

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

Evan Lim and Tallulah Bowden

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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"

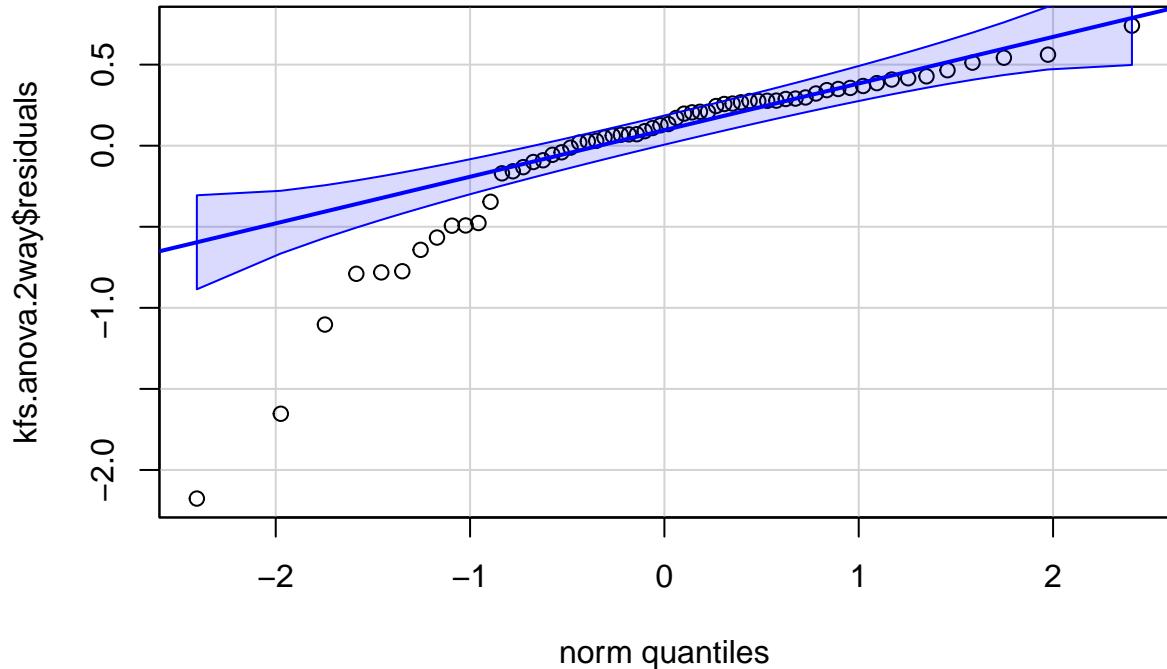
```

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

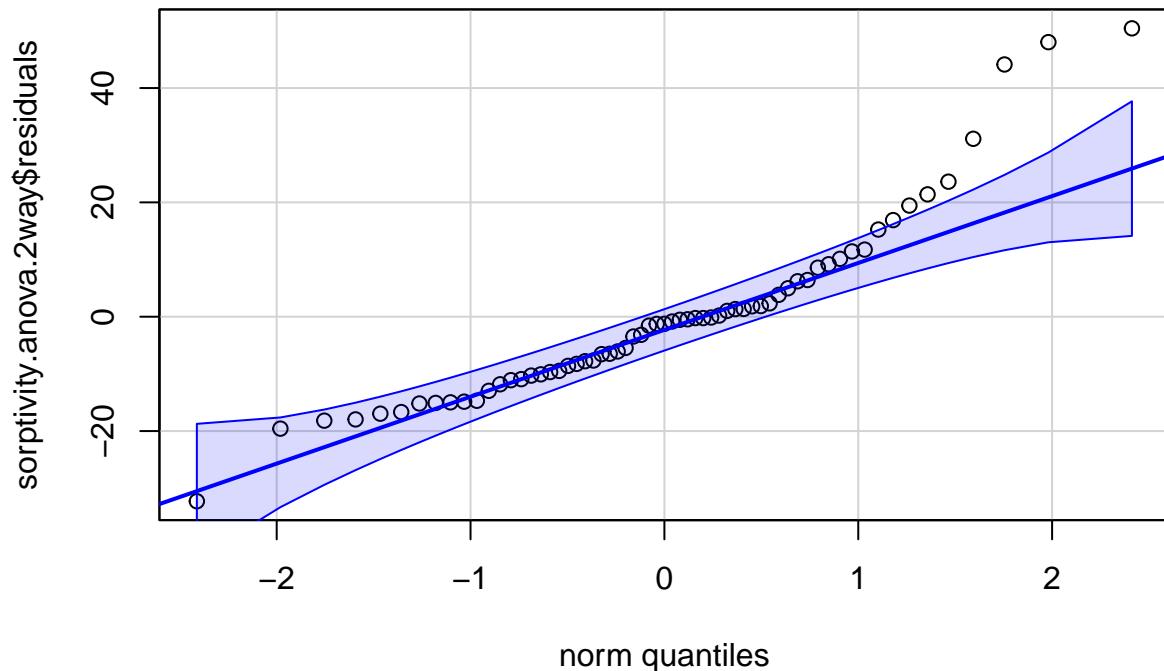
5.1.2 Assumptions

First, we test for normality and variance.

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



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



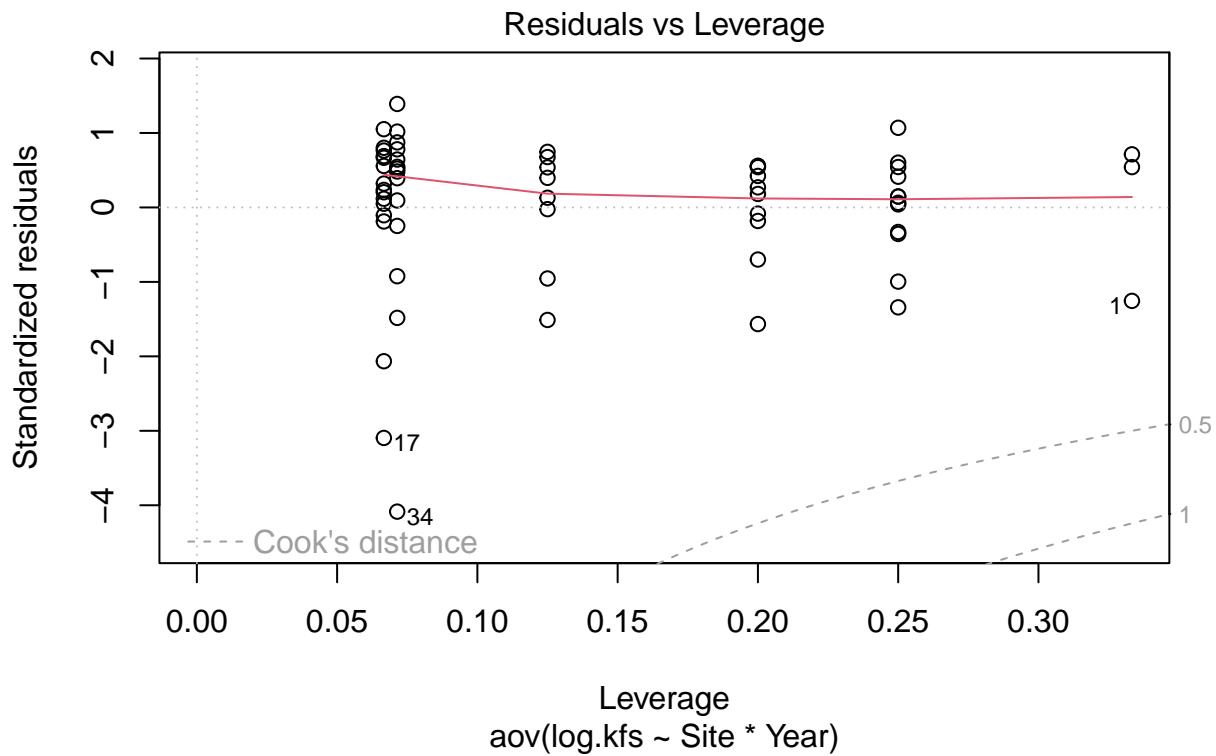
```
#homogeneity of variances
leveneTest(kfs.anova.2way) #original value after outlier removal p = 0.02207. data was then log transfo
```

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

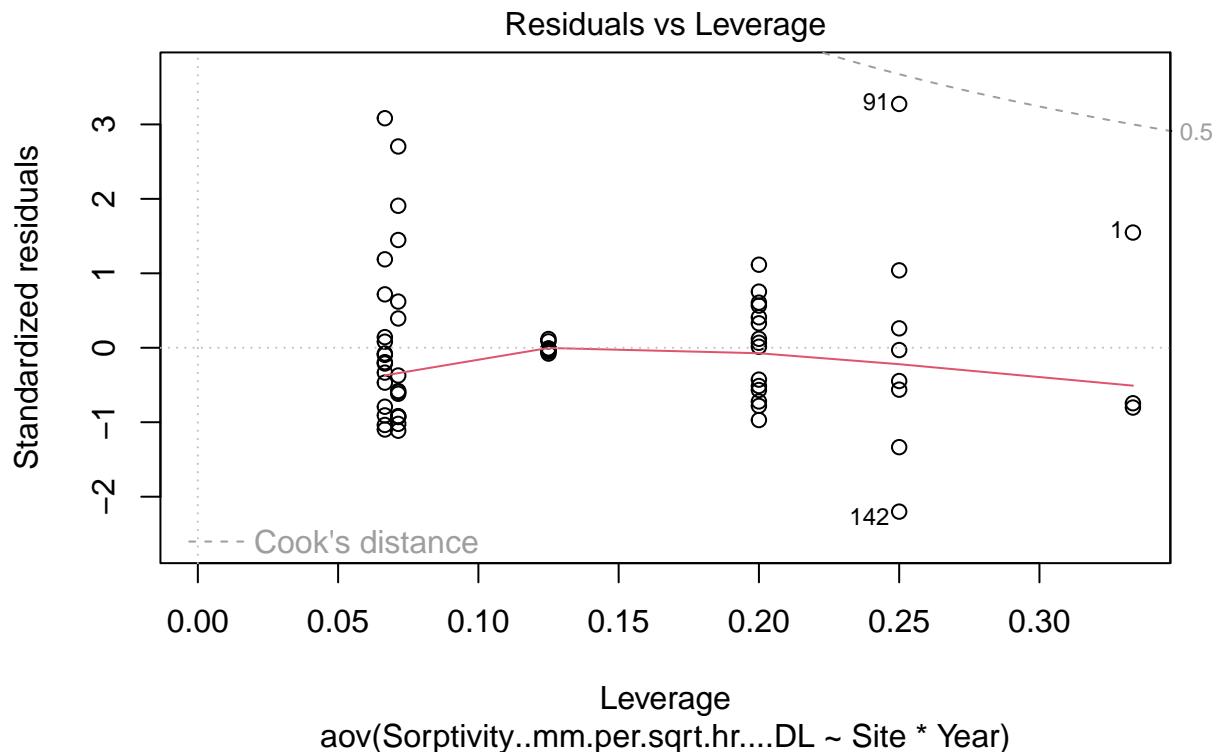
```
leveneTest(sorptivity.anova.2way)
```

```
## 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.
```



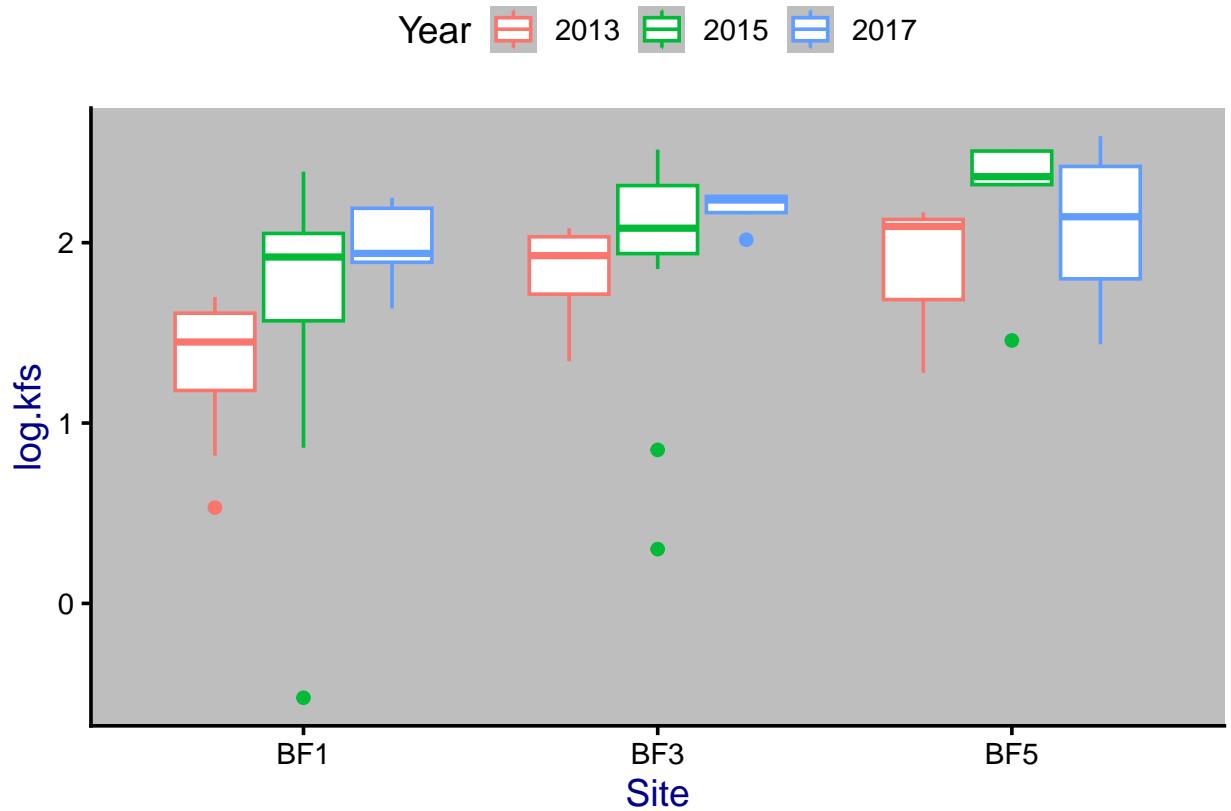
```
plot(sorptivity.anova.2way, which = 5)
```



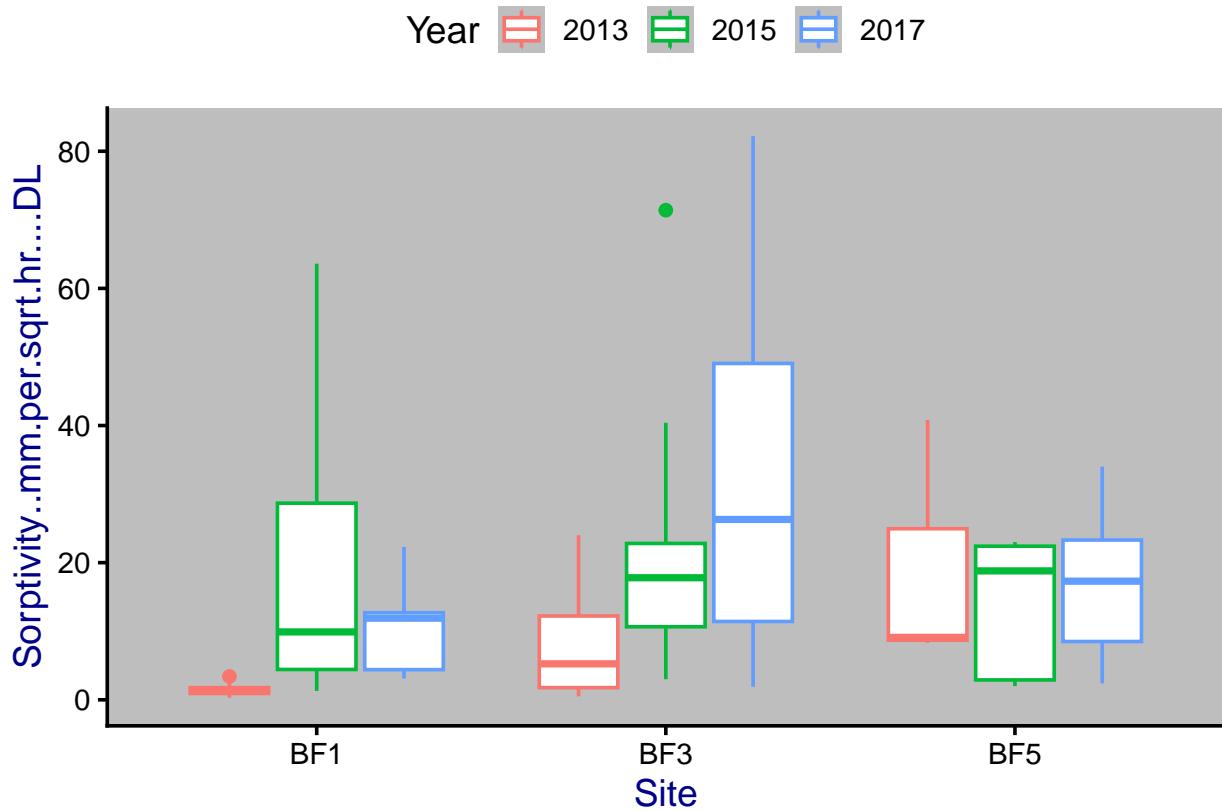
5.1.3 Residuals

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  4.0133333 -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     a
##      BF5.2015     ab
##      BF3.2017     ab
##      BF1.2017     bc
##      BF3.2015     c
##      BF5.2013     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      29.676667 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      27.036667 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      20.976667 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()

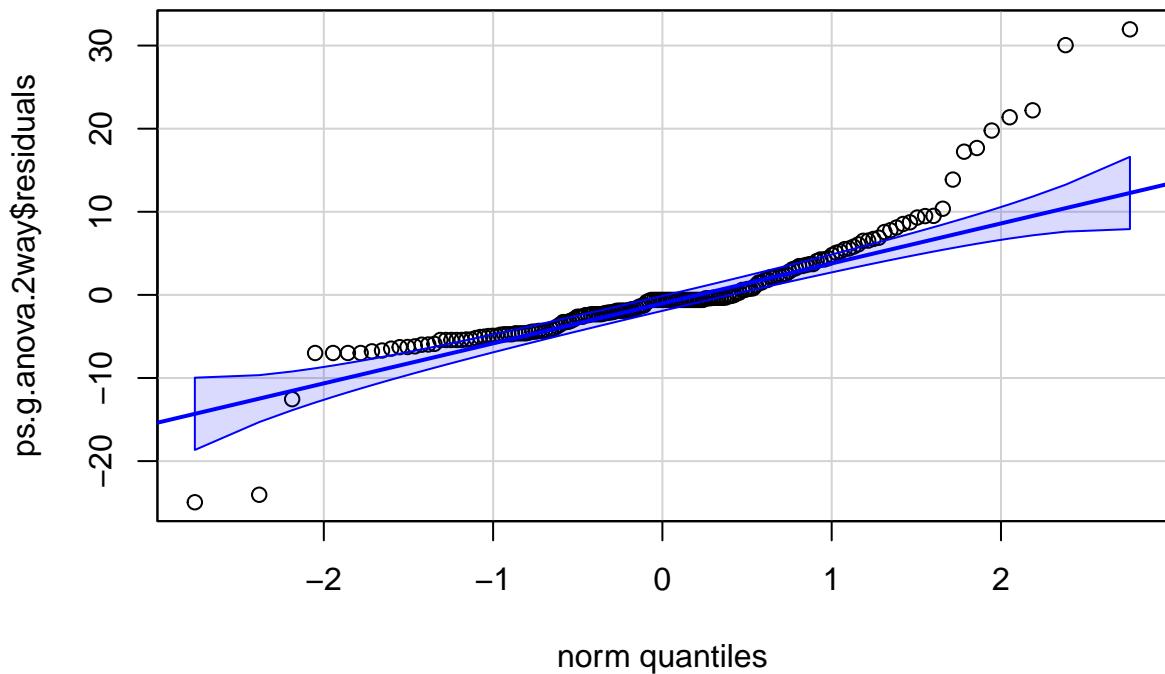
```

5.2.1 Assumptions

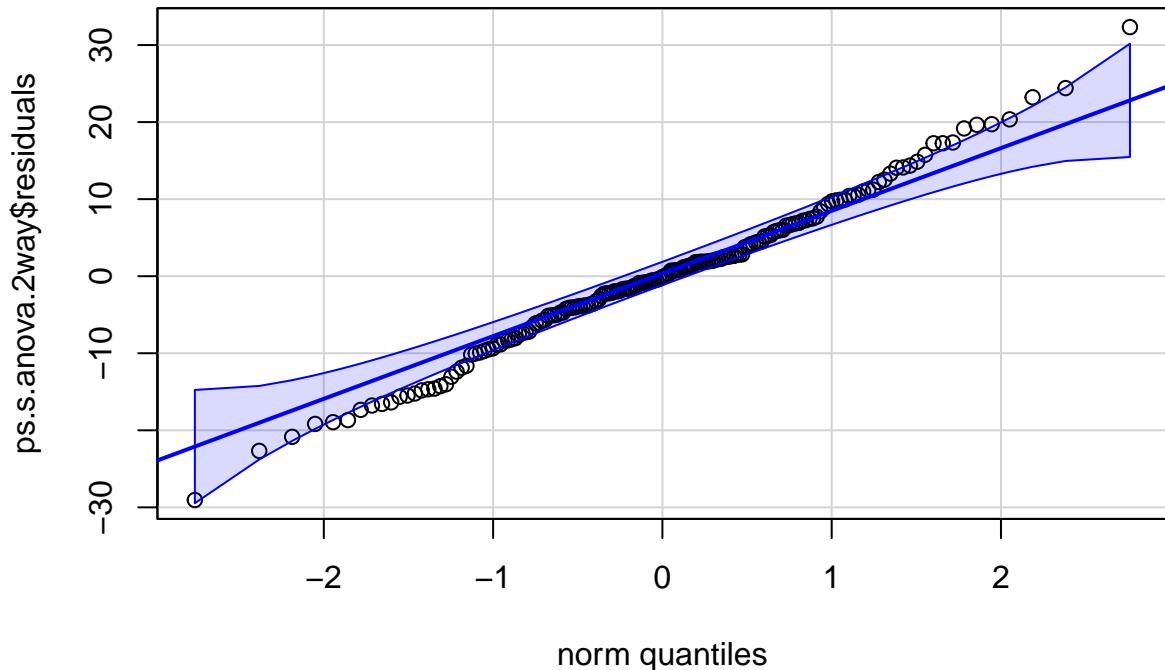
```

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

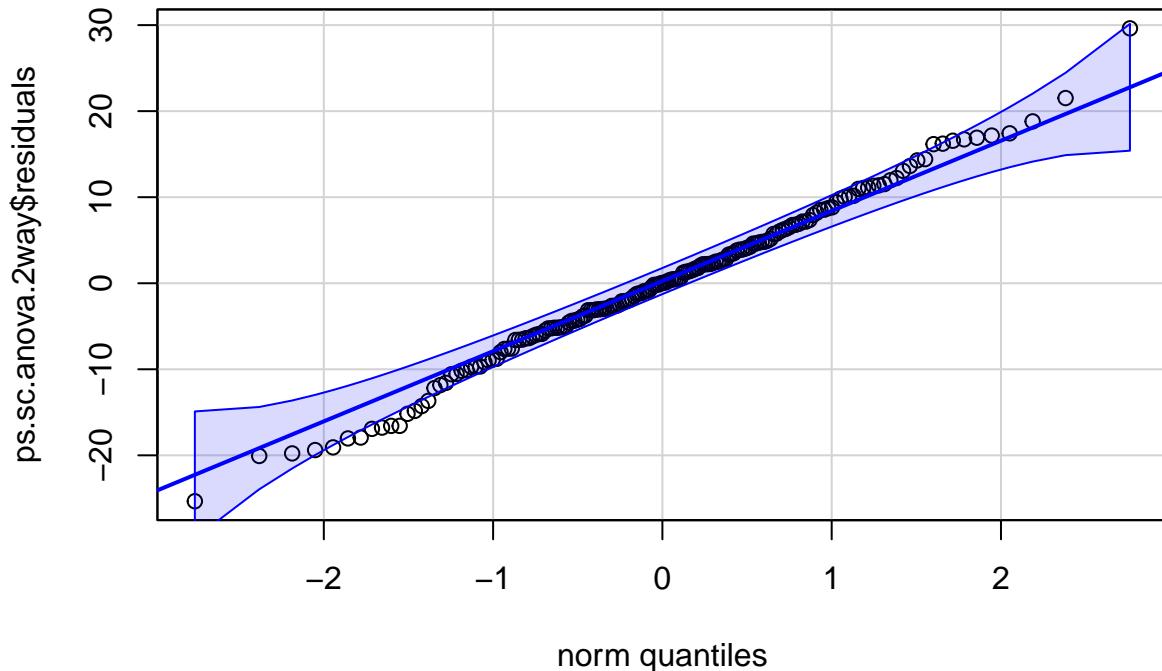
```



```
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, untransn

## 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, untransn

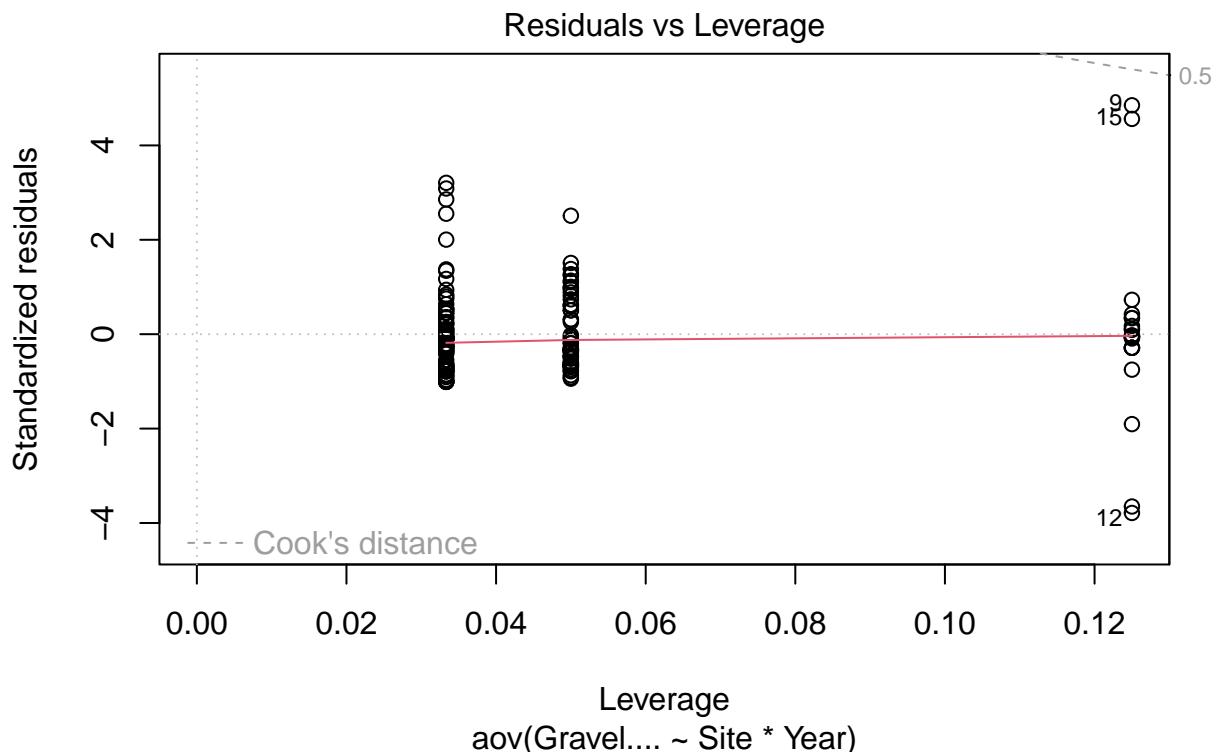
## Levene's Test for Homogeneity of Variance (center = median)
##          Df F value    Pr(>F)
## group     8  6.1011 7.027e-07 ***
```

```

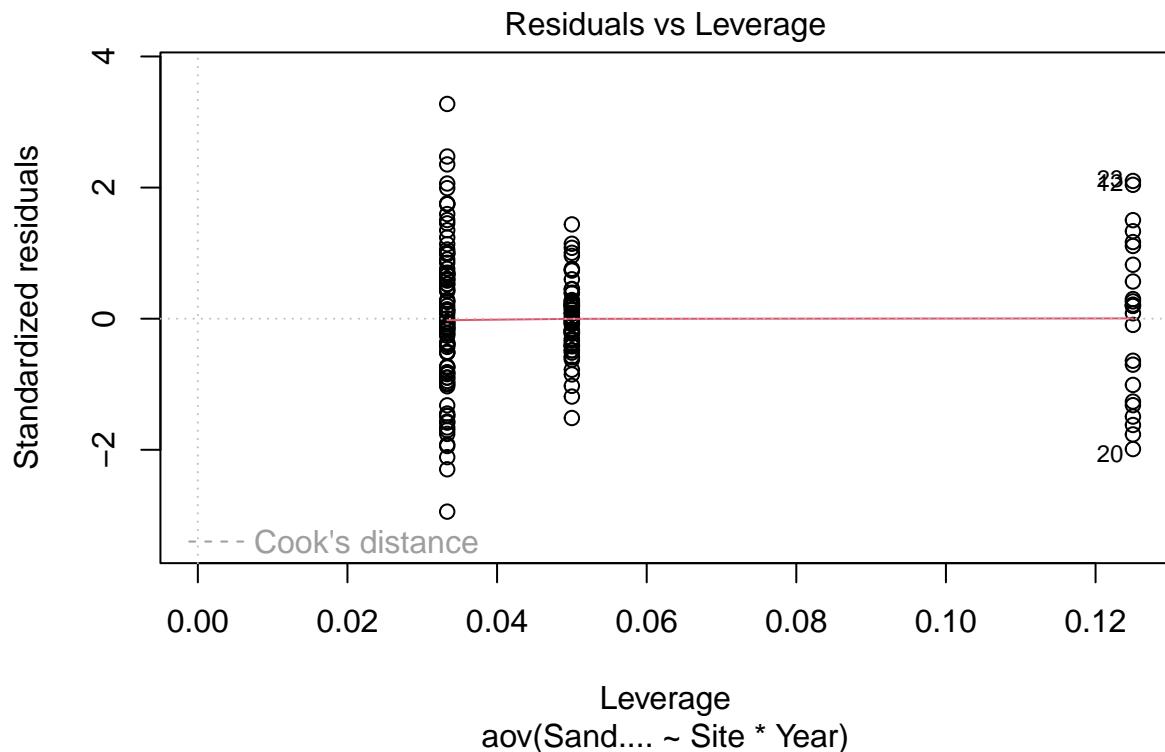
##      165
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

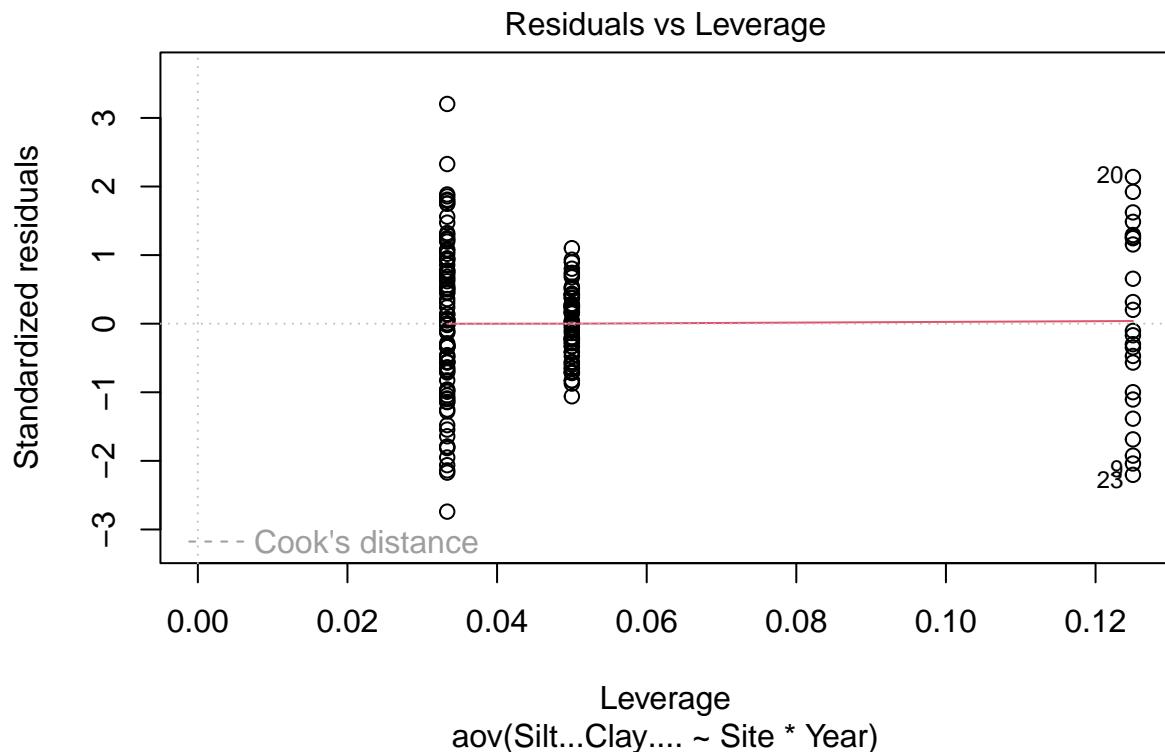
#outliers
plot(ps.g.anova.2way, which = 5)

```



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

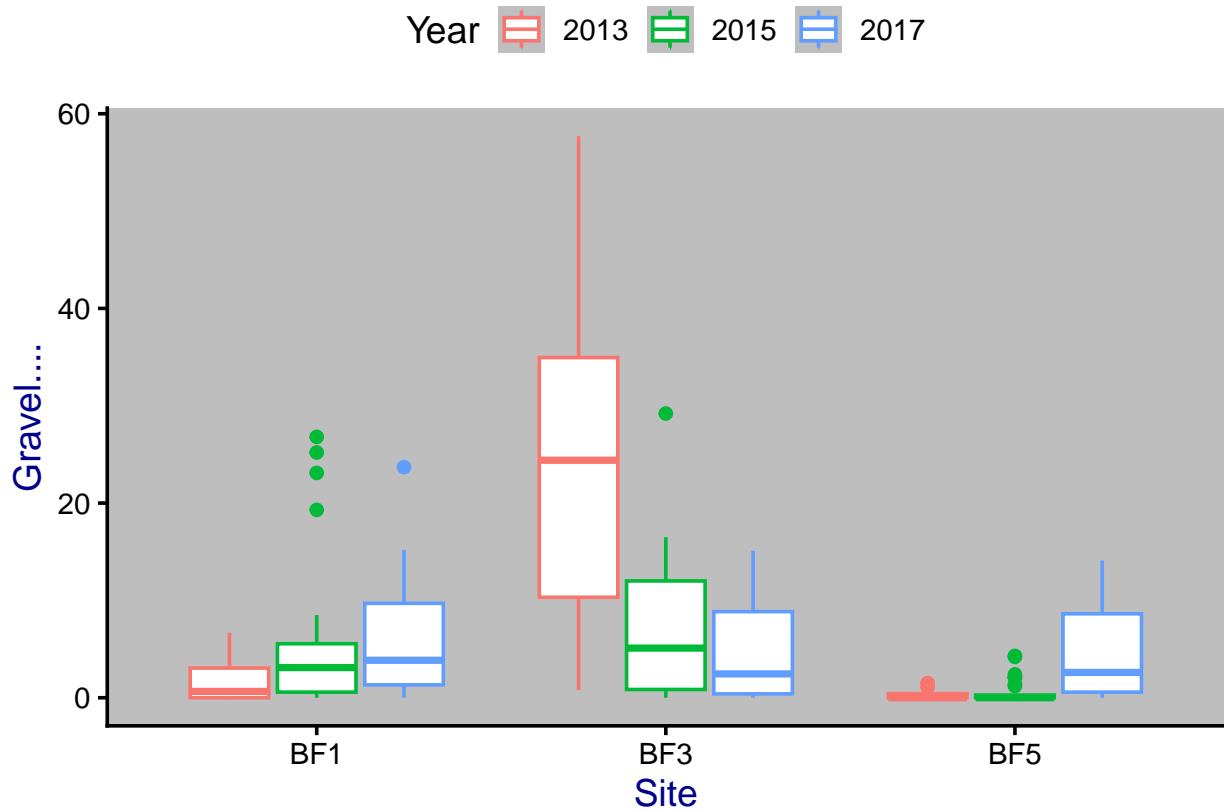




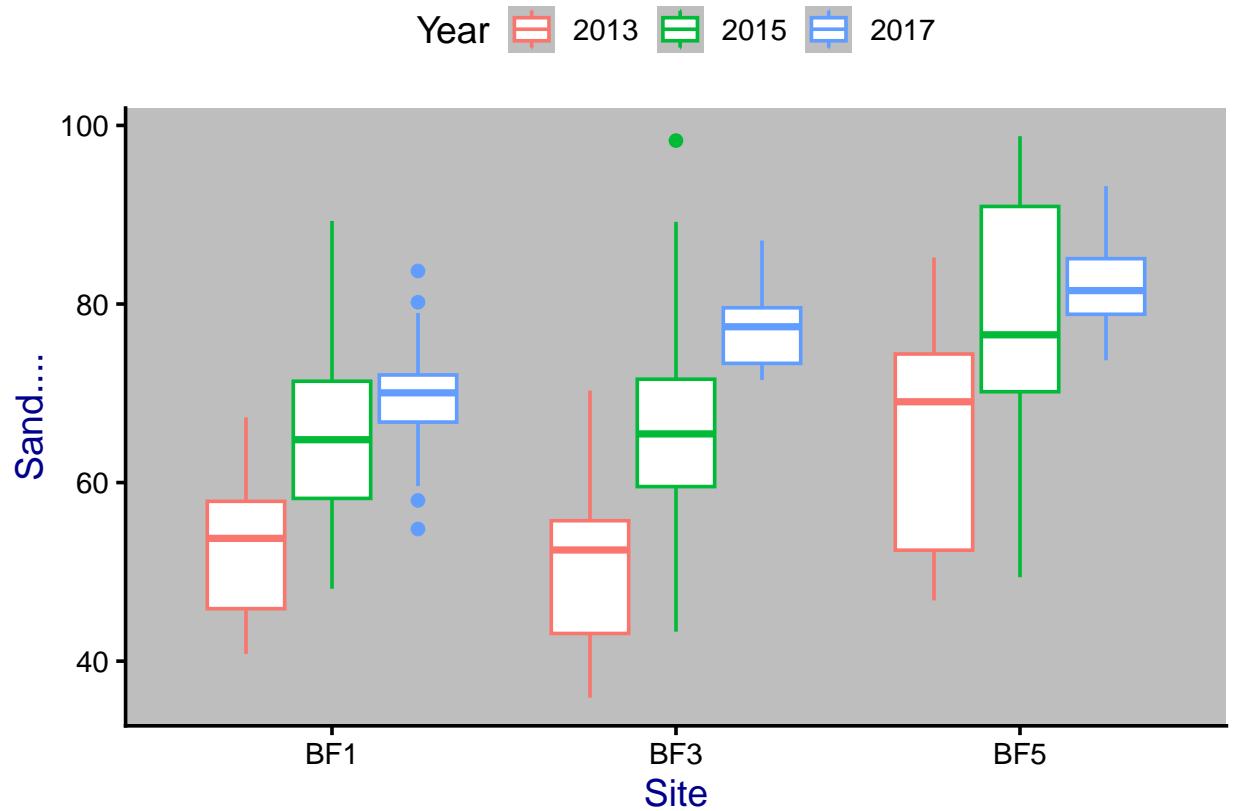
```
### 5.2.3 Residuals
```

5.2.4 Plots

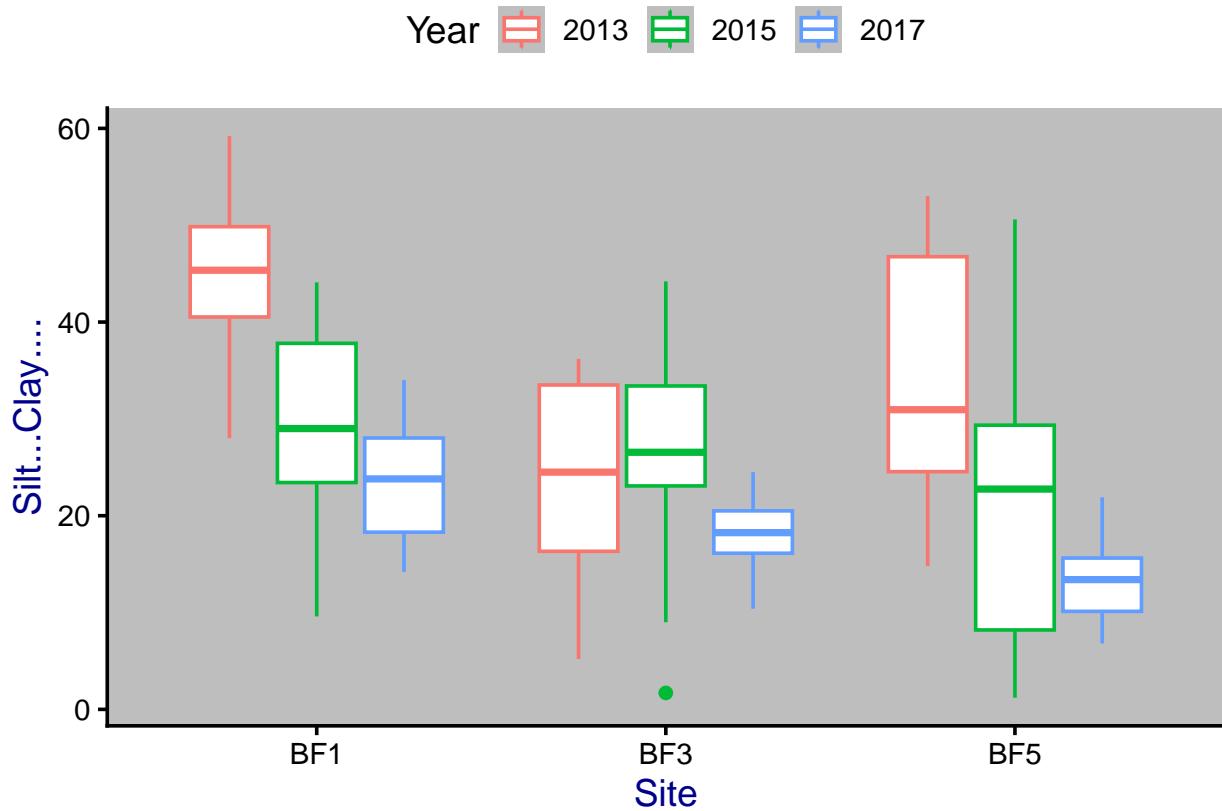
```
print(ps.g.anova.plot)
```



```
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()

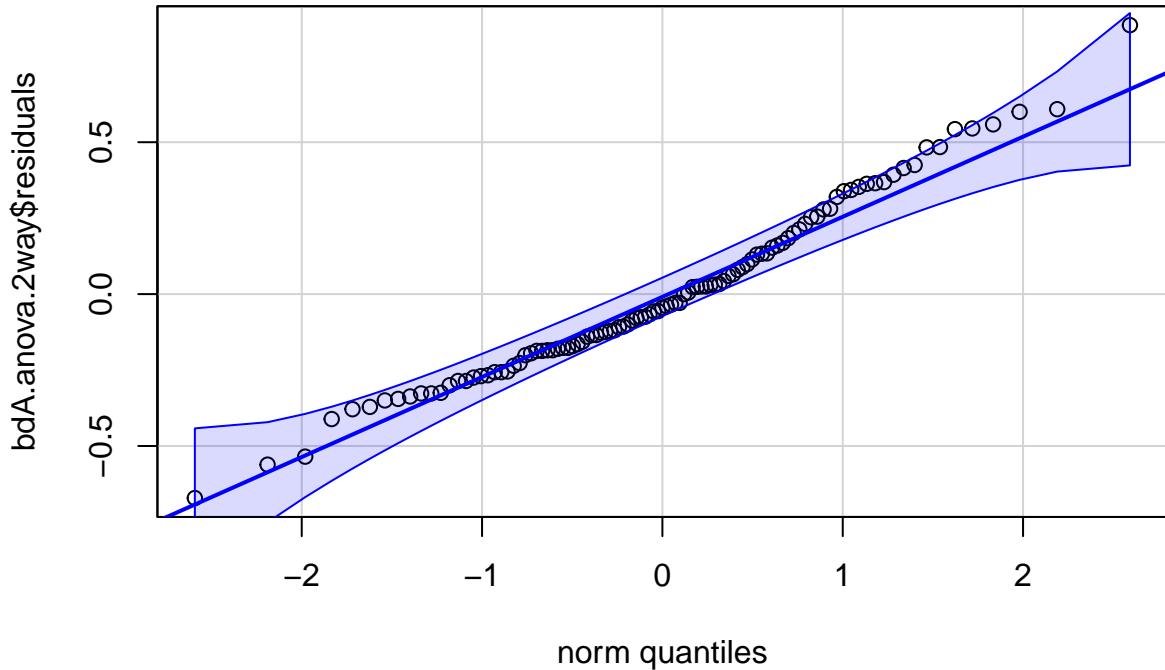
```

5.3.2 Assumptions

```

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

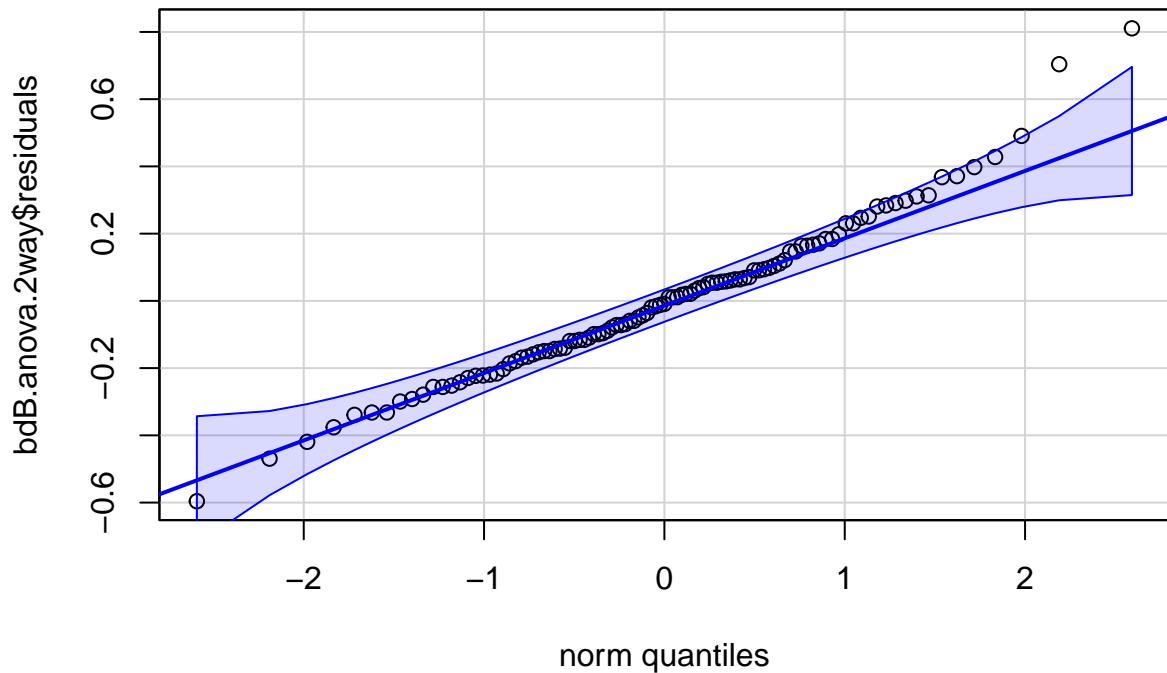
```



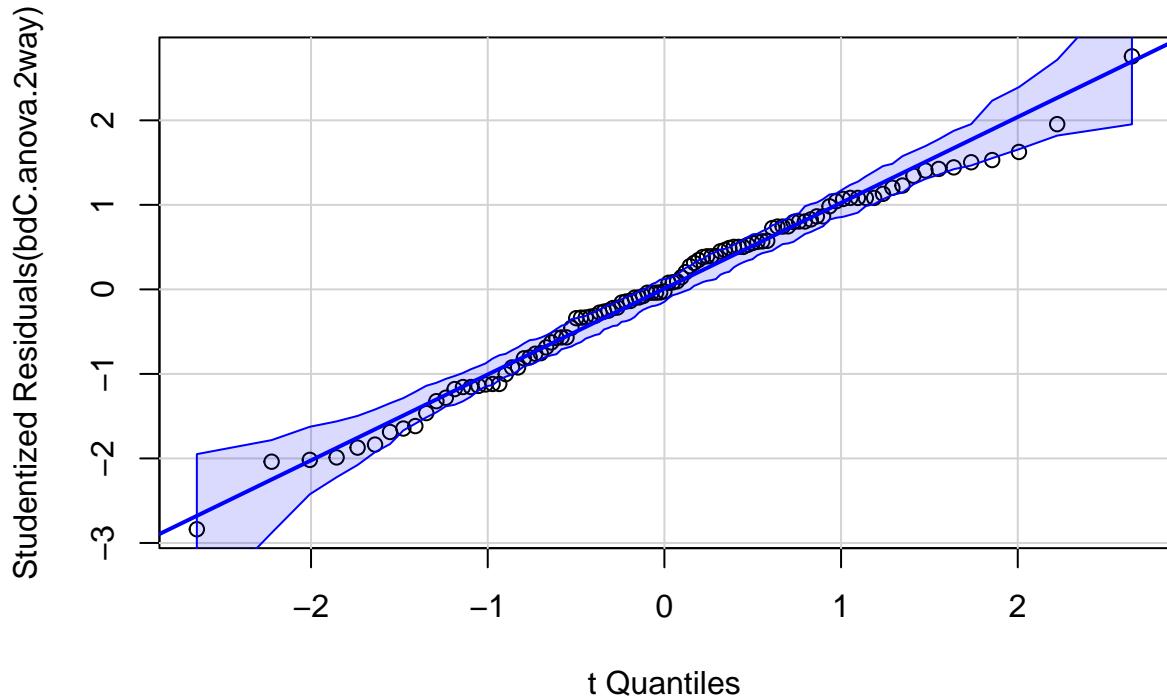
```

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

```



```
qqPlot(bdB.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
```

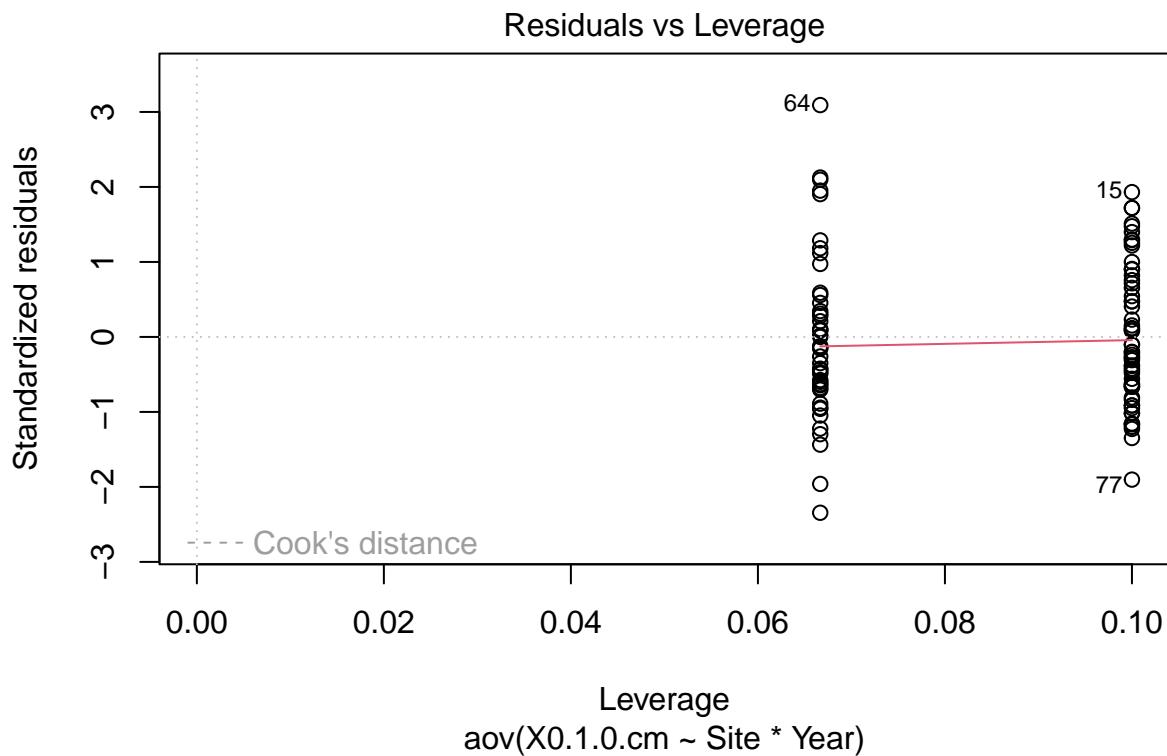
```
leveneTest(bdB.anova.2way)
```

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

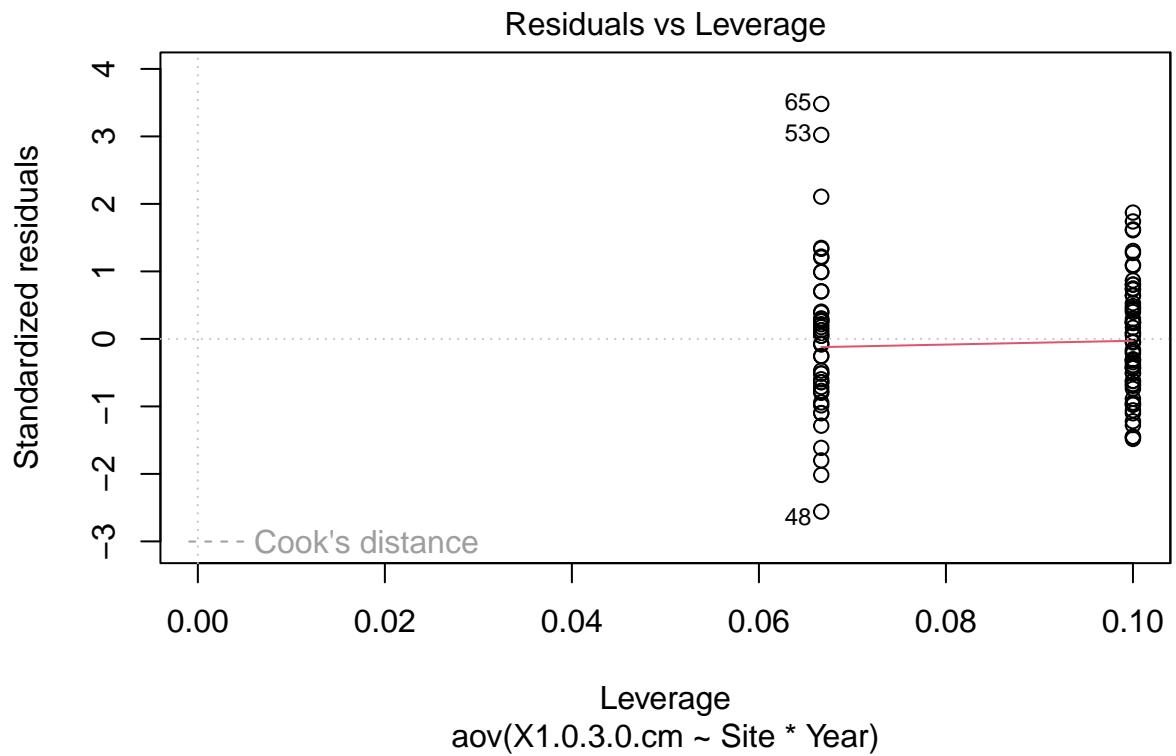
```
leveneTest(bdC.anova.2way)
```

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

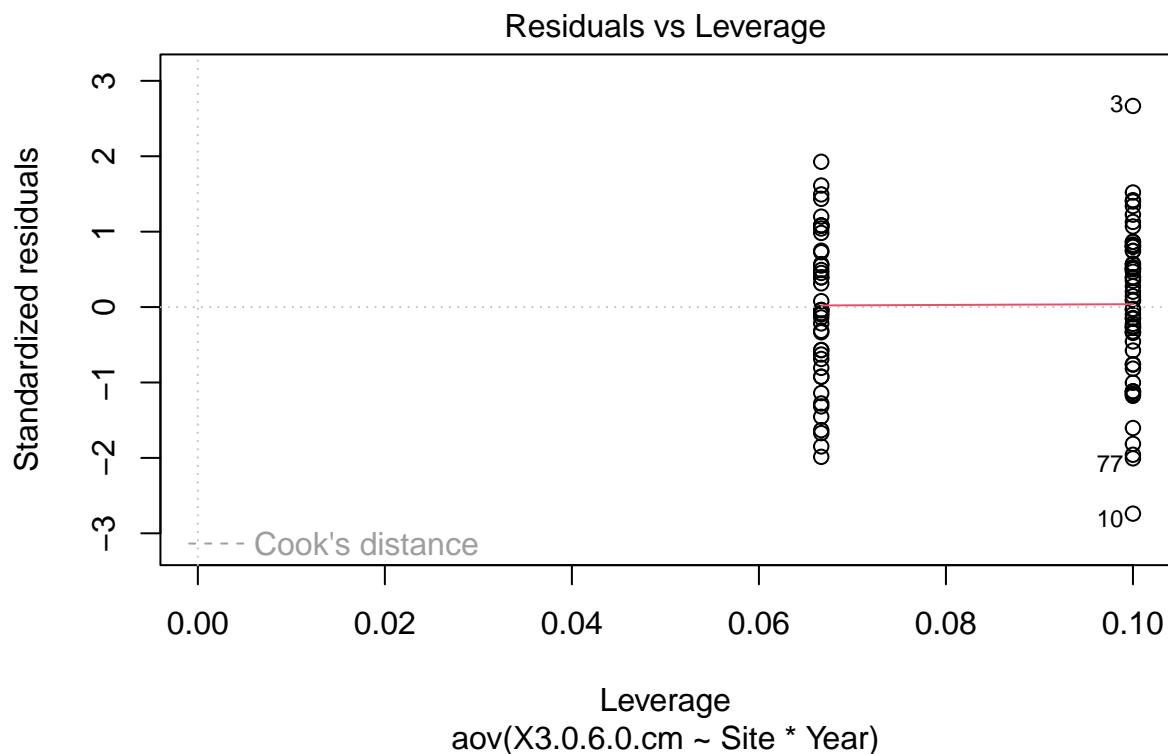
```
#outliers  
plot(bdA.anova.2way, which = 5)
```



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



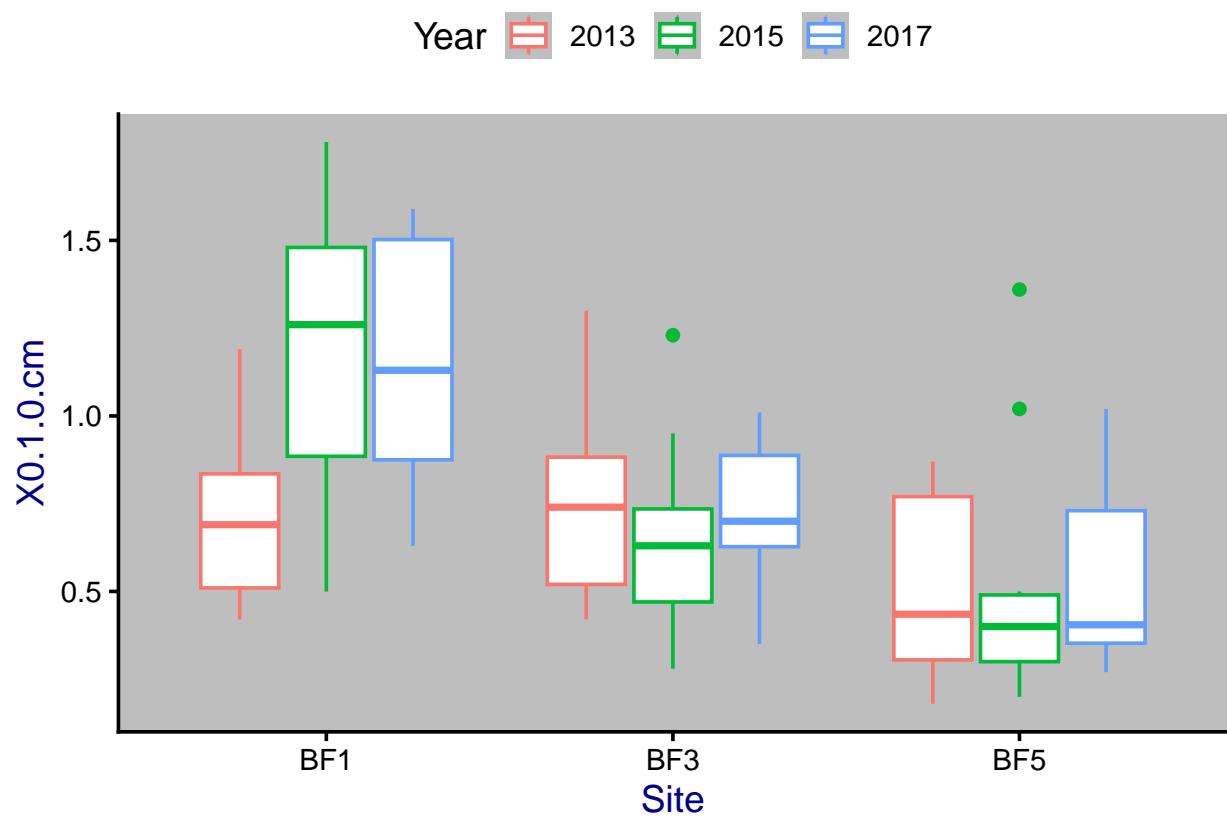
```
plot(bdC.anova.2way, which = 5)
```



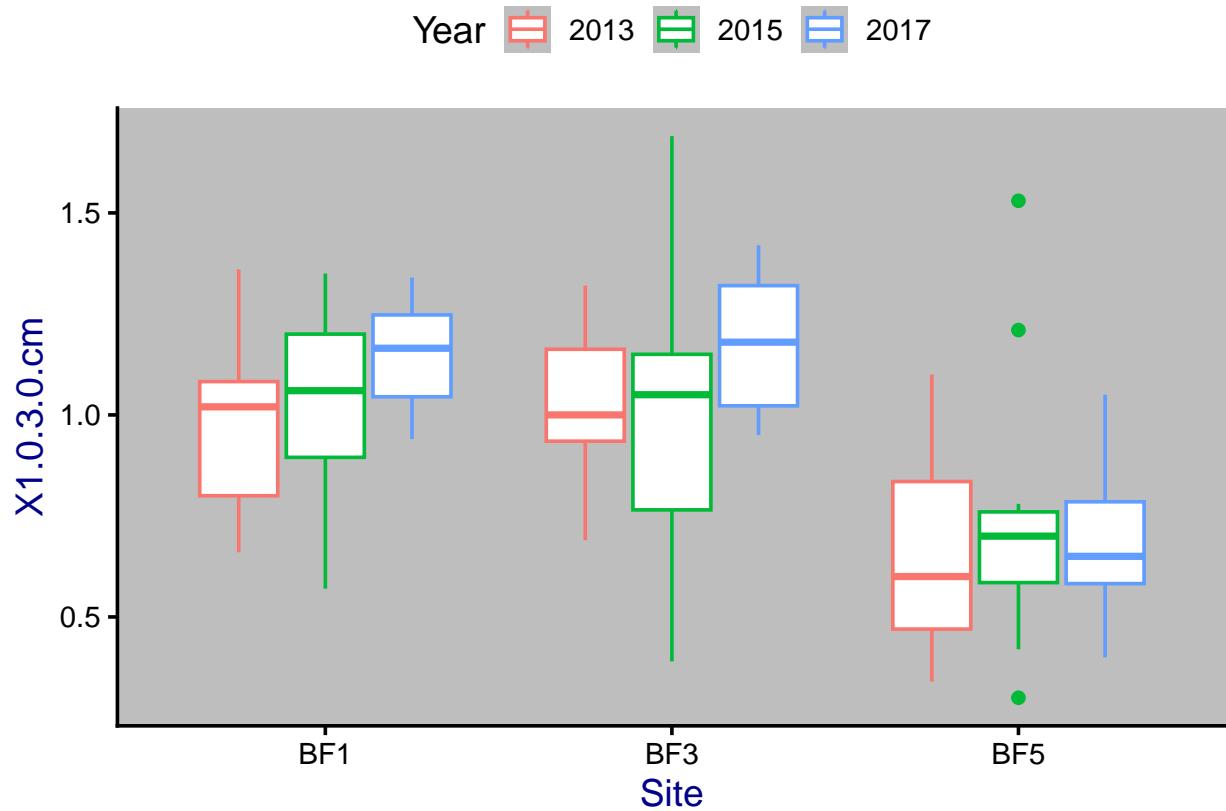
```
### 5.3.3 Residuals
```

5.3.4 Plots

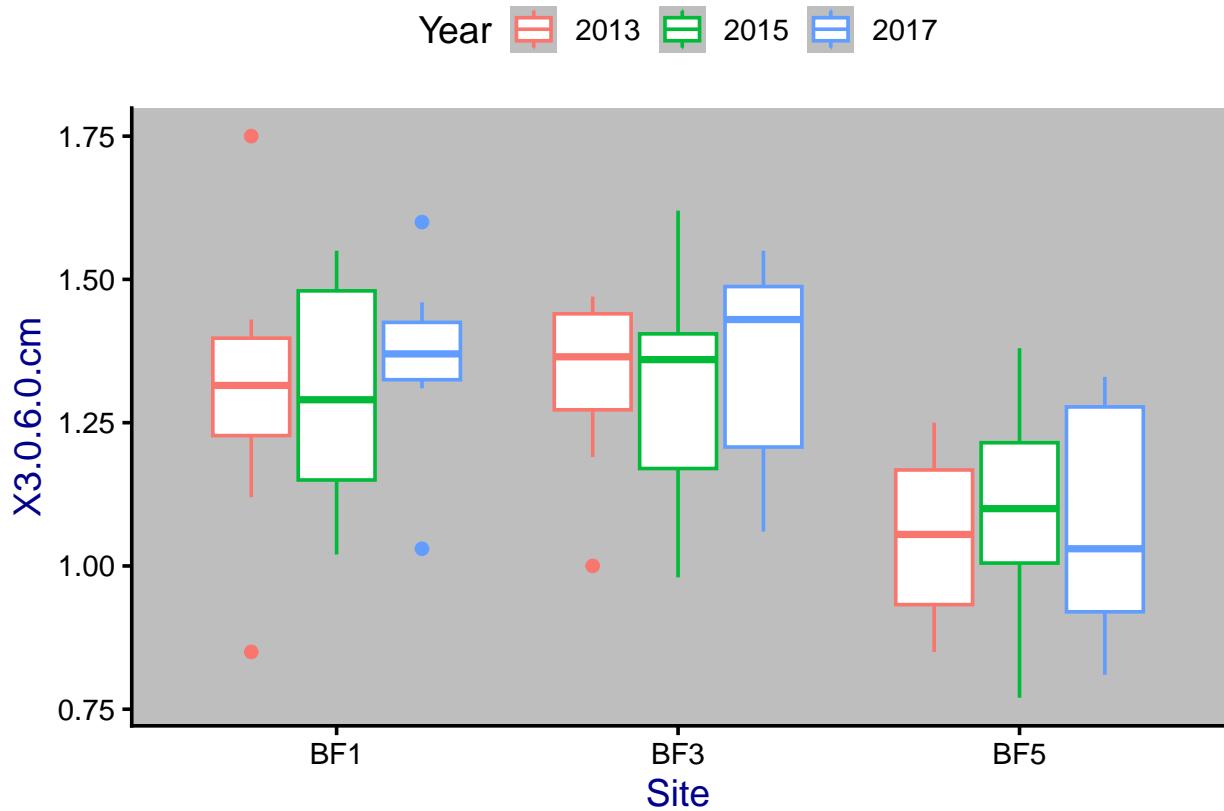
```
print(bdA.anova.plot)
```



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



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



6. Summary and Conclusions

7. References

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