Using Normalized Difference Vegetation Index to assess midseason N status and predict final grain yield in rice.

R Markdown

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When you click the **Knit** button a document will be generated that includes both content as well as the output of any embedded R code chunks within the document. You can embed an R code chunk like this:

```r
Sys.time()
```

```
## [1] "2019-02-27 08:32:39 PST"
```

These are the packages needed for the analysis

```
## -- Attaching packages --------------------------------------------------- tidyverse 1.2.1 --

## v tibble  2.0.1     v purrr   0.3.0
## v tidyr   0.8.2     v dplyr   0.7.8
## v readr   1.3.1     v stringr 1.4.0
## v tibble  2.0.1     v forcats 0.3.0

## -- Conflicts ------------------------------------------------------ tidyverse_conflicts() --
## x dplyr::filter() masks stats::filter()
## x dplyr::lag()    masks stats::lag()

## For news about 'ggpmisc', please, see https://www.r4photobiology.info/

## For on-line documentation see https://docs.r4photobiology.info/ggpmisc/

##
## Attaching package: 'gridExtra'

## The following object is masked from 'package:dplyr':
##
##     combine

##
## Attaching package: 'nlme'

## The following object is masked from 'package:dplyr':
##
##     collapse

## Loading required package: carData

##
## Attaching package: 'car'

## The following object is masked from 'package:dplyr':
##
##     recode

## The following object is masked from 'package:purrr':
##
##     some
```

```
##
##   This is piecewiseSEM version 2.0.2
##
##   If you have used the package before, it is strongly recommended you read Section 3 of the vignette
##
##   Questions or bugs can be addressed to <jlefcheck@bigelow.org>
```

```
## Loading required package: sp
```

```
##
## Attaching package: 'raster'
```

```
## The following object is masked from 'package:nlme':
##
##     getData
```

```
## The following object is masked from 'package:dplyr':
##
##     select
```

```
## The following object is masked from 'package:tidyr':
##
##     extract
```

GREENSEEKER CONVERSION

Getting the linear regression conversion from GreenSeeker_1 to GreenSeeker_2

From the paper – "two GreenSeekers were used to measure NDVI in this study (GreenSeeker 1 in 2015 and GreenSeeker 2 from 2016 to 2018). Consistent differences between the two devices were detected by plotting side by side NDVI measurements (n = 105). Differences were normalized by adjusting NDVI values based on the resulting fitted linear regression equation (Fig. S1)."

Figure S1

```
GS_data <- read_csv(file = "greenseeker_comparison.csv")
```

```
## Parsed with column specification:
## cols(
##   Greenseeker1_NDVI1 = col_double(),
##   Greenseeker1_NDVI2 = col_double(),
##   Greenseeker2_NDVI1 = col_double(),
##   Greenseeker2_NDVI2 = col_double()
## )
```

```
str(GS_data)
```

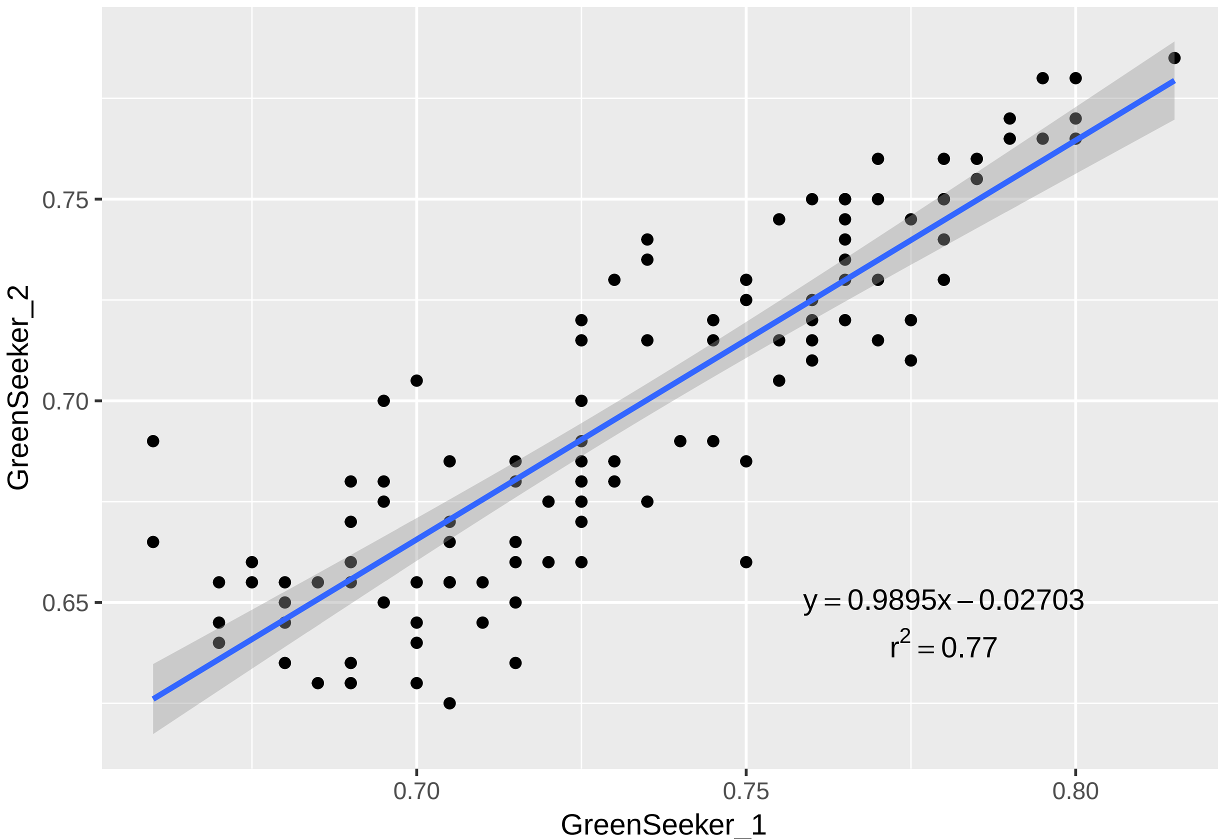
```
## Classes 'spec_tbl_df', 'tbl_df', 'tbl' and 'data.frame': 105 obs. of  4 variables:
##  $ Greenseeker1_NDVI1: num  0.69 0.71 0.72 0.75 0.78 0.77 0.69 0.7 0.7 0.68 ...
##  $ Greenseeker1_NDVI2: num  0.71 0.72 0.73 0.78 0.78 0.79 0.72 0.71 0.7 0.68 ...
##  $ Greenseeker2_NDVI1: num  0.64 0.69 0.69 0.72 0.75 0.74 0.68 0.68 0.65 0.64 ...
##  $ Greenseeker2_NDVI2: num  0.65 0.68 0.69 0.72 0.75 0.72 0.65 0.66 0.66 0.65 ...
##  - attr(*, "spec")=
##   .. cols(
```

```
##   ..   Greenseeker1_NDVI1 = col_double(),
##   ..   Greenseeker1_NDVI2 = col_double(),
##   ..   Greenseeker2_NDVI1 = col_double(),
##   ..   Greenseeker2_NDVI2 = col_double()
##   .. )
```

```
GS_data <- GS_data %>%
  rowwise() %>%
  mutate(GreenSeeker_1 = mean(c(Greenseeker1_NDVI1 , Greenseeker1_NDVI2)),
         GreenSeeker_2 = mean(c(Greenseeker2_NDVI1 , Greenseeker2_NDVI2))) #takes the mean of GreenSeek

greenmod1 <- lm(GreenSeeker_2 ~ GreenSeeker_1 , data = GS_data) #creates a linear regression of GreenSe

summary(greenmod1) #the resulting equation is GreenSeeker_2 = -0.02703 + 0.98950 * GreenSeeker_1
```

```
##
## Call:
## lm(formula = GreenSeeker_2 ~ GreenSeeker_1, data = GS_data)
##
## Residuals:
##       Min        1Q    Median        3Q       Max
## -0.055099 -0.015309  0.000426  0.014429  0.063957
##
## Coefficients:
##                Estimate Std. Error t value Pr(>|t|)
## (Intercept)   -0.02703    0.03936  -0.687    0.494
## GreenSeeker_1  0.98950    0.05368  18.434   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.0209 on 103 degrees of freedom
## Multiple R-squared:  0.7674, Adjusted R-squared:  0.7651
## F-statistic: 339.8 on 1 and 103 DF,  p-value: < 2.2e-16
```

```
label_eqn <- paste("y == 0.9895 * x - 0.02703")
label_r2 <- paste("r^2 == 0.77")

greenplot <- ggplot(data = GS_data, aes(x = GreenSeeker_1 , y = GreenSeeker_2 )) +
  geom_point(mapping = aes(GreenSeeker_1, GreenSeeker_2) , data = GS_data) +
  geom_smooth( data = GS_data , aes(x = GreenSeeker_1 , y = GreenSeeker_2 ) , method = lm, formula = y
  annotate("text" , x = 0.78 , y = 0.65 , label = label_eqn , parse = TRUE) +
  annotate("text" , x = 0.78 , y = 0.64 , label = label_r2 , parse = TRUE ) #generates a plot of the da

greenplot
```




```
ggsave("Figure_S1.tiff" , greenplot , device = "tiff" )
```

```
## Saving 6.5 x 4.5 in image
```

DATA

The following chunk processes the PI NDVI data into a single data frame with only the relevant columns. The N trial data is processed seperately from the Farm Survey data and then merged into a single data frame.

N Trial NDVI Data

```
ntrial_data <- read_csv("N_trial_data.csv")
```

```
## Warning: Missing column names filled in: 'X16' [16], 'X17' [17],
## 'X18' [18], 'X19' [19], 'X20' [20], 'X21' [21], 'X22' [22], 'X23' [23],
## 'X24' [24]
```

```
## Parsed with column specification:
## cols(
##   .default = col_double(),
##   site_year = col_character(),
##   NDVI_1 = col_character(),
##   NDVI_2 = col_character(),
##   NDVI_3 = col_character(),
##   NDVI_4 = col_character(),
```

```
##   X16 = col_logical(),
##   X17 = col_logical(),
##   X18 = col_logical(),
##   X19 = col_logical(),
##   X20 = col_logical(),
##   X21 = col_logical(),
##   X22 = col_logical(),
##   X23 = col_logical(),
##   X24 = col_logical()
## )
```

```
## See spec(...) for full column specifications.
```

```
ntrial_data <- ntrial_data[c(1:231), c(1:15)] #removes the empty rows and columns from the data frame

ntrial_data$block <- factor(ntrial_data$block)
ntrial_data$plot <- factor(ntrial_data$plot)
ntrial_data$plot_id <- factor(ntrial_data$plot_id)
ntrial_data$N_level <- factor(ntrial_data$N_level)
ntrial_data$exp_plot_number <- factor(ntrial_data$exp_plot_number)
ntrial_data$site_year <- factor(ntrial_data$site_year , levels = c("Arbuckle-15" , "RES-15" , "RES-16"
ntrial_data$NDVI_1 <- as.numeric(as.character(ntrial_data$NDVI_1))
```

```
## Warning: NAs introduced by coercion
```

```
ntrial_data$NDVI_2 <- as.numeric(as.character(ntrial_data$NDVI_2))
```

```
## Warning: NAs introduced by coercion
```

```
ntrial_data$NDVI_3 <- as.numeric(as.character(ntrial_data$NDVI_3))
```

```
## Warning: NAs introduced by coercion
```

```
ntrial_data$NDVI_4 <- as.numeric(as.character(ntrial_data$NDVI_4)) #gets the data right
```

```
## Warning: NAs introduced by coercion
```

```
str(ntrial_data)
```

```
## Classes 'tbl_df', 'tbl' and 'data.frame':    231 obs. of  15 variables:
##  $ site_year        : Factor w/ 10 levels "Arbuckle-15",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ exp_plot_number   : Factor w/ 28 levels "101","102","103",..: 1 2 3 4 5 8 9 10 11 12 ...
##  $ block             : Factor w/ 40 levels "1","2","3","4",..: 1 1 1 1 1 2 2 2 2 2 ...
##  $ plot              : Factor w/ 7 levels "1","2","3","4",..: 1 2 3 4 5 1 2 3 4 5 ...
##  $ plot_id           : Factor w/ 231 levels "1","2","3","4",..: 1 2 3 4 5 6 7 8 9 10 ...
##  $ N_level           : Factor w/ 12 levels "0","45","75",..: 6 11 1 3 8 1 8 6 11 3 ...
##  $ biomass_plus_bag_g: num  414 472 281 386 455 304 402 322 418 336 ...
##  $ paper_bag_g       : num  45 45 45 45 45 45 45 45 45 45 ...
##  $ num_of_paper_bags : num  1 1 1 1 1 1 1 1 1 1 ...
##  $ sample_weight_mg  : num  4.84 5.12 4.78 5.15 4.93 ...
##  $ sample_N_ug       : num  117.1 153.4 64.9 92.9 116 ...
##  $ NDVI_1            : num  0.77 0.82 0.56 0.72 0.79 0.7 0.81 0.82 0.82 0.73 ...
##  $ NDVI_2            : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ NDVI_3            : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ NDVI_4            : num  NA NA NA NA NA NA NA NA NA NA ...
```

```
ntrial_data <-  ntrial_data %>%
  mutate( biomass_dry_wt = biomass_plus_bag_g - (paper_bag_g * num_of_paper_bags) ,
          aboveground_biomass = (biomass_dry_wt / 0.50) / 1000 , #ring size 0.5 m^2
```

```
          n_content = sample_N_ug / sample_weight_mg ,
          N_Uptake = aboveground_biomass * n_content) #processes the data

ntrial_data <- ntrial_data %>%
  rowwise() %>%
  mutate(NDVI = mean(c( NDVI_1 , NDVI_2 , NDVI_3 , NDVI_4) , na.rm = T)) #takes average of four NDVI re

ntrial_data <- ntrial_data %>%
  mutate(NDVI = case_when(site_year == "Arbuckle-15" ~ -0.02703 + 0.98950*NDVI,
                          site_year == "RES-15" ~ -0.02703 + 0.98950*NDVI,
                          site_year == "RES-16" ~ NDVI,
                          site_year == "Davis-16" ~ NDVI,
                          site_year == "Nicolaus-17" ~ NDVI,
                          site_year == "Williams-17" ~ NDVI,
                          site_year == "Nicolaus-18" ~ NDVI,
                          site_year == "Arbuckle-18" ~ NDVI,
                          site_year == "Marysville-18" ~ NDVI,
                          site_year == "Biggs-18" ~ NDVI)) #normailizes the data for the two greenseeke

ntrial_data <- dplyr::select(ntrial_data ,
                      site_year,
                    exp_plot_number,
                    block,
                    plot,
                    N_level,
                    aboveground_biomass,
                    n_content,
                    N_Uptake,
                    NDVI) #selects the relevant columns

ntrial_data$site_year <- factor(ntrial_data$site_year , levels = c("Arbuckle-15" , "RES-15" , "Davis-16
```

Farm Survey NDVI Data

```
farmsurvey_data <- read_csv("farm_survey_data.csv")
```

```
## Warning: Missing column names filled in: 'X16' [16], 'X17' [17],
## 'X18' [18], 'X19' [19], 'X20' [20], 'X21' [21]

## Parsed with column specification:
## cols(
##   .default = col_double(),
##   site_year = col_character(),
##   exp_plot_number = col_character(),
##   plot = col_character(),
##   NDVI_2 = col_character(),
##   NDVI_3 = col_character(),
##   NDVI_4 = col_character(),
##   X16 = col_logical(),
##   X17 = col_logical(),
##   X18 = col_logical(),
##   X19 = col_logical(),
##   X20 = col_logical(),
```

```
##   X21 = col_logical()
## )
```

```
## See spec(...) for full column specifications.
```

```r
farmsurvey_data <- farmsurvey_data[c(1:58), c(1:15)] #removes the extra rows and columns from the data

farmsurvey_data$block <- factor(farmsurvey_data$block)
farmsurvey_data$plot <- factor(farmsurvey_data$plot)
farmsurvey_data$plot_id <- factor(farmsurvey_data$plot_id)
farmsurvey_data$N_level <- factor(farmsurvey_data$N_level)
farmsurvey_data$exp_plot_number <- factor(farmsurvey_data$exp_plot_number)
farmsurvey_data$site_year <- factor(farmsurvey_data$site_year)
farmsurvey_data$NDVI_1 <- as.numeric(as.character(farmsurvey_data$NDVI_1))
farmsurvey_data$NDVI_2 <- as.numeric(as.character(farmsurvey_data$NDVI_2))
```

```
## Warning: NAs introduced by coercion
```

```r
farmsurvey_data$NDVI_3 <- as.numeric(as.character(farmsurvey_data$NDVI_3))
```

```
## Warning: NAs introduced by coercion
```

```r
farmsurvey_data$NDVI_4 <- as.numeric(as.character(farmsurvey_data$NDVI_4)) #gets the data right
```

```
## Warning: NAs introduced by coercion
```

```r
str(farmsurvey_data)
```

```
## Classes 'tbl_df', 'tbl' and 'data.frame':    58 obs. of  15 variables:
##  $ site_year         : Factor w/ 1 level "Farm Survey-15": 1 1 1 1 1 1 1 1 1 1 ...
##  $ exp_plot_number   : Factor w/ 29 levels "001","002","003",..: 1 1 2 2 3 3 4 4 5 5 ...
##  $ block             : Factor w/ 1 level "25": 1 1 1 1 1 1 1 1 1 1 ...
##  $ plot              : Factor w/ 2 levels "a","b": 1 2 1 2 1 2 1 2 1 2 ...
##  $ plot_id           : Factor w/ 58 levels "1","2","3","4",..: 1 2 3 4 5 6 7 8 9 10 ...
##  $ N_level           : Factor w/ 1 level "175": 1 1 1 1 1 1 1 1 1 1 ...
##  $ biomass_plus_bag_g: num  275 318 379 374 334 349 350 359 328 346 ...
##  $ paper_bag_g       : num  45 45 45 45 45 45 45 45 45 45 ...
##  $ num_of_paper_bags : num  1 1 1 1 1 1 1 1 1 1 ...
##  $ sample_weight_mg  : num  4.9 5.19 4.69 4.95 4.67 ...
##  $ sample_N_ug       : num  136 140 120 119 149 ...
##  $ NDVI_1            : num  0.82 0.76 0.84 0.84 0.85 0.86 0.84 0.84 0.85 0.85 ...
##  $ NDVI_2            : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ NDVI_3            : num  NA NA NA NA NA NA NA NA NA NA ...
##  $ NDVI_4            : num  NA NA NA NA NA NA NA NA NA NA ...
```

```r
farmsurvey_data <- farmsurvey_data %>%
  filter(plot == "a" | plot == "b") %>%
  group_by(exp_plot_number) %>%
  summarize(biomass_plus_bag_g = mean(biomass_plus_bag_g) , sample_weight_mg = mean(sample_weight_mg) ,

farmsurvey_data <- farmsurvey_data %>%
  mutate(site_year = factor("Farm Survey-15") , block = factor("41") , plot = factor("ab") , plot_id = 

farmsurvey_data <- dplyr::select(farmsurvey_data,
                                 site_year ,
                                 exp_plot_number ,
                                 block ,
                                 plot ,
```

```
                                N_level ,
                                biomass_plus_bag_g ,
                                paper_bag_g ,
                                num_of_paper_bags ,
                                sample_weight_mg ,
                                sample_N_ug ,
                                NDVI_1 ,
                                NDVI_2 ,
                                NDVI_3 ,
                                NDVI_4)#makes df identical to n_trial_data

farmsurvey_data <-  farmsurvey_data %>%
  mutate( biomass_dry_wt = biomass_plus_bag_g - (paper_bag_g * num_of_paper_bags) ,
          aboveground_biomass = (biomass_dry_wt / 0.50) / 1000 , #ring size 0.50 m^2
          n_content = sample_N_ug / sample_weight_mg ,
          N_Uptake = aboveground_biomass * n_content) #processes the data

farmsurvey_data <- farmsurvey_data %>%
  rowwise() %>%
  mutate(NDVI = mean(c( NDVI_1 , NDVI_2 , NDVI_3 , NDVI_4) , na.rm = T)) #mean NDVI

farmsurvey_data <-farmsurvey_data[1:28 , ] #removes outlier

farmsurvey_data <- farmsurvey_data %>%
  mutate(NDVI = -0.02703 + 0.98950*NDVI) #adjusts NDVI readings using eqn from above

farmsurvey_data <- dplyr::select(farmsurvey_data ,
                      site_year,
                    exp_plot_number,
                    block,
                    plot,
                    N_level,
                    aboveground_biomass,
                    n_content,
                    N_Uptake,
                    NDVI) #selects relevant columns
```

NDVI Data

```
ndvi_data <- bind_rows(list(ntrial_data, farmsurvey_data)) #binds both df
```

```
## Warning in bind_rows_(x, .id): Unequal factor levels: coercing to character

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): Unequal factor levels: coercing to character

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector
```

```
## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): Unequal factor levels: coercing to character

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): Unequal factor levels: coercing to character

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): Unequal factor levels: coercing to character

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector

## Warning in bind_rows_(x, .id): binding character and factor vector,
## coercing into character vector
```

```
ndvi_data <- tibble::rowid_to_column(ndvi_data, "plot_id")

ndvi_data <- dplyr::select (ndvi_data,
                           site_year,
                           exp_plot_number,
                           block,
                           plot,
                           plot_id,
                           N_level,
                           aboveground_biomass,
                           n_content,
                           N_Uptake,
                           NDVI)

ndvi_data$block <- factor(ndvi_data$block) #changes block to a factor
ndvi_data$plot <- factor(ndvi_data$plot) #changes plot to a factor
ndvi_data$plot_id <- factor(ndvi_data$plot_id)
ndvi_data$N_level <- factor(ndvi_data$N_level)
ndvi_data$exp_plot_number <- factor(ndvi_data$exp_plot_number)
ndvi_data$site_year <- factor(ndvi_data$site_year , levels = c("Arbuckle-15" , "Farm Survey-15" , "RES-
```

Table 3

```
summary(subset(ndvi_data, site_year == "Arbuckle-15")) #this subsets the ndvi data just by Arbuckle-15
```

```
##           site_year  exp_plot_number     block        plot      plot_id
##  Arbuckle-15    :20  101    : 1      1      :5   1      :4   1      : 1
##  Farm Survey-15: 0   102    : 1      2      :5   2      :4   2      : 1
##  RES-15        : 0   103    : 1      3      :5   3      :4   3      : 1
```

```
##  Davis-16       : 0   104    : 1      4      :5   4      :4   4      : 1
##  RES-16         : 0   105    : 1      10     :0   5      :4   5      : 1
##  Nicolaus-17    : 0   201    : 1      11     :0   6      :0   6      : 1
##  (Other)        : 0   (Other):14      (Other):0   (Other):0   (Other):14
##     N_level  aboveground_biomass   n_content        N_Uptake
##  0      :4   Min.   :0.3400      Min.   :13.58   Min.   : 4.885
##  125    :4   1st Qu.:0.5600      1st Qu.:17.98   1st Qu.:10.546
##  175    :4   Median :0.6610      Median :21.38   Median :13.280
##  225    :4   Mean   :0.6334      Mean   :21.44   Mean   :14.144
##  75     :4   3rd Qu.:0.7335      3rd Qu.:24.41   3rd Qu.:18.209
##  120    :0   Max.   :0.8540      Max.   :30.52   Max.   :25.577
##  (Other):0
##       NDVI
##  Min.   :0.4875
##  1st Qu.:0.6854
##  Median :0.7398
##  Mean   :0.7057
##  3rd Qu.:0.7670
##  Max.   :0.7844
##
```

```r
summary(subset(ndvi_data, site_year == "RES-15"))
```

```
##           site_year  exp_plot_number     block        plot      plot_id
##  RES-15         :20   101    : 1      5      :5   1      :4   21     : 1
##  Arbuckle-15    : 0   102    : 1      6      :5   2      :4   22     : 1
##  Farm Survey-15: 0    103    : 1      7      :5   3      :4   23     : 1
##  Davis-16       : 0   104    : 1      8      :5   4      :4   24     : 1
##  RES-16         : 0   105    : 1      1      :0   5      :4   25     : 1
##  Nicolaus-17    : 0   201    : 1      10     :0   6      :0   26     : 1
##  (Other)        : 0   (Other):14      (Other):0   (Other):0   (Other):14
##     N_level  aboveground_biomass   n_content        N_Uptake
##  0      :4   Min.   :0.3520      Min.   :11.86   Min.   : 4.174
##  125    :4   1st Qu.:0.4615      1st Qu.:17.90   1st Qu.: 8.592
##  175    :4   Median :0.5120      Median :23.55   Median :12.658
##  225    :4   Mean   :0.5084      Mean   :23.84   Mean   :12.647
##  75     :4   3rd Qu.:0.5770      3rd Qu.:30.78   3rd Qu.:18.156
##  120    :0   Max.   :0.6540      Max.   :37.30   Max.   :23.051
##  (Other):0
##       NDVI
##  Min.   :0.5271
##  1st Qu.:0.6928
##  Median :0.7745
##  Mean   :0.7339
##  3rd Qu.:0.7943
##  Max.   :0.8042
##
```

```r
summary(subset(ndvi_data, site_year == "Farm Survey-15"))
```

```
##           site_year  exp_plot_number     block         plot
##  Farm Survey-15:28   001    : 1      41     :28   ab     :28
##  Arbuckle-15    : 0   002    : 1      1      : 0   1      : 0
##  RES-15         : 0   003    : 1      10     : 0   2      : 0
##  Davis-16       : 0   004    : 1      11     : 0   3      : 0
```

```
##  RES-16         : 0   005    : 1      12     : 0   4      : 0
##  Nicolaus-17    : 0   006    : 1      13     : 0   5      : 0
##  (Other)        : 0   (Other):22      (Other): 0   (Other): 0
##     plot_id      N_level    aboveground_biomass   n_content
##  232    : 1   175    :28   Min.   :0.1260      Min.   :10.91
##  233    : 1   0      : 0   1st Qu.:0.4577      1st Qu.:16.84
##  234    : 1   120    : 0   Median :0.5120      Median :21.81
##  235    : 1   125    : 0   Mean   :0.5090      Mean   :21.93
##  236    : 1   150    : 0   3rd Qu.:0.6085      3rd Qu.:26.49
##  237    : 1   180    : 0   Max.   :0.7260      Max.   :33.62
##  (Other):22   (Other): 0
##     N_Uptake           NDVI
##  Min.   : 1.375   Min.   :0.1758
##  1st Qu.: 8.189   1st Qu.:0.5357
##  Median :11.280   Median :0.7200
##  Mean   :11.488   Mean   :0.6458
##  3rd Qu.:15.058   3rd Qu.:0.7819
##  Max.   :19.636   Max.   :0.8190
##
```

```r
summary(subset(ndvi_data, site_year == "Davis-16"))
```

```
##           site_year  exp_plot_number     block        plot      plot_id
##  Davis-16       :20   101    : 1      13     :5   1      :4   61     : 1
##  Arbuckle-15    : 0   102    : 1      14     :5   2      :4   62     : 1
##  Farm Survey-15: 0   103    : 1      15     :5   3      :4   63     : 1
##  RES-15         : 0   104    : 1      16     :5   4      :4   64     : 1
##  RES-16         : 0   105    : 1      1      :0   5      :4   65     : 1
##  Nicolaus-17    : 0   201    : 1      10     :0   6      :0   66     : 1
##  (Other)        : 0   (Other):14      (Other):0   (Other):0   (Other):14
##     N_level  aboveground_biomass   n_content        N_Uptake
##  0      :4   Min.   :0.1332      Min.   :14.61   Min.   : 2.030
##  125    :4   1st Qu.:0.2258      1st Qu.:17.42   1st Qu.: 4.016
##  175    :4   Median :0.2792      Median :20.62   Median : 5.919
##  225    :4   Mean   :0.2609      Mean   :21.52   Mean   : 5.888
##  75     :4   3rd Qu.:0.3001      3rd Qu.:25.21   3rd Qu.: 7.968
##  120    :0   Max.   :0.3714      Max.   :31.73   Max.   :11.467
##  (Other):0
##       NDVI
##  Min.   :0.5567
##  1st Qu.:0.6458
##  Median :0.6667
##  Mean   :0.6665
##  3rd Qu.:0.6917
##  Max.   :0.7233
##
```

```r
summary(subset(ndvi_data, site_year == "RES-16"))
```

```
##           site_year  exp_plot_number     block        plot      plot_id
##  RES-16         :20   101    : 1      10     :5   1      :4   41     : 1
##  Arbuckle-15    : 0   102    : 1      11     :5   2      :4   42     : 1
##  Farm Survey-15: 0   103    : 1      12     :5   3      :4   43     : 1
##  RES-15         : 0   104    : 1      9      :5   4      :4   44     : 1
##  Davis-16       : 0   105    : 1      1      :0   5      :4   45     : 1
```

```
##  Nicolaus-17   : 0   201    : 1      13     :0   6      :0   46     : 1  
##  (Other)       : 0   (Other):14      (Other):0   (Other):0   (Other):14  
##     N_level  aboveground_biomass   n_content        N_Uptake     
##  0      :4   Min.   :0.1466      Min.   :18.48   Min.   : 3.086  
##  125    :4   1st Qu.:0.3016      1st Qu.:22.26   1st Qu.: 6.294  
##  175    :4   Median :0.3578      Median :28.51   Median :11.187  
##  225    :4   Mean   :0.3428      Mean   :28.58   Mean   :10.324  
##  75     :4   3rd Qu.:0.4108      3rd Qu.:33.50   3rd Qu.:13.442  
##  120    :0   Max.   :0.4960      Max.   :38.83   Max.   :19.260  
##  (Other):0                                                       
##       NDVI       
##  Min.   :0.3567  
##  1st Qu.:0.6167  
##  Median :0.6850  
##  Mean   :0.6382  
##  3rd Qu.:0.7233  
##  Max.   :0.7467  
## 
```

```r
summary(subset(ndvi_data, site_year == "Nicolaus-17"))
```

```
##           site_year  exp_plot_number     block         plot      plot_id   
##  Nicolaus-17   :28   101    : 1      22     :8   1      :4   109    : 1  
##  Arbuckle-15   : 0   102    : 1      23     :7   2      :4   110    : 1  
##  Farm Survey-15: 0   103    : 1      24     :7   3      :4   111    : 1  
##  RES-15        : 0   104    : 1      21     :6   4      :4   112    : 1  
##  Davis-16      : 0   105    : 1      1      :0   5      :4   113    : 1  
##  RES-16        : 0   106    : 1      10     :0   6      :4   114    : 1  
##  (Other)       : 0   (Other):22      (Other):0   (Other):4   (Other):22  
##     N_level  aboveground_biomass   n_content        N_Uptake     
##  0      :4   Min.   :0.3970      Min.   :15.54   Min.   : 6.171  
##  125    :4   1st Qu.:0.4785      1st Qu.:21.14   1st Qu.:10.062  
##  175    :4   Median :0.5412      Median :25.22   Median :13.893  
##  225    :4   Mean   :0.5559      Mean   :25.73   Mean   :14.766  
##  275    :4   3rd Qu.:0.6301      3rd Qu.:31.24   3rd Qu.:19.986  
##  45     :4   Max.   :0.7426      Max.   :36.12   Max.   :24.021  
##  (Other):4                                                       
##       NDVI       
##  Min.   :0.4933  
##  1st Qu.:0.6417  
##  Median :0.6850  
##  Mean   :0.6842  
##  3rd Qu.:0.7733  
##  Max.   :0.8000  
## 
```

```r
summary(subset(ndvi_data, site_year == "Williams-17"))
```

```
##           site_year  exp_plot_number     block         plot      plot_id   
##  Williams-17   :28   101    : 1      17     :7   1      :4   81     : 1  
##  Arbuckle-15   : 0   102    : 1      18     :7   2      :4   82     : 1  
##  Farm Survey-15: 0   103    : 1      19     :7   3      :4   83     : 1  
##  RES-15        : 0   104    : 1      20     :7   4      :4   84     : 1  
##  Davis-16      : 0   105    : 1      1      :0   5      :4   85     : 1  
##  RES-16        : 0   106    : 1      10     :0   6      :4   86     : 1  
```

```
## (Other)       : 0   (Other):22      (Other):0   (Other):4   (Other):22
##     N_level  aboveground_biomass   n_content        N_Uptake
## 0       :4   Min.   :0.2740      Min.   :12.34   Min.   : 3.381
## 125     :4   1st Qu.:0.5010      1st Qu.:16.59   1st Qu.: 9.050
## 175     :4   Median :0.5512      Median :22.70   Median :11.876
## 225     :4   Mean   :0.5471      Mean   :22.06   Mean   :12.459
## 275     :4   3rd Qu.:0.6156      3rd Qu.:27.58   3rd Qu.:16.687
## 45      :4   Max.   :0.7270      Max.   :30.61   Max.   :19.430
## (Other):4
##       NDVI
## Min.   :0.3567
## 1st Qu.:0.6733
## Median :0.7650
## Mean   :0.7058
## 3rd Qu.:0.7967
## Max.   :0.8233
##
```

```
summary(subset(ndvi_data, site_year == "Arbuckle-18"))
```

```
##           site_year  exp_plot_number     block        plot      plot_id
## Arbuckle-18    :24   101     : 1      29     :6   1      :4   161    : 1
## Arbuckle-15    : 0   102     : 1      30     :6   2      :4   162    : 1
## Farm Survey-15: 0   103     : 1      31     :6   3      :4   163    : 1
## RES-15         : 0   104     : 1      32     :6   4      :4   164    : 1
## Davis-16       : 0   105     : 1      1      :0   5      :4   165    : 1
## RES-16         : 0   106     : 1      10     :0   6      :4   166    : 1
## (Other)        : 0   (Other):18      (Other):0   (Other):0   (Other):18
##     N_level  aboveground_biomass   n_content        N_Uptake
## 0       :4   Min.   :0.0730      Min.   :12.12   Min.   : 0.9657
## 120     :4   1st Qu.:0.3015      1st Qu.:18.10   1st Qu.: 5.0762
## 150     :4   Median :0.3402      Median :21.45   Median : 7.5737
## 180     :4   Mean   :0.3397      Mean   :21.43   Mean   : 7.6532
## 210     :4   3rd Qu.:0.4258      3rd Qu.:25.88   3rd Qu.:10.4248
## 90      :4   Max.   :0.8006      Max.   :30.22   Max.   :16.0598
## (Other):0
##       NDVI
## Min.   :0.1467
## 1st Qu.:0.6062
## Median :0.6800
## Mean   :0.6070
## 3rd Qu.:0.7244
## Max.   :0.7525
##
```

```
summary(subset(ndvi_data, site_year == "Biggs-18"))
```

```
##           site_year  exp_plot_number     block        plot      plot_id
## Biggs-18       :23   102     : 1      37     :6   1      :4   209    : 1
## Arbuckle-15    : 0   103     : 1      39     :6   2      :4   210    : 1
## Farm Survey-15: 0   104     : 1      40     :6   3      :4   211    : 1
## RES-15         : 0   105     : 1      38     :5   4      :4   212    : 1
## Davis-16       : 0   106     : 1      1      :0   5      :4   213    : 1
## RES-16         : 0   201     : 1      10     :0   6      :3   214    : 1
## (Other)        : 0   (Other):17      (Other):0   (Other):0   (Other):17
```

```
##     N_level  aboveground_biomass   n_content        N_Uptake
##  0      :4   Min.   :0.1962      Min.   :10.38   Min.   : 2.037
##  120    :4   1st Qu.:0.4857      1st Qu.:17.76   1st Qu.:10.175
##  150    :4   Median :0.5422      Median :23.39   Median :12.570
##  180    :4   Mean   :0.5019      Mean   :21.48   Mean   :11.359
##  210    :4   3rd Qu.:0.5859      3rd Qu.:25.58   3rd Qu.:14.422
##  90     :3   Max.   :0.6812      Max.   :32.94   Max.   :19.341
##  (Other):0
##       NDVI
##  Min.   :0.3625
##  1st Qu.:0.7037
##  Median :0.7475
##  Mean   :0.6931
##  3rd Qu.:0.7712
##  Max.   :0.7925
##
```

```r
summary(subset(ndvi_data, site_year == "Marysville-18"))
```

```
##           site_year  exp_plot_number     block          plot       plot_id
##  Marysville-18 :24   101     : 1      33     :6   1      :4   185    : 1
##  Arbuckle-15    : 0   102     : 1      34     :6   2      :4   186    : 1
##  Farm Survey-15: 0   103     : 1      35     :6   3      :4   187    : 1
##  RES-15         : 0   104     : 1      36     :6   4      :4   188    : 1
##  Davis-16       : 0   105     : 1      1      :0   5      :4   189    : 1
##  RES-16         : 0   106     : 1      10     :0   6      :4   190    : 1
##  (Other)        : 0   (Other):18      (Other):0   (Other):0   (Other):18
##     N_level  aboveground_biomass   n_content        N_Uptake
##  0      :4   Min.   :0.2384      Min.   :16.05   Min.   : 3.826
##  120    :4   1st Qu.:0.4505      1st Qu.:29.29   1st Qu.:13.828
##  150    :4   Median :0.4864      Median :32.14   Median :15.784
##  180    :4   Mean   :0.4604      Mean   :29.88   Mean   :14.202
##  210    :4   3rd Qu.:0.5079      3rd Qu.:33.75   3rd Qu.:16.954
##  90     :4   Max.   :0.5472      Max.   :36.99   Max.   :20.240
##  (Other):0
##       NDVI
##  Min.   :0.4500
##  1st Qu.:0.6669
##  Median :0.6950
##  Mean   :0.6619
##  3rd Qu.:0.7206
##  Max.   :0.7500
##
```

```r
summary(subset(ndvi_data, site_year == "Nicolaus-18"))
```

```
##           site_year  exp_plot_number     block          plot       plot_id
##  Nicolaus-18    :24   101     : 1      25     :6   1      :4   137    : 1
##  Arbuckle-15    : 0   102     : 1      26     :6   2      :4   138    : 1
##  Farm Survey-15: 0   103     : 1      27     :6   3      :4   139    : 1
##  RES-15         : 0   104     : 1      28     :6   4      :4   140    : 1
##  Davis-16       : 0   105     : 1      1      :0   5      :4   141    : 1
##  RES-16         : 0   106     : 1      10     :0   6      :4   142    : 1
##  (Other)        : 0   (Other):18      (Other):0   (Other):0   (Other):18
##     N_level  aboveground_biomass   n_content        N_Uptake
```

```
##  0      :4   Min.   :0.3242      Min.   :13.07   Min.   : 4.603
##  120    :4   1st Qu.:0.5630      1st Qu.:20.85   1st Qu.:11.428
##  150    :4   Median :0.6332      Median :23.96   Median :15.108
##  180    :4   Mean   :0.6069      Mean   :23.32   Mean   :14.603
##  210    :4   3rd Qu.:0.6835      3rd Qu.:27.21   3rd Qu.:18.685
##  90     :4   Max.   :0.7282      Max.   :30.69   Max.   :22.352
##  (Other):0
##       NDVI
##  Min.   :0.5825
##  1st Qu.:0.7125
##  Median :0.7375
##  Mean   :0.7170
##  3rd Qu.:0.7575
##  Max.   :0.7725
##
```

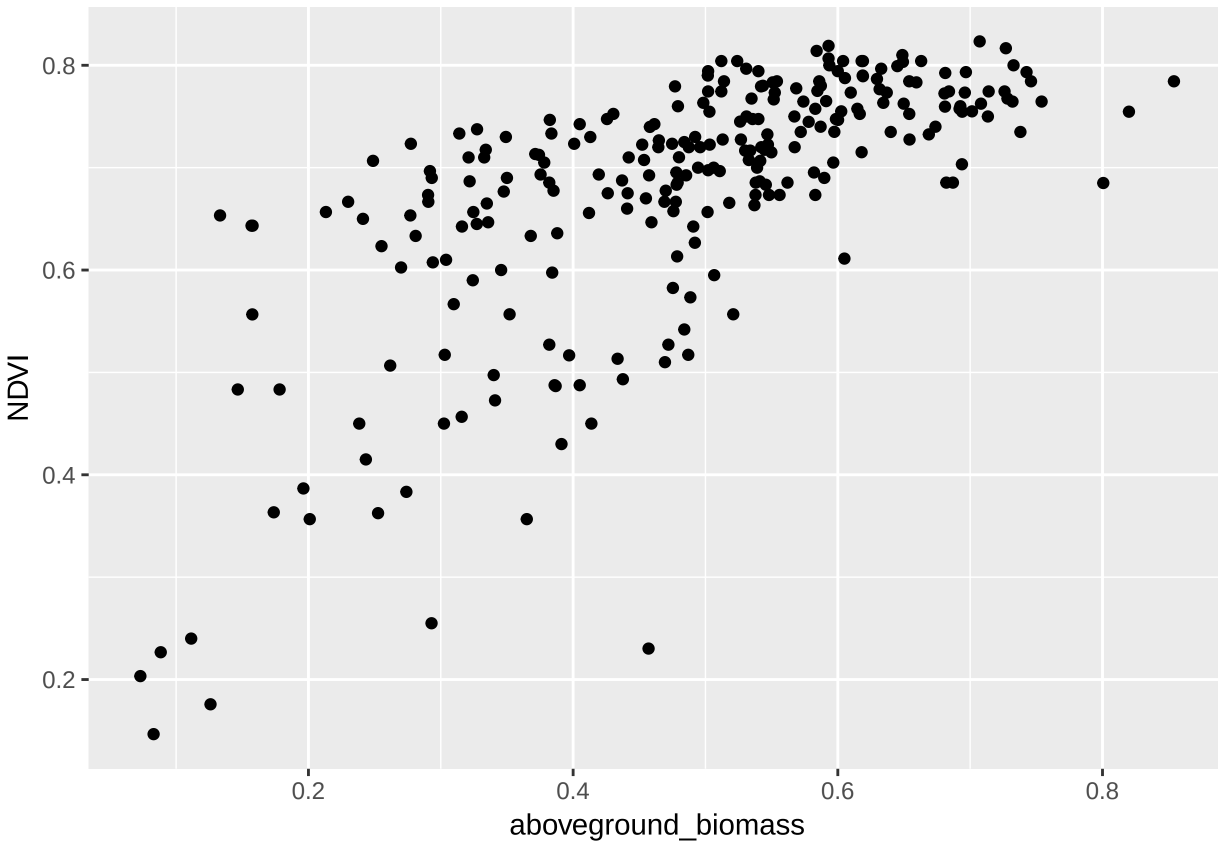
```r
summary(ndvi_data)
```

```
##           site_year   exp_plot_number     block          plot
##  Farm Survey-15: 28   102    : 10     41     : 28   1      :40
##  Nicolaus-17   : 28   103    : 10     22     :  8   2      :40
##  Williams-17   : 28   104    : 10     17     :  7   3      :40
##  Arbuckle-18   : 24   105    : 10     18     :  7   4      :40
##  Marysville-18 : 24   201    : 10     19     :  7   5      :40
##  Nicolaus-18   : 24   202    : 10     20     :  7   ab     :28
##  (Other)       :103   (Other):199     (Other):195   (Other):31
##     plot_id       N_level    aboveground_biomass   n_content
##  1      :  1   175    :52   Min.   :0.0730      Min.   :10.38
##  2      :  1   0      :40   1st Qu.:0.3820      1st Qu.:18.55
##  3      :  1   125    :24   Median :0.5018      Median :23.54
##  4      :  1   225    :24   Mean   :0.4840      Mean   :23.73
##  5      :  1   75     :24   3rd Qu.:0.5930      3rd Qu.:28.51
##  6      :  1   120    :16   Max.   :0.8540      Max.   :38.83
##  (Other):253   (Other):79
##     N_Uptake             NDVI
##  Min.   : 0.9657   Min.   :0.1467
##  1st Qu.: 7.4993   1st Qu.:0.6533
##  Median :11.6888   Median :0.7133
##  Mean   :11.8929   Mean   :0.6776
##  3rd Qu.:16.0854   3rd Qu.:0.7612
##  Max.   :25.5772   Max.   :0.8233
##
```

MODELS

Aboveground Biomass

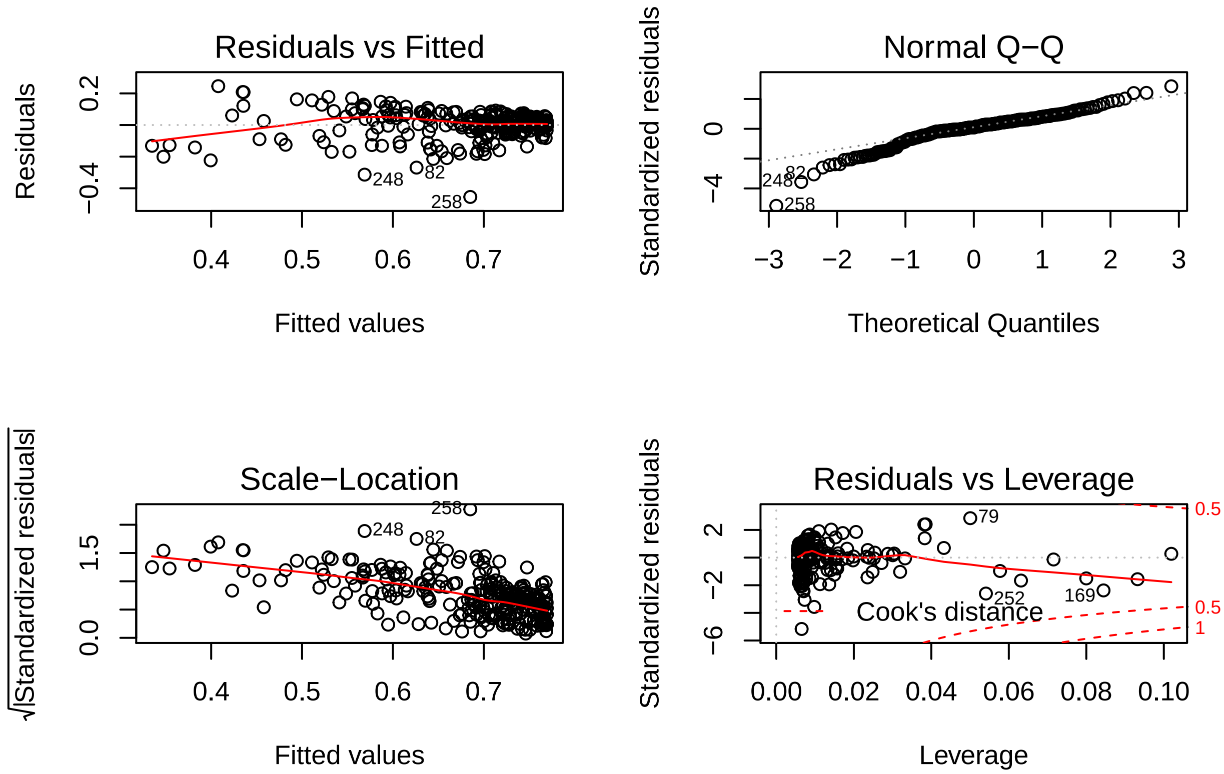
```r
ggplot(data = ndvi_data, aes(x = aboveground_biomass , y = NDVI)) +
                    geom_point(mapping = aes(aboveground_biomass, NDVI), data = ndvi_data) #visualizes
```




```r
aboveground_biomass2 <- ndvi_data$aboveground_biomass^2
abv.quad <- lm(NDVI ~ aboveground_biomass + aboveground_biomass2 , ndvi_data)
summary(abv.quad)
```

```
##
## Call:
## lm(formula = NDVI ~ aboveground_biomass + aboveground_biomass2,
##     data = ndvi_data)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.45491 -0.03436  0.00818  0.05326  0.24556
##
## Coefficients:
##                       Estimate Std. Error t value Pr(>|t|)
## (Intercept)            0.23756    0.03769   6.303 1.27e-09 ***
## aboveground_biomass    1.40068    0.16878   8.299 6.08e-15 ***
## aboveground_biomass2 -0.92184    0.18122  -5.087 7.04e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.08836 on 256 degrees of freedom
## Multiple R-squared:  0.518,  Adjusted R-squared:  0.5143
## F-statistic: 137.6 on 2 and 256 DF,  p-value: < 2.2e-16
```

```r
par(mfrow = c(2, 2))
plot(abv.quad) #residuals are acceptable
```




```
abv.quad.fit <- fitted(abv.quad)
abv.quad.df <- data.frame(ndvi_data$aboveground_biomass, abv.quad.fit)

abv_r2 <- summary(abv.quad)$adj.r.squared
abv_a <- as.numeric(as.character(coef(abv.quad)[3]))
abv_b <- as.numeric(as.character(coef(abv.quad)[2]))
abv_c <- as.numeric(as.character(coef(abv.quad)[1]))
abvsym_x <- (-abv_b) / (2*abv_a)
abvsym_y <- abv_a*(abvsym_x^2) + abv_b*abvsym_x + abv_c

abveqn <- paste("y == -0.92x^2 + 1.4x + 0.24")

abv_r2
```

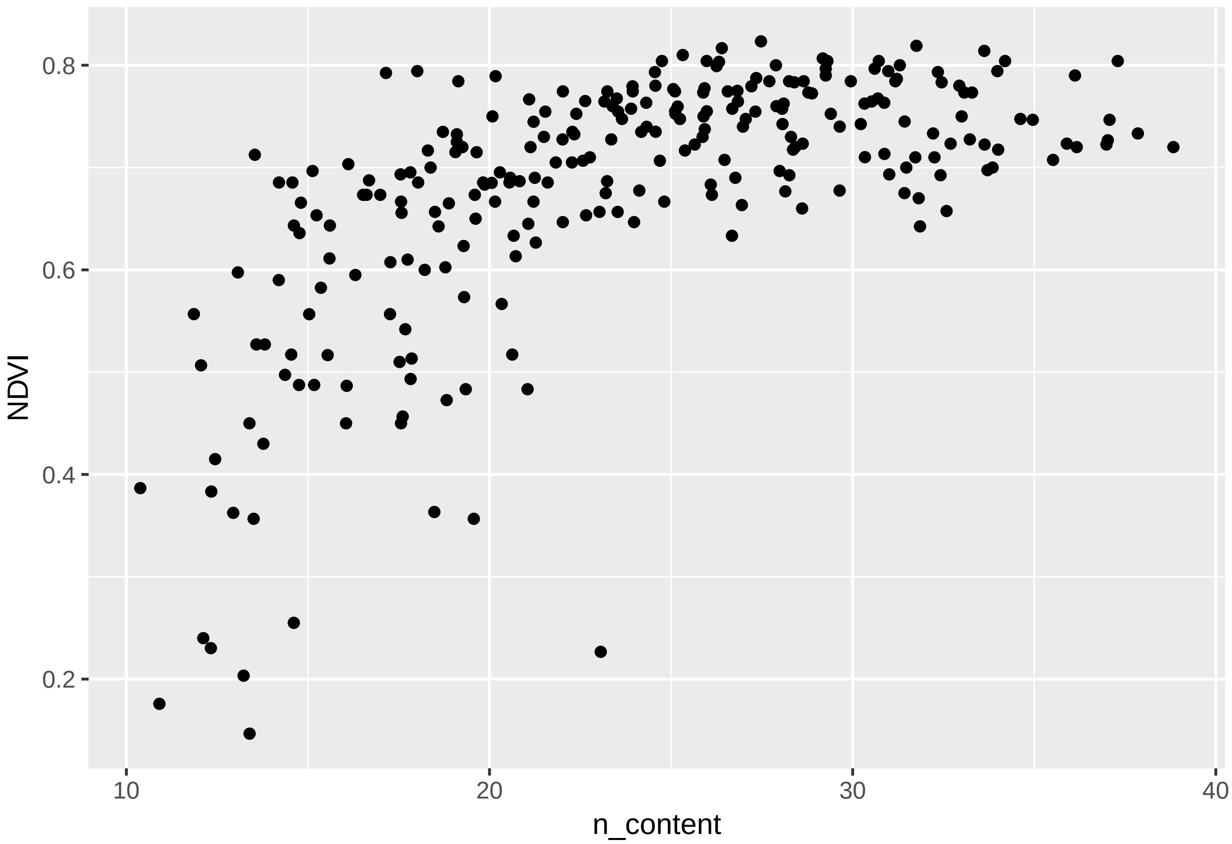
```
## [1] 0.5142801
```

```
abvsym_y
```

```
## [1] 0.7696272
```

N Concentration

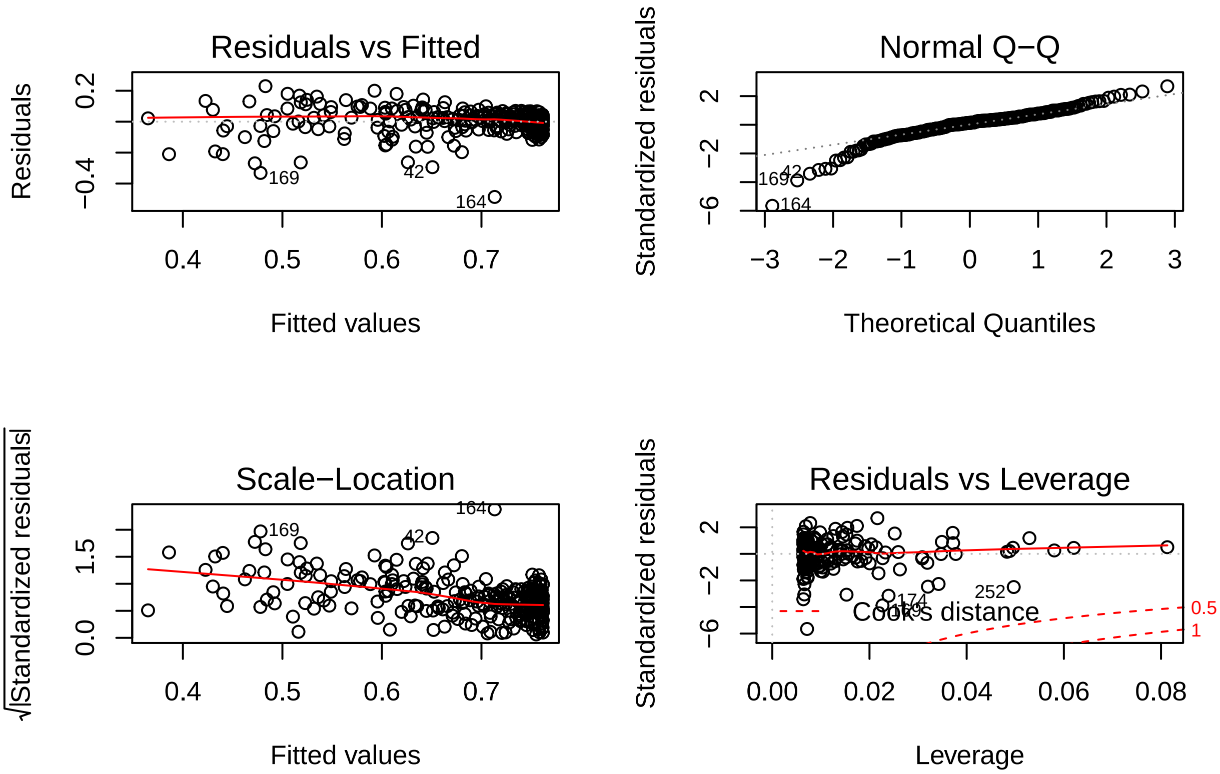
```
ggplot(data = ndvi_data, aes(x= n_content , y= NDVI)) +
         geom_point(mapping = aes(n_content, NDVI) , data = ndvi_data) #visualizes the data
```




```
n_content2 <- ndvi_data$n_content^2
ncon.quad <- lm(NDVI ~ n_content + n_content2, ndvi_data)
summary(ncon.quad)
```

```
##
## Call:
## lm(formula = NDVI ~ n_content + n_content2, data = ndvi_data)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.48663 -0.03919  0.01167  0.04283  0.22954
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) -0.1702197  0.0659651  -2.580   0.0104 *
## n_content    0.0623754  0.0057011  10.941   <2e-16 ***
## n_content2  -0.0010435  0.0001173  -8.896   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.08637 on 256 degrees of freedom
## Multiple R-squared:  0.5395, Adjusted R-squared:  0.5359
## F-statistic:   150 on 2 and 256 DF,  p-value: < 2.2e-16
```

```
par(mfrow = c(2, 2))
plot(ncon.quad) #residuals are acceptable
```




```
ncon.quad.fit <- fitted(ncon.quad)
ncfit.df <- data.frame(ndvi_data$n_content, ncon.quad.fit)

ncon_r2 <- summary(ncon.quad)$adj.r.squared
ncon_a <- as.numeric(as.character(coef(ncon.quad)[3]))
ncon_b <- as.numeric(as.character(coef(ncon.quad)[2]))
ncon_c <- as.numeric(as.character(coef(ncon.quad)[1]))
nconsym_x <- (-ncon_b) / (2*ncon_a)
nconsym_y <- ncon_a*(nconsym_x^2) + ncon_b*nconsym_x + ncon_c

nconeqn <- paste("y == -0.17 + 0.06*x - 0.001*x^2")

ncon_r2
```

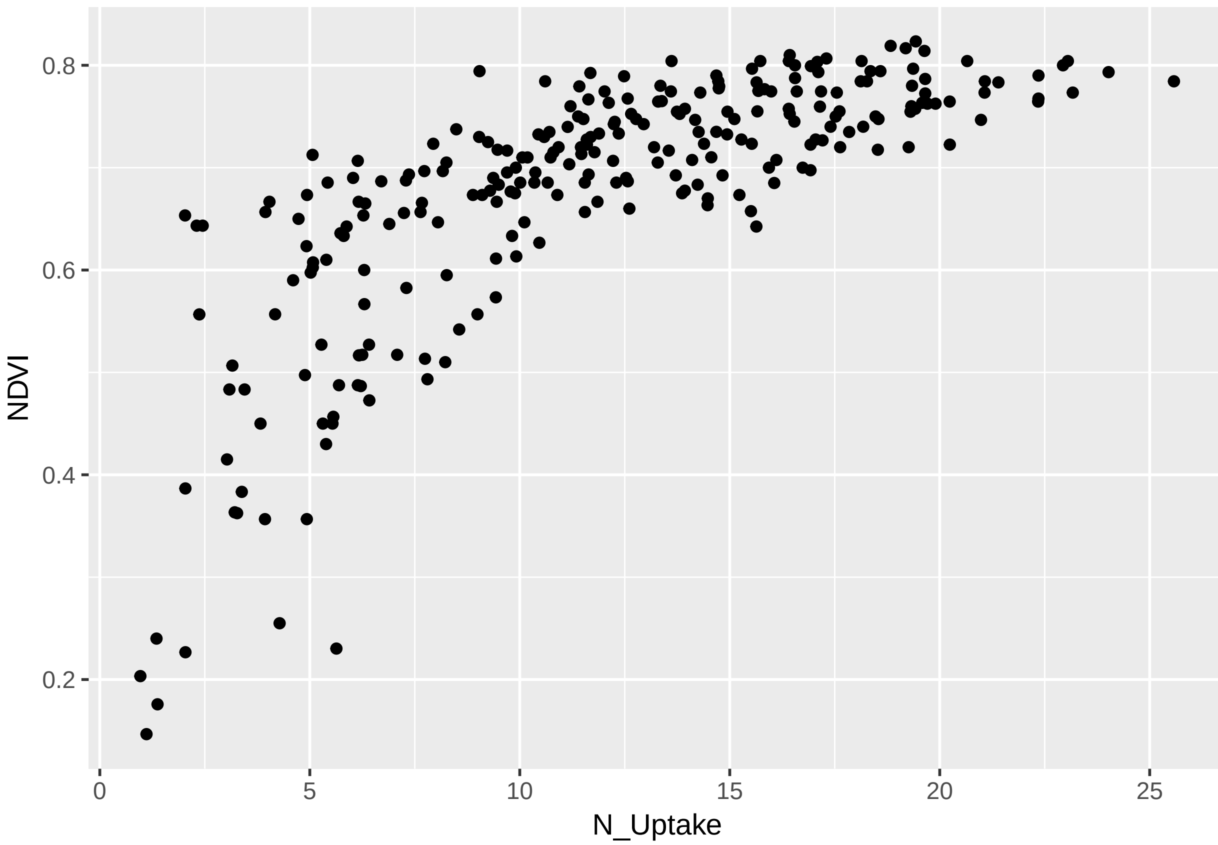
```
## [1] 0.5359407
```

```
nconsym_y
```

```
## [1] 0.7618864
```

N Uptake

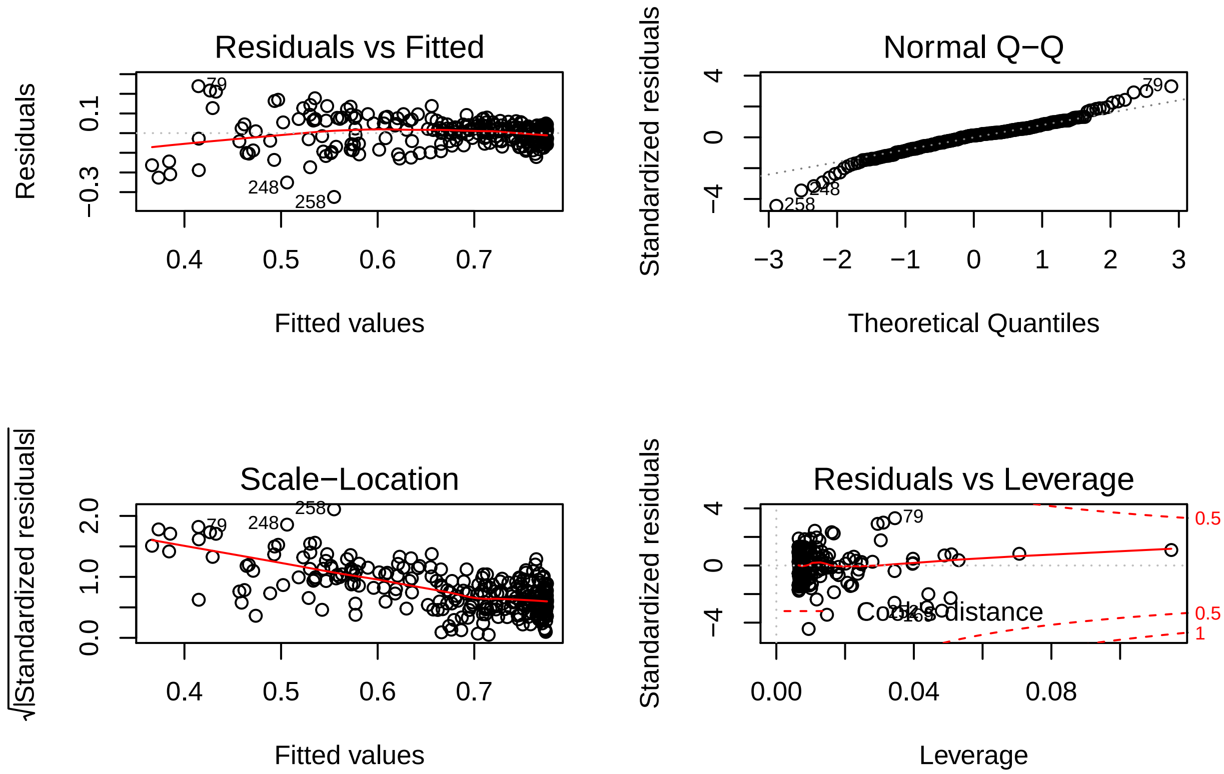
```
ggplot(data = ndvi_data , aes(x = N_Uptake , y = NDVI)) +
  geom_point(mapping = aes(N_Uptake , NDVI), data = ndvi_data) #visualizes the data
```




```r
N_Uptake2 <- ndvi_data$N_Uptake^2
nup.quad <- lm(NDVI ~ N_Uptake + N_Uptake2 , ndvi_data)
summary(nup.quad)
```

```
##
## Call:
## lm(formula = NDVI ~ N_Uptake + N_Uptake2, data = ndvi_data)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.32464 -0.03989  0.00853  0.03927  0.23885
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept)  0.3202576  0.0194828  16.438   <2e-16 ***
## N_Uptake     0.0491128  0.0034762  14.128   <2e-16 ***
## N_Uptake2   -0.0013252  0.0001403  -9.444   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.0734 on 256 degrees of freedom
## Multiple R-squared:  0.6674, Adjusted R-squared:  0.6648
## F-statistic: 256.9 on 2 and 256 DF,  p-value: < 2.2e-16
```

```r
par(mfrow = c(2, 2))
plot(nup.quad) #residuals are acceptable
```




```
nup.quad.fit <- fitted(nup.quad)
nup.quad.df <- data.frame(ndvi_data$N_Uptake , nup.quad.fit)

nup_r2 <- summary(nup.quad)$adj.r.squared
nup_a <- as.numeric(as.character(coef(nup.quad)[3]))
nup_b <- as.numeric(as.character(coef(nup.quad)[2]))
nup_c <- as.numeric(as.character(coef(nup.quad)[1]))
nupsym_x <- (-nup_b) / (2*nup_a)
nupsym_y <- nup_a*(nupsym_x^2) + nup_b*nupsym_x + nup_c

nupeqn <- paste("y == 0.32 + 0.05*x -0.001*x^2")

nup_r2
```

```
## [1] 0.6648292
```

```
nupsym_y
```

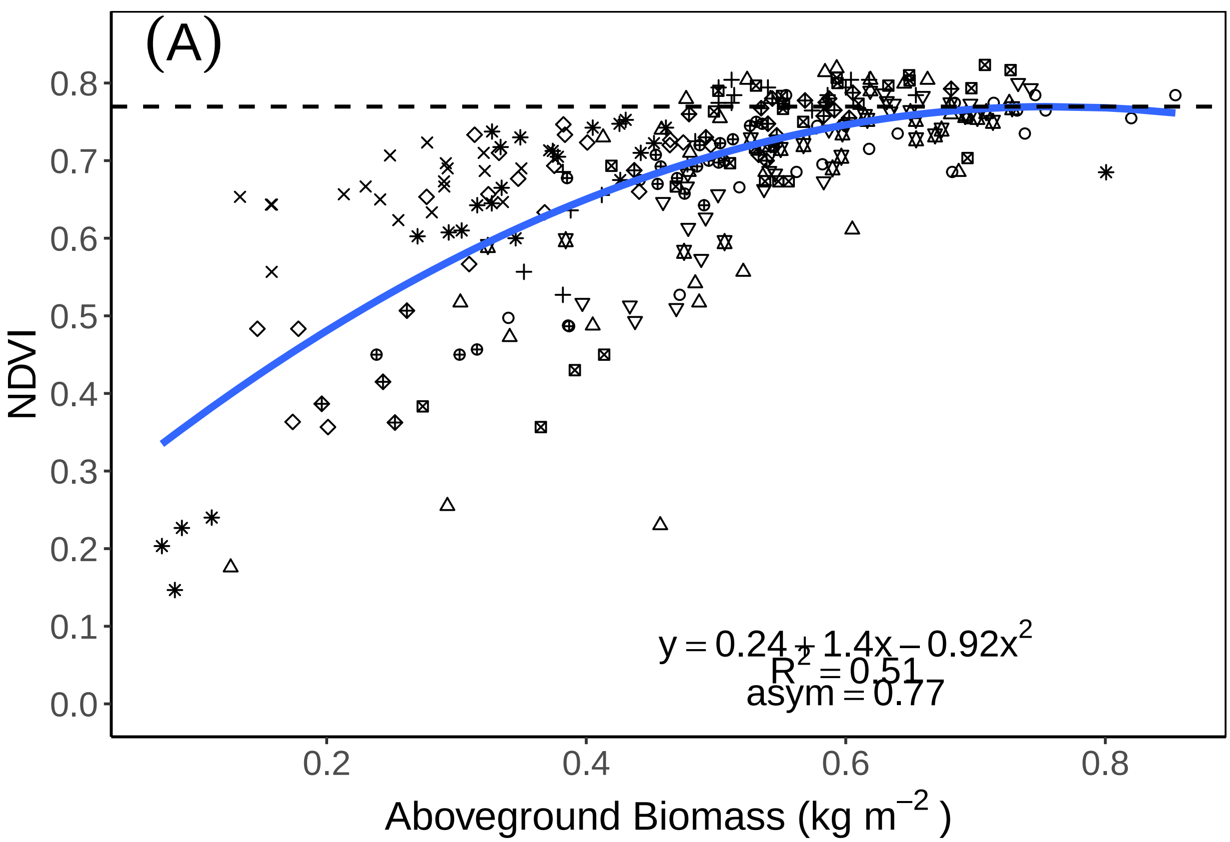
```
## [1] 0.7753028
```

PLOTS

Aboveground Biomass Plot

```
a <- ggplot( data = ndvi_data , aes ( x = aboveground_biomass , y = NDVI)) +
  geom_point(mapping = aes(aboveground_biomass , NDVI, shape = factor(site_year)) , data = ndvi_data )
  theme_classic() +
  labs( x = "Aboveground Biomass (kg m"^-2~")" , y = "NDVI" , shape = "Site Year" ) +
```

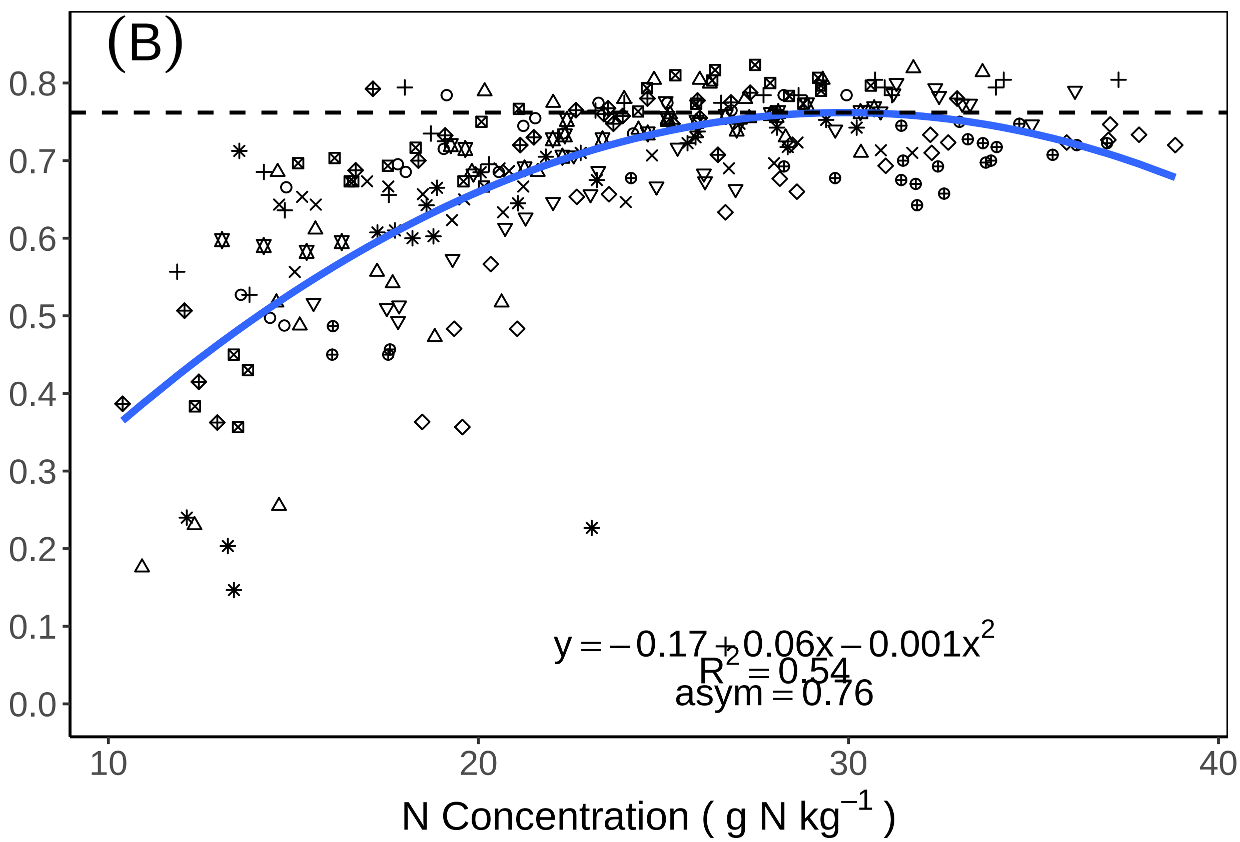
```
  theme(legend.position = "none") +
  theme(axis.title = element_text(size = 15)) +
  theme(axis.text = element_text(size = 13)) +
  theme(legend.text = element_text(size = 11)) +
  theme(legend.title = element_text(size = 11)) +
  scale_shape_manual(values = seq(0:10)) +
  coord_cartesian(ylim=c(0,0.85)) +
  scale_y_continuous(breaks = c(0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80)) +
  scale_x_continuous(breaks = c(0, .2, .4, .6, .8, 1, 1.2, 1.4)) +
  theme(panel.background = element_rect(fill = "white", color = "grey0")) +
  geom_line(data = abv.quad.df, aes( x = ndvi_data$aboveground_biomass , y = abv.quad.fit), size = 1.3
  geom_hline( yintercept = abvsym_y , size = 0.7 , color = "black" , lty = 2) +
  annotate("text" , x = .09, y = 0.85, label = "(A)", color="black", size = 7, parse = TRUE) +
  annotate("text" , x = .60 , y = 0.08 , label = "y == 0.24 + 1.4*x -0.92*x^2" , size = 5, parse = TRUE
  annotate("text" , x = .60 , y = 0.05 , label = "R^2 == 0.51" , size = 5, parse = TRUE) +
  annotate("text" , x = .60 , y = 0.01 , label = "asym == 0.77" , size = 5, parse = TRUE)


a
```



N Concentration Plot

```
b <- ggplot( data = ndvi_data , aes ( x = n_content , y = NDVI)) +
  geom_point(mapping = aes(n_content , NDVI , shape = site_year) , data = ndvi_data ) +
  theme_classic() +
```

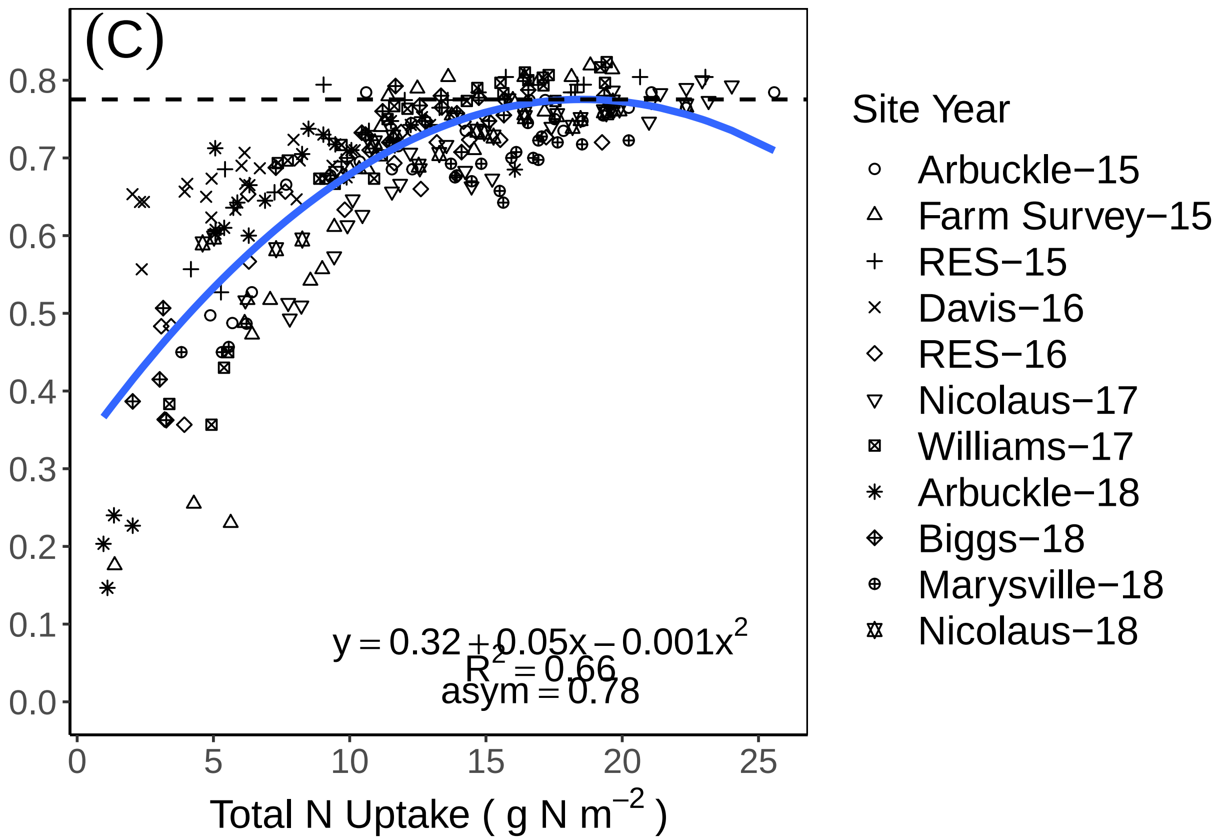
```
  labs( x = "N Concentration ( g N kg"^-1~")", y = NULL, shape = "Site Year" ) +
  theme(legend.position = "none") +
  theme(axis.title = element_text(size = 15)) +
  theme(axis.text = element_text(size = 13)) +
  theme(legend.text = element_text(size = 11)) +
  theme(legend.title = element_text(size = 11)) +
  scale_shape_manual(values = seq(0:10)) +
  coord_cartesian(ylim=c(0,0.85)) +
  scale_y_continuous(breaks = c(0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80)) +
  scale_x_continuous(breaks = c(0, 10, 20, 30, 40, 50)) +
  theme(panel.background = element_rect(fill = "white", color = "grey0")) +
  geom_line(data = ncfit.df, aes( x = ndvi_data$n_content , y = ncon.quad.fit), size = 1.3 , color = "#3
  geom_hline( yintercept = nconsym_y , size = 0.7 , color = "black" , lty = 2) +
  annotate("text", x = 11, y = 0.85, label = "(B)", color="black", size = 7, parse = TRUE) +
  annotate("text" , x = 28 , y = 0.08 , label = nconeqn , size = 5 , parse = TRUE) +
  annotate("text" , x = 28 , y = 0.05 , label = "R^2 == 0.54" , size = 5 ,  parse = TRUE) +
  annotate("text" , x = 28 , y = 0.01 , label = "asym == 0.76" , size = 5 ,  parse = TRUE)

b
```



N Uptake Plot

```
c <- ggplot( data = ndvi_data , aes ( x = N_Uptake , y = NDVI)) +
  geom_point(mapping = aes(N_Uptake , NDVI, shape = site_year) , data = ndvi_data ) +
  theme_classic() +
```

```r
  labs( x = "Total N Uptake ( g N m"^-2~")" , y = NULL,  shape = "Site Year") +
  theme(axis.title = element_text(size = 15)) +
  theme(axis.text = element_text(size = 13)) +
  theme(legend.text = element_text(size = 15)) +
  theme(legend.title = element_text(size = 15)) +
  scale_shape_manual(values = seq(0:10)) +
  coord_cartesian(ylim=c(0,0.85)) +
  scale_y_continuous(breaks = c(0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80)) +
  scale_x_continuous(breaks = c(0, 5, 10, 15, 20, 25, 30)) +
  theme(panel.background = element_rect(fill = "white", color = "grey0")) +
  geom_line(data = nup.quad.df , aes( x = ndvi_data$N_Uptake , y = nup.quad.fit), size = 1.3 , color =
  geom_hline( yintercept = nupsym_y , size = 0.7 , color = "black" , lty = 2) +
  annotate("text", x = 1.75, y = 0.85, label = "(C)", color="black", size = 7, parse = TRUE) +
  annotate("text" , x = 17 , y = 0.08 , label = nupeqn , size = 5 , parse = TRUE) +
  annotate("text" , x = 17 , y = 0.05 , label = "R^2 == 0.66" , size = 5 , parse = TRUE) +
  annotate("text" , x = 17 , y = 0.01 , label = "asym == 0.78" , size = 5  , parse = TRUE)

c
```




```r
g_legend <- function(c){
  tmp <- ggplot_gtable(ggplot_build(c))
  leg <- which(sapply(tmp$grobs, function(x) x$name) == "guide-box")
  legend <- tmp$grobs[[leg]]
  return(legend)}
legend <- g_legend(c) #extract the legend from plot c

c <- c +
```

```
  theme(legend.position = "none")
```

```
c
```

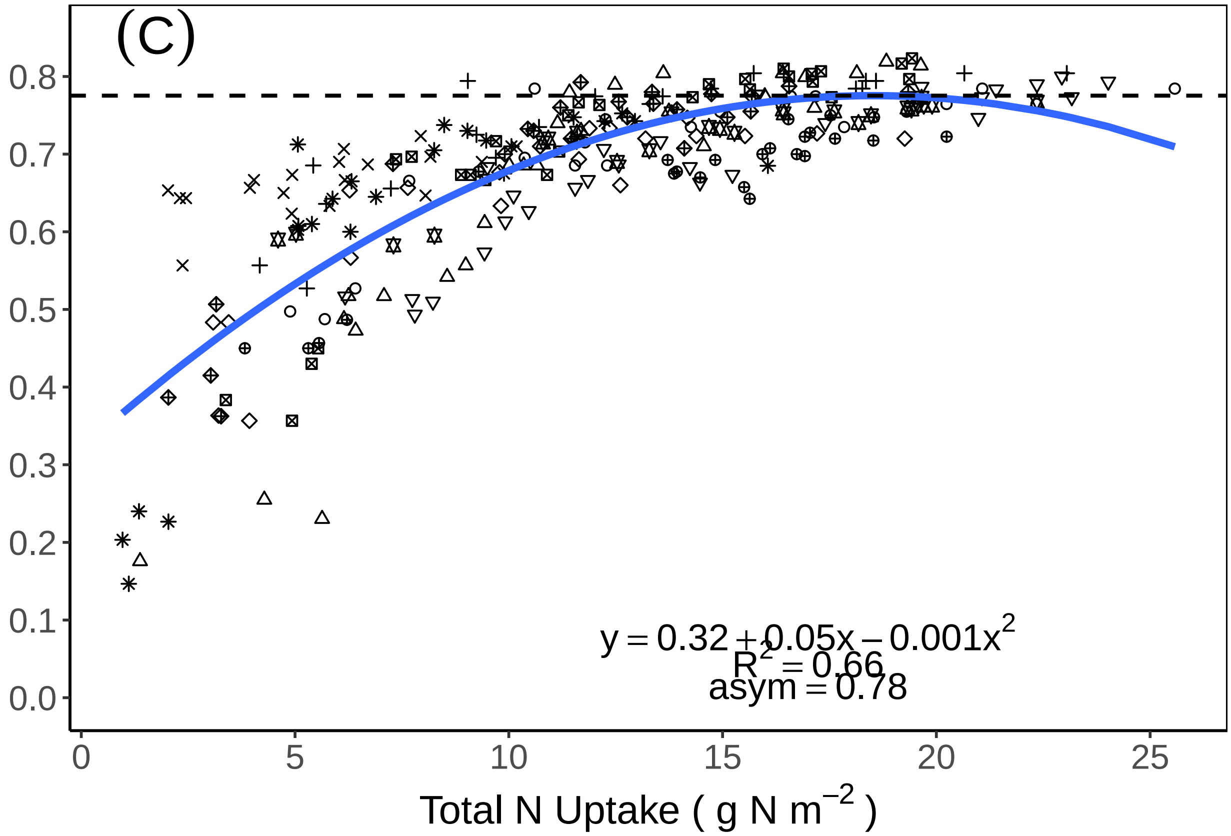
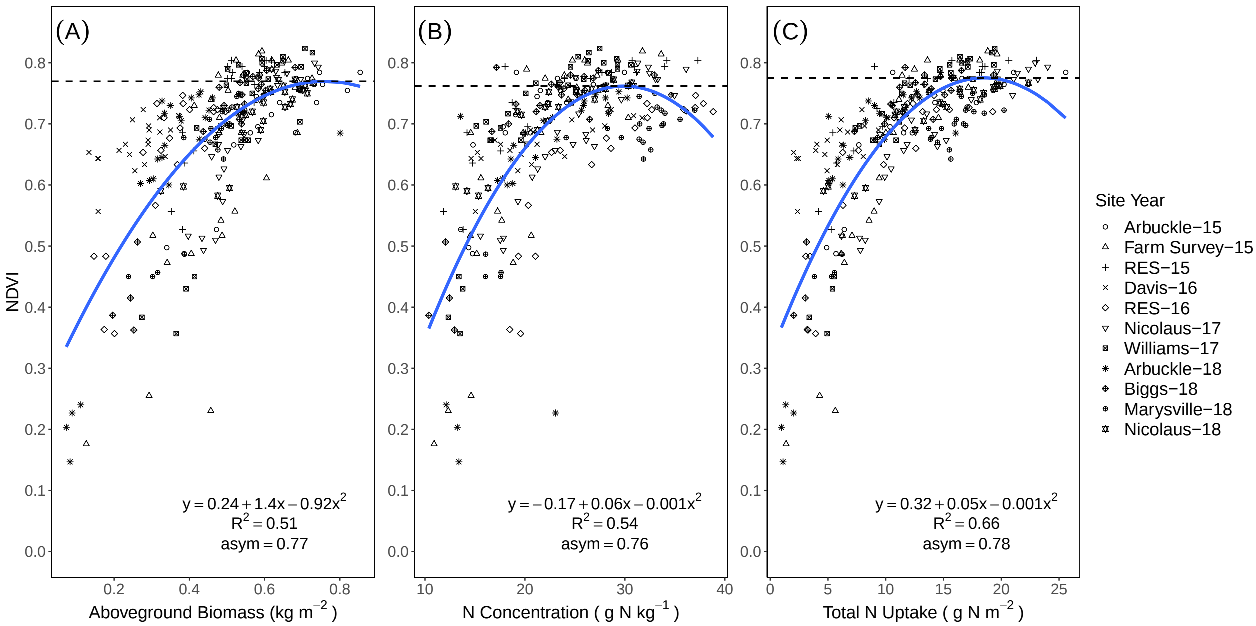


Figure 2

```
zz <- grid.arrange(arrangeGrob(a,
                               b,
                               c,
                               legend,
                               ncol = 4,
                               nrow = 1,
                               widths = c(1.3,1.2,1.2,.6)))
```




```
ggsave("Figure_2.tiff" , zz,  device = "tiff")
```

```
## Saving 15 x 7.5 in image
```

YIELD DATA

Dataframe

the code below processes the yield data into a single dataframe with the relevant columns. The N Uptake and NDVI data is extracted from the NDVI dataframe. Overall, the steps are pretty obvious. I guess the only thing would be worthy of noting is that "A's" clean grain weight data had already subtracted the paper bag weight, while my data included this value. Thus, tare2 only subtracts the paper bag weight from my data.

```
yield_data <- read_csv("yield_data.csv" )
```

```
## Parsed with column specification:
## cols(
##   site_year = col_character(),
##   exp_plot_number = col_double(),
##   block = col_double(),
##   plot = col_double(),
##   plot_id = col_double(),
##   N_level = col_double(),
##   tare1 = col_double(),
##   fw1_plus_tare1 = col_double(),
##   fw2_plus_tare1 = col_double(),
##   ss_fw_plus_tare1 = col_double(),
##   clean_grain_odw_plus_tare2 = col_double(),
##   tare2 = col_double(),
##   yc_clean_grain_odw_plus_tare_3 = col_double(),
##   tare_3 = col_double()
```

```
## )
```

```r
yield_data$exp_plot_number <- factor(yield_data$exp_plot_number)
yield_data$block <- factor(yield_data$block)
yield_data$plot <- factor(yield_data$plot)
yield_data$plot_id <- factor(yield_data$plot_id)
yield_data$N_level <- factor(yield_data$N_level)
yield_data$site_year <- factor(yield_data$site_year , levels = c("Arbuckle-15" , "RES-15" , "RES-16" ,
str(yield_data)
```

```
## Classes 'spec_tbl_df', 'tbl_df', 'tbl' and 'data.frame': 231 obs. of  14 variables:
##  $ site_year                      : Factor w/ 10 levels "Arbuckle-15",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ exp_plot_number                : Factor w/ 28 levels "101","102","103",..: 1 2 3 4 5 8 9 10 11 12
##  $ block                          : Factor w/ 40 levels "1","2","3","4",..: 1 1 1 1 1 2 2 2 2 2 ...
##  $ plot                           : Factor w/ 7 levels "1","2","3","4",..: 1 2 3 4 5 1 2 3 4 5 ...
##  $ plot_id                        : Factor w/ 231 levels "1","2","3","4",..: 1 2 3 4 5 6 7 8 9 10 ...
##  $ N_level                        : Factor w/ 12 levels "0","45","75",..: 6 11 1 3 8 1 8 6 11 3 ...
##  $ tare1                          : num  1224 1224 1224 1224 1224 ...
##  $ fw1_plus_tare1                 : num  5352 5418 4086 5512 5714 ...
##  $ fw2_plus_tare1                 : num  1224 1224 1224 1224 1224 ...
##  $ ss_fw_plus_tare1               : num  1880 2170 1792 2180 2192 ...
##  $ clean_grain_odw_plus_tare2     : num  178 243 132 266 255 ...
##  $ tare2                          : num  0 0 0 0 0 0 0 0 0 0 ...
##  $ yc_clean_grain_odw_plus_tare_3: num  7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 ...
##  $ tare_3                         : num  7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 ...
##  - attr(*, "spec")=
##   .. cols(
##   ..   site_year = col_character(),
##   ..   exp_plot_number = col_double(),
##   ..   block = col_double(),
##   ..   plot = col_double(),
##   ..   plot_id = col_double(),
##   ..   N_level = col_double(),
##   ..   tare1 = col_double(),
##   ..   fw1_plus_tare1 = col_double(),
##   ..   fw2_plus_tare1 = col_double(),
##   ..   ss_fw_plus_tare1 = col_double(),
##   ..   clean_grain_odw_plus_tare2 = col_double(),
##   ..   tare2 = col_double(),
##   ..   yc_clean_grain_odw_plus_tare_3 = col_double(),
##   ..   tare_3 = col_double()
##   .. )
```

```r
yield_data$fw1_minus_tare1 <- yield_data$fw1_plus_tare1 - yield_data$tare1

yield_data$fw2_minus_tare1 <- yield_data$fw2_plus_tare1 - yield_data$tare1

yield_data$fw_net <- yield_data$fw1_minus_tare1 + yield_data$fw2_minus_tare1

yield_data$ss_fw_net <- yield_data$ss_fw_plus_tare1 - yield_data$tare1

yield_data$ratio <- yield_data$ss_fw_net / yield_data$fw_net

yield_data$clean_grain_1 <- yield_data$clean_grain_odw_plus_tare2 - yield_data$tare2
```

```r
yield_data$clean_grain_2 <- yield_data$yc_clean_grain_odw_plus_tare_3 - yield_data$tare_3

yield_data$clean_grain_2 <- yield_data$clean_grain_2 * yield_data$ratio #this essntially subsamples the

yield_data$clean_grain_m2 <- (yield_data$clean_grain_1 + yield_data$clean_grain_2) / yield_data$ratio

yield_data$grain_yield <- yield_data$clean_grain_m2 * 10

yield_data$grain_yield <- yield_data$grain_yield*(98.1/86) #this corrects the grain yield values to 14%

head(yield_data)
```

```
## # A tibble: 6 x 23
##   site_year exp_plot_number block plot  plot_id N_level tare1
##   <fct>     <fct>           <fct> <fct> <fct>   <fct>   <dbl>
## 1 Arbuckle~ 101             1     1     1       125      1224
## 2 Arbuckle~ 102             1     2     2       225      1224
## 3 Arbuckle~ 103             1     3     3       0        1224
## 4 Arbuckle~ 104             1     4     4       75       1224
## 5 Arbuckle~ 105             1     5     5       175      1224
## 6 Arbuckle~ 201             2     1     6       0        1224
## # ... with 16 more variables: fw1_plus_tare1 <dbl>, fw2_plus_tare1 <dbl>,
## #   ss_fw_plus_tare1 <dbl>, clean_grain_odw_plus_tare2 <dbl>, tare2 <dbl>,
## #   yc_clean_grain_odw_plus_tare_3 <dbl>, tare_3 <dbl>,
## #   fw1_minus_tare1 <dbl>, fw2_minus_tare1 <dbl>, fw_net <dbl>,
## #   ss_fw_net <dbl>, ratio <dbl>, clean_grain_1 <dbl>,
## #   clean_grain_2 <dbl>, clean_grain_m2 <dbl>, grain_yield <dbl>
```

```r
tail(yield_data)
```

```
## # A tibble: 6 x 23
##   site_year exp_plot_number block plot  plot_id N_level tare1
##   <fct>     <fct>           <fct> <fct> <fct>   <fct>   <dbl>
## 1 Biggs-18  401             40    1     226     90       1098
## 2 Biggs-18  402             40    2     227     210      1098
## 3 Biggs-18  403             40    3     228     0        1098
## 4 Biggs-18  404             40    4     229     180      1098
## 5 Biggs-18  405             40    5     230     150      1098
## 6 Biggs-18  406             40    6     231     120      1098
## # ... with 16 more variables: fw1_plus_tare1 <dbl>, fw2_plus_tare1 <dbl>,
## #   ss_fw_plus_tare1 <dbl>, clean_grain_odw_plus_tare2 <dbl>, tare2 <dbl>,
## #   yc_clean_grain_odw_plus_tare_3 <dbl>, tare_3 <dbl>,
## #   fw1_minus_tare1 <dbl>, fw2_minus_tare1 <dbl>, fw_net <dbl>,
## #   ss_fw_net <dbl>, ratio <dbl>, clean_grain_1 <dbl>,
## #   clean_grain_2 <dbl>, clean_grain_m2 <dbl>, grain_yield <dbl>
```

```r
str(yield_data)
```

```
## Classes 'spec_tbl_df', 'tbl_df', 'tbl' and 'data.frame': 231 obs. of  23 variables:
##  $ site_year                     : Factor w/ 10 levels "Arbuckle-15",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ exp_plot_number               : Factor w/ 28 levels "101","102","103",..: 1 2 3 4 5 8 9 10 11 12
##  $ block                         : Factor w/ 40 levels "1","2","3","4",..: 1 1 1 1 1 2 2 2 2 2 ...
##  $ plot                          : Factor w/ 7 levels "1","2","3","4",..: 1 2 3 4 5 1 2 3 4 5 ...
##  $ plot_id                       : Factor w/ 231 levels "1","2","3","4",..: 1 2 3 4 5 6 7 8 9 10 ...
##  $ N_level                       : Factor w/ 12 levels "0","45","75",..: 6 11 1 3 8 1 8 6 11 3 ...
```

```
##  $ tare1                         : num  1224 1224 1224 1224 1224 ...
##  $ fw1_plus_tare1                : num  5352 5418 4086 5512 5714 ...
##  $ fw2_plus_tare1                : num  1224 1224 1224 1224 1224 ...
##  $ ss_fw_plus_tare1              : num  1880 2170 1792 2180 2192 ...
##  $ clean_grain_odw_plus_tare2    : num  178 243 132 266 255 ...
##  $ tare2                         : num  0 0 0 0 0 0 0 0 0 0 ...
##  $ yc_clean_grain_odw_plus_tare_3: num  7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 ...
##  $ tare_3                        : num  7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 7.01 ...
##  $ fw1_minus_tare1               : num  4128 4194 2862 4288 4490 ...
##  $ fw2_minus_tare1               : num  0 0 0 0 0 0 0 0 0 0 ...
##  $ fw_net                        : num  4128 4194 2862 4288 4490 ...
##  $ ss_fw_net                     : num  656 946 568 956 968 ...
##  $ ratio                         : num  0.159 0.226 0.198 0.223 0.216 ...
##  $ clean_grain_1                 : num  178 243 132 266 255 ...
##  $ clean_grain_2                 : num  0 0 0 0 0 0 0 0 0 0 ...
##  $ clean_grain_m2                : num  1121 1076 665 1193 1183 ...
##  $ grain_yield                   : num  12791 12274 7587 13605 13492 ...
##  - attr(*, "spec")=
##   .. cols(
##   ..   site_year = col_character(),
##   ..   exp_plot_number = col_double(),
##   ..   block = col_double(),
##   ..   plot = col_double(),
##   ..   plot_id = col_double(),
##   ..   N_level = col_double(),
##   ..   tare1 = col_double(),
##   ..   fw1_plus_tare1 = col_double(),
##   ..   fw2_plus_tare1 = col_double(),
##   ..   ss_fw_plus_tare1 = col_double(),
##   ..   clean_grain_odw_plus_tare2 = col_double(),
##   ..   tare2 = col_double(),
##   ..   yc_clean_grain_odw_plus_tare_3 = col_double(),
##   ..   tare_3 = col_double()
##   .. )
```

```r
nup <- data.frame(ndvi_data$site_year , ndvi_data$N_Uptake , ndvi_data$NDVI) #calls the N Uptake values
str(nup)
```

```
## 'data.frame':    259 obs. of  3 variables:
##  $ ndvi_data.site_year: Factor w/ 11 levels "Arbuckle-15",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ ndvi_data.N_Uptake : num  17.84 25.58 6.41 12.3 19.3 ...
##  $ ndvi_data.NDVI     : num  0.735 0.784 0.527 0.685 0.755 ...
```

```r
nup <- nup[!(nup$ndvi_data.site_year == "Farm Survey-15"),] #deletes Farm Survey since it doesnt have y
str(nup)
```

```
## 'data.frame':    231 obs. of  3 variables:
##  $ ndvi_data.site_year: Factor w/ 11 levels "Arbuckle-15",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ ndvi_data.N_Uptake : num  17.84 25.58 6.41 12.3 19.3 ...
##  $ ndvi_data.NDVI     : num  0.735 0.784 0.527 0.685 0.755 ...
```

```r
head(nup)
```

```
##   ndvi_data.site_year ndvi_data.N_Uptake ndvi_data.NDVI
## 1         Arbuckle-15          17.843952       0.734885
## 2         Arbuckle-15          25.577198       0.784360
```

```
## 3         Arbuckle-15           6.410093      0.527090
## 4         Arbuckle-15          12.299746      0.685410
## 5         Arbuckle-15          19.304427      0.754675
## 6         Arbuckle-15           7.670085      0.665620
```

```r
tail(nup)
```

```
##     ndvi_data.site_year ndvi_data.N_Uptake ndvi_data.NDVI
## 226            Biggs-18          14.104389      0.7075000
## 227            Biggs-18          11.681729      0.7925000
## 228            Biggs-18           3.156508      0.5066667
## 229            Biggs-18          15.657989      0.7550000
## 230            Biggs-18          10.581186      0.7300000
## 231            Biggs-18           9.905855      0.7000000
```

```r
summary(nup)
```

```
##     ndvi_data.site_year ndvi_data.N_Uptake ndvi_data.NDVI
##  Nicolaus-17  :28       Min.   : 0.9657    Min.   :0.1467
##  Williams-17  :28       1st Qu.: 7.4993    1st Qu.:0.6567
##  Arbuckle-18  :24       Median :11.8504    Median :0.7133
##  Marysville-18:24       Mean   :11.9420    Mean   :0.6814
##  Nicolaus-18  :24       3rd Qu.:16.2583    3rd Qu.:0.7575
##  Biggs-18     :23       Max.   :25.5772    Max.   :0.8233
##  (Other)      :80
```

```r
yield <- yield_data$grain_yield #calls the grain yield values from yield data


yield_data <- data.frame( nup, yield) #creates a dataframe with these three columns, that are needed fo
head(yield_data)
```

```
##   ndvi_data.site_year ndvi_data.N_Uptake ndvi_data.NDVI     yield
## 1         Arbuckle-15          17.843952      0.734885 12791.283
## 2         Arbuckle-15          25.577198      0.784360 12273.760
## 3         Arbuckle-15           6.410093      0.527090  7586.925
## 4         Arbuckle-15          12.299746      0.685410 13604.600
## 5         Arbuckle-15          19.304427      0.754675 13492.167
## 6         Arbuckle-15           7.670085      0.665620 11388.668
```

```r
tail(yield_data)
```

```
##     ndvi_data.site_year ndvi_data.N_Uptake ndvi_data.NDVI     yield
## 226            Biggs-18          14.104389      0.7075000 12740.258
## 227            Biggs-18          11.681729      0.7925000 12069.239
## 228            Biggs-18           3.156508      0.5066667  7655.621
## 229            Biggs-18          15.657989      0.7550000 12411.614
## 230            Biggs-18          10.581186      0.7300000 12775.161
## 231            Biggs-18           9.905855      0.7000000 12628.612
```

```r
colnames(yield_data) <- c(  "site_year" , "n_uptake" , "ndvi" , "yield" )
head(yield_data)
```

```
##     site_year  n_uptake     ndvi     yield
## 1 Arbuckle-15 17.843952 0.734885 12791.283
## 2 Arbuckle-15 25.577198 0.784360 12273.760
## 3 Arbuckle-15  6.410093 0.527090  7586.925
## 4 Arbuckle-15 12.299746 0.685410 13604.600
```

```
## 5 Arbuckle-15 19.304427 0.754675 13492.167
## 6 Arbuckle-15  7.670085 0.665620 11388.668
```

```r
str(yield_data)
```

```
## 'data.frame':    231 obs. of  4 variables:
##  $ site_year: Factor w/ 11 levels "Arbuckle-15",..: 1 1 1 1 1 1 1 1 1 1 ...
##  $ n_uptake : num  17.84 25.58 6.41 12.3 19.3 ...
##  $ ndvi     : num  0.735 0.784 0.527 0.685 0.755 ...
##  $ yield    : num  12791 12274 7587 13605 13492 ...
```

```r
yield_data$site_year <- factor(yield_data$site_year , levels = c("Arbuckle-15" , "RES-15" , "Davis-16"
```

Table 4

```r
summary(subset(yield_data, site_year == "Arbuckle-15")) #this subsets the yield data just by Arbuckle-1
```

```
##        site_year     n_uptake           ndvi             yield
##  Arbuckle-15:20   Min.   : 4.885   Min.   :0.4875   Min.   : 6469
##  RES-15     : 0   1st Qu.:10.546   1st Qu.:0.6854   1st Qu.:11337
##  Davis-16   : 0   Median :13.280   Median :0.7398   Median :13176
##  RES-16     : 0   Mean   :14.144   Mean   :0.7057   Mean   :12072
##  Nicolaus-17: 0   3rd Qu.:18.209   3rd Qu.:0.7670   3rd Qu.:13824
##  Williams-17: 0   Max.   :25.577   Max.   :0.7844   Max.   :14529
##  (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "RES-15"))
```

```
##        site_year     n_uptake           ndvi             yield
##  RES-15     :20   Min.   : 4.174   Min.   :0.5271   Min.   : 5235
##  Arbuckle-15: 0   1st Qu.: 8.592   1st Qu.:0.6928   1st Qu.:11317
##  Davis-16   : 0   Median :12.658   Median :0.7745   Median :12621
##  RES-16     : 0   Mean   :12.647   Mean   :0.7339   Mean   :11753
##  Nicolaus-17: 0   3rd Qu.:18.156   3rd Qu.:0.7943   3rd Qu.:12942
##  Williams-17: 0   Max.   :23.051   Max.   :0.8042   Max.   :14140
##  (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "Davis-16"))
```

```
##        site_year     n_uptake           ndvi             yield
##  Davis-16   :20   Min.   : 2.030   Min.   :0.5567   Min.   : 6664
##  Arbuckle-15: 0   1st Qu.: 4.016   1st Qu.:0.6458   1st Qu.: 8497
##  RES-15     : 0   Median : 5.919   Median :0.6667   Median :10457
##  RES-16     : 0   Mean   : 5.888   Mean   :0.6665   Mean   :10599
##  Nicolaus-17: 0   3rd Qu.: 7.968   3rd Qu.:0.6917   3rd Qu.:12557
##  Williams-17: 0   Max.   :11.467   Max.   :0.7233   Max.   :13969
##  (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "RES-16"))
```

```
##        site_year     n_uptake           ndvi             yield
##  RES-16     :20   Min.   : 3.086   Min.   :0.3567   Min.   : 6653
##  Arbuckle-15: 0   1st Qu.: 6.294   1st Qu.:0.6167   1st Qu.:10623
##  RES-15     : 0   Median :11.187   Median :0.6850   Median :11700
##  Davis-16   : 0   Mean   :10.324   Mean   :0.6382   Mean   :11246
##  Nicolaus-17: 0   3rd Qu.:13.442   3rd Qu.:0.7233   3rd Qu.:12358
```

```
## Williams-17: 0   Max.   :19.260   Max.   :0.7467   Max.   :14675
## (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "Nicolaus-17"))
```

```
##        site_year     n_uptake          ndvi            yield
## Nicolaus-17:28   Min.   : 6.171   Min.   :0.4933   Min.   :10345
## Arbuckle-15: 0   1st Qu.:10.062   1st Qu.:0.6417   1st Qu.:11432
## RES-15     : 0   Median :13.893   Median :0.6850   Median :12042
## Davis-16   : 0   Mean   :14.766   Mean   :0.6842   Mean   :12005
## RES-16     : 0   3rd Qu.:19.986   3rd Qu.:0.7733   3rd Qu.:12460
## Williams-17: 0   Max.   :24.021   Max.   :0.8000   Max.   :13375
## (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "Williams-17"))
```

```
##        site_year     n_uptake          ndvi            yield
## Williams-17:28   Min.   : 3.381   Min.   :0.3567   Min.   : 6096
## Arbuckle-15: 0   1st Qu.: 9.050   1st Qu.:0.6733   1st Qu.: 9132
## RES-15     : 0   Median :11.876   Median :0.7650   Median :10924
## Davis-16   : 0   Mean   :12.459   Mean   :0.7058   Mean   :10159
## RES-16     : 0   3rd Qu.:16.687   3rd Qu.:0.7967   3rd Qu.:11341
## Nicolaus-17: 0   Max.   :19.430   Max.   :0.8233   Max.   :12829
## (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "Arbuckle-18"))
```

```
##        site_year     n_uptake           ndvi            yield
## Arbuckle-18:24   Min.   : 0.9657   Min.   :0.1467   Min.   : 2948
## Arbuckle-15: 0   1st Qu.: 5.0762   1st Qu.:0.6062   1st Qu.: 9566
## RES-15     : 0   Median : 7.5737   Median :0.6800   Median :10646
## Davis-16   : 0   Mean   : 7.6532   Mean   :0.6070   Mean   : 9980
## RES-16     : 0   3rd Qu.:10.4248   3rd Qu.:0.7244   3rd Qu.:12354
## Nicolaus-17: 0   Max.   :16.0598   Max.   :0.7525   Max.   :13648
## (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "Biggs-18"))
```

```
##        site_year     n_uptake          ndvi            yield
## Biggs-18   :23   Min.   : 2.037   Min.   :0.3625   Min.   : 6767
## Arbuckle-15: 0   1st Qu.:10.175   1st Qu.:0.7037   1st Qu.:11593
## RES-15     : 0   Median :12.570   Median :0.7475   Median :12207
## Davis-16   : 0   Mean   :11.359   Mean   :0.6931   Mean   :11468
## RES-16     : 0   3rd Qu.:14.422   3rd Qu.:0.7712   3rd Qu.:12684
## Nicolaus-17: 0   Max.   :19.341   Max.   :0.7925   Max.   :13069
## (Other)    : 0
```

```r
summary(subset(yield_data, site_year == "Marysville-18"))
```

```
##          site_year     n_uptake          ndvi            yield
## Marysville-18:24   Min.   : 3.826   Min.   :0.4500   Min.   : 8046
## Arbuckle-15  : 0   1st Qu.:13.828   1st Qu.:0.6669   1st Qu.:10887
## RES-15       : 0   Median :15.784   Median :0.6950   Median :11352
## Davis-16     : 0   Mean   :14.202   Mean   :0.6619   Mean   :11000
## RES-16       : 0   3rd Qu.:16.954   3rd Qu.:0.7206   3rd Qu.:11490
## Nicolaus-17  : 0   Max.   :20.240   Max.   :0.7500   Max.   :12246
## (Other)      : 0
```

```r
summary(subset(yield_data, site_year == "Nicolaus-18"))
```

```
##         site_year     n_uptake           ndvi             yield      
##  Nicolaus-18:24   Min.   : 4.603   Min.   :0.5825   Min.   : 8961  
##  Arbuckle-15: 0   1st Qu.:11.428   1st Qu.:0.7125   1st Qu.:12688  
##  RES-15     : 0   Median :15.108   Median :0.7375   Median :13289  
##  Davis-16   : 0   Mean   :14.603   Mean   :0.7170   Mean   :12793  
##  RES-16     : 0   3rd Qu.:18.685   3rd Qu.:0.7575   3rd Qu.:13794  
##  Nicolaus-17: 0   Max.   :22.352   Max.   :0.7725   Max.   :14391  
##  (Other)    : 0
```

```r
summary(yield_data)
```

```
##           site_year     n_uptake             ndvi             yield      
##  Nicolaus-17   :28   Min.   : 0.9657   Min.   :0.1467   Min.   : 2948  
##  Williams-17   :28   1st Qu.: 7.4993   1st Qu.:0.6567   1st Qu.:10442  
##  Arbuckle-18   :24   Median :11.8504   Median :0.7133   Median :11741  
##  Marysville-18:24   Mean   :11.9420   Mean   :0.6814   Mean   :11291  
##  Nicolaus-18   :24   3rd Qu.:16.2583   3rd Qu.:0.7575   3rd Qu.:12773  
##  Biggs-18      :23   Max.   :25.5772   Max.   :0.8233   Max.   :14675  
##  (Other)       :80
```

```r
yield_avgs <- yield_data %>%
  group_by(site_year) %>%
  summarise(avg_yield = mean(yield)) #average yield for all sites

yield_avgs
```

```
## # A tibble: 10 x 2
##    site_year     avg_yield
##    <fct>             <dbl>
##  1 Arbuckle-15      12072.
##  2 RES-15           11753.
##  3 Davis-16         10599.
##  4 RES-16           11246.
##  5 Nicolaus-17      12005.
##  6 Williams-17      10159.
##  7 Arbuckle-18       9980.
##  8 Biggs-18         11468.
##  9 Marysville-18    11000.
## 10 Nicolaus-18      12793.
```

```r
cv(yield_avgs$avg_yield)
```

```
## [1] 7.901049
```

Model (Yield ~ N Uptake)

```r
set.seed(10)

lin.mod <- lm(yield ~ n_uptake, data = yield_data)
segmented.mod <- segmented(lin.mod , seg.Z = ~n_uptake, psi = 9)
summary(segmented.mod)
```

```
##
```

```
##  ***Regression Model with Segmented Relationship(s)***
##
## Call:
## segmented.lm(obj = lin.mod, seg.Z = ~n_uptake, psi = 9)
##
## Estimated Break-Point(s):
##    Est. St.Err
##  9.397  0.451
##
## Meaningful coefficients of the linear terms:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  4707.63     422.66   11.14   <2e-16 ***
## n_uptake      805.77      69.91   11.53   <2e-16 ***
## U1.n_uptake  -800.46      75.65  -10.58       NA
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 1332 on 227 degrees of freedom
## Multiple R-Squared: 0.6397,  Adjusted R-squared: 0.6349
##
## Convergence attained in 5 iterations with relative change 1.091534e-05
```

```r
my.fitted <- fitted(segmented.mod)
my.model <- data.frame(yield_data$n_uptake , my.fitted)
mse.seg.mod<- mean(residuals(segmented.mod)^2)
rmse.seg.mod <- sqrt(mse.seg.mod)
rmse.seg.mod
```

```
## [1] 1320.506
```

```r
confint.segmented(segmented.mod)
```

```
## $n_uptake
##     Est. CI(95%).l CI(95%).u
##  9.39736   8.50782   10.2869
```

```r
pscore.test(lin.mod, seg.Z = ~n_uptake, k = 10)
```

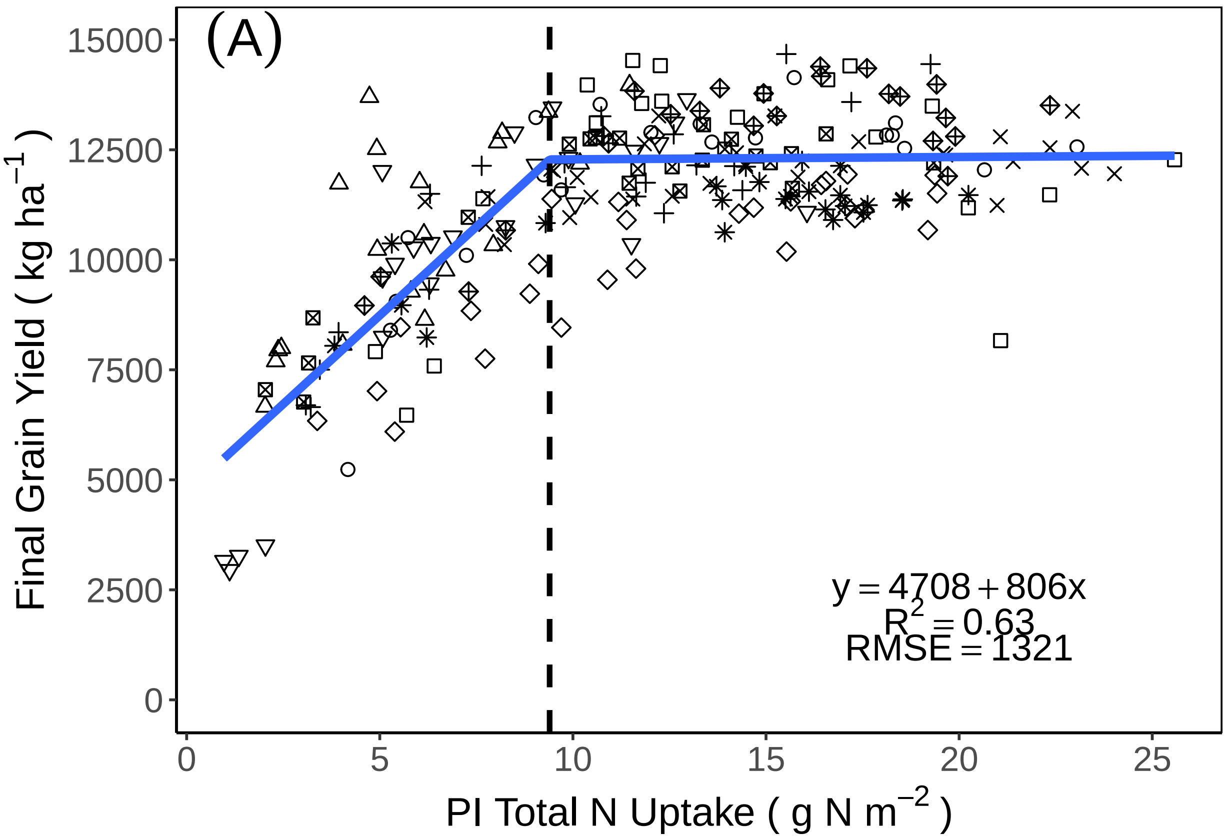
```
##
##  Score test for one change in the slope
##
## data:  formula = yield ~ n_uptake ,   method = lm
## model = gaussian , link = identity
## segmented variable = n_uptake
## observed value = -9.1617, n.points = 10, p-value < 2.2e-16
## alternative hypothesis: two.sided
```

```r
breakpoint <- segmented.mod$psi[2]
prediction <- nup_a*(breakpoint^2) + nup_b*breakpoint + nup_c
prediction
```

```
## [1] 0.664761
```

Plot (Yield ~ N Uptake)

```r
aaa <- ggplot(data = yield_data , aes(x = n_uptake , y = yield )) +
  geom_point(mapping = aes(n_uptake , yield , shape = site_year) , data = yield_data, size = 2) +
  theme_classic() +
  labs( x = "PI Total N Uptake ( g N m"^-2~")" , y = "Final Grain Yield ( kg ha"^-1~")", shape = "Site-Y
  theme(axis.title = element_text(size = 15)) +
  theme(axis.text = element_text(size = 13)) +
  theme(legend.text = element_text(size = 11)) +
  theme(legend.title = element_text(size = 13)) +
  scale_shape_manual(values = seq(0,10)) +
  theme(legend.position = "none") +
  theme(panel.background = element_rect(fill = "white", color = "grey0")) +
  scale_x_continuous(breaks = c(0, 5, 10, 15, 20, 25, 30)) +
  scale_y_continuous(breaks = c(0, 2500, 5000, 7500, 10000, 12500, 15000)) +
  expand_limits(y = 0) +
  geom_line(data = my.model, aes(x = yield_data$n_uptake , y = my.fitted), size = 1.5 , color = "#3366FF
  geom_vline( xintercept = segmented.mod$psi[2] , color = "black" , lty = 2 , size = 1)

label_aaa_1 <- paste("(A)")
label_aaa_2 <- paste(" y == 4708 + 806 * x")
label_aaa_3 <- paste("R^2 == 0.63")
label_aaa_4 <- paste("RMSE == 1321")

aaa <- aaa + annotate("text", x = 1.5, y = 15000, label = label_aaa_1, color="black", size = 7, parse =
aaa <- aaa + annotate("text", x = 20, y = 2500, label = label_aaa_2, color="black", size = 5, parse = TR
aaa <- aaa + annotate("text", x = 20, y = 1900, label = label_aaa_3, color="black", size = 5, parse = TR
aaa <- aaa + annotate("text", x = 20, y = 1200, label = label_aaa_4, color="black", size = 5, parse = TR

aaa
```



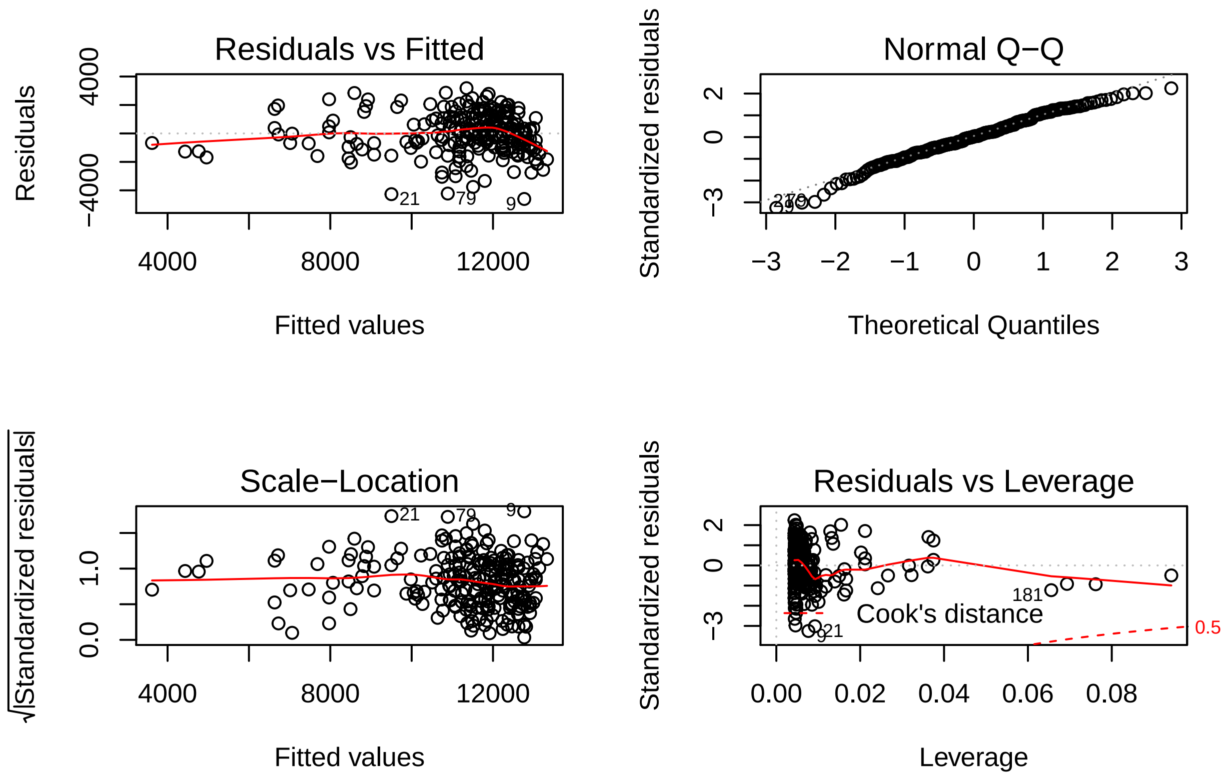
Model (Yield ~ NDVI)

```
fm1yield.lm <- lm(yield ~ ndvi, data = yield_data)
summary(fm1yield.lm)
```

```
##
## Call:
## lm(formula = yield ~ ndvi, data = yield_data)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -4605.3  -866.4    48.3  1013.5  3180.8
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   1513.5      551.1   2.746   0.0065 **
## ndvi         14349.3      797.0  18.005   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 1422 on 229 degrees of freedom
## Multiple R-squared:  0.586,  Adjusted R-squared:  0.5842
## F-statistic: 324.2 on 1 and 229 DF,  p-value: < 2.2e-16
```

```
#tests of normality, linear regression assumptions follow
par(mfrow=c(2,2))
```

```r
plot(fm1yield.lm)
```




```r
acf(fm1yield.lm$residuals)
cor.test(yield_data$ndvi, fm1yield.lm$residuals)
```

```
##
##  Pearson's product-moment correlation
##
## data:  yield_data$ndvi and fm1yield.lm$residuals
## t = 2.0689e-15, df = 229, p-value = 1
## alternative hypothesis: true correlation is not equal to 0
## 95 percent confidence interval:
##  -0.1290777  0.1290777
## sample estimates:
##          cor
## 1.367174e-16
```

```r
mean(fm1yield.lm$residuals)
```

```
## [1] 1.095343e-13
```

```r
x<- resid(fm1yield.lm)
shapiro.test(x)
```

```
##
##  Shapiro-Wilk normality test
##
## data:  x
## W = 0.98648, p-value = 0.02762
```

```r
mse.yield.mod<- mean(residuals(fm1yield.lm)^2)
mse.yield.mod
```

```
## [1] 2003482
```

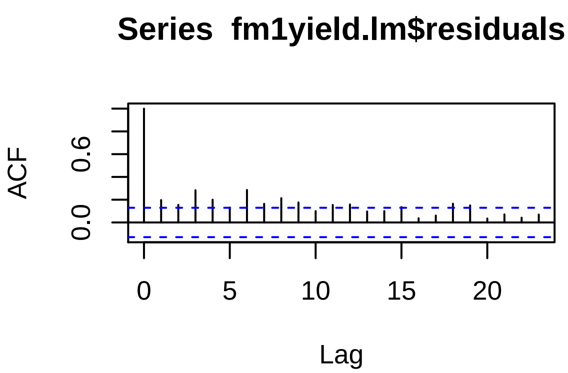
```r
rmse.yield.mod <- sqrt(mse.yield.mod)
rmse.yield.mod
```

```
## [1] 1415.444
```

```r
var(yield_data$ndvi)
```

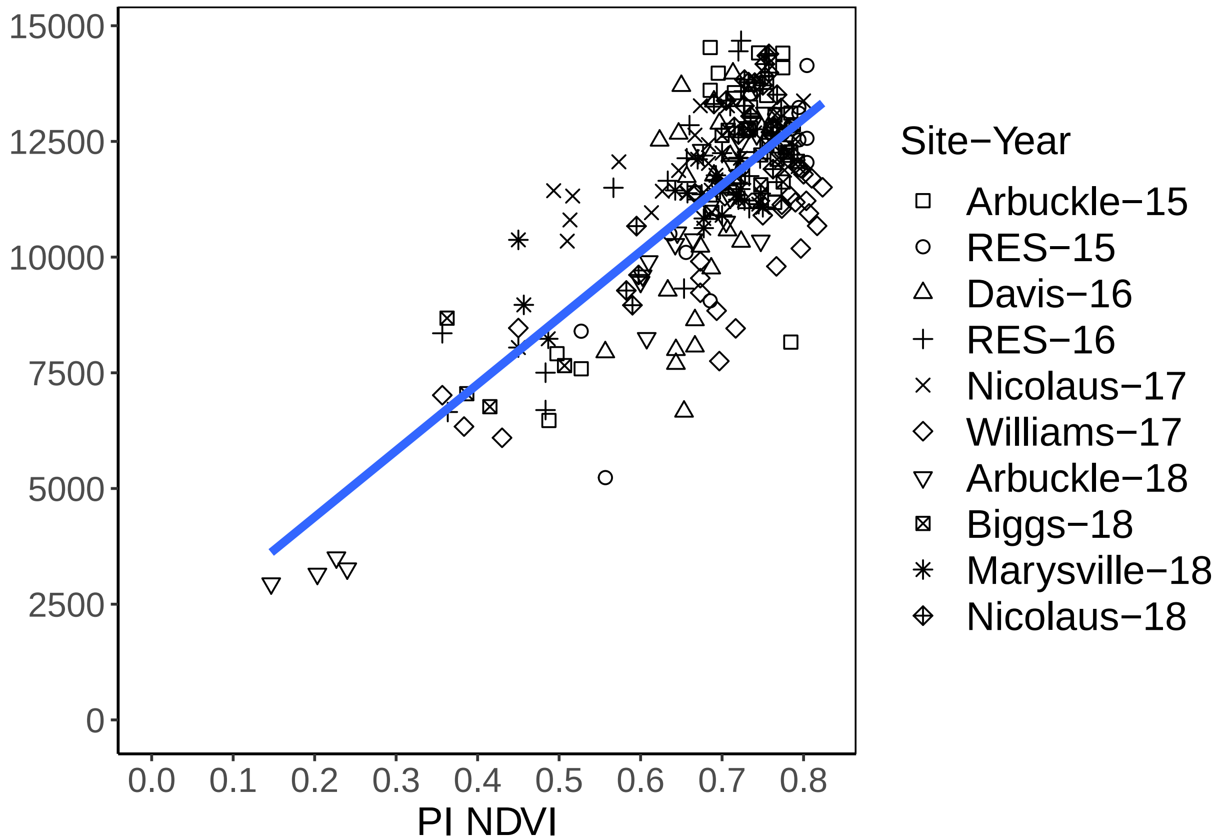
```
## [1] 0.01383443
```

```r
predicted_fm1yield <- fitted(fm1yield.lm)
fitted_fm1yield <- data.frame(yield_data$ndvi , predicted_fm1yield)
```

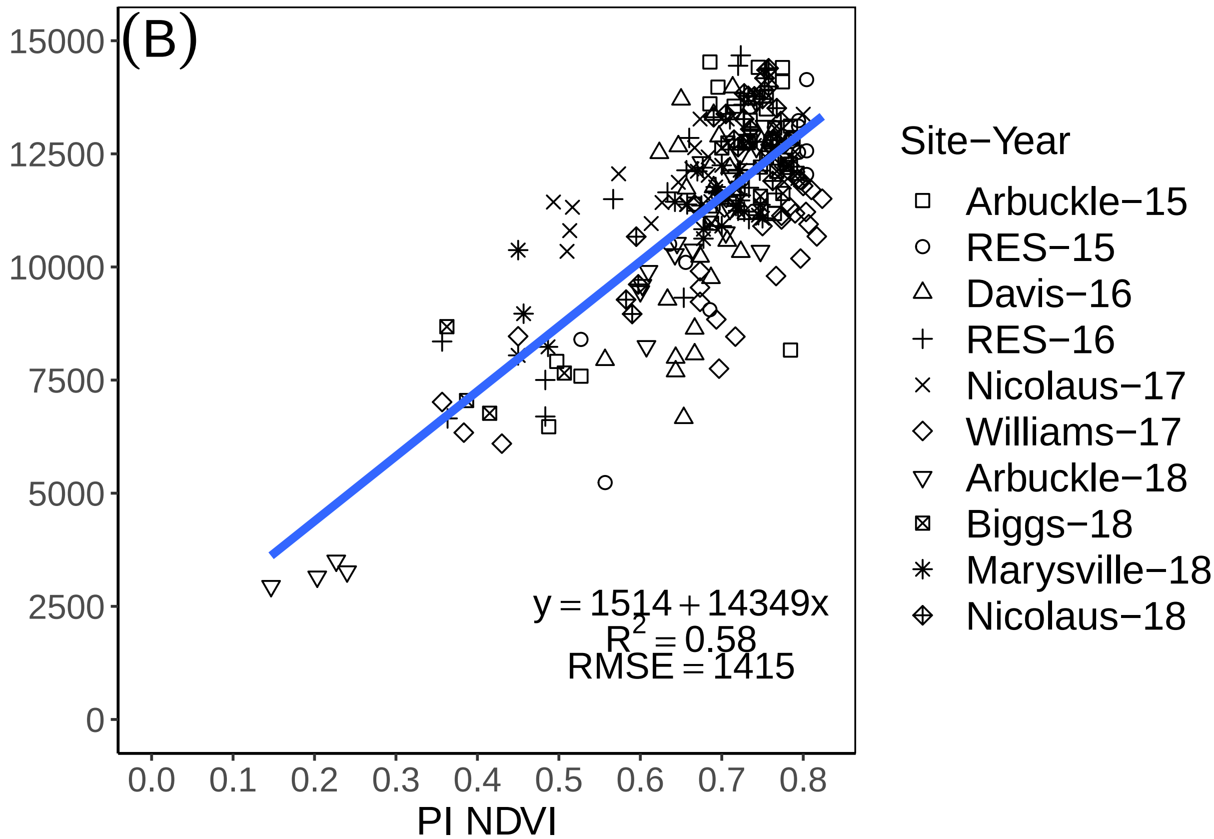


Plot Yield ~ NDVI

```r
bbb <- ggplot(data = yield_data , aes(x = ndvi , y = yield )) +
  geom_point(mapping = aes(ndvi , yield , shape = site_year) , data = yield_data, size = 2) +
  theme_classic() +
  labs( x = "PI NDVI" , y = NULL, shape = "Site-Year") +
 theme(axis.title = element_text(size = 15)) +
  theme(axis.text = element_text(size = 13)) +
  theme(legend.text = element_text(size = 15)) +
  theme(legend.title = element_text(size = 15)) +
  scale_shape_manual(values = seq(0,10)) +
  theme(plot.title = element_text(size = 15, hjust = .5)) +
  theme(panel.background = element_rect(fill = "white", color = "grey0")) +
  scale_x_continuous(breaks = c(0, 0.10, .20, .30, .40, .50, .60, .70, .80, .90, 1.0)) +
  scale_y_continuous(breaks = c(0, 2500, 5000, 7500, 10000, 12500, 15000)) +
  expand_limits(x = 0, y = 0) +
  geom_line(data = fitted_fm1yield, aes(x = yield_data$ndvi , y = predicted_fm1yield) , size = 1.5 , co

bbb
```




```
label_bbb_1 <- paste("(B)")
label_bbb_2 <- paste(" y == 1514 + 14349 * x")
label_bbb_3 <- paste("R^2 == 0.58")
label_bbb_4 <- paste("RMSE == 1415")

bbb <- bbb + annotate("text", x = .01, y = 15000, label = label_bbb_1, color="black", size = 7, parse =
bbb <- bbb + annotate("text", x = .65, y = 2500, label = label_bbb_2, color="black", size = 5, parse =
bbb <- bbb + annotate("text", x = .65, y = 1900, label = label_bbb_3, color="black", size = 5, parse =
bbb <- bbb + annotate("text", x = .65, y = 1200, label = label_bbb_4, color="black", size = 5, parse =

bbb
```




```
g_legend <- function(bbb){
  tmp <- ggplot_gtable(ggplot_build(bbb))
  leg <- which(sapply(tmp$grobs, function(x) x$name) == "guide-box")
  legend <- tmp$grobs[[leg]]
  return(legend)}
legend3 <- g_legend(bbb) #extracts the legend from plot c

bbb <- bbb +
  theme(legend.position = "none")



bbb
```

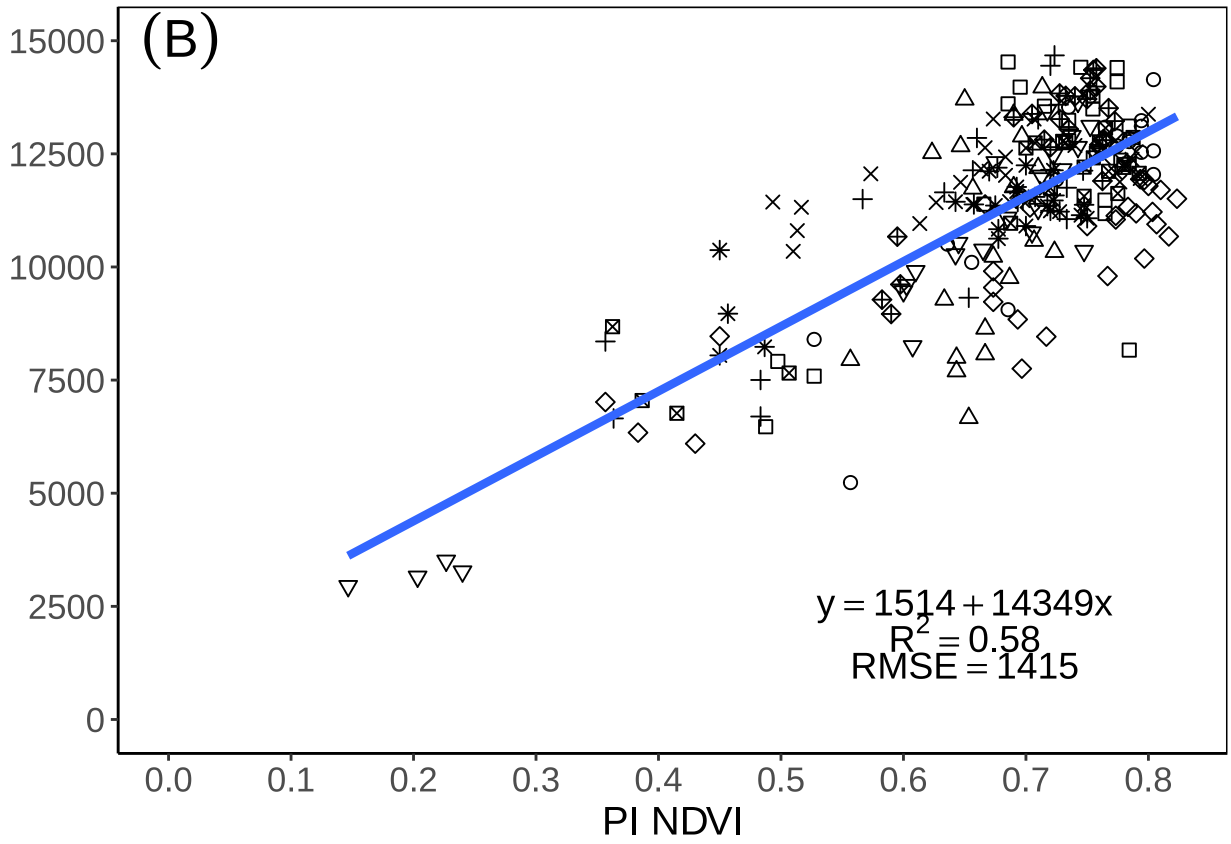
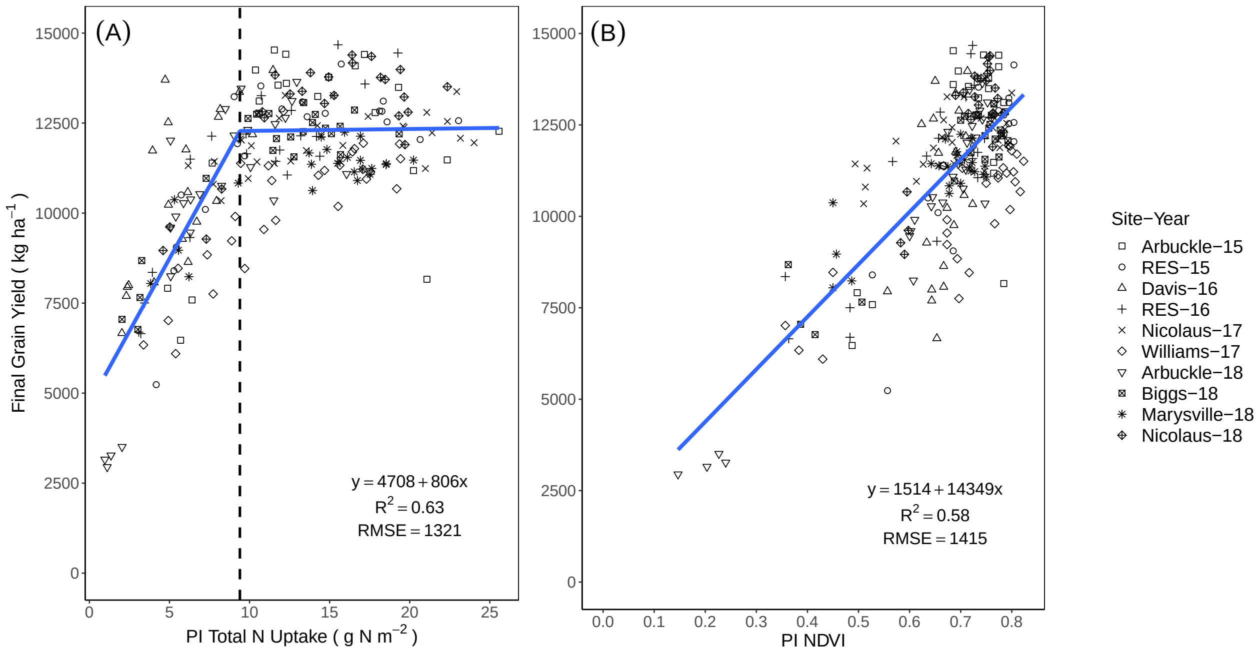


Figure 3

```
zzz <- grid.arrange(arrangeGrob(aaa,
                                bbb,
                                legend3,
                                ncol = 3,
                                nrow = 1,
                           widths = c(3,3,1.5)))
```




```r
ggsave("Figure_3.tiff" , zzz,  device = "tiff" )
```

```
## Saving 15 x 7.5 in image
```

```r
Sys.time()
```

```
## [1] "2019-02-27 08:32:55 PST"
```