

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

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
```

R Markdown

This is an R Markdown document. Markdown is a simple formatting syntax for authoring HTML, PDF, and MS Word documents. For more details on using R Markdown see <http://rmarkdown.rstudio.com>.

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:

```
Sys.time()
```

```
## [1] "2019-03-19 15:48:55 PDT"
```

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 = "DATA/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

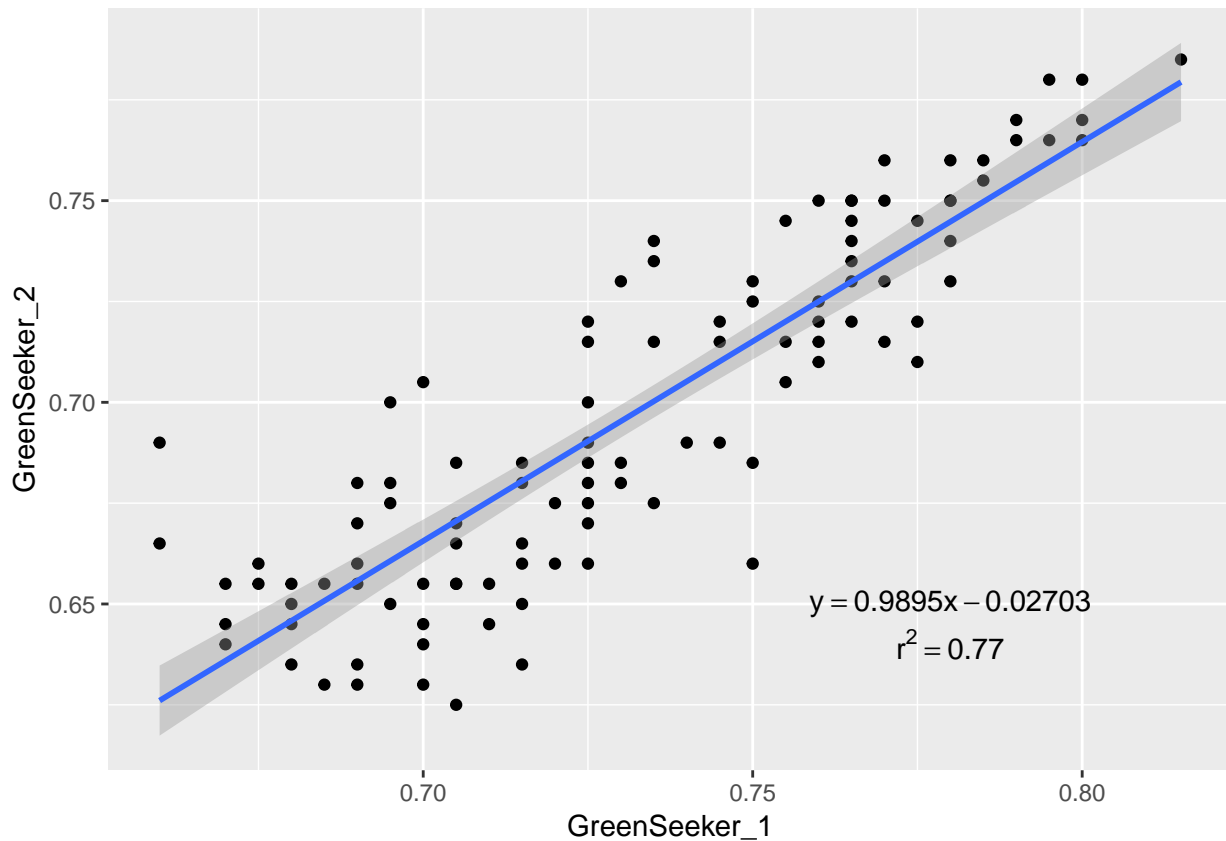
##
## Call:
## lm(formula = GreenSeeker_2 ~ GreenSeeker_1, data = GS_data)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.055099 -0.015309  0.000426  0.014429  0.063957
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -0.02703    0.03936  -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("FIGURES/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 separately from the Farm Survey data and then merged into a single data frame.

N Trial NDVI Data

```
ntrial_data <- read_csv(file = "DATA/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)) #normalizes the data for the two greenseeker

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(file = "DATA/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.
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
farmsurvey_data$NDVI_3 <- as.numeric(as.character(farmsurvey_data$NDVI_3))

## Warning: NAs introduced by coercion
farmsurvey_data$NDVI_4 <- as.numeric(as.character(farmsurvey_data$NDVI_4)) #gets the data right

## Warning: NAs introduced by coercion
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 ...

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 m2
          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): 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-15"))

```

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
##
```

```
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
##
```

```
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
##
```

```
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
##
```

```
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
##
```

```
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
##
```

```
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
##
```

```
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
##
```

```
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
##
```

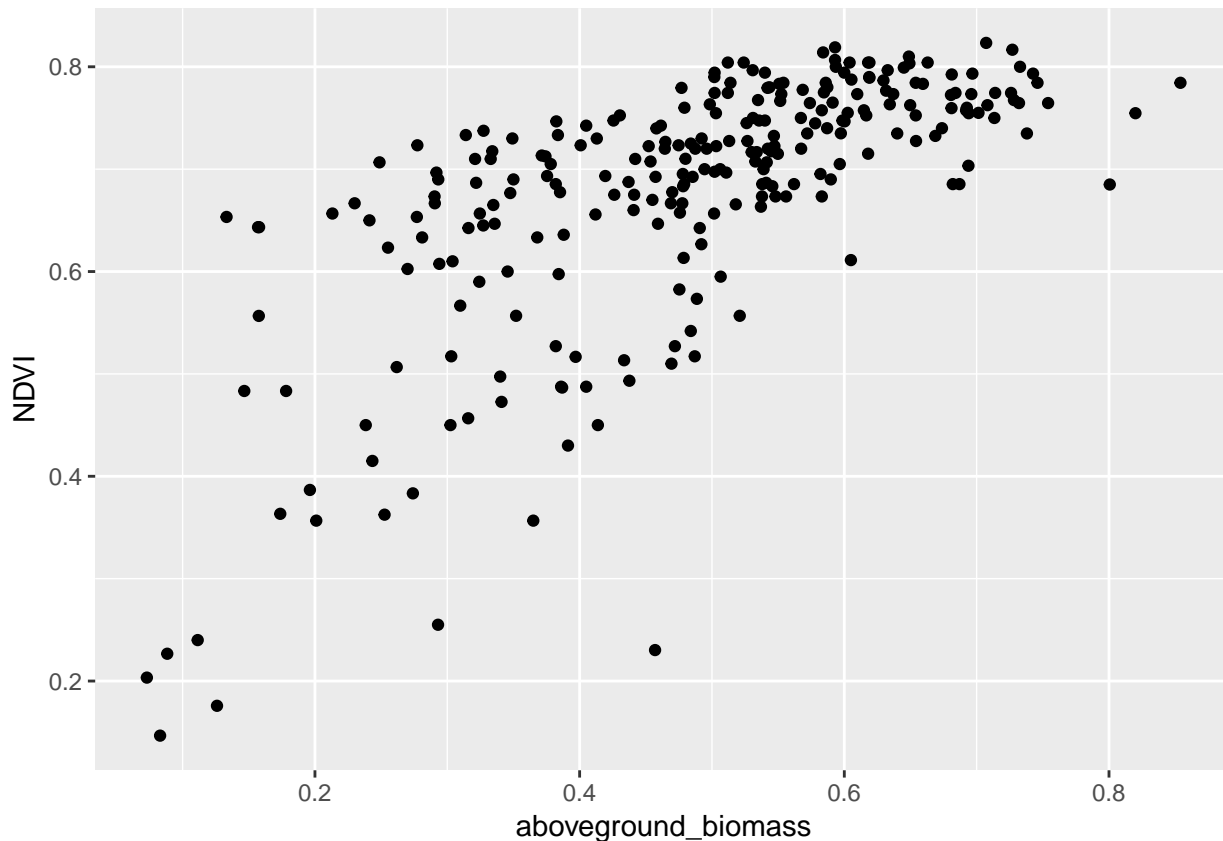
```
summary(ndvi_data)
```

```
##      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

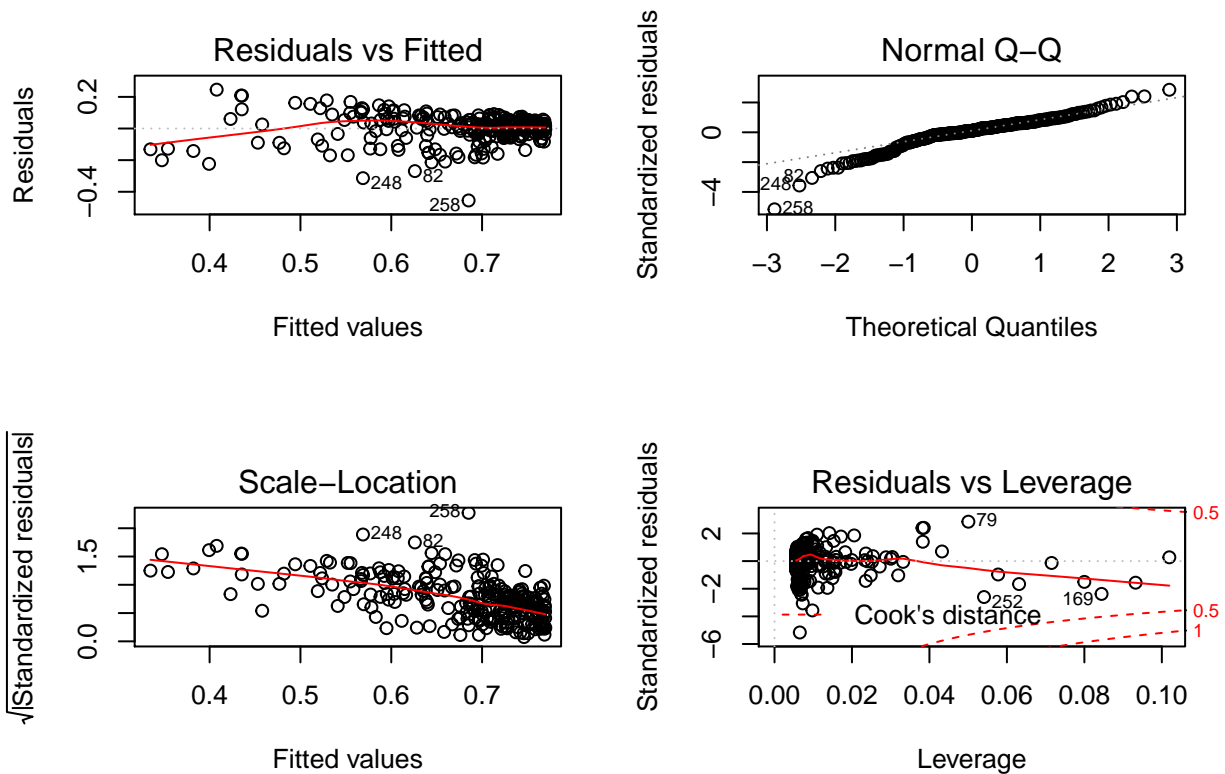
```
ggplot(data = ndvi_data, aes(x = aboveground_biomass , y = NDVI)) +
  geom_point(mapping = aes(aboveground_biomass, NDVI), data = ndvi_data) #visualizes
```



```
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
```

```
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
```

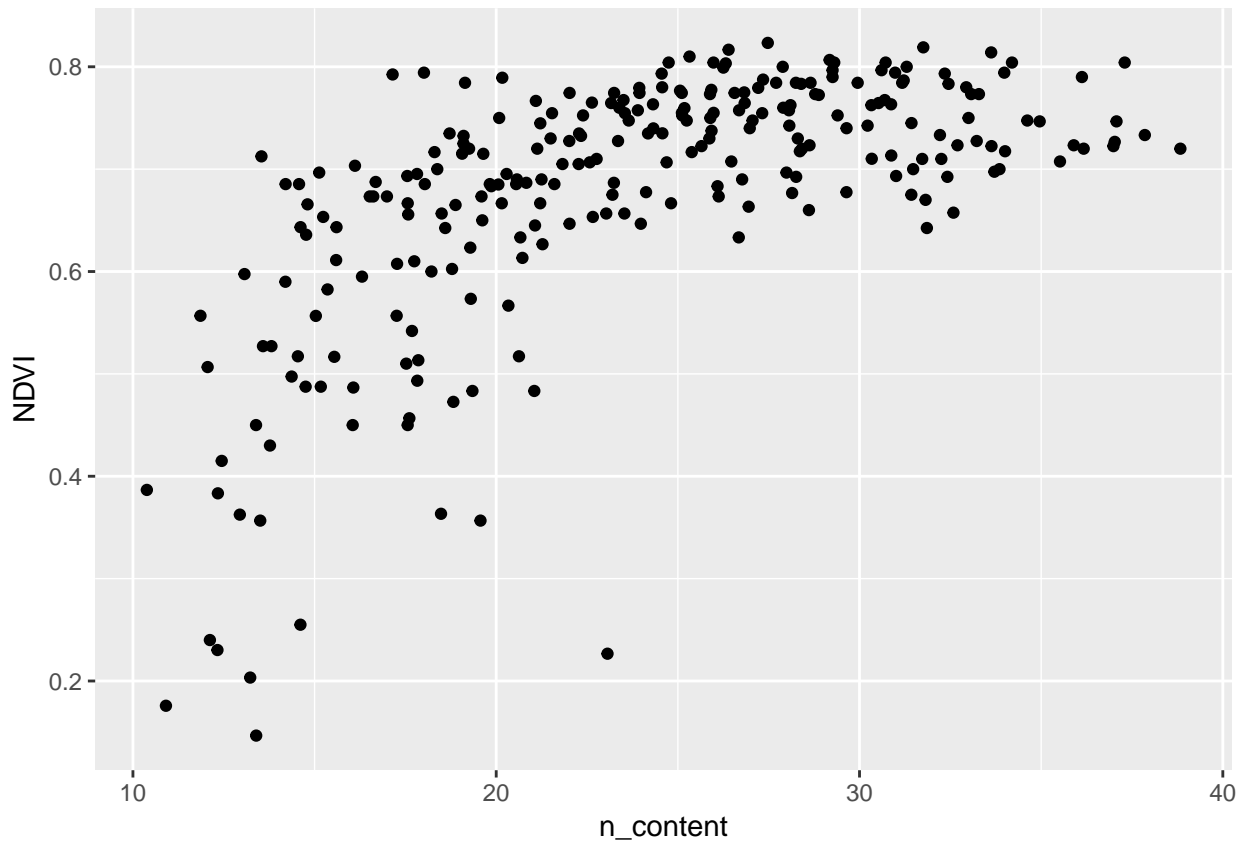
```
## [1] 0.5142801
```

```
abvsym_y
```

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

N Concentration

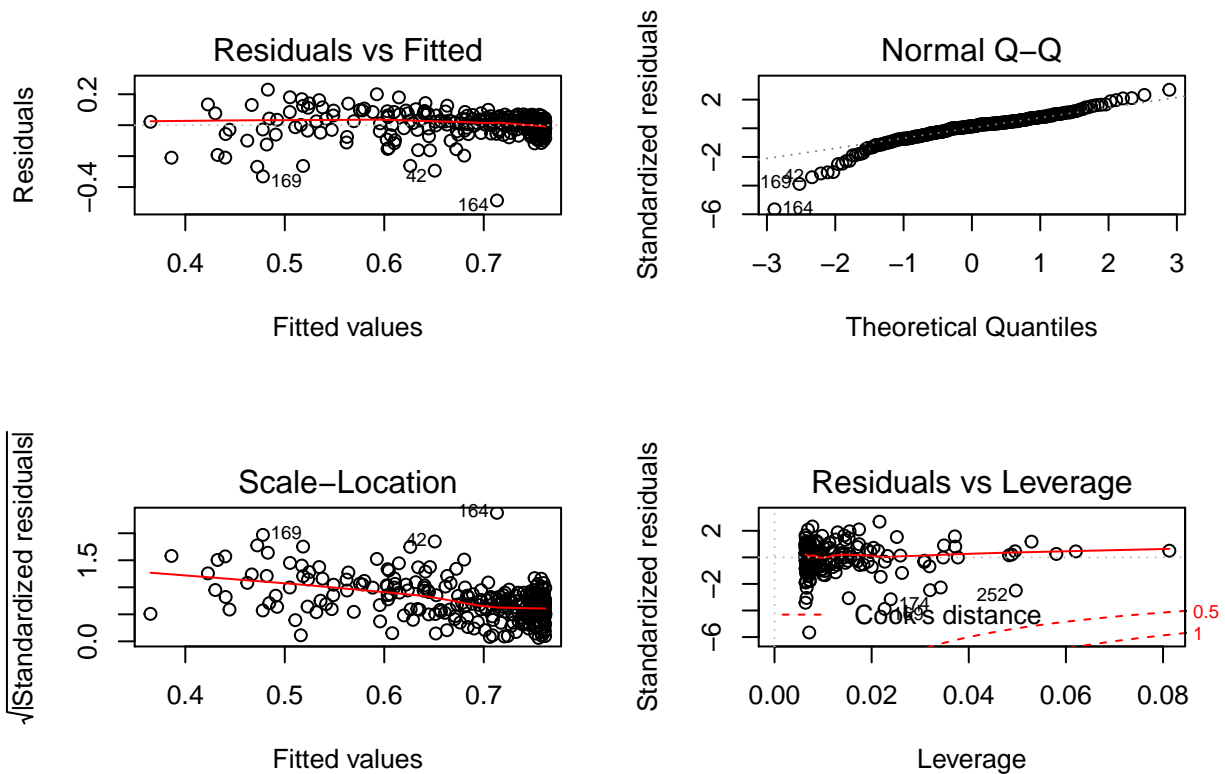
```
ggplot(data = ndvi_data, aes(x= n_content , y= NDVI)) +
  geom_point(mapping = aes(n_content, NDVI) , data = ndvi_data) #visualizes the data
```



```
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")

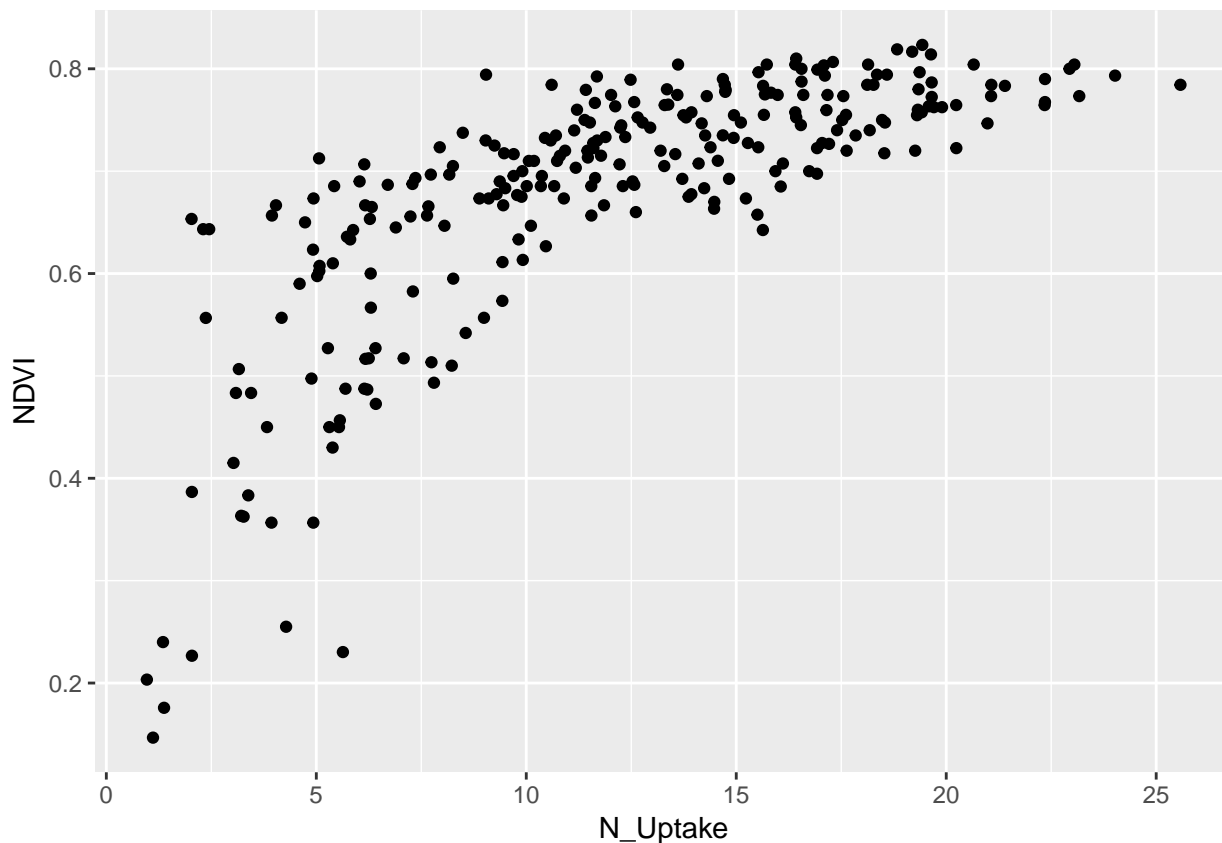
ncon_r2

## [1] 0.5359407
nconsym_y

## [1] 0.7618864
```

N Uptake

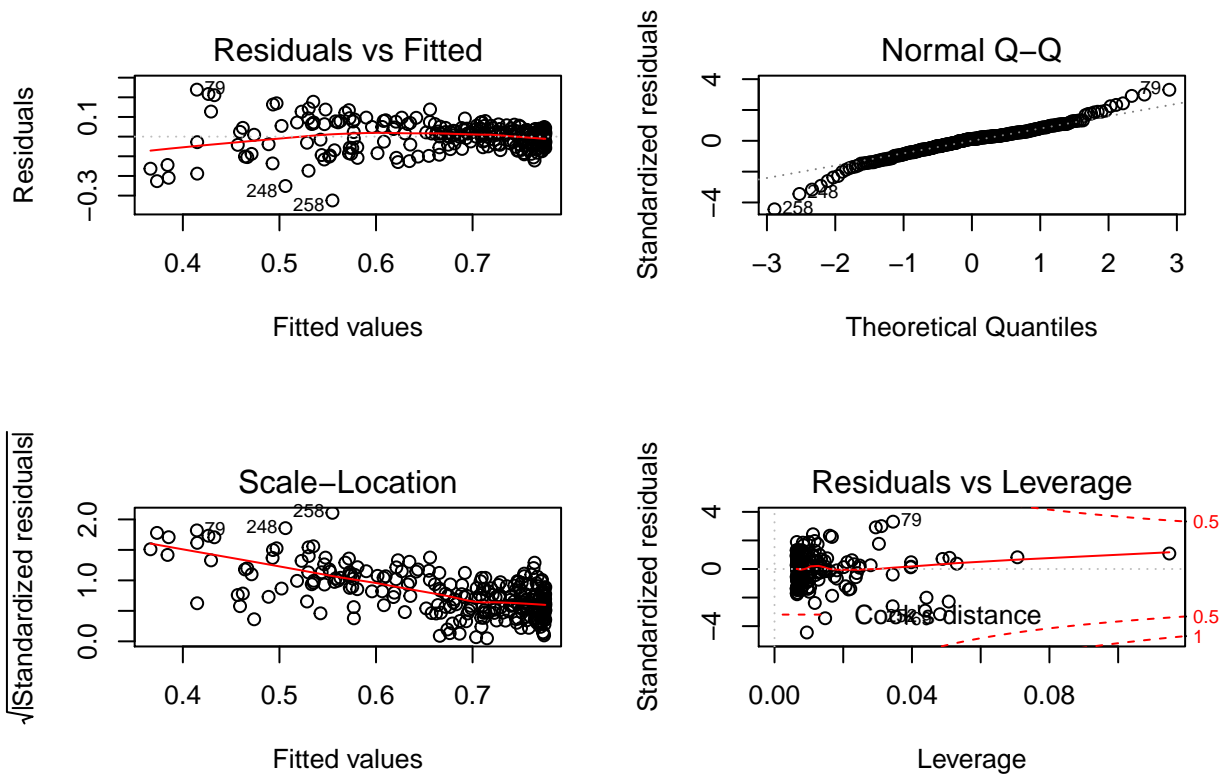
```
ggplot(data = ndvi_data , aes(x = N_Uptake , y = NDVI)) +
  geom_point(mapping = aes(N_Uptake , NDVI), data = ndvi_data) #visualizes the data
```



```
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
```

```
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

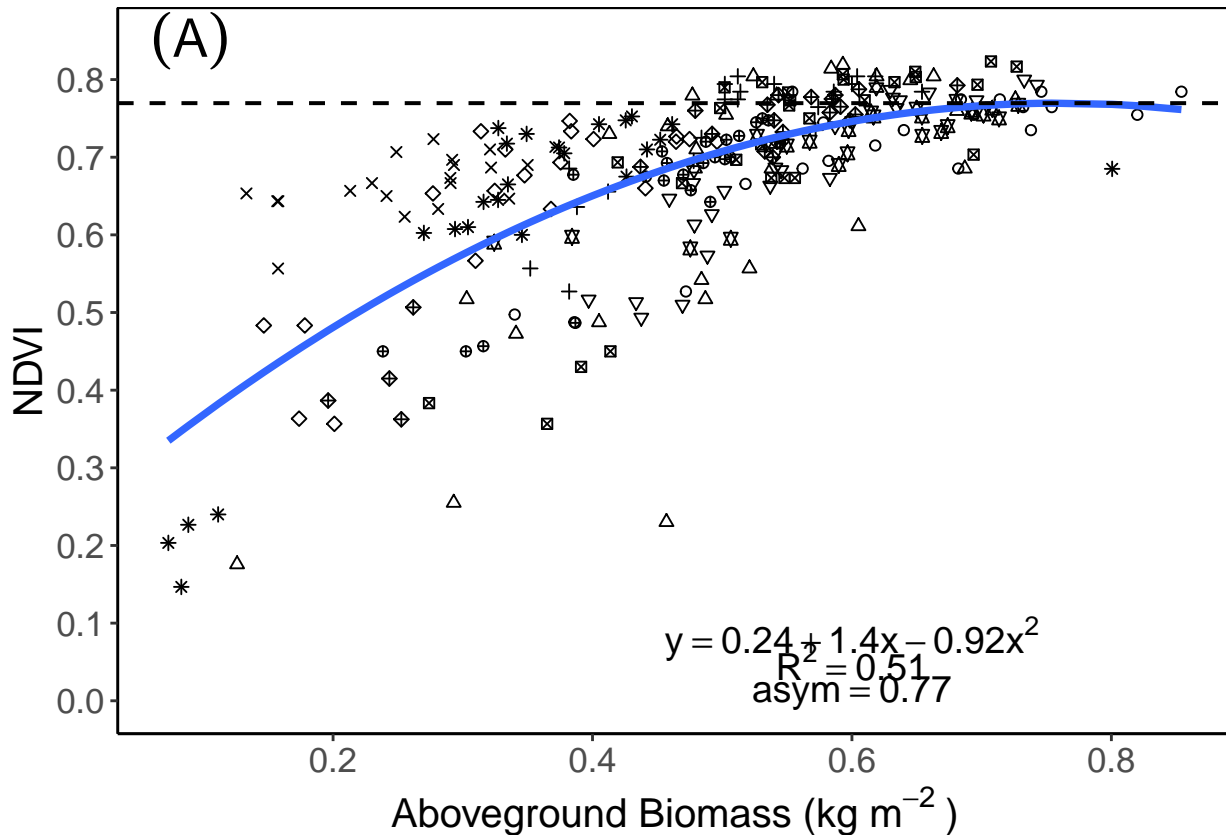
```
a <- ggplot( data = ndvi_data , aes ( x = aboveground_biomass , y = NDVI)) +
  geom_point(mapping = aes(aboveground_biomass , NDVI, shape = factor(site_year)) , data = ndvi_data ) +
  theme_classic() +
  labs( x = "Aboveground Biomass (kg m^-2)" , y = "NDVI" , shape = "Site Year" ) +
```

```

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() +

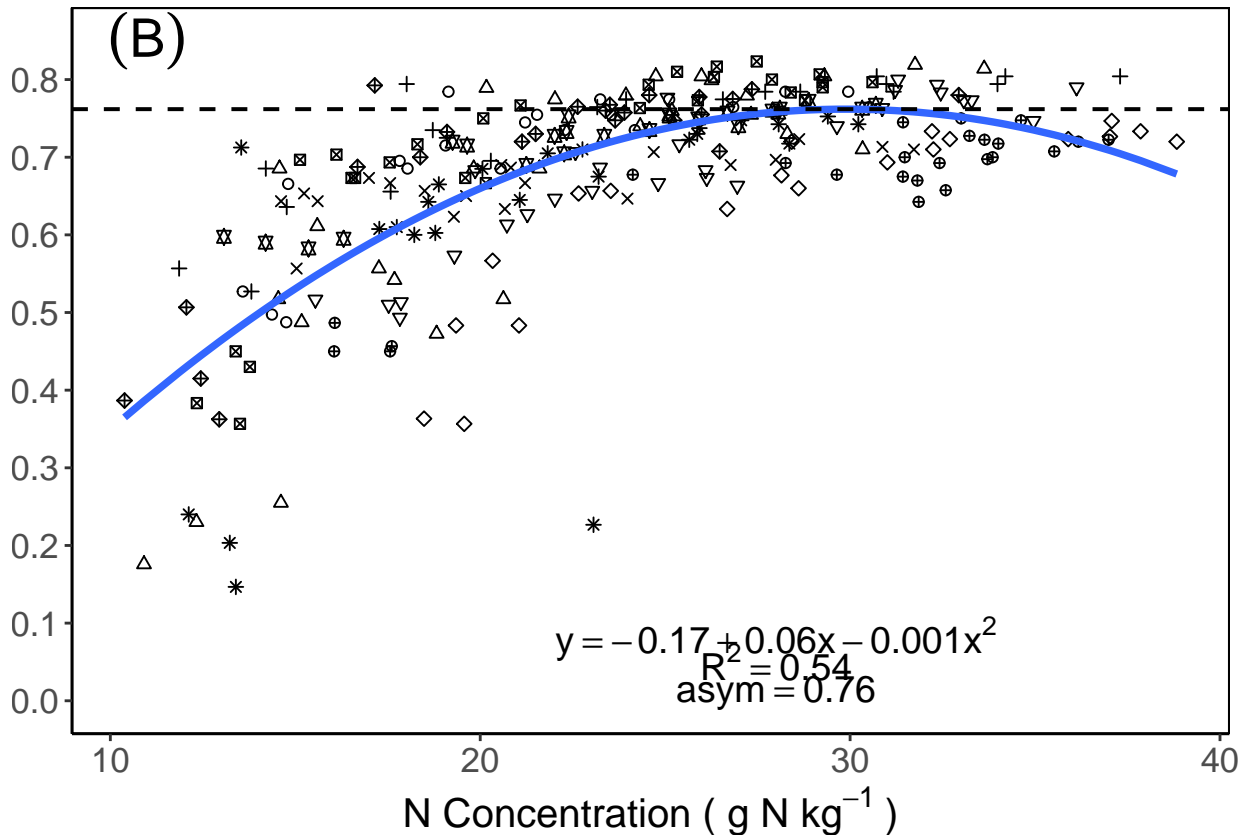
```

```

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 = "#0000FF") +
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 = "R2 == 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() +

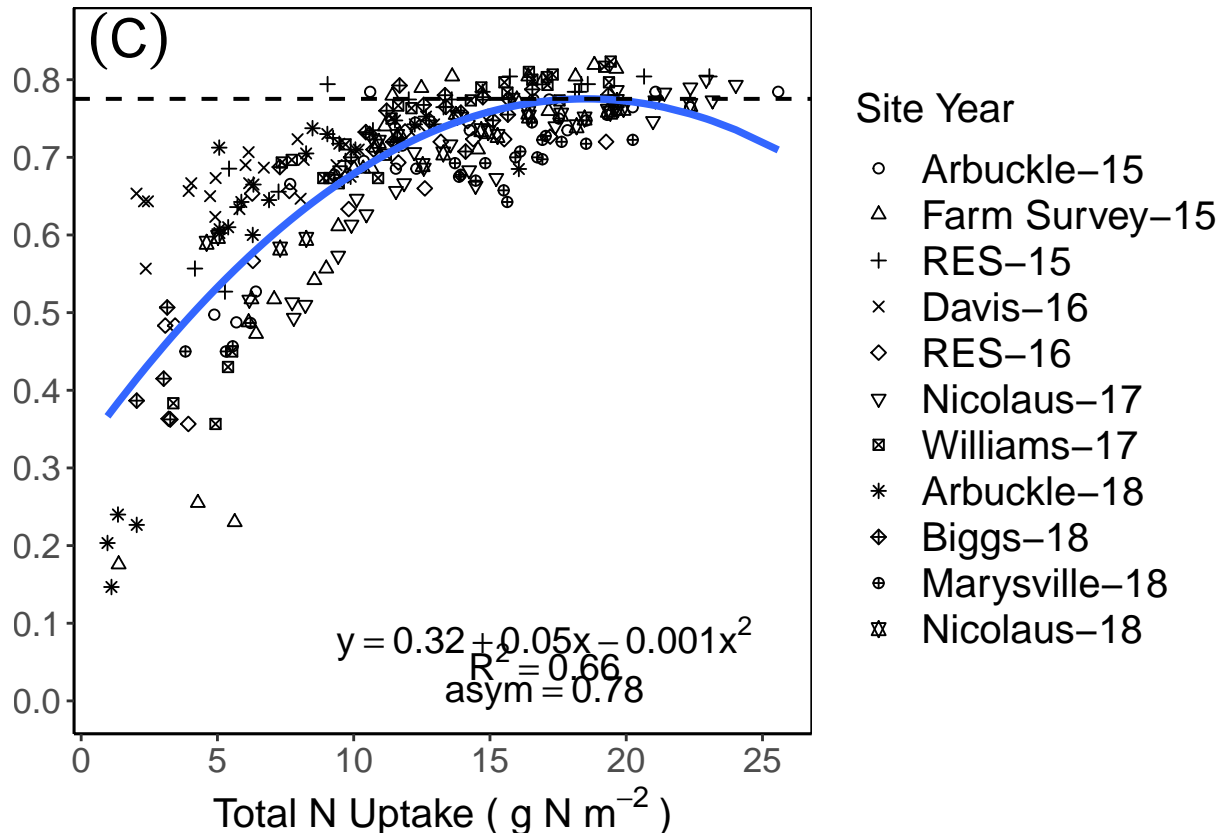
```

```

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 = "blue") +
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 = "R2 == 0.66" , size = 5 , parse = TRUE) +
annotate("text", x = 17 , y = 0.01 , label = "asym == 0.78" , size = 5 , parse = TRUE)

```

c



```

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

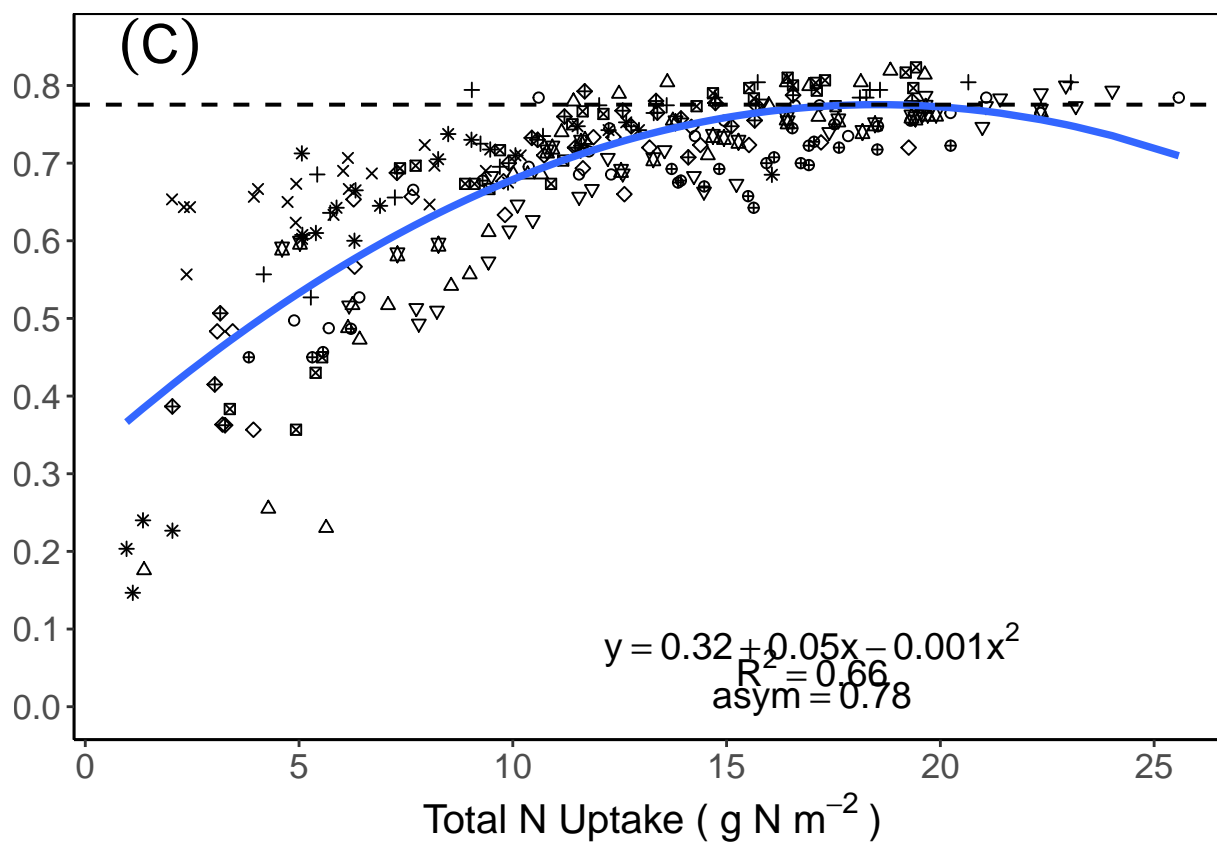
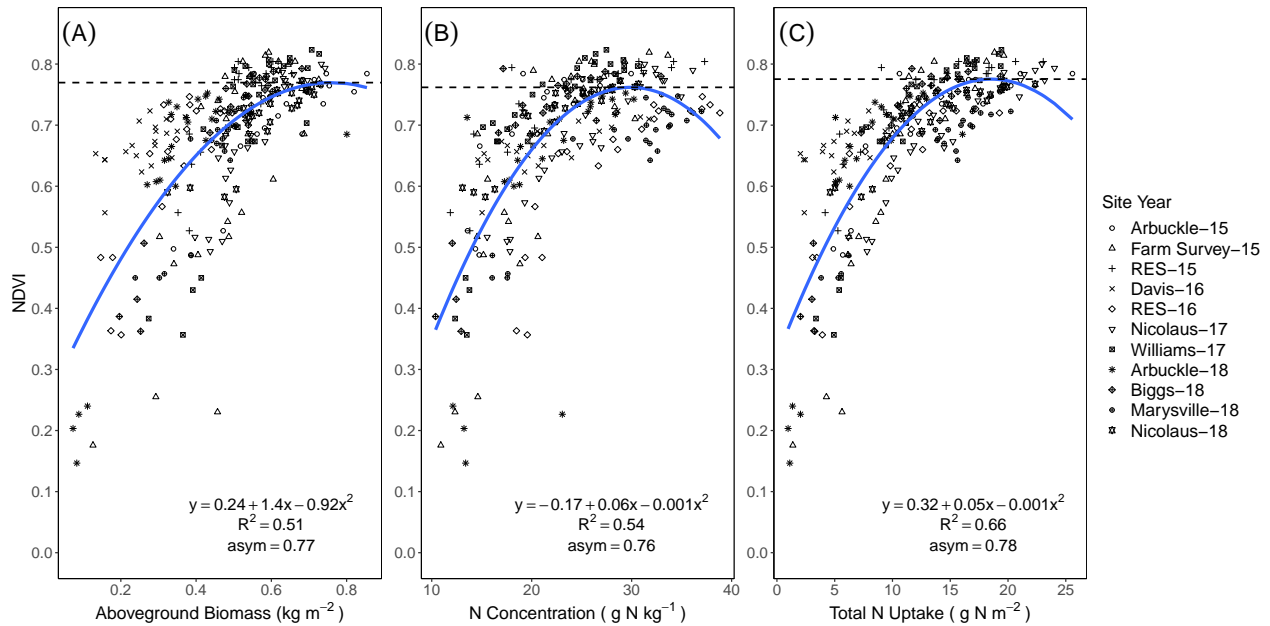


Figure 2

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



```
ggsave("FIGURES/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(file = "DATA/yeild_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()
## )
```

```
## )

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()
## .. )

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
```

```

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 essentially 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>

```

```
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>

```

```
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()
## .. )

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 ...

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 ...

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
```

```
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
```

```
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
```

```
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 for
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
```

```
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
```

```
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
```

```
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 ...
```

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

Table 4

```
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 | | | |

```
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 | | | |

```
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 | | | |

```
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
```

```
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
```

```
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
```

```
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
```

```
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
```

```
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
```



```
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
```

```
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
```

```
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.
```

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

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

Model (Yield ~ N Uptake)

```
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

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

confint.segmented(segmented.mod)

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

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

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

## [1] 0.664761

```

Plot (Yield ~ N Uptake)

```

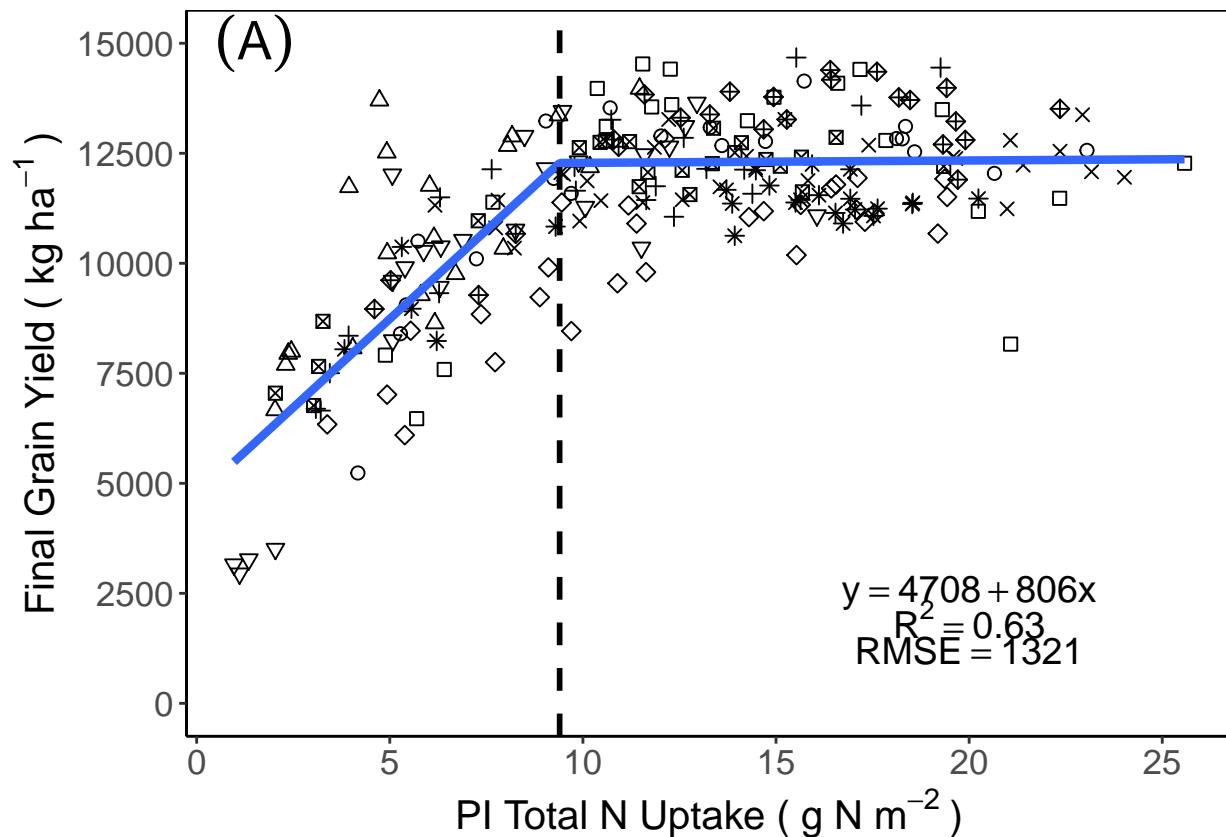
aaa <- ggplot(data = yield_data , aes(x = n_uptake , y = yield )) +
  geom_point(mapping = aes(n_uptake , yield , shape = site_year) , data = yield_data, size = 2) +
  theme_classic() +
  labs( x = "PI Total N Uptake ( g N m-2)" , y = "Final Grain Yield ( kg ha-1)" , shape = "Site-year")
  theme(axis.title = 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("R2 == 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 = TRUE)
aaa <- aaa + annotate("text", x = 20, y = 2500, label = label_aaa_2, color="black", size = 5, parse = TRUE)
aaa <- aaa + annotate("text", x = 20, y = 1900, label = label_aaa_3, color="black", size = 5, parse = TRUE)
aaa <- aaa + annotate("text", x = 20, y = 1200, label = label_aaa_4, color="black", size = 5, parse = TRUE)

aaa

```

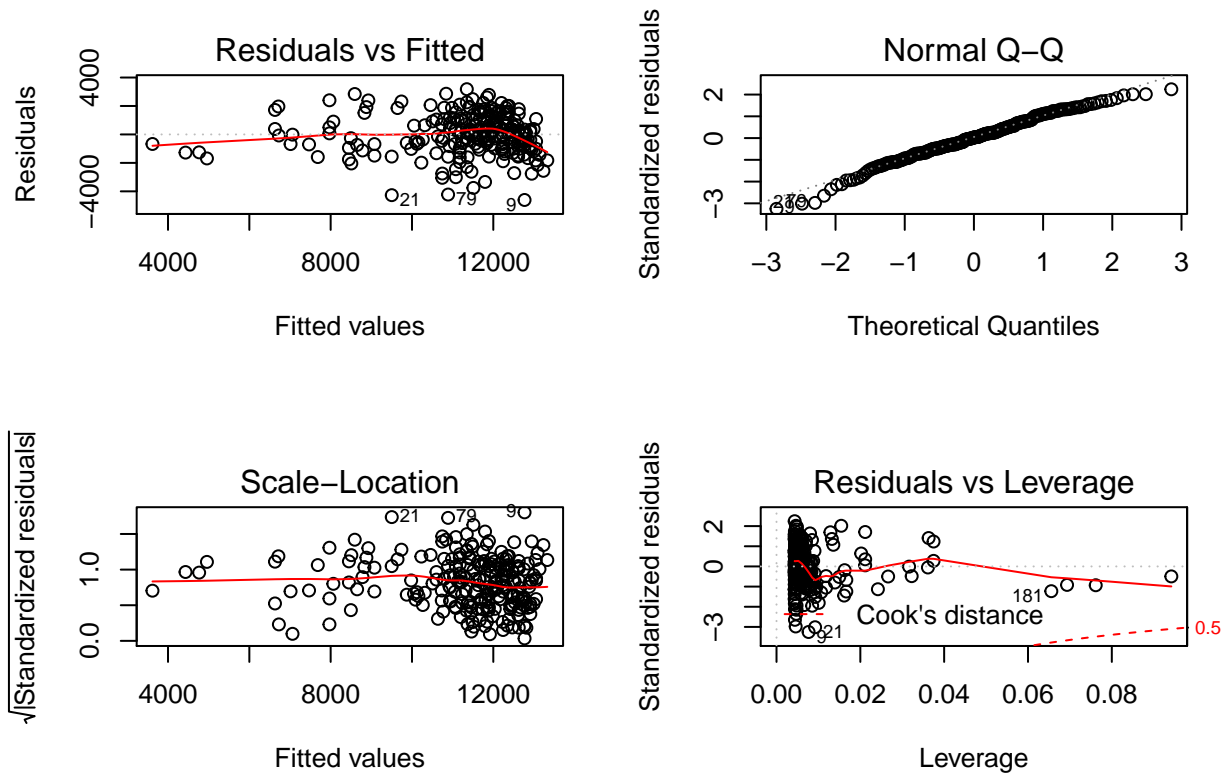


Model (Yield ~ NDVI)

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

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



```
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
```

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

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

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

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

```

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

## [1] 2003482

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

## [1] 1415.444

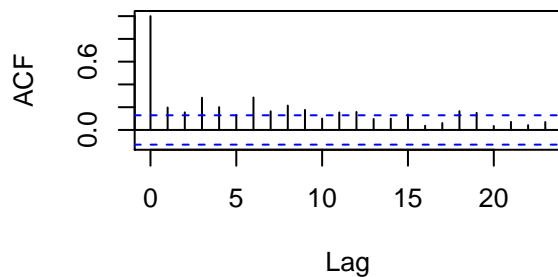
var(yield_data$ndvi)

## [1] 0.01383443

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

```

Series fm1yield.lm\$residuals

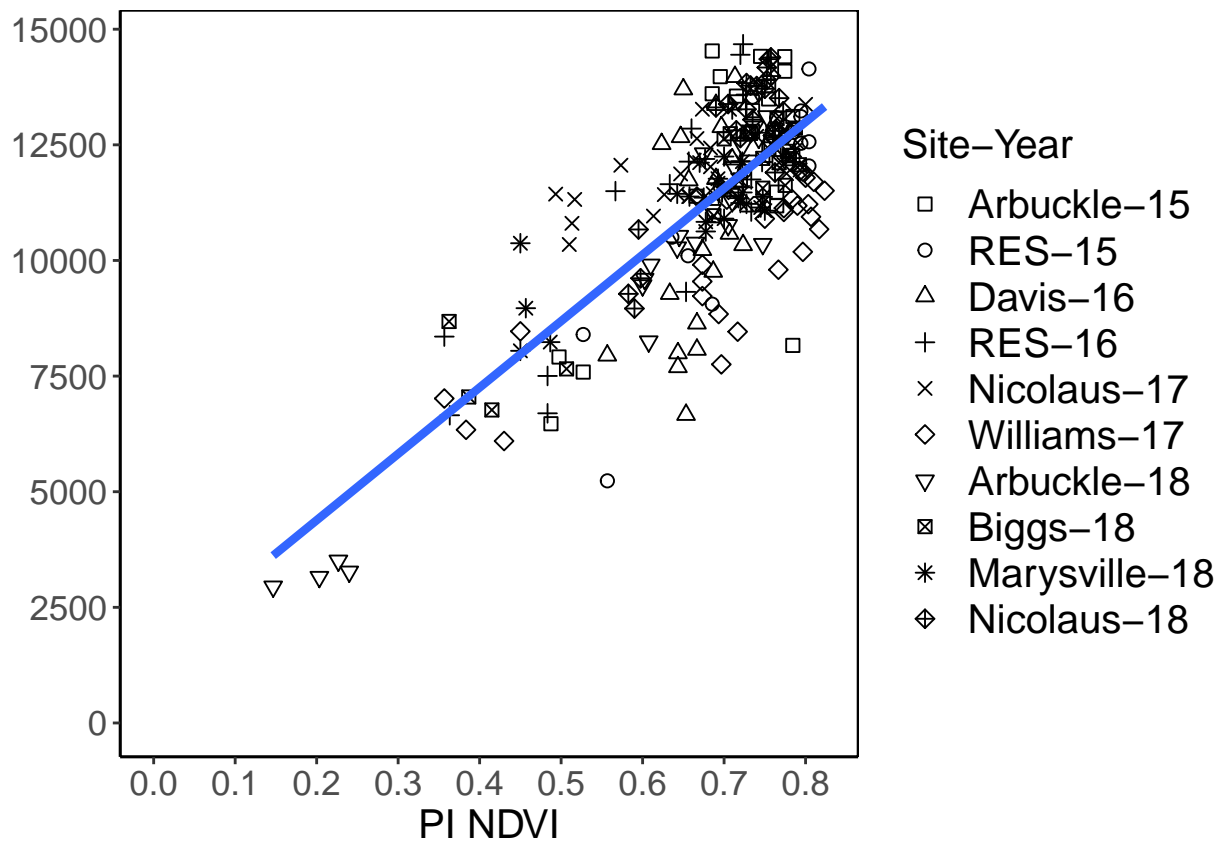


Plot Yield ~ NDVI

```

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 , col
bbb

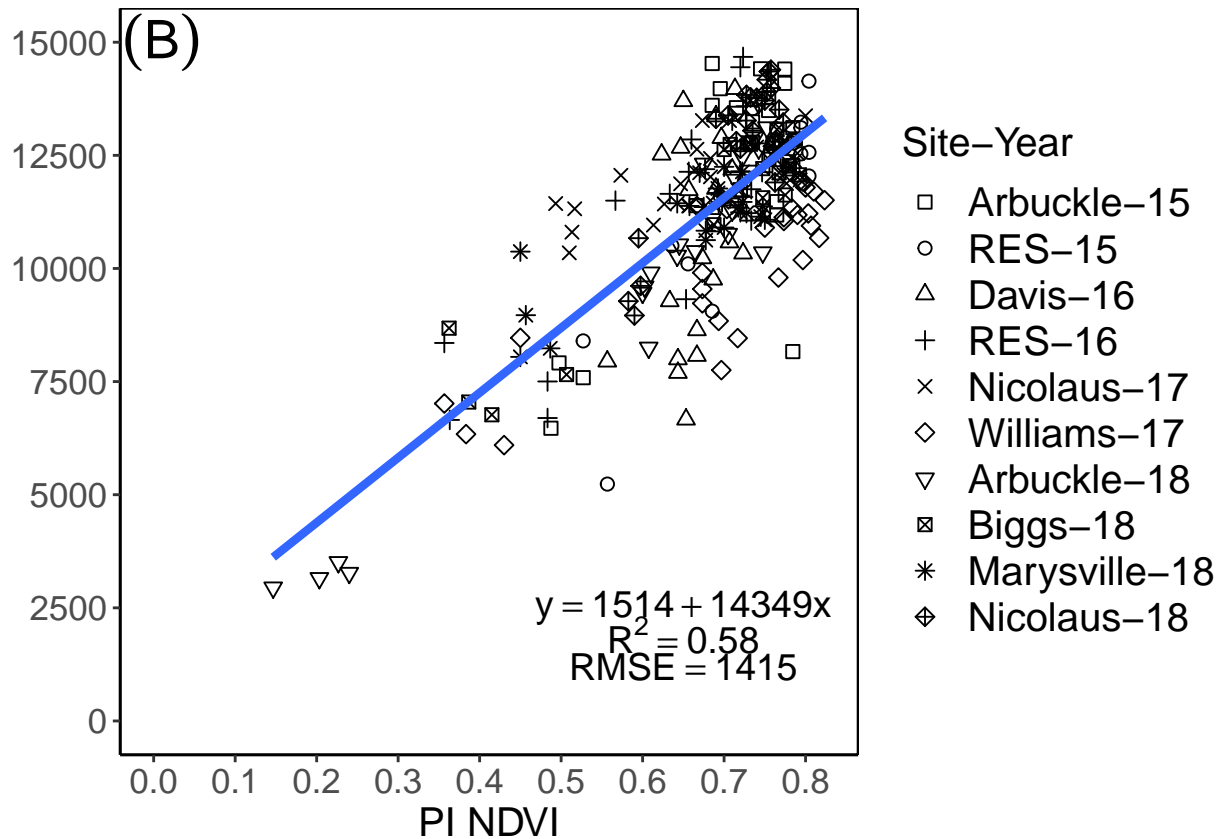
```



```
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 = TRUE)
bbb <- bbb + annotate("text", x = .65, y = 2500, label = label_bbb_2, color="black", size = 5, parse = TRUE)
bbb <- bbb + annotate("text", x = .65, y = 1900, label = label_bbb_3, color="black", size = 5, parse = TRUE)
bbb <- bbb + annotate("text", x = .65, y = 1200, label = label_bbb_4, color="black", size = 5, parse = TRUE)

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
```

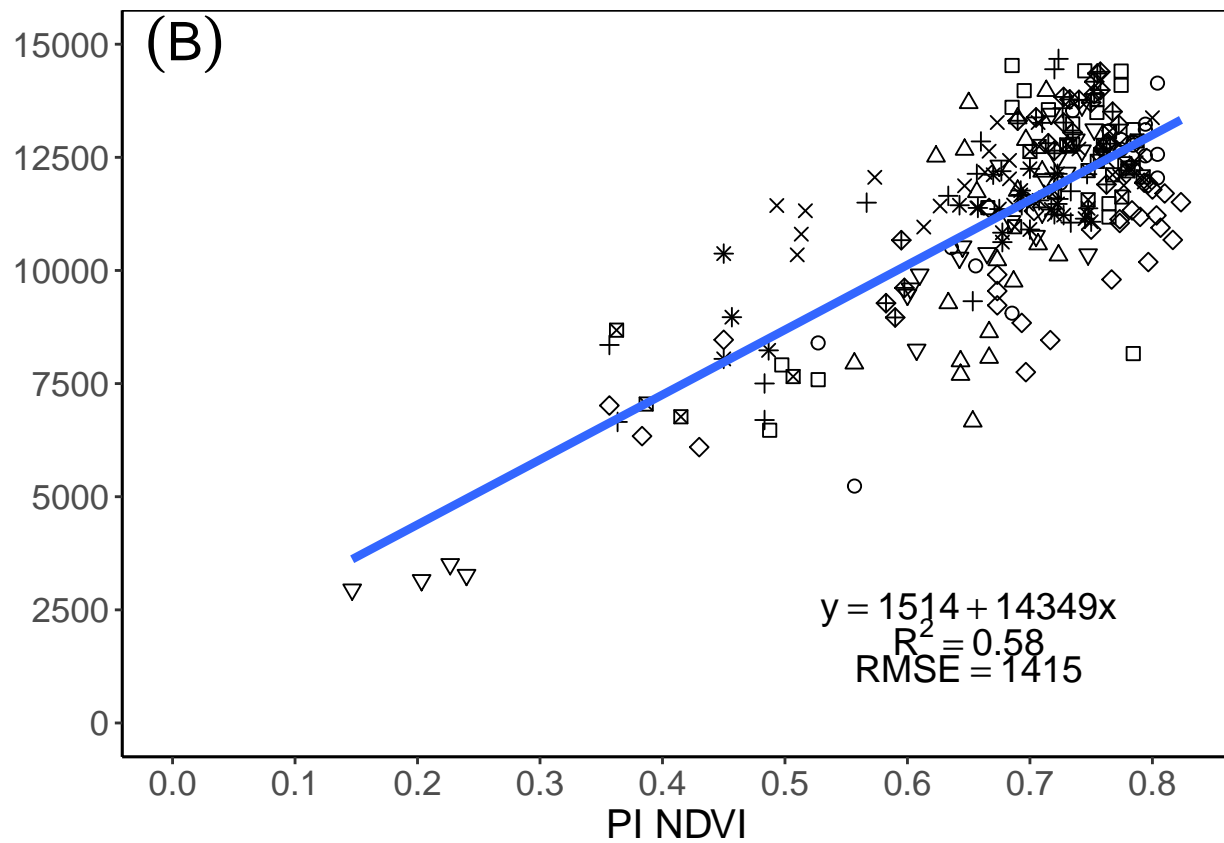
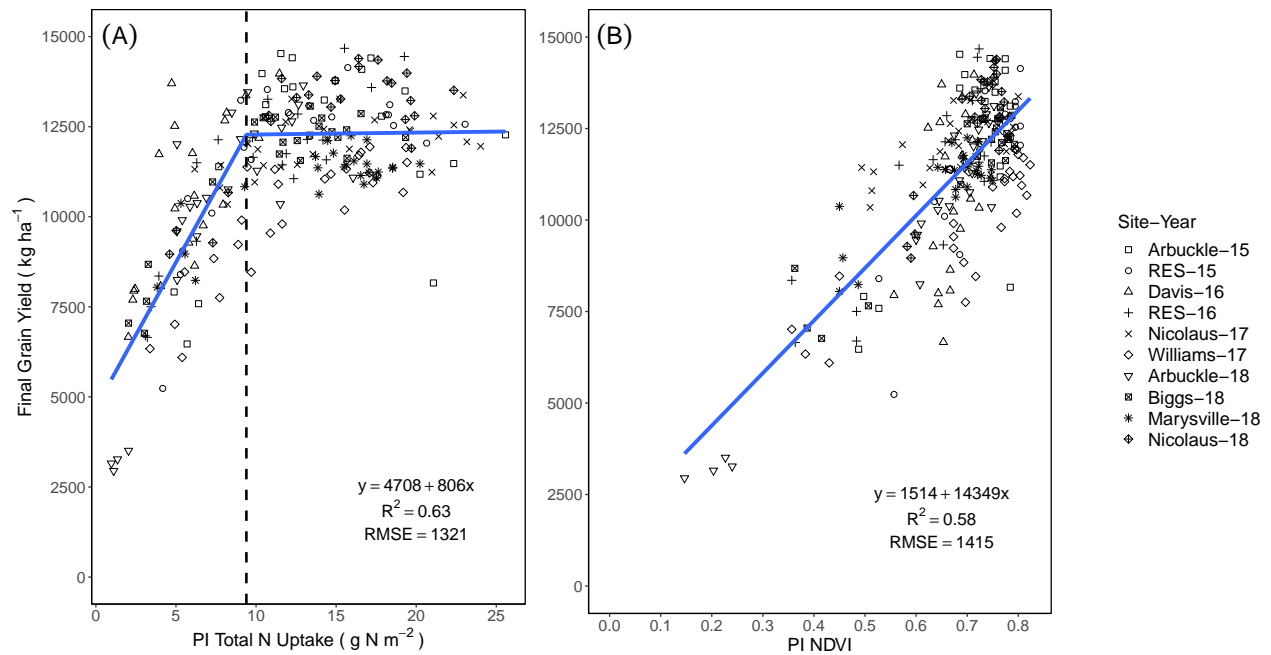



Figure 3

```

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

```



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

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

```
Sys.time()
```

```
## [1] "2019-03-19 15:49:09 PDT"
```