013 0.15366667 -0.02852662 0.3358599 0.1157868
## 2017-2015 0.05166667 -0.11465228 0.2179856 0.7406456
##
## $'Site:Year'
##           diff           lwr           upr           p adj
## BF3:2013-BF1:2013 0.051000000 -0.36970021 0.47170021 0.9999853
## BF5:2013-BF1:2013 -0.199000000 -0.61970021 0.22170021 0.8523311
## BF1:2015-BF1:2013 0.465333333 0.08128834 0.84937832 0.0064483
## BF3:2015-BF1:2013 -0.076000000 -0.46004499 0.30804499 0.9994017
## BF5:2015-BF1:2013 -0.231333333 -0.61537832 0.15271166 0.6074686
## BF1:2017-BF1:2013 0.459000000 0.03829979 0.87970021 0.0217715
## BF3:2017-BF1:2013 0.023000000 -0.39770021 0.44370021 1.0000000
## BF5:2017-BF1:2013 -0.169000000 -0.58970021 0.25170021 0.9362031
## BF5:2013-BF3:2013 -0.250000000 -0.67070021 0.17070021 0.6249084
## BF1:2015-BF3:2013 0.414333333 0.03028834 0.79837832 0.0244429
## BF3:2015-BF3:2013 -0.127000000 -0.51104499 0.25704499 0.9797208
## BF5:2015-BF3:2013 -0.282333333 -0.66637832 0.10171166 0.3332336
## BF1:2017-BF3:2013 0.408000000 -0.01270021 0.82870021 0.0646782
## BF3:2017-BF3:2013 -0.028000000 -0.44870021 0.39270021 0.9999999
## BF5:2017-BF3:2013 -0.220000000 -0.64070021 0.20070021 0.7689994
## BF1:2015-BF5:2013 0.664333333 0.28028834 1.04837832 0.0000114
## BF3:2015-BF5:2013 0.123000000 -0.26104499 0.50704499 0.9834158
## BF5:2015-BF5:2013 -0.032333333 -0.41637832 0.35171166 0.9999992
## BF1:2017-BF5:2013 0.658000000 0.23729979 1.07870021 0.0001016
## BF3:2017-BF5:2013 0.222000000 -0.19870021 0.64270021 0.7601569
## BF5:2017-BF5:2013 0.030000000 -0.39070021 0.45070021 0.9999998
## BF3:2015-BF1:2015 -0.541333333 -0.88483361 -0.19783305 0.0000873
## BF5:2015-BF1:2015 -0.696666667 -1.04016695 -0.35316639 0.0000002
## BF1:2017-BF1:2015 -0.006333333 -0.39037832 0.37771166 1.0000000
## BF3:2017-BF1:2015 -0.442333333 -0.82637832 -0.05828834 0.0119806
## BF5:2017-BF1:2015 -0.634333333 -1.01837832 -0.25028834 0.0000325
## BF5:2015-BF3:2015 -0.155333333 -0.49883361 0.18816695 0.8812829
## BF1:2017-BF3:2015 0.535000000 0.15095501 0.91904499 0.0008392
## BF3:2017-BF3:2015 0.099000000 -0.28504499 0.48304499 0.9960650
## BF5:2017-BF3:2015 -0.093000000 -0.47704499 0.29104499 0.9974517
## BF1:2017-BF5:2015 0.690333333 0.30628834 1.07437832 0.0000045
## BF3:2017-BF5:2015 0.254333333 -0.12971166 0.63837832 0.4783253
## BF5:2017-BF5:2015 0.062333333 -0.32171166 0.44637832 0.9998632
## BF3:2017-BF1:2017 -0.436000000 -0.85670021 -0.01529979 0.0362178
## BF5:2017-BF1:2017 -0.628000000 -1.04870021 -0.20729979 0.0002500
## BF5:2017-BF3:2017 -0.192000000 -0.61270021 0.22870021 0.8757685
```

```
bdA.interaction <- with(all_bd, interaction(Site, Year))
bdA.anova.2way2 <- aov(data = all_bd, X0.1.0.cm ~ bdA.interaction)
bdA.groups <- HSD.test(bdA.anova.2way2, "bdA.interaction", group = TRUE)
bdA.groups
```

```
## $statistics
##      MSerror Df      Mean      CV
## 0.08785788 96 0.7442857 39.82453
##
## $parameters
##      test      name.t ntr StudentizedRange alpha
## Tukey bdA.interaction 9      4.488305 0.05
##
## $means
##      X0.1.0.cm      std r      se Min Max  Q25  Q50  Q75
## BF1.2013 0.7060000 0.2421753 10 0.09373254 0.42 1.19 0.5100 0.690 0.8350
## BF1.2015 1.1713333 0.3977053 15 0.07653229 0.50 1.78 0.8850 1.260 1.4800
## BF1.2017 1.1650000 0.3525542 10 0.09373254 0.63 1.59 0.8750 1.130 1.5025
## BF3.2013 0.7570000 0.2977714 10 0.09373254 0.42 1.30 0.5200 0.740 0.8825
## BF3.2015 0.6300000 0.2485386 15 0.07653229 0.28 1.23 0.4700 0.630 0.7350
## BF3.2017 0.7290000 0.1975657 10 0.09373254 0.35 1.01 0.6275 0.700 0.8875
## BF5.2013 0.5070000 0.2637360 10 0.09373254 0.18 0.87 0.3050 0.435 0.7700
## BF5.2015 0.4746667 0.3121782 15 0.07653229 0.20 1.36 0.3000 0.400 0.4900
## BF5.2017 0.5370000 0.2514425 10 0.09373254 0.27 1.02 0.3525 0.405 0.7300
##
## $comparison
## NULL
##
## $groups
##      X0.1.0.cm groups
## BF1.2015 1.1713333      a
## BF1.2017 1.1650000     ab
## BF3.2013 0.7570000     bc
## BF3.2017 0.7290000      c
## BF1.2013 0.7060000      c
## BF3.2015 0.6300000      c
## BF5.2017 0.5370000      c
## BF5.2013 0.5070000      c
## BF5.2015 0.4746667      c
##
## attr("class")
## [1] "group"
```

```
bdA.anova.plot <- ggplot(all_bd, aes(y = X0.1.0.cm, x = Site, color = Year)) +
  geom_boxplot()
```

```
#1-3 cm
bdB.anova.2way <- aov(data = all_bd,
                      X1.0.3.0.cm ~ Site * Year)
summary(bdB.anova.2way)
```

```
##      Df Sum Sq Mean Sq F value  Pr(>F)
```

```
## Site      2  3.044  1.5221  26.191 8.37e-10 ***
## Year      2  0.197  0.0987   1.698   0.188
## Site:Year  4  0.181  0.0453   0.779   0.541
## Residuals 96  5.579  0.0581
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(bdB.anova.2way)
```

```
## Tukey multiple comparisons of means
## 95% family-wise confidence level
##
## Fit: aov(formula = X1.0.3.0.cm ~ Site * Year, data = all_bd)
##
## $Site
##          diff          lwr          upr          p adj
## BF3-BF1 -0.007428571 -0.1446162  0.1297590 0.9908815
## BF5-BF1 -0.364857143 -0.5020448 -0.2276695 0.0000000
## BF5-BF3 -0.357428571 -0.4946162 -0.2202410 0.0000000
##
## $Year
##          diff          lwr          upr          p adj
## 2015-2013 0.01722222 -0.11804660 0.1524910 0.9506474
## 2017-2013 0.10500000 -0.04317957 0.2531796 0.2154399
## 2017-2015 0.08777778 -0.04749104 0.2230466 0.2747822
##
## $'Site:Year'
##          diff          lwr          upr          p adj
## BF3:2013-BF1:2013 0.03700000 -0.305159567 0.379159567 0.9999940
## BF5:2013-BF1:2013 -0.32000000 -0.662159567 0.022159567 0.0858215
## BF1:2015-BF1:2013 0.04733333 -0.265014189 0.359680856 0.9999186
## BF3:2015-BF1:2013 -0.00600000 -0.318347522 0.306347522 1.0000000
## BF5:2015-BF1:2013 -0.27266667 -0.585014189 0.039680856 0.1380641
## BF1:2017-BF1:2013 0.16400000 -0.178159567 0.506159567 0.8428789
## BF3:2017-BF1:2013 0.18100000 -0.161159567 0.523159567 0.7577125
## BF5:2017-BF1:2013 -0.31300000 -0.655159567 0.029159567 0.1008256
## BF5:2013-BF3:2013 -0.35700000 -0.699159567 -0.014840433 0.0339852
## BF1:2015-BF3:2013 0.01033333 -0.302014189 0.322680856 1.0000000
## BF3:2015-BF3:2013 -0.04300000 -0.355347522 0.269347522 0.9999609
## BF5:2015-BF3:2013 -0.30966667 -0.622014189 0.002680856 0.0538484
## BF1:2017-BF3:2013 0.12700000 -0.215159567 0.469159567 0.9592678
## BF3:2017-BF3:2013 0.14400000 -0.198159567 0.486159567 0.9179281
## BF5:2017-BF3:2013 -0.35000000 -0.692159567 -0.007840433 0.0408693
## BF1:2015-BF5:2013 0.36733333 0.054985811 0.679680856 0.0093540
## BF3:2015-BF5:2013 0.31400000 0.001652478 0.626347522 0.0477481
## BF5:2015-BF5:2013 0.04733333 -0.265014189 0.359680856 0.9999186
## BF1:2017-BF5:2013 0.48400000 0.141840433 0.826159567 0.0006497
## BF3:2017-BF5:2013 0.50100000 0.158840433 0.843159567 0.0003556
## BF5:2017-BF5:2013 0.00700000 -0.335159567 0.349159567 1.0000000
## BF3:2015-BF1:2015 -0.05333333 -0.332705450 0.226038784 0.9995407
## BF5:2015-BF1:2015 -0.32000000 -0.599372117 -0.040627883 0.0127716
## BF1:2017-BF1:2015 0.11666667 -0.195680856 0.429014189 0.9577481
## BF3:2017-BF1:2015 0.13366667 -0.178680856 0.446014189 0.9103819
## BF5:2017-BF1:2015 -0.36033333 -0.672680856 -0.047985811 0.0117581
```

```
## BF5:2015-BF3:2015 -0.26666667 -0.546038784 0.012705450 0.0734139
## BF1:2017-BF3:2015 0.17000000 -0.142347522 0.482347522 0.7282994
## BF3:2017-BF3:2015 0.18700000 -0.125347522 0.499347522 0.6153664
## BF5:2017-BF3:2015 -0.30700000 -0.619347522 0.005347522 0.0579263
## BF1:2017-BF5:2015 0.43666667 0.124319144 0.749014189 0.0007913
## BF3:2017-BF5:2015 0.45366667 0.141319144 0.766014189 0.0004108
## BF5:2017-BF5:2015 -0.04033333 -0.352680856 0.272014189 0.9999761
## BF3:2017-BF1:2017 0.01700000 -0.325159567 0.359159567 1.0000000
## BF5:2017-BF1:2017 -0.47700000 -0.819159567 -0.134840433 0.0008291
## BF5:2017-BF3:2017 -0.49400000 -0.836159567 -0.151840433 0.0004566
```

```
bdB.interaction <- with(all_bd, interaction(Site, Year))
bdB.anova.2way2 <- aov(data = all_bd, X1.0.3.0.cm ~ bdB.interaction)
bdB.groups <- HSD.test(bdB.anova.2way2, "bdB.interaction", group = TRUE)
bdB.groups
```

```
## $statistics
##      MSerror Df      Mean      CV
## 0.05811559 96 0.9350476 25.78176
##
## $parameters
##      test      name.t ntr StudentizedRange alpha
## Tukey bdB.interaction 9      4.488305 0.05
##
## $means
##      X1.0.3.0.cm      std r      se Min Max Q25 Q50 Q75
## BF1.2013 0.9920000 0.2355514 10 0.07623358 0.66 1.36 0.8000 1.020 1.0825
## BF1.2015 1.0393333 0.2148576 15 0.06224446 0.57 1.35 0.8950 1.060 1.2000
## BF1.2017 1.1560000 0.1368048 10 0.07623358 0.94 1.34 1.0450 1.165 1.2475
## BF3.2013 1.0290000 0.1939330 10 0.07623358 0.69 1.32 0.9350 1.000 1.1625
## BF3.2015 0.9860000 0.3202410 15 0.06224446 0.39 1.69 0.7650 1.050 1.1500
## BF3.2017 1.1730000 0.1738486 10 0.07623358 0.95 1.42 1.0225 1.180 1.3200
## BF5.2013 0.6720000 0.2651540 10 0.07623358 0.34 1.10 0.4700 0.600 0.8350
## BF5.2015 0.7193333 0.3031376 15 0.06224446 0.30 1.53 0.5850 0.700 0.7600
## BF5.2017 0.6790000 0.1824189 10 0.07623358 0.40 1.05 0.5825 0.650 0.7850
##
## $comparison
## NULL
##
## $groups
##      X1.0.3.0.cm groups
## BF3.2017 1.1730000 a
## BF1.2017 1.1560000 a
## BF1.2015 1.0393333 a
## BF3.2013 1.0290000 ab
## BF1.2013 0.9920000 abc
## BF3.2015 0.9860000 abc
## BF5.2015 0.7193333 bc
## BF5.2017 0.6790000 c
## BF5.2013 0.6720000 c
##
## attr(,"class")
## [1] "group"
```

```
bdB.anova.plot <- ggplot(all_bd, aes(y = X1.0.3.0.cm, x = Site, color = Year)) +
  geom_boxplot()
```

```
#3-6 cm
bdC.anova.2way <- aov(data = all_bd,
                      X3.0.6.0.cm ~ Site * Year)
summary(bdC.anova.2way)
```

```
##           Df Sum Sq Mean Sq F value    Pr(>F)
## Site         2  1.3394   0.6697   21.746 1.62e-08 ***
## Year         2  0.0315   0.0158    0.512   0.601
## Site:Year     4  0.0487   0.0122    0.395   0.812
## Residuals    96  2.9565   0.0308
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
TukeyHSD(bdC.anova.2way)
```

```
##      Tukey multiple comparisons of means
##      95% family-wise confidence level
##
## Fit: aov(formula = X3.0.6.0.cm ~ Site * Year, data = all_bd)
##
## $Site
##           diff           lwr           upr           p adj
## BF3-BF1  0.003714286 -0.0961532  0.1035818 0.9956876
## BF5-BF1 -0.237714286 -0.3375818 -0.1378468 0.0000005
## BF5-BF3 -0.241428571 -0.3412961 -0.1415611 0.0000003
##
## $Year
##           diff           lwr           upr           p adj
## 2015-2013 0.006222222 -0.09224845  0.1046929 0.9876040
## 2017-2013 0.041666667 -0.06620255  0.1495359 0.6293162
## 2017-2015 0.035444444 -0.06302623  0.1339151 0.6686437
##
## $'Site:Year'
##           diff           lwr           upr           p adj
## BF3:2013-BF1:2013 0.020000000 -0.22907945  2.690794e-01 0.9999994
## BF5:2013-BF1:2013 -0.260000000 -0.50907945 -1.092055e-02 0.0338396
## BF1:2015-BF1:2013 -0.009333333 -0.23671072  2.180441e-01 1.0000000
## BF3:2015-BF1:2013 -0.012666667 -0.24004405  2.147107e-01 1.0000000
## BF5:2015-BF1:2013 -0.199333333 -0.42671072  2.804405e-02 0.1343857
## BF1:2017-BF1:2013  0.058000000 -0.19107945  3.070794e-01 0.9980663
## BF3:2017-BF1:2013  0.056000000 -0.19307945  3.050794e-01 0.9984933
## BF5:2017-BF1:2013 -0.229000000 -0.47807945  2.007945e-02 0.0972727
## BF5:2013-BF3:2013 -0.280000000 -0.52907945 -3.092055e-02 0.0157853
## BF1:2015-BF3:2013 -0.029333333 -0.25671072  1.980441e-01 0.9999763
## BF3:2015-BF3:2013 -0.032666667 -0.26004405  1.947107e-01 0.9999458
## BF5:2015-BF3:2013 -0.219333333 -0.44671072  8.044051e-03 0.0675388
## BF1:2017-BF3:2013  0.038000000 -0.21107945  2.870794e-01 0.9999144
## BF3:2017-BF3:2013  0.036000000 -0.21307945  2.850794e-01 0.9999433
## BF5:2017-BF3:2013 -0.249000000 -0.49807945  7.944548e-05 0.0501386
```



```
## BF1:2015-BF5:2013 0.250666667 0.02328928 4.780441e-01 0.0195133
## BF3:2015-BF5:2013 0.247333333 0.01995595 4.747107e-01 0.0224626
## BF5:2015-BF5:2013 0.060666667 -0.16671072 2.880441e-01 0.9950187
## BF1:2017-BF5:2013 0.318000000 0.06892055 5.670794e-01 0.0031880
## BF3:2017-BF5:2013 0.316000000 0.06692055 5.650794e-01 0.0034836
## BF5:2017-BF5:2013 0.031000000 -0.21807945 2.800794e-01 0.9999820
## BF3:2015-BF1:2015 -0.003333333 -0.20670585 2.000392e-01 1.0000000
## BF5:2015-BF1:2015 -0.190000000 -0.39337252 1.337252e-02 0.0865026
## BF1:2017-BF1:2015 0.067333333 -0.16004405 2.947107e-01 0.9899956
## BF3:2017-BF1:2015 0.065333333 -0.16204405 2.927107e-01 0.9918002
## BF5:2017-BF1:2015 -0.219666667 -0.44704405 7.710718e-03 0.0667200
## BF5:2015-BF3:2015 -0.186666667 -0.39003918 1.670585e-02 0.0984406
## BF1:2017-BF3:2015 0.070666667 -0.15671072 2.980441e-01 0.9863098
## BF3:2017-BF3:2015 0.068666667 -0.15871072 2.960441e-01 0.9886287
## BF5:2017-BF3:2015 -0.216333333 -0.44371072 1.104405e-02 0.0752963
## BF1:2017-BF5:2015 0.257333333 0.02995595 4.847107e-01 0.0146410
## BF3:2017-BF5:2015 0.255333333 0.02795595 4.827107e-01 0.0159714
## BF5:2017-BF5:2015 -0.029666667 -0.25704405 1.977107e-01 0.9999741
## BF3:2017-BF1:2017 -0.002000000 -0.25107945 2.470794e-01 1.0000000
## BF5:2017-BF1:2017 -0.287000000 -0.53607945 -3.792055e-02 0.0119241
## BF5:2017-BF3:2017 -0.285000000 -0.53407945 -3.592055e-02 0.0129280
```

```
bdC.interaction <- with(all_bd, interaction(Site, Year))
bdC.anova.2way2 <- aov(data = all_bd, X3.0.6.0.cm ~ bdC.interaction)
bdC.groups <- HSD.test(bdC.anova.2way2, "bdC.interaction", group = TRUE)
bdC.groups
```

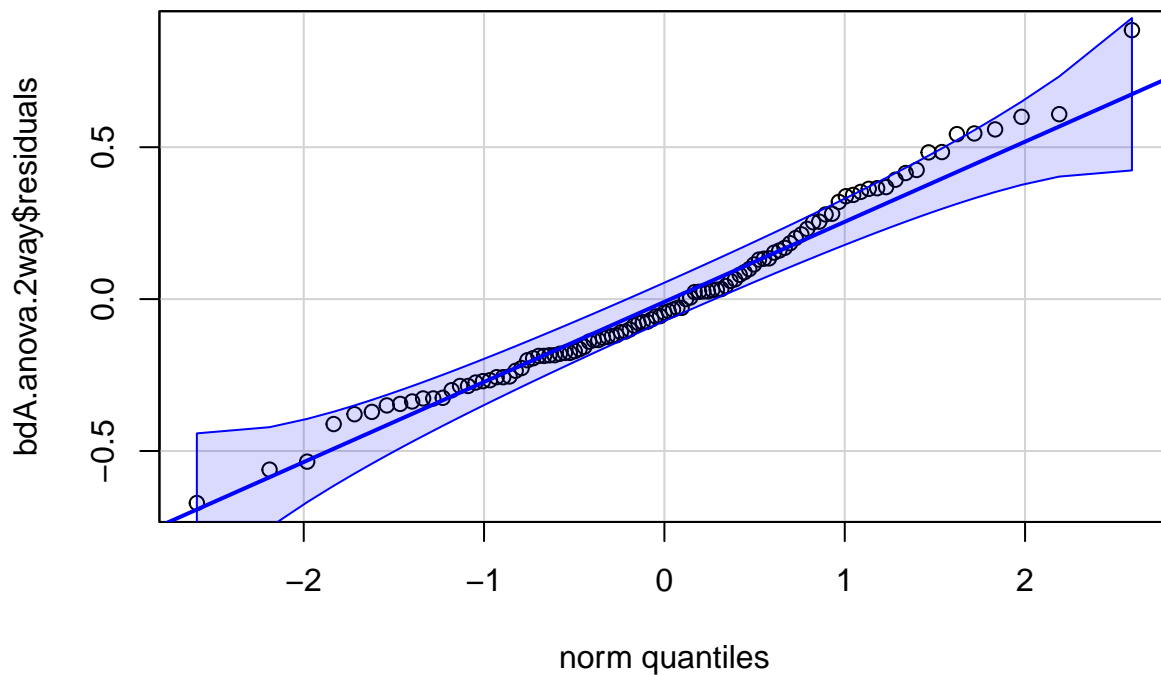
```
## $statistics
##      MSerror Df      Mean      CV
## 0.03079719 96 1.240571 14.146
##
## $parameters
##      test      name.t ntr StudentizedRange alpha
## Tukey bdC.interaction 9      4.488305 0.05
##
## $means
##      X3.0.6.0.cm      std r      se Min Max Q25 Q50 Q75
## BF1.2013 1.306000 0.2314783 10 0.05549521 0.85 1.75 1.2275 1.315 1.3975
## BF1.2015 1.296667 0.1826655 15 0.04531165 1.02 1.55 1.1500 1.290 1.4800
## BF1.2017 1.364000 0.1447757 10 0.05549521 1.03 1.60 1.3250 1.370 1.4250
## BF3.2013 1.326000 0.1473620 10 0.05549521 1.00 1.47 1.2725 1.365 1.4400
## BF3.2015 1.293333 0.1842229 15 0.04531165 0.98 1.62 1.1700 1.360 1.4050
## BF3.2017 1.362000 0.1731923 10 0.05549521 1.06 1.55 1.2075 1.430 1.4875
## BF5.2013 1.046000 0.1424547 10 0.05549521 0.85 1.25 0.9325 1.055 1.1675
## BF5.2015 1.106667 0.1591794 15 0.04531165 0.77 1.38 1.0050 1.100 1.2150
## BF5.2017 1.077000 0.1945393 10 0.05549521 0.81 1.33 0.9200 1.030 1.2775
##
## $comparison
## NULL
##
## $groups
##      X3.0.6.0.cm groups
## BF1.2017 1.364000 a
## BF3.2017 1.362000 a
```

```
## BF3.2013      1.326000      ab
## BF1.2013      1.306000      ab
## BF1.2015      1.296667      ab
## BF3.2015      1.293333      ab
## BF5.2015      1.106667      bc
## BF5.2017      1.077000      bc
## BF5.2013      1.046000      c
##
## attr("class")
## [1] "group"
```

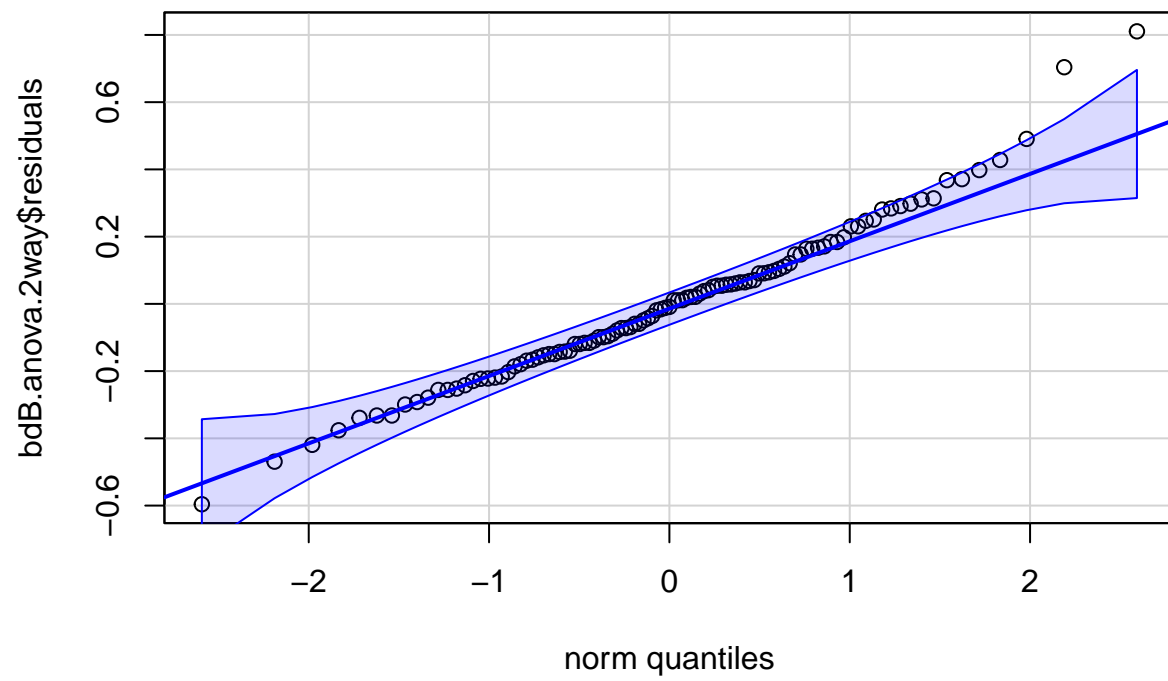
```
bdC.anova.plot <- ggplot(all_bd, aes(y = X3.0.6.0.cm, x = Site, color = Year)) +
  geom_boxplot()
```

5.3.2 Assumptions

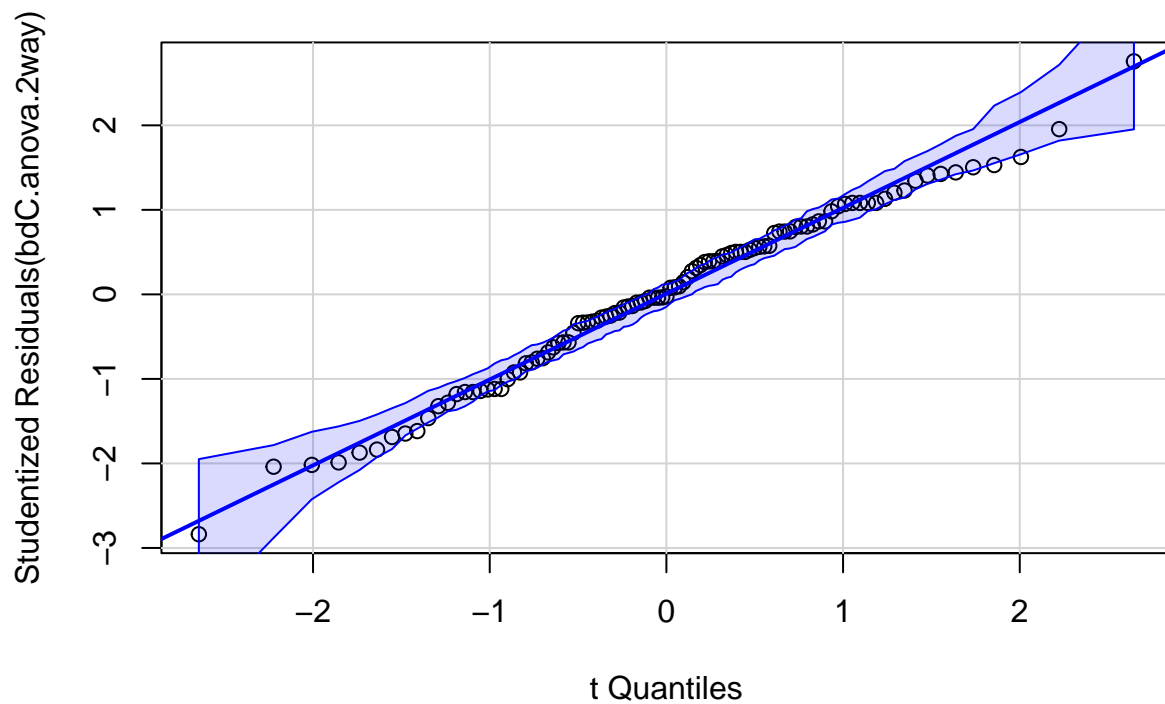
```
#normality
qqPlot(bdA.anova.2way$residuals, id = F)
```



```
qqPlot(bdB.anova.2way$residuals, id = F)
```



```
qqPlot(bdC.anova.2way, id = F)
```



```
#homogeneity of variances
leveneTest(bdA.anova.2way)
```

```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value Pr(>F)
## group 8  1.2933 0.2562
##      96
```

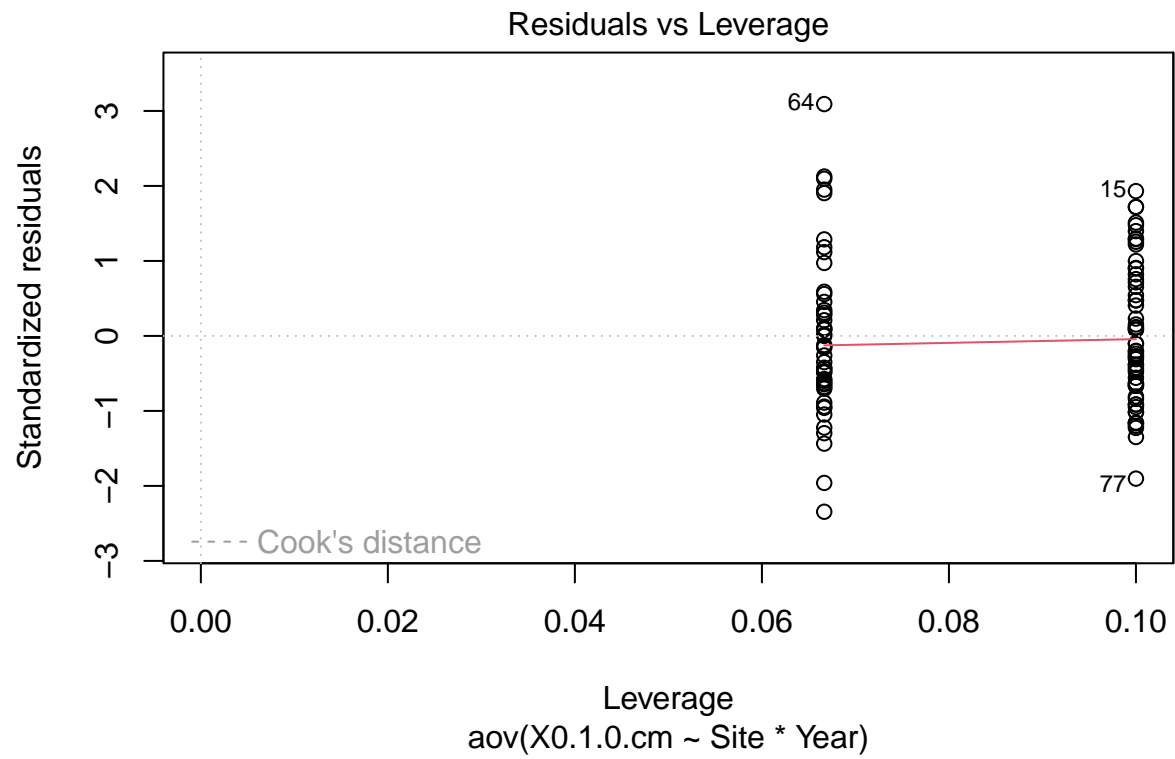
```
leveneTest(bdB.anova.2way)
```

```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value Pr(>F)
## group 8  0.7243 0.6696
##      96
```

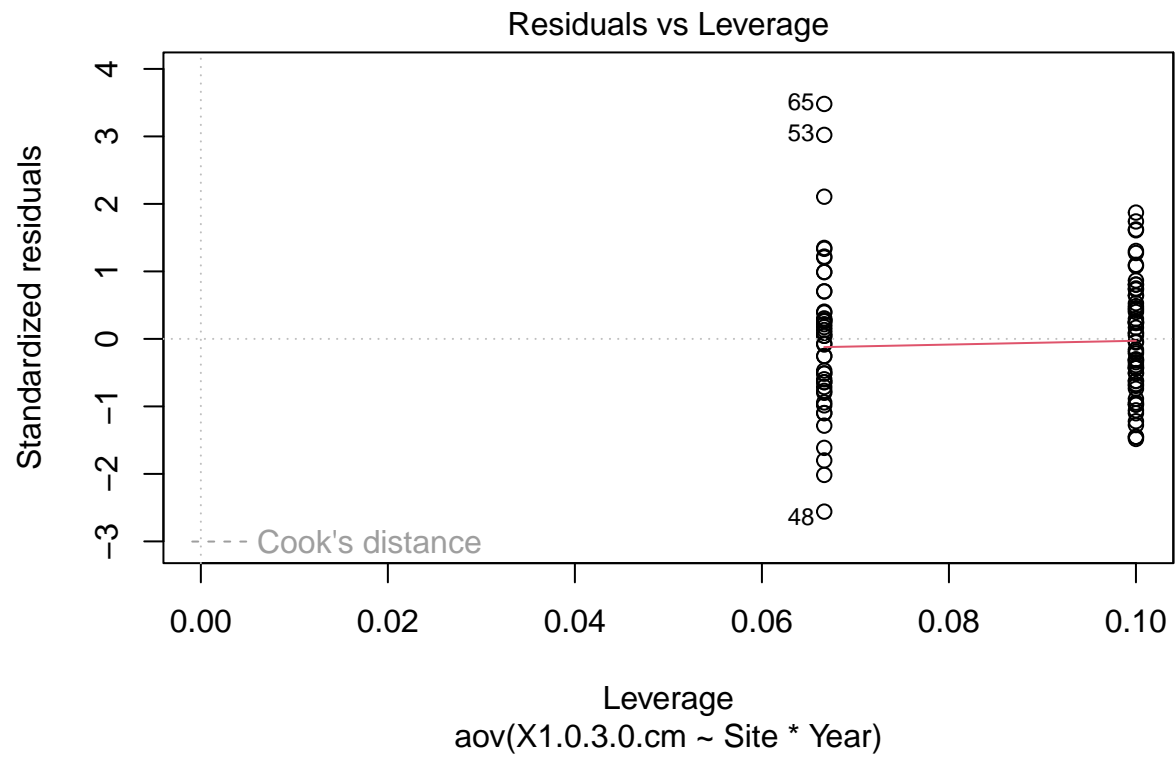
```
leveneTest(bdC.anova.2way)
```

```
## Levene's Test for Homogeneity of Variance (center = median)
##      Df F value Pr(>F)
## group 8  0.4454 0.8907
##      96
```

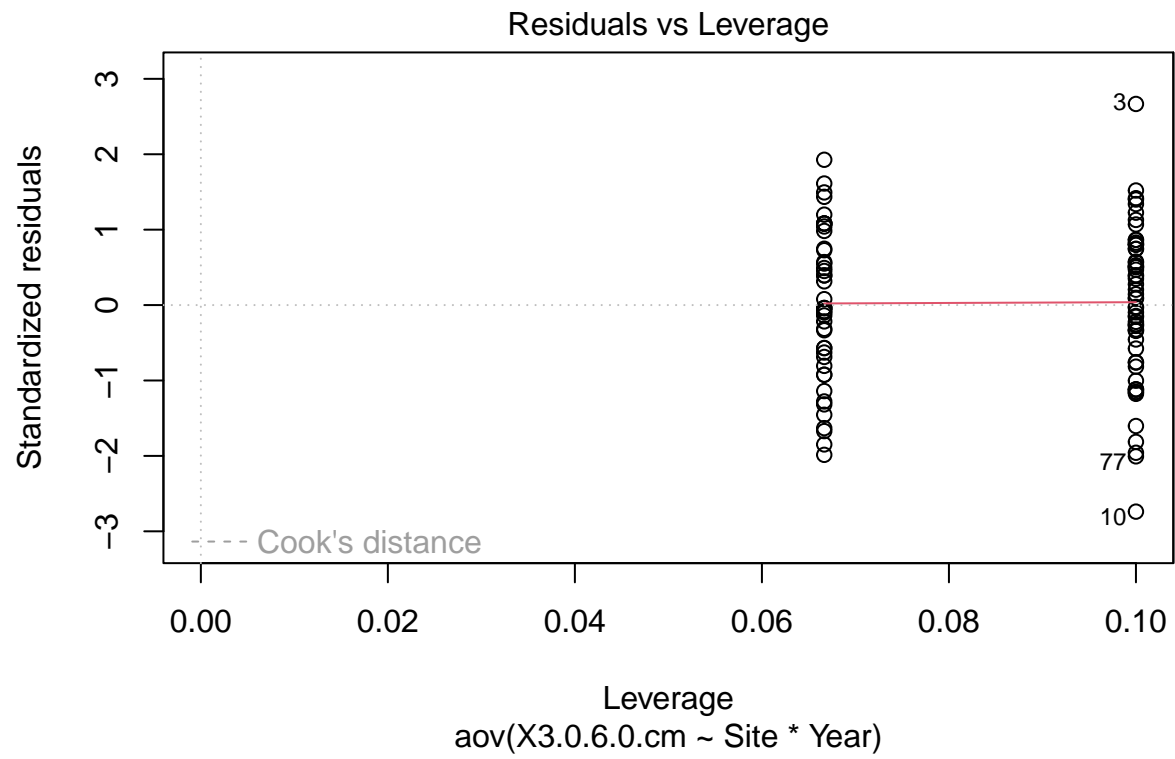
```
#outliers
plot(bdA.anova.2way, which = 5)
```



```
plot(bdB.anova.2way, which = 5)
```



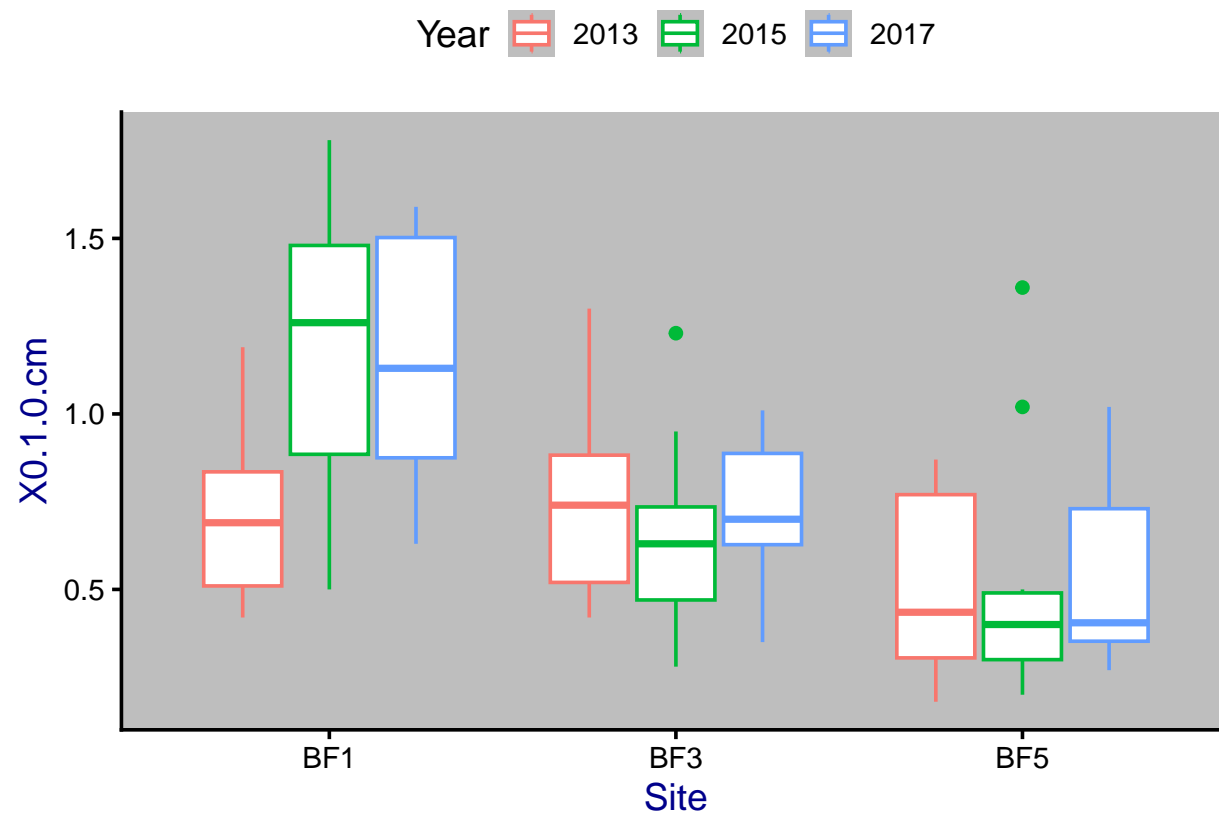
```
plot(bdC.anova.2way, which = 5)
```



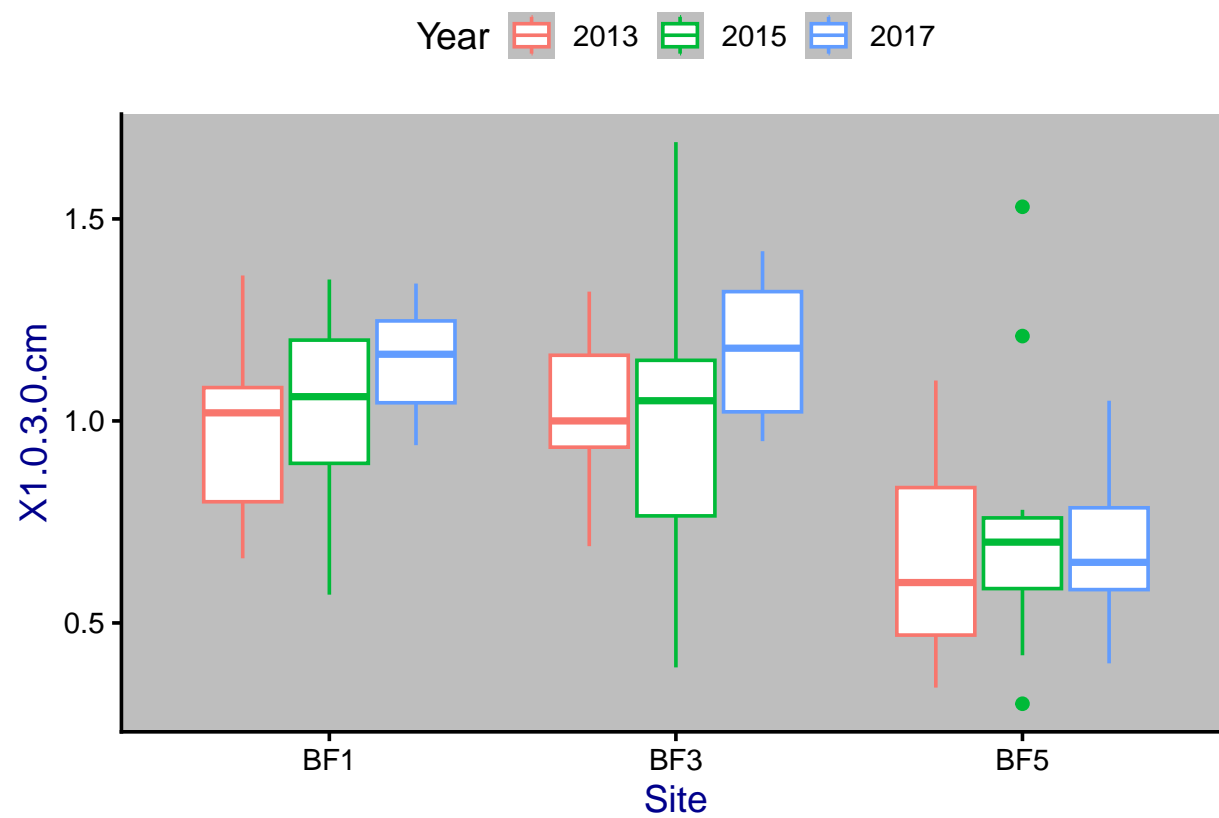
5.3.3 Residuals

5.3.4 Plots

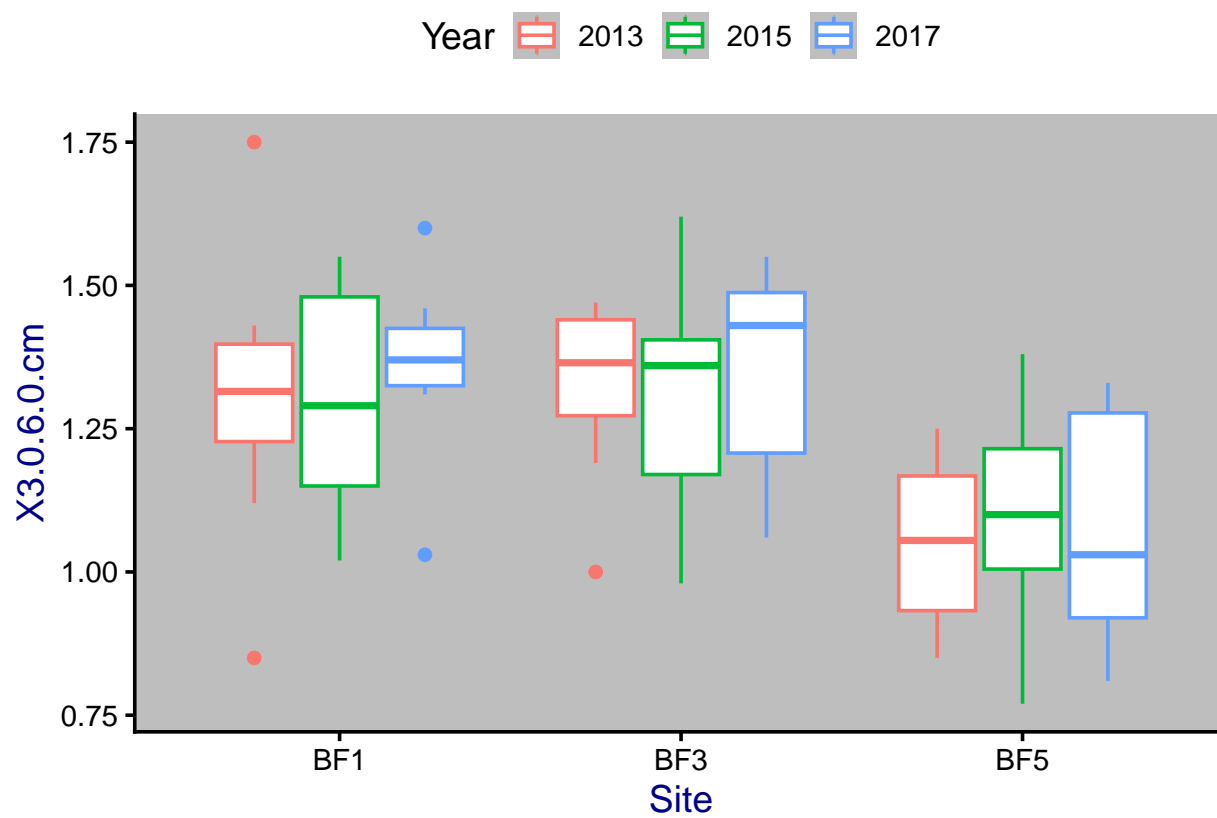
```
print(bdA.anova.plot)
```



```
print(bdB.anova.plot)
```

```
print(bdC.anova.plot)
```



6. Summary and Conclusions

7. References

<add references here if relevant, otherwise delete this section>