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Re: *Assignment # or* SCC *id# number for client work*

RESEARCH FIELD: Engineering, Biology

PROJECT TITLE: Examine the effect of scalp hair on thermal load under various climates

1.0 - PROJECT DESCRIPTION

In this project, we analyzed a dataset coming from a designed experiment. Using a full-body thermal manikin in a climate-controlled chamber, experiments were conducted to examine the effect of scalp hair on heat loss under various climate conditions. The curly scalp hair may have evolved as a result of selective pressures to reduce the heat loss on an increasingly large human brain. We want to test the following hypotheses proposed by our client: 1, the presence of hair will reduce heat loss under various climate conditions; 2, the curly hair might reduce more heat loss than straight hair does under various climate conditions; 3, the difference in heat loss between curly and straight hair is greater when there is solar radiation.

There are two types of experiments: one with dry hair and the other with wet hair. The climate conditions include three different speeds of wind(V_{wind}=0.3, 1, 2.5m/s), solar radiation (on/off). There are four types of scalp hair tested in the experiments: no hair, hair with low curvature, hair with mid curvature and hair with high curvature. In the experiments, the temperature of the manikin ($T_{manikin}$) was controlled to stay constant, and the energy spent to keep the temperature was measured as the heat loss. The dataset comprised with 72 samples from dry experiments and 48 samples from wet experiments. For each combination of climate conditions and hair curvature, there are two trials in the wet experiments and three trials in the dry experiments.

1.1 - RESEARCH QUESTIONS

Question 1 Whether the presence of hair can reduce the heat loss?
Question 2: whether the curlier hair can reduce more heat loss than less curly hair?
Question 3: whether the curlier hair lead to larger heat loss when there is solar radiation?

1.2 - STATISTICAL QUESTIONS

Question 1: What is the effect of having hair on the heat loss?
Question 2: What is the effect of hair curvature on the heat loss?
Question 3: whether the effect of hair curvature on the heat loss depend on the solar radiation?

1.3 - VARIABLES OF INTEREST

Variable name	Role in the model	Definition & measurement
$T_{ambient}$	predictor	The temperature in the chamber
$T_{manikin}$	predictor	The temperature in the manikin skin
wind	predictor	The speed of wind(0.3, 1.0, 2.5m/s)

wig	predictor	Type of hair (nude, lowCurv, midCurv, highCurv) on the manikin
Radiation	predictor	Whether there is solar radiation (on, off)
Dry_wet	predictor	Whether the scalp is dry or sweaty (dry, wet)
Heat loss	response	The energy per unit area used to keep manikin temperature constant(W/m^2)
Insulation	response	The corrected energy used to keep manikin temperature constant, representing the thermal resistance per unit area ($W/m^2 \cdot K$); when the insulation is lower, the heat loss is greater

1.4 - STUDY DIAGRAM

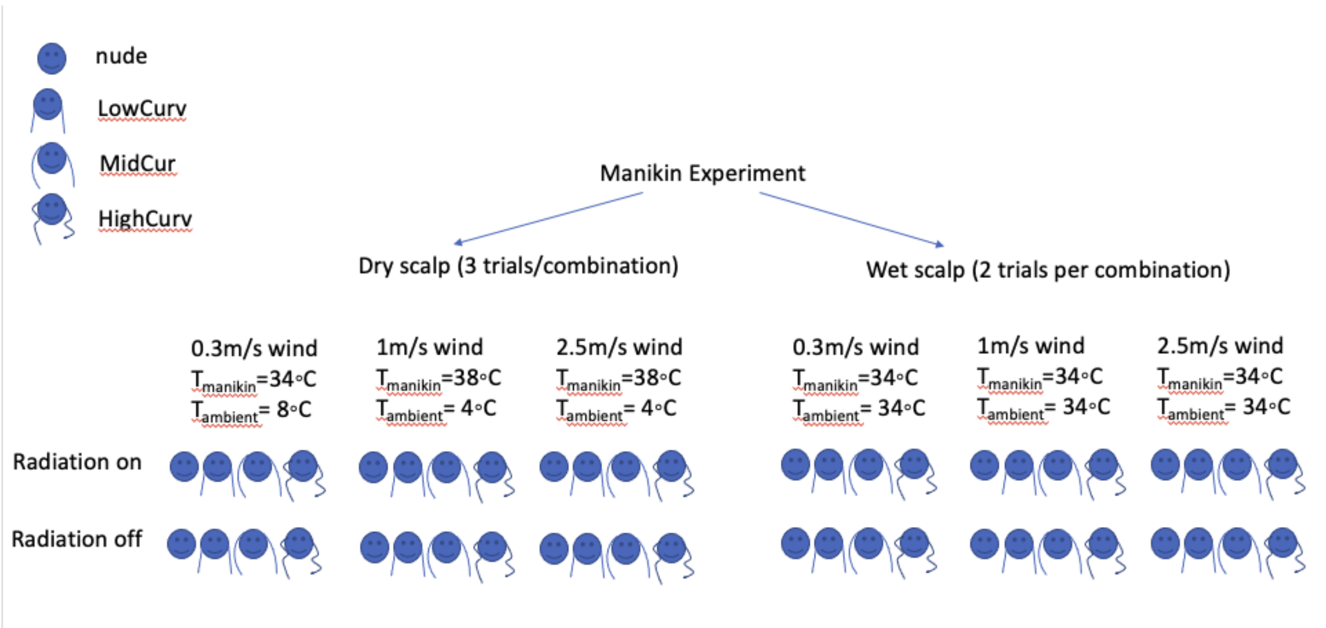


Figure 1 Study Diagram

2.0 - EXPLORATORY DATA ANALYSIS (EDA)

Since the dry measurements were taken at two different temperatures - one with $T_{manikin}$=34◦C and $T_{ambient}$= 8◦C, and another with $T_{manikin}$= 38◦C and $T_{ambient}$= 4◦C., the temperature setting variation might contribute to the difference in the heat loss. Therefore, for dry measurements, we will use Insulation, corrected energy used to keep manikin temperature constant, as the response variable, to control for temperature variation.

For wet experiments, the measurements are based on heat exchange rather than dry heat loss. These measurements were taken with the temperature settings $T_{manikin}$= 34◦C and $T_{ambient}$= 34◦C. The measurements have been converted to heat loss for comparative purposes. we will use heat loss as the response variable for wet experiments.

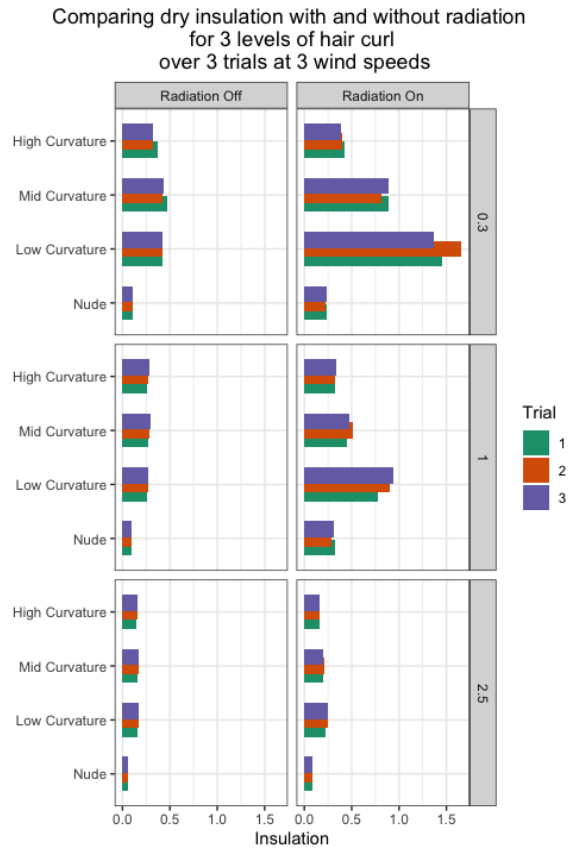


Figure 3 Bar charts of the insulation from manikin hair in the dry experiments. Three trials are filled with three colors. There are six combinations of radiation off/on and three wind speeds. Each combination is plotted in a separate panel.

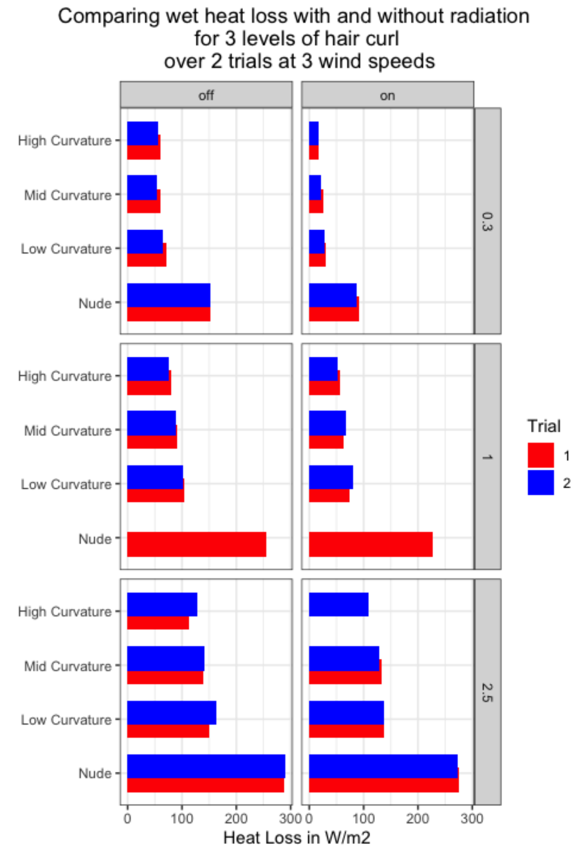


Figure 2 Bar charts of the heat loss from manikin hair in the wet experiments. Two trials are filled with two colors. There are six combinations of radiation off/on and three wind speeds. Each combination is plotted in a separate panel.

From the exploratory data analysis, we can see that the differences between trials under same experiment condition combination are much smaller than the differences between trials under different experimental conditions (Fig2, Fig3). We will treat each trial as one independent sample

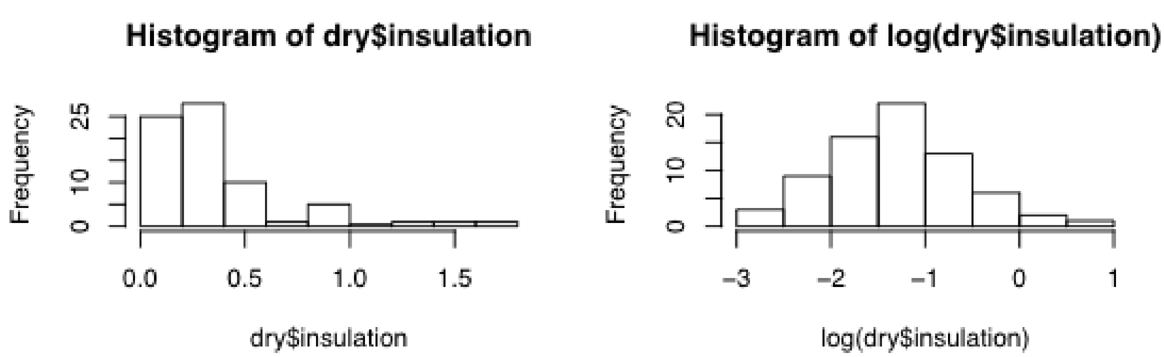


Figure 4 Histograms of insulation and log insulation

instead of taking the mean of trials. As for missing data in wet experiments, we ignore the samples with missing heat loss data.
To get an idea about the distribution of response variable data in dry experiments, we made a histogram of insulation in dry experiments (Fig 4). The distribution of insulation data seems right-skewed. Then we applied a log transformation to the insulation, which made the distribution close to

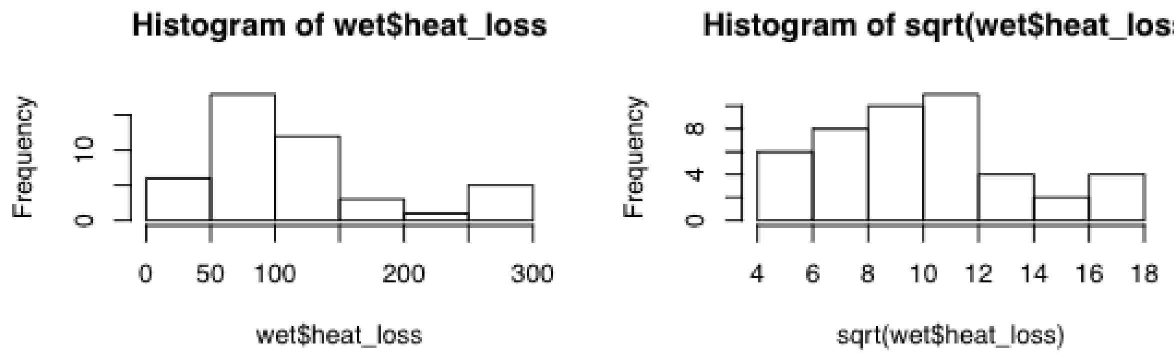


Figure 5 Histograms of heat loss and square root of heat loss

normal (Fig 4).
To get an idea about the distribution of response variable data in wet experiments, we made a histogram of heat loss in wet experiments (Fig 5). The distribution of heat loss seems right-skewed. Then we applied a square root transformation to the insulation, which made the distribution closer to normal (Fig 5).
Then we tested the correlation between the heat loss and wind speed in both dry and wet experiments. The correlation coefficient between square rooted heat loss and wind speed is 0.68 in wet experiments, indicating a strong positive association. The correlation coefficient between log transformed insulation and wind speed is -0.61, indicating a strong negative association.

3.0 –STATISTICAL ANALYSIS

In order to test the effect of having hair on the heat loss, we include a new binary variable (with _hair) representing whether the manikin has hair or not. And then we build two linear regression model (dry_model1, wet_model1) to dry data and wet data respectively. For dry data, log insulation was taken as reponse variable, while for wet data, square roote of heat loss was taken as response variable. The predictors in both models are the same, including wind, radiation and with_hair.

The fitted regression model for dry experiments (dry_model1) was:

$$\log(insulation) = -1.44 - 0.49 * wind + 0.41 * radiation + 0.98 * with\_hair$$
$$\beta_{with\_hair} = 0.98, p\ value < 2e - 16$$
$$Adjusted\ R^2 = 0.83$$

The regression coefficient can be interpretated in the following way: the log insulation would increase by 0.98 $\sqrt{\mathrm{W/m2 \cdot K}}$ if a nude manikin has hair.

The fitted regression model for wet experiments (wet_model1) was:

$$\sqrt{Heat\ loss} = 11.06 + 2.35 * wind - 1.14 * radiation - 5.17 * with\_hair$$
$$Adjusted\ R^2 = 0.91$$
$$\beta_{with\_hair} = -5.17, p\ value < 2e - 16$$

The regression coefficient can be interpretated in the following way: the square root of heat loss would decrease by $5.17\ \sqrt{\mathrm{W/m2}}$ if a nude manikin has hair.
Because regression coefficients for the with_hair in two models are significantly different from zero. We can conclude that the presence of hair will increase the insulation in dry experiments and lower the heat loss in the wet experiments. To summarize, having hair reduces the heat loss no matter whether the scalp is dry or wet.

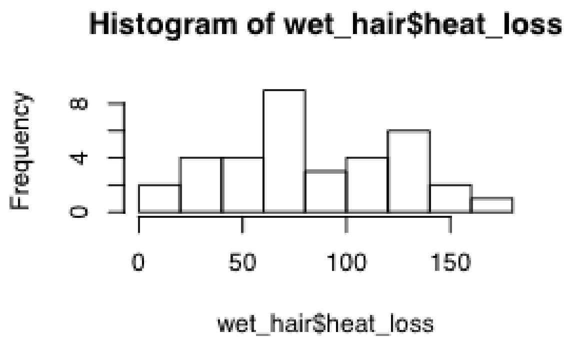


Figure 6 Histrogram of heat loss from reduced data

In order to test whether the extent of curvature affects the heat loss, we exclude nude samples and build statistical models using the reduced data including merely samples with hair. Multiple linear regression was used to test if curvature of hair significantly affect the heat loss in both dry and wet scalp conditions, by controlling for wind speed and radiation. We introduced two binary dummy variables(MidCurvature, HighCurvature), respectively representing whether the hair on Manikin is mid curved or not, high curved or not. We plotted the distribution of heat loss in the reduced data (Fig 6) and found the distribution of heat loss in the wet reduced data close to normal distribution, therefore no transformation would be used.

The fitted regression model for dry experiments (dry_model2) was:

$$\log(insulation) = -0.20 - 0.52 * wind + 0.36 * radiation - 0.50 * HighCurvature - 0.20 * MidCurvature$$
$$Adjusted\ R^2 = 0.85$$
$$\beta_{HighCurvature} = -0.50, p\ value = 1.86e-07;$$
$$\beta_{MidCurvature} = -0.20, p\ value = 0.02;$$

The log insulation will decrease by 0.5, if the Manikin with low curvature hair changes to a high curvature; the log insulation will decrease by 0.2 if the manikin with low curvature hair changes to the mid curvature. To summarize, manikin with either high or mid curvature hair has lower insulation (greater heat loss) compared to the manikin with low curvature hair. Manikin with high curvature has even lower insulation and greater heat loss compared to the manikin with mid curvature hair.

The fitted regression model for wet experiments was(wet_model2):

$$Heat\ loss = 43.80 + 40.45 * wind - 17.74 * radiation - 22.08 * HighCurvature - 10.18 * MidCurvature$$
$$Adjusted\ R^2 = 0.96$$
$$\beta_{HighCurvature} = -22.08, p\ value = 1.13e-06$$
$$\beta_{MidCurvature} = -10.18, p\ value = 0.0074$$

Manikin with high curvature hair has lower heat loss compared to the manikin with low curvature hair. By replacing the low curvature hair with a high curvature hair, the heat loss would decrease by 22.08. Manikin with mid curvature hair has lower heat loss compared to the manikin with low curvature hair. By replacing the low curvature hair with a mid curvature hair, the heat loss would decrease by 10.18.
In conclusion, heat loss would increase if hair get curlier when the scalp is dry; the heat loss would decrease if the hair get curlier when the scalp is wet.

In order to test whether the effect of hair curvature on the heat loss depend on the solar radiation condition, we add to the multiple linear regression models the interaction terms between MidCurvature and radiation, as well as the interaction term between HighCurvature and radiation. The fitted regression model for dry experiments (dry_model3) was:
Insulation=0.84-0.21*wind+0.41*radiation-0.30*HighCurvature-0.17*MidCurvature-0.38*radiation* HighCurvature-0.26*radiation*MidCurvature

$$\log(insulation) = -0.20 - 0.52 * wind + 0.66 * radiation - 0.50 * HighCurvature - 0.20 * MidCurvature - 0.56 * HighCurvature * radiation - 0.33 * MidCurvature * radiation$$
$$Adjusted\ R^2 = 0.92$$

Since the regression coefficients for both interaction terms are significantly different from zero,

$$\beta_{HighCurvature:radiation} = -0.56, p\ value = 4.80e-08$$
$$\beta_{MidCurvature:radiation} = -0.33, \quad p\ value = 0.0033$$

we can summarize that the effect of hair curvature on the heat loss depends on the solar radiation when the scalp is dry. Specifically, with the presence of solar radiation, the log insulation will decrease by 1.06(0.50+0.56) when the low curvature hair change into high curvauture; while log insulation will only decrease by 0.50 when there is no radiation. With the presence of solar radiation, the log insulation will decrease by 0.53(0.20+0.33) when the low curvature hair change into mid curvauture; while log insulation will only decrease by 0.20 when there is no radiation. Therefore, given the dry scalp, when there is solar radiation, curlier hair reduces more insulation and leads to larger heat loss, comparing to the absence of solar radiation.

The fitted regression model for wet experiments was(wet_model3):

$$Heat\ loss = 43.81 + 40.44 * wind - 19.68 * radiation - 22.10 * HighCurvature - 10.18 * MidCurvature + 1.66 * HighCurvature * radiation + 4.15 * MidCurvature * radiation$$

Since the regression coefficients for both interaction terms in wet_model3 are not significantly different from zero,

$$\beta_{HighCurvature:radiation} = 1.66, p\ value = 0.75528$$
$$\beta_{MidCurvature:radiation} = 4.15, p\ value = 0.42569$$

we can summarize that the effect of hair curvature on the heat loss when the scalp is wet does not depend on the solar radiation.

4.0 - RECOMMENDATIONS

We checked the assumptions of linear regression by plotting the diagnostic plots of the six models (Appendix). From the scatter plots of residuals and fitted values, we can say that in the six models, linear relationship assumptions were satisfied. We found that in all the six models, the residuals do not have strong non-linear patterns because the residuals were almost equally spread around a nearly horizontal line (colored in red).
From the Q-Q plots, we can see that the residuals are normally distributed. The residuals almost follow a straight line.
From the scale-location plots, we can see that assumption of equal variance (homoscedasticity) has been satisfied. The residuals seem equally spread around the horizontal line.
From the residuals-leverage plots, we can see that there are no outliers influential to the analysis because all the data points are inside the Cook's distance (dashed line in red)

- Question 1: Whether the presence of hair can reduce the heat loss?

having hair reduces the heat loss in both dry and wet experiments

- Question 2: whether the curly hair can reduce the heat loss?

When the scalp is dry, controlling for wind and solar radiation, the curly hair will increase heat loss compared to the low curvature hair (straight hair)
When the scalp is wet, controlling for wind and solar radiation, the curly hair can reduce heat loss compared to the low curvature hair (straight hair)

- Question 3: whether the curlier hair lead to larger heat loss when there is solar radiation?

When the scalp is dry, curlier hair reduces more insulation and leads to larger heat loss when there is solar radiation. When the scalp is wet, the effect of hair curvature on the heat loss does not depend on the solar radiation.

5.0 – RESOURCES

Multiple regression: https://www.investopedia.com/terms/m/mlr.asp
Dummy variable: https://conjointly.com/kb/dummy-variables/

6.0 - CONSIDERATIONS

In this experiment, we only consider one scenario where the ambient temperature is not higher than the skin temperature. Only in this scenario, we can assume higher insulation represent lower heat loss. Therefore, the effects of wind speed and solar radiation on the heat loss also depend on this prerequisite or scenario. It might be troublesome to extrapolate the model without checking the difference between ambient temperature and skin temperature.

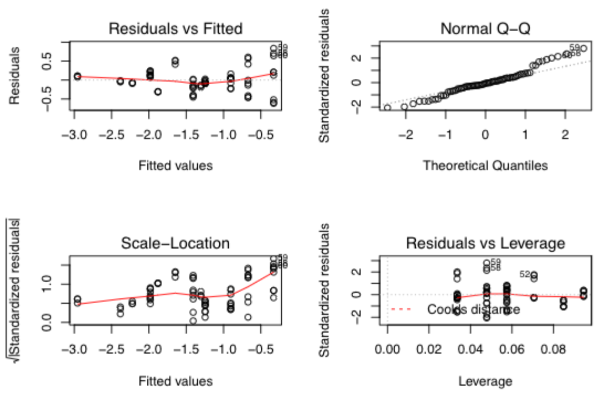
The effects of different hair type on the heat loss might be dependent on the climate condition. Such dependency can be tested by adding interaction term of hair and climate condition into the multiple linear regression model. For example, you can run code like this:

```
dry_model1 <- lm(insulation ~ wind + radiation + with_hair + with_hair:wind + with_hair:radiation, data=dry)
```

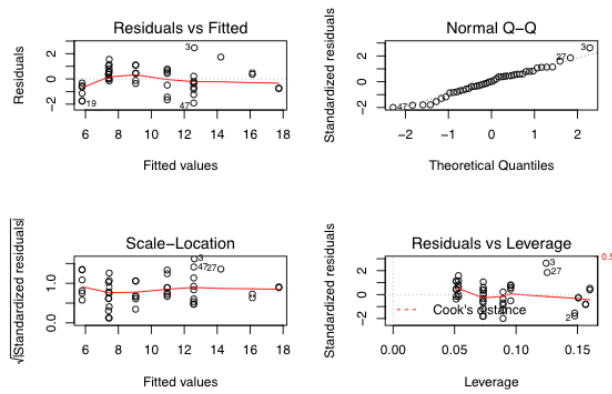
If the regression coefficient for the interaction term is significant, it indicates that the effect of having hair on the heat loss depends on wind or radiation.

There is an alternative approach to look at the interaction between hair curvature and the radiation, we can look at the difference of heat loss with and without radiation, introducing a new variable called solar influx.

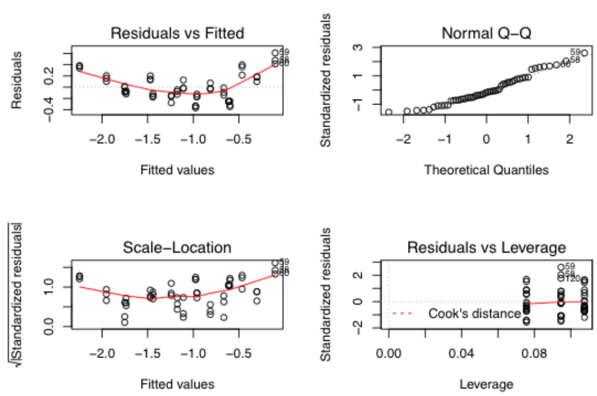
Appendix



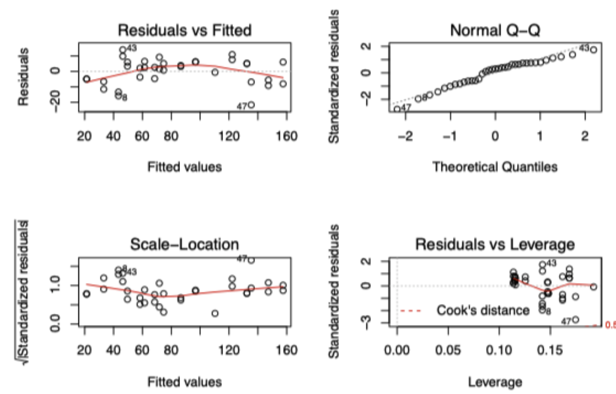
Supplementary Figure 2 diagnostic plots of dry_model1



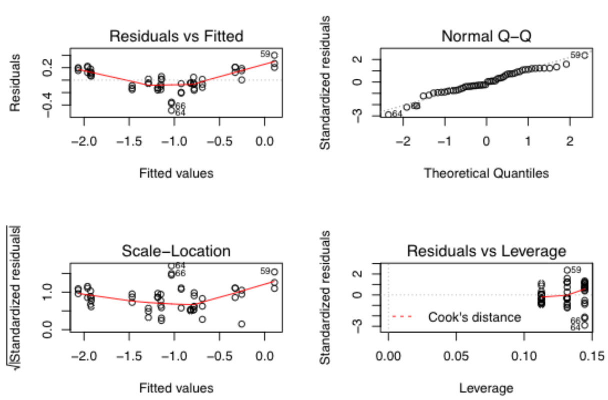
Supplementary Figure 1 Diagnostic plots of wet_model1



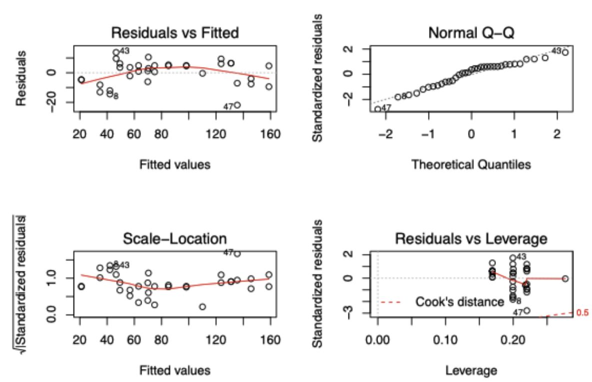
Supplementary Figure 6 Diagnostic plots of dry_model2



Supplementary Figure 5 Diagnostic plots of wet_model2



Supplementary Figure 4 Diagnostic plots of dry_model3



Supplementary Figure 3 Diagnostic plots of wet_model3