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## Introduction

The supply of water to crops is critical to successful agriculture. Lack of water in the soil can lead to an inferior yield or the crops dying. Yet too much water can also be detrimental if the crop becomes waterlogged. The amount of water in the soil around the crop is critical to a successful outcome for the farmer. Water can be gained by rainfall and irrigation and lost due to evaporation and drainage. Rainfall, evaporation are climate and weather dependent, whilst the loss of water due to drainage through the soil will depend on the texture of the soil. A sandy soil will lose water quickly whereas a clay soil will hold more water. Also water excess to that which the soil can absorb can be lost due to runoff (Queensland Government, 2013). This report concerns soil data that was collected and published by Felix M. Riese and Sina Keller in May 2017 in Karlsruhe, Germany. The data includes readings of soil moisture, soil temperature and hyperspectral data. The last of these will indicate the colours present in the soil, which is useful as the colour of soil provides an indication of soil composition and properties (Queensland Government, 2013). Using a Cubert UHD 285 hyperspectral snapshot camera recording 50\*50 images, 125 spectral bands ranging from 450nm to 950nm were recorded for each soil sample, with a spectral resolution of 4nm. Soil moisture – as a percentage – was measured using a TRIME-PICO time-domain reflectometry (TDR) sensor, at a depth of 2 cm.

This data was used to build regression models predicting soil moisture based on soil temperature and the hyperspectral data. Predicting soil moisture will assist farmers to know whether given specific soil and weather, there will be a suitable quantity of soil water for their crops. Both linear regression models and logistic regression models were fit. The former included models predicting soil moisture from soil temperature alone, as well as from soil temperature and hyperspectral data.

## Methods

The data was read into an R data frame (using RStudio). The index of each observation was removed as not being an appropriate predictor. Temperature was measured from degrees Celsius to Kelvin, an absolute scale. Some visualisations were created which provide a general overview of the data.

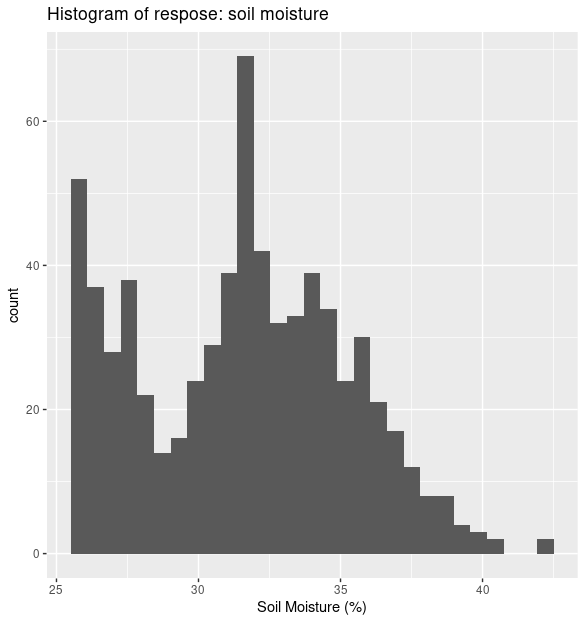
The first linear model fitted modelled soil moisture as a function of soil temperature alone. Then, various transformations were considered for both the response and explanatory variable. Some linear models were created modelling soil moisture or a transformation thereof as a function of a single variable – either soil temperature itself or a transformation thereof, whilst others included multiple regressors. Three models were fitted on modified data in which the soil temperature and moisture were averaged over each hour in which recordings were made, to reduce the problem of autocorrelation amongst samples taken in close succession.

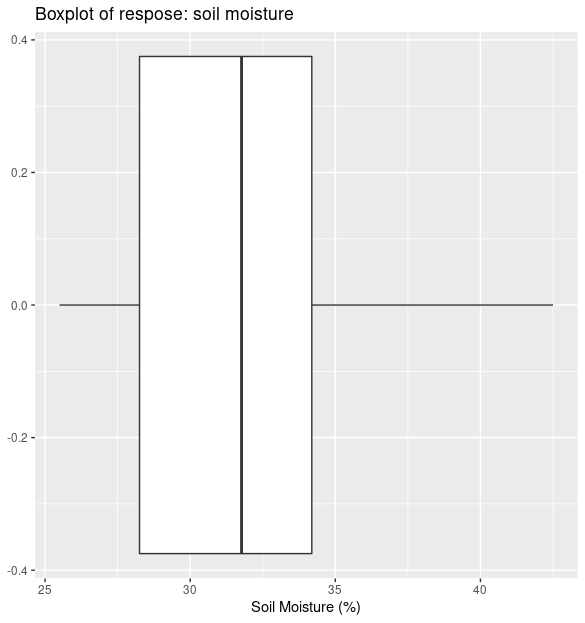
Next, linear models were fitted predicting soil moisture in terms of both soil temperature and hyperspectral data. In many of these models, the transformed response variable , where y the response variable soil moisture, is as used. As there were 125 hyperspectral bands, attempts were made to reduce the number of predictors by including only some of these, and also by replacing the hyperspectral bands with principle components thereof.

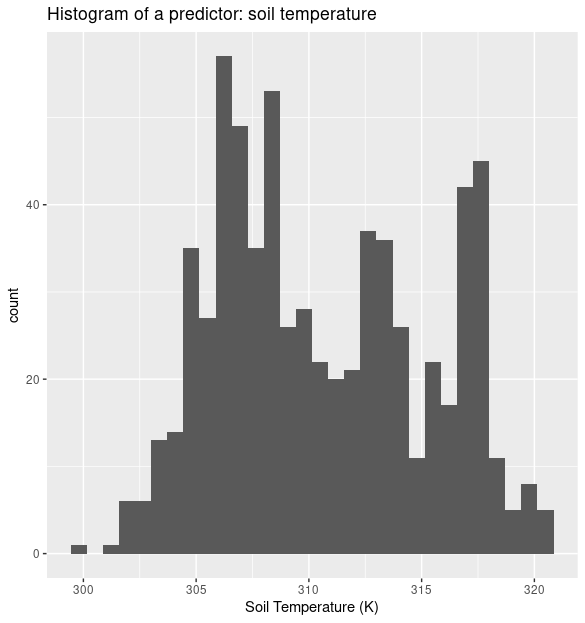
Logistic models were also fit to predict whether the soil moisture was in the range 30% to 40% or not, and to predict whether the soil moisture was greater than 38% or not.

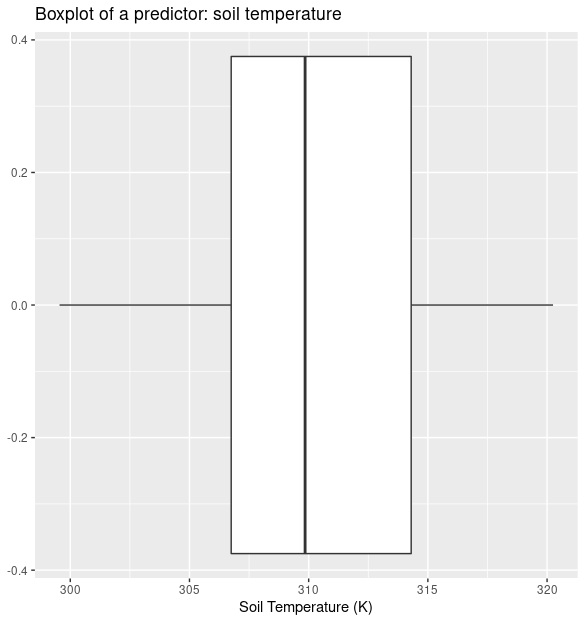
## Results

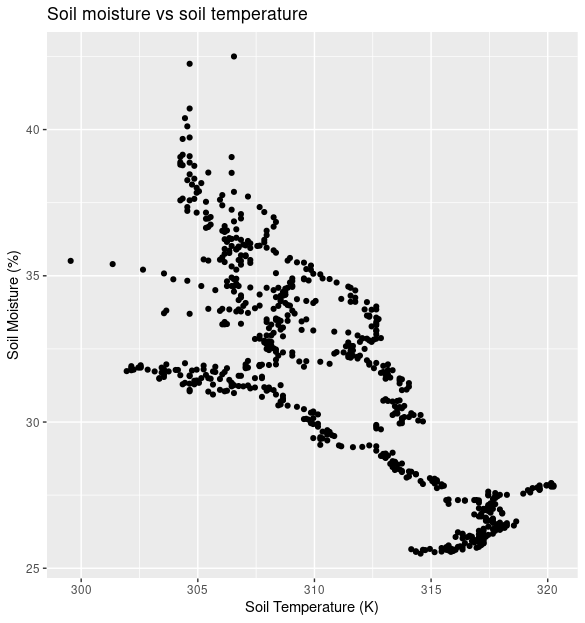
### Analysis of response variable and select predictors

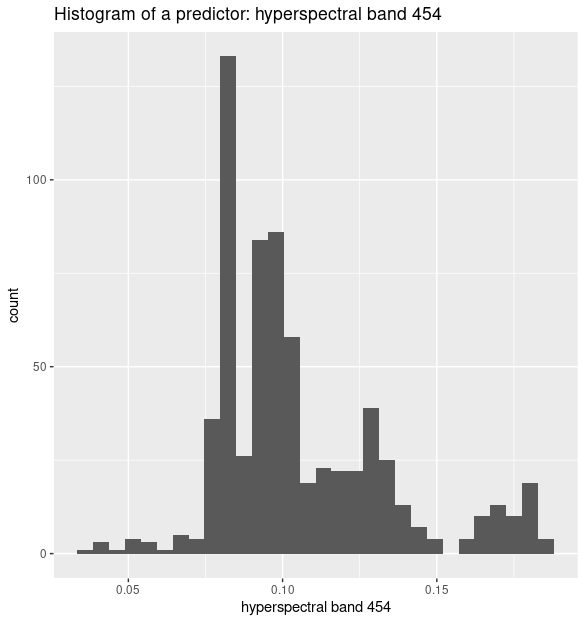


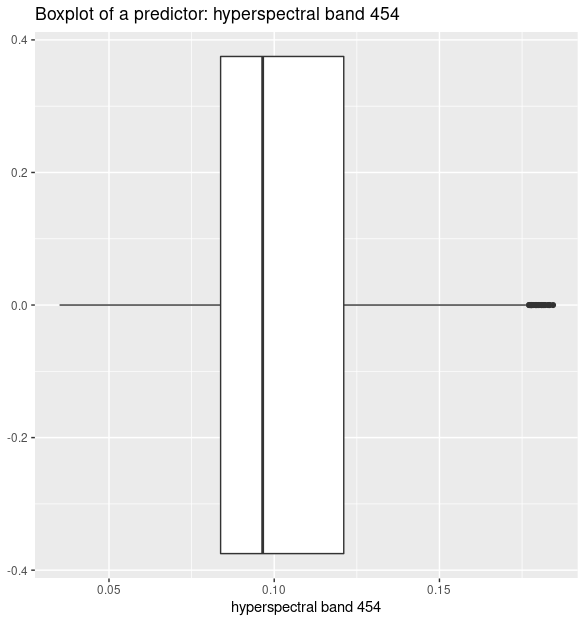


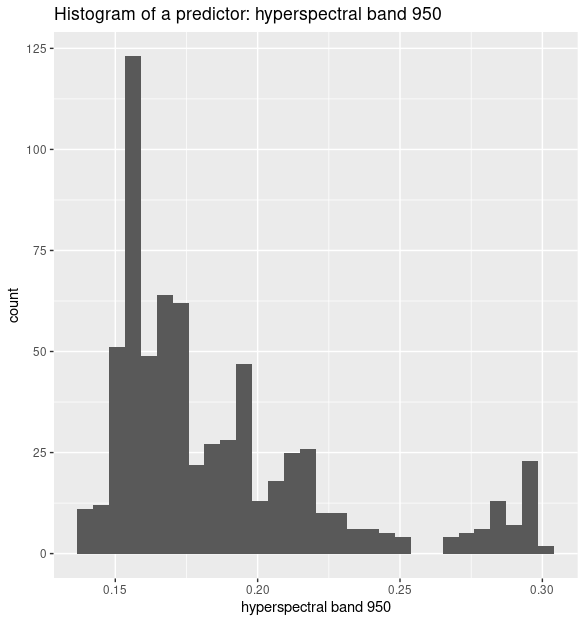


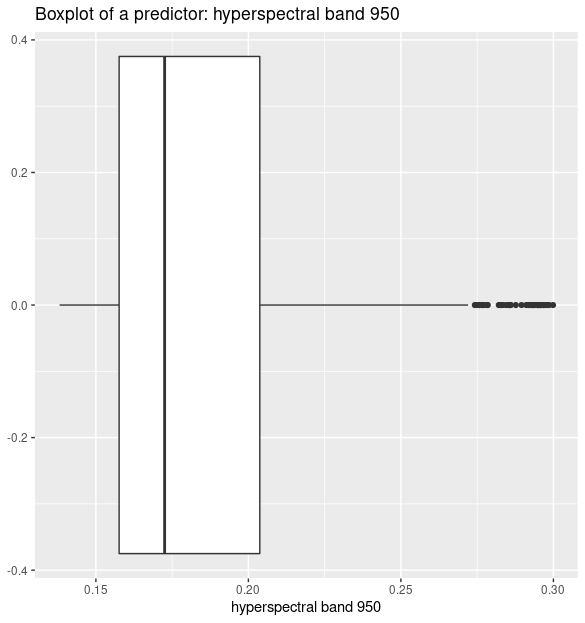










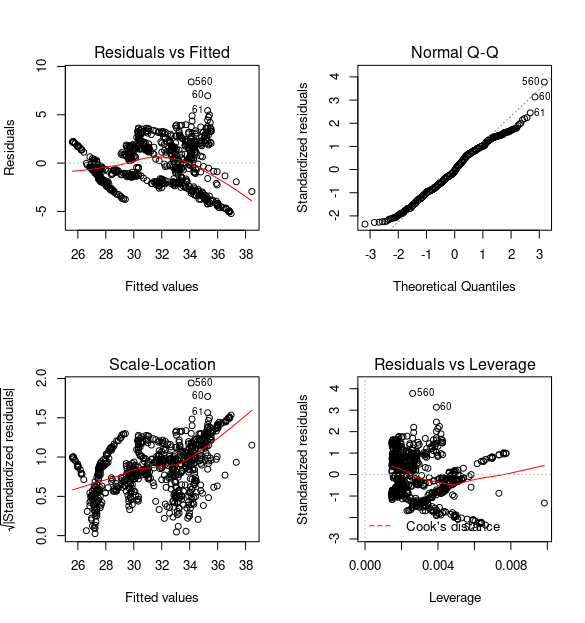


### Linear regression models predicting soil moisture using only soil temperature

Fitting a simple linear model of soil moisture against soil temperature, that is a model of the form

where x is the soil temperature and y the soil moisture, does not produce an adequate model, as can be seen from the plots below.

##### Linear Regression Model 1



The linearity assumption is shown to be clearly violated, as seen by fact that the residuals, when plotted against the fitted values, are not randomly distributed about zero. Instead, multiple strands of tightly bunched residuals are seen showing a downward trend across the fitted values. Also the Normal Q-Q plot shows many of the larger residuals as well as some of the smaller residuals tending away from the quantile-quantile line. There is also evidently increasing variance, judging from the Scale-Location plot. There do not appear to be any concerns however with extreme values being unduly influential, based on the Residuals vs Leverage plot.

The assumptions of the linear regression model are violated, as is also shown by formal statistical tests. The hypothesis of normally distributed residuals is rejected, with a p-value of 1.645 \*10-5 given by the Shapiro-Wilk test.

Shapiro-Wilk normality test

data: resid(linear\_model1)

W = 0.98761, p-value = 1.645e-05

The hypothesis of constant variance is also rejected.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 99.63153, Df = 1, p = < 2.22e-16

The Durbin-Watson test for correlated first lags of residuals also indicated that these were in fact correlated. The hypothesis of uncorrelated first lags was rejected with p-value approximately zero.

lag Autocorrelation D-W Statistic p-value

1 0.9368186 0.1262797 0

Alternative hypothesis: rho != 0

The coefficient and intercept of this inadequate model are seen in the summary output by R.

Residuals:

Min 1Q Median 3Q Max

-5.2198 -1.6504 -0.1106 1.7742 8.3914

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 224.11644 5.69646 39.34 <2e-16 \*\*\*

absolute\_soil\_temperature -0.61983 0.01834 -33.80 <2e-16 \*\*\*

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.225 on 677 degrees of freedom

Multiple R-squared: 0.628, Adjusted R-squared: 0.6274

F-statistic: 1143 on 1 and 677 DF, p-value: < 2.2e-16

As the model does not satisfy the assumptions of linear models, assessing the significance of the model with the usual analysis using F-statistic (derived from the sum of squares both of the regression and the residuals) is not reliable. Neither will assessing the significance of the intercept and slope using t-tests.

The non-constant variance problem was addressed by transformation of the response.

##### Linear Regression Model 2

The response variable, soil moisture, was raised to the power -0.828. This exponent was chosen as being that which maximised the log-likelihood, and therefore also the likelihood. A model, then, was created of the form

where x is the soil temperature and y is the soil moisture. R produced the following summary.

Residuals:

Min 1Q Median 3Q Max

-0.0091061 -0.0027418 0.0000486 0.0024876 0.0076447

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -2.452e-01 8.392e-03 -29.22 <2e-16 \*\*\*

absolute\_soil\_temperature 9.759e-04 2.701e-05 36.13 <2e-16 \*\*\*

---

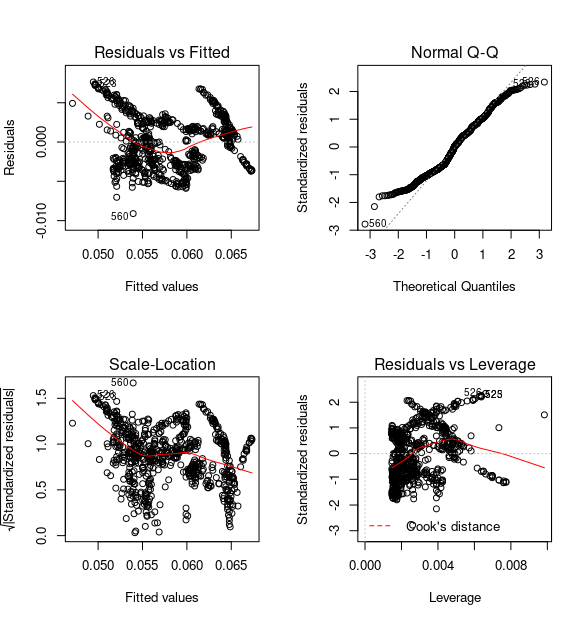
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.003278 on 677 degrees of freedom

Multiple R-squared: 0.6585, Adjusted R-squared: 0.658

F-statistic: 1306 on 1 and 677 DF, p-value: < 2.2e-16

However, this model also proved to be not adequate, as the following residual plots show.



There are still tightly bunched strands of residuals on a downward trend, and the Normal Q-Q plot appears worse than the previous one – the residuals appear more clearly not to be normally distributed. As for the Scale-Location plot, it still shows non-constant variance. The variance is now decreasing across fitted values rather than increasing. Raising the response to a negative power has reversed the order of the fitted values of the observations: those observations which previously had the largest fitted values now have the smallest, and those which had the smallest fitted values now have the largest. This model also has no influential extreme values. The results of the formal statistical tests testing for satisfaction of the assumptions of linear regression models are below.

Shapiro-Wilk normality test

data: resid(linear\_model2)

W = 0.97473, p-value = 1.944e-09

This model fails to satisfy the normally distributed residuals assumption, that hypothesis being rejected with the Shapiro-Wilk test giving a p-value much less than 0.05.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 30.25464, Df = 1, p = 3.7888e-08

The non-constant variance score test gives a p-value of 3.7888 \* 10-8 for the hypothesis that the variance is constant, so that hypothesis is rejected. This model assumption of constant variance is violated.

lag Autocorrelation D-W Statistic p-value

1 0.9504121 0.09910135 0

Alternative hypothesis: rho != 0

As with the previous model, the Durbin-Watson test firmly rejects the hypothesis of uncorrelated residuals.

Several other transformations were also tried for the explanatory variable, the soil temperature. However, none of these solved the problem of creating a linear model satisfying the assumptions of linear regression models. Nor did adding multiple polynomial terms of soil temperature solve the problem. One of the main reasons for these was that the observations were taken in 2 minute intervals on each of the recording sessions in May 2017. This means that there is autocorrelation between samples, with multiple samples taken in close succession recording similar soil moisture and temperature readings.

#### Simpler Models Using Time-Aggregated Data

##### Linear Regression Model 3

One approach that did reduce this problem was to aggregrate all samples taken within the same hour, by taking the average soil moisture and temperature within that hour. There were in total 31 hourly averages for soil moisture and temperature in the aggregated data set. A linear model was created modelling the average moisture against the average temperature, of the form

y = β\_0 + β\_1 \* x

where x is the (average ) temperature for that hour, and y is the (average) soil moisture in that hour. The following summary was output.

Residuals:

Min 1Q Median 3Q Max

-5.093 -1.651 -0.146 1.705 5.090

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 243.83992 29.13274 8.370 3.17e-09 \*\*\*

temperature -0.68334 0.09382 -7.284 5.07e-08 \*\*\*

---

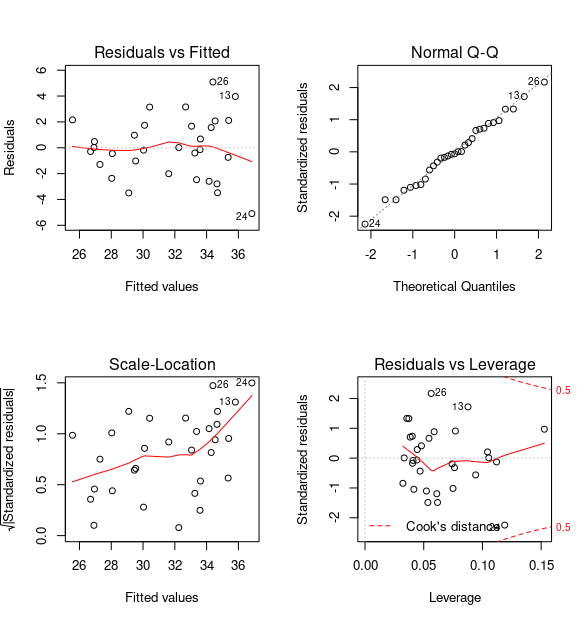
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.415 on 29 degrees of freedom

Multiple R-squared: 0.6466, Adjusted R-squared: 0.6344

F-statistic: 53.05 on 1 and 29 DF, p-value: 5.067e-08

The following residual plots show that the data far more closely aligns, with the linear model’s assumptions, though there are still some concerns.

The linearity assumption seems to be reasonable, and the Normal Q-Q plot supports the hypothesis tha the residuals are normally distributed. There still seems to be some increase in the variance as the fitted values increase. Based on the Scale-Location plot, it seems that for fitted values larger than 33, the variance increases. It also suggests that the variance is increasing for fitted values between 26 and 30. This could be cubic behaviour in the variance. The Residuals vs Leverage plot indicates that there are no influential points beyond the 0.5 Cook’s distance curve. The results of the statistical tests on the model’s assumptions are shown below.

Shapiro-Wilk normality test

data: resid(simple\_model1)

W = 0.98971, p-value = 0.9883

This test fails to reject the normally distributed residuals hypothesis with a p-value close to 0.99. Both the normal Q-Q plot and the Shapiro-Wilk test are consistent with this assumption.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 4.833299, Df = 1, p = 0.027915

The non-constant variance test rejects the hypothesis of constant variance at the 5% significance level. However, the p-value is much larger than for the previous models.

lag Autocorrelation D-W Statistic p-value

1 0.3261663 1.344206 0.034

Alternative hypothesis: rho != 0

The Durbin-Watson test rejects the null hypothesis of uncorrelated first lags amongst residuals at the 5% significance level. But this p-value also is much larger than for previous models.

Overall, this model appears much more in line with the assumptions of linear models than previous models. Yet it still fails to meet the non-constant variance and the independent residuals hypotheses at the 5% significance level. As the variance displays possible cubic behaviour across fitted values, the response was transformed by taking the reciprocal of its square root. This produced a model which was summarised as follows.

##### Linear Regression Model 4

Residuals:

Min 1Q Median 3Q Max

-0.0117187 -0.0048653 -0.0002669 0.0048419 0.0136697

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -0.4331490 0.0783450 -5.529 5.84e-06 \*\*\*

temperature 0.0019707 0.0002523 7.811 1.30e-08 \*\*\*

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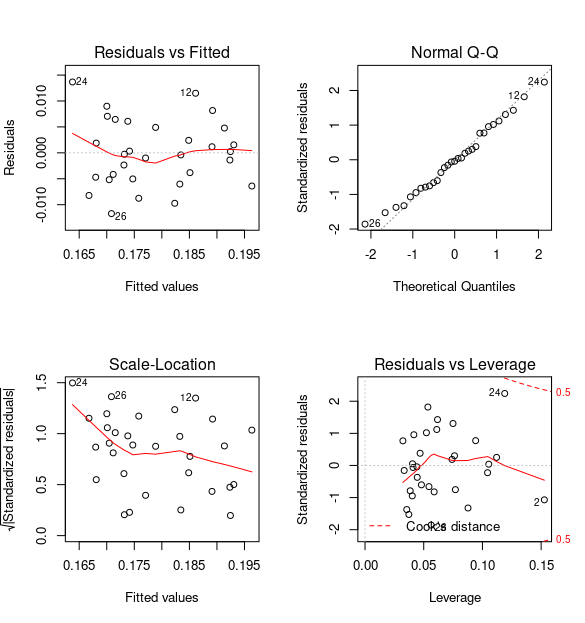
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.006495 on 29 degrees of freedom

Multiple R-squared: 0.6778, Adjusted R-squared: 0.6667

F-statistic: 61.01 on 1 and 29 DF, p-value: 1.296e-08

Plots of the residuals were again produced.



These plots show that the transformation has reversed the direction of changing variance. Now, the variance decreases for increasing fitted values. There is again no trend showing in the plot of residuals against fitted values, the Normal Q-Q plot is again consistent with the hypothesis of normally distributed residuals, the Scale-Location plot still raises concerns about non-constant variance, and there are no influential extreme observations according to the Residuals vs Leverage plot. Yet the Scale-Location plot is arguably better here, the observations appearing more randomly distributed, not following the trend as much.

The Shapiro-Wilk test failed to reject the hypothesis of normally distributed residuals.

Shapiro-Wilk normality test

data: resid(simple\_model3)

W = 0.98424, p-value = 0.9164

Not only is there lack of ground to reject the assumption of normality, but this time we cannot reject the hypothesis of constant variance based on the non-constant variance score test either.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 1.875848, Df = 1, p = 0.17081

But there is still some concern about the residuals being correlated, the Durbin-Watson test rejecting the uncorrelated residuals assumption at the 5% significance level.

lag Autocorrelation D-W Statistic p-value

1 0.3789161 1.239143 0.018

Alternative hypothesis: rho != 0

This model, which is of the form

where y is the (average hourly) soil moisture and x is the (average hourly) soil temperature, implies that

=(

which implies that

This functional form has the convenient property that it will never predict a negative soil moisture, which is physically impossible.

### Linear regression models predicting soil moisture from soil temperature and hyperspectral image data

Next, various models were fitted including both the temperature and the hyperspectral variables – on the whole set of 679 observations, not the aggregated hourly data.

Because the best model of soil moisture in terms of soil temperature alone used the transformation of the reciprocal of the square root on the response, namely soil moisture, it was considered appropriate to apply this relationship between the two variables, which is similar – though not identical - to replacing the soil temperature with the reciprocal of its square, when building a model also including hyperspectral data. Each transformation was tried to see which resulted in a better model.

##### Linear Regression Model 5

Firstly, the model including the reciprocal of the square of soil temperature, rather than the soil temperature itself was fitted. It is summarised by R as follows.

Residuals:

Min 1Q Median 3Q Max

-3.8103 -0.6552 -0.0277 0.6001 6.2044

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 1.232e+01 4.681e+00 2.632 0.008728 \*\*

`454` -9.658e+01 2.053e+01 -4.703 3.24e-06 \*\*\*

`458` 6.525e+01 5.242e+01 1.245 0.213727

`462` 3.294e+02 8.648e+01 3.809 0.000155 \*\*\*

`466` 8.593e+01 1.141e+02 0.753 0.451605

`470` -3.231e+02 1.302e+02 -2.482 0.013368 \*

`474` 1.656e+02 1.380e+02 1.199 0.230872

`478` -1.655e+02 1.163e+02 -1.423 0.155402

`482` -1.001e+02 1.404e+02 -0.713 0.476228

`486` -4.654e+02 1.493e+02 -3.117 0.001921 \*\*

`490` 8.252e+01 1.330e+02 0.621 0.535082

`494` 6.720e+02 1.447e+02 4.643 4.30e-06 \*\*\*

`498` 1.574e+02 1.504e+02 1.047 0.295764

`502` 1.161e+02 1.382e+02 0.840 0.401373

`506` 2.611e+02 1.321e+02 1.977 0.048567 \*

`510` 2.417e+02 1.384e+02 1.747 0.081232 .

`514` 1.158e+02 1.507e+02 0.769 0.442297

`518` 2.929e+02 1.502e+02 1.950 0.051636 .

`522` 4.049e+02 1.405e+02 2.882 0.004109 \*\*

`526` 1.854e+01 1.407e+02 0.132 0.895183

`530` -3.687e+01 1.446e+02 -0.255 0.798801

`534` 3.704e+01 1.462e+02 0.253 0.800040

`538` -3.445e+02 1.481e+02 -2.326 0.020396 \*

`542` 1.544e+02 1.389e+02 1.112 0.266707

`546` -1.954e+02 1.527e+02 -1.280 0.200999

`550` 1.541e+02 1.441e+02 1.069 0.285363

`554` 1.741e+02 1.486e+02 1.172 0.241756

`558` 9.223e+01 1.495e+02 0.617 0.537553

`562` -4.346e+02 1.546e+02 -2.811 0.005118 \*\*

`566` 1.683e+01 1.401e+02 0.120 0.904409

`570` 1.032e+02 1.569e+02 0.658 0.511006

`574` -3.659e+02 1.517e+02 -2.412 0.016169 \*

`578` -6.726e+01 1.470e+02 -0.457 0.647505

`582` 1.887e+01 1.585e+02 0.119 0.905263

`586` -1.928e+02 1.515e+02 -1.272 0.203806

`590` -1.001e+02 1.544e+02 -0.649 0.516792

`594` -1.525e+02 1.479e+02 -1.031 0.302840

`598` -2.931e+02 1.339e+02 -2.189 0.029046 \*

`602` -6.682e+01 1.455e+02 -0.459 0.646267

`606` 2.263e+02 1.525e+02 1.484 0.138403

`610` -6.773e+01 1.690e+02 -0.401 0.688773

`614` -2.635e+02 1.687e+02 -1.561 0.118989

`618` 4.128e+01 1.619e+02 0.255 0.798866

`622` -2.763e+02 1.579e+02 -1.749 0.080784 .

`626` 1.409e+02 1.558e+02 0.904 0.366347

`630` -2.638e+02 1.701e+02 -1.551 0.121550

`634` 2.133e+01 1.568e+02 0.136 0.891841

`638` -5.372e+01 1.503e+02 -0.357 0.720969

`642` -1.073e+02 1.555e+02 -0.690 0.490565

`646` 1.537e+02 1.712e+02 0.898 0.369705

`650` -4.756e+02 1.735e+02 -2.741 0.006328 \*\*

`654` 2.388e+02 1.801e+02 1.326 0.185450

`658` 9.570e+01 1.737e+02 0.551 0.581971

`662` -1.307e+01 1.743e+02 -0.075 0.940257

`666` 8.746e+01 1.880e+02 0.465 0.642035

`670` -4.963e+01 2.059e+02 -0.241 0.809557

`674` 4.422e+01 1.869e+02 0.237 0.813045

`678` 2.260e+02 1.762e+02 1.283 0.200169

`682` 2.351e+01 2.084e+02 0.113 0.910211

`686` 1.357e+02 2.093e+02 0.648 0.517060

`690` -4.614e+02 1.814e+02 -2.544 0.011246 \*

`694` 3.620e+02 1.964e+02 1.844 0.065753 .

`698` -2.591e+02 2.045e+02 -1.267 0.205655

`702` 1.750e+02 1.817e+02 0.964 0.335666

`706` -2.723e+02 2.245e+02 -1.213 0.225716

`710` 1.041e+02 2.146e+02 0.485 0.627845

`714` -8.823e+01 1.995e+02 -0.442 0.658433

`718` -3.600e+02 2.097e+02 -1.717 0.086605 .

`722` 6.077e+02 1.996e+02 3.045 0.002440 \*\*

`726` -3.921e+02 2.102e+02 -1.866 0.062622 .

`730` 4.008e+01 2.176e+02 0.184 0.853954

`734` 2.855e+02 2.265e+02 1.260 0.208045

`738` 3.452e+01 2.095e+02 0.165 0.869173

`742` 2.386e+02 2.144e+02 1.113 0.266281

`746` 1.553e+02 2.220e+02 0.700 0.484519

`750` 2.139e+02 2.114e+02 1.012 0.312171

`754` -8.712e+01 2.172e+02 -0.401 0.688454

`758` -1.691e+02 2.241e+02 -0.755 0.450787

`762` 3.424e+02 2.227e+02 1.537 0.124861

`766` -6.505e+02 2.239e+02 -2.905 0.003816 \*\*

`770` 5.290e+02 2.084e+02 2.539 0.011388 \*

`774` 1.325e+01 2.257e+02 0.059 0.953194

`778` -2.691e+02 2.153e+02 -1.249 0.212038

`782` -6.607e+01 2.194e+02 -0.301 0.763428

`786` 4.870e+01 2.015e+02 0.242 0.809088

`790` -2.169e+02 2.242e+02 -0.968 0.333665

`794` 2.770e+02 2.270e+02 1.220 0.222853

`798` -8.381e+00 2.260e+02 -0.037 0.970427

`802` 2.814e+02 2.354e+02 1.195 0.232558

`806` 1.645e+02 2.237e+02 0.735 0.462423

`810` -3.797e+01 2.325e+02 -0.163 0.870311

`814` -1.681e+02 2.194e+02 -0.766 0.443921

`818` 8.479e+01 2.161e+02 0.392 0.694890

`822` -5.695e+01 2.166e+02 -0.263 0.792728

`826` 3.426e+02 2.081e+02 1.646 0.100274

`830` -1.018e+01 2.105e+02 -0.048 0.961451

`834` -1.431e+02 2.207e+02 -0.648 0.517198

`838` -3.030e+02 2.159e+02 -1.403 0.161057

`842` 2.616e+02 2.156e+02 1.213 0.225520

`846` 2.612e+01 2.145e+02 0.122 0.903125

`850` -9.979e+01 2.074e+02 -0.481 0.630571

`854` -2.141e+02 2.010e+02 -1.066 0.287098

`858` 3.022e+02 1.909e+02 1.583 0.114064

`862` -2.100e+02 1.752e+02 -1.198 0.231238

`866` -6.905e+01 1.919e+02 -0.360 0.719146

`870` 7.147e+01 2.063e+02 0.346 0.729107

`874` 6.562e+01 1.973e+02 0.333 0.739623

`878` -3.055e+01 1.901e+02 -0.161 0.872415

`882` -3.255e+00 1.870e+02 -0.017 0.986117

`886` -3.967e+02 1.865e+02 -2.127 0.033843 \*

`890` 3.391e+02 1.786e+02 1.898 0.058165 .

`894` -1.921e+02 1.834e+02 -1.047 0.295352

`898` 3.159e+02 1.924e+02 1.642 0.101202

`902` -4.710e+02 1.825e+02 -2.581 0.010115 \*

`906` 2.529e+02 1.723e+02 1.468 0.142696

`910` 1.955e+02 1.720e+02 1.137 0.255993

`914` -2.523e+02 1.734e+02 -1.455 0.146334

`918` -6.594e+01 1.661e+02 -0.397 0.691465

`922` 3.434e+01 1.602e+02 0.214 0.830321

`926` 1.039e+02 1.509e+02 0.689 0.491198

`930` -7.043e+01 1.568e+02 -0.449 0.653449

`934` -2.081e+02 1.479e+02 -1.407 0.159932

`938` 2.036e+02 1.338e+02 1.521 0.128713

`942` 2.819e+02 1.424e+02 1.980 0.048254 \*

`946` -3.675e+02 1.412e+02 -2.604 0.009473 \*\*

`950` 9.122e+01 7.747e+01 1.178 0.239502

temp.squared.reciprocal 2.281e+06 4.306e+05 5.296 1.71e-07 \*\*\*

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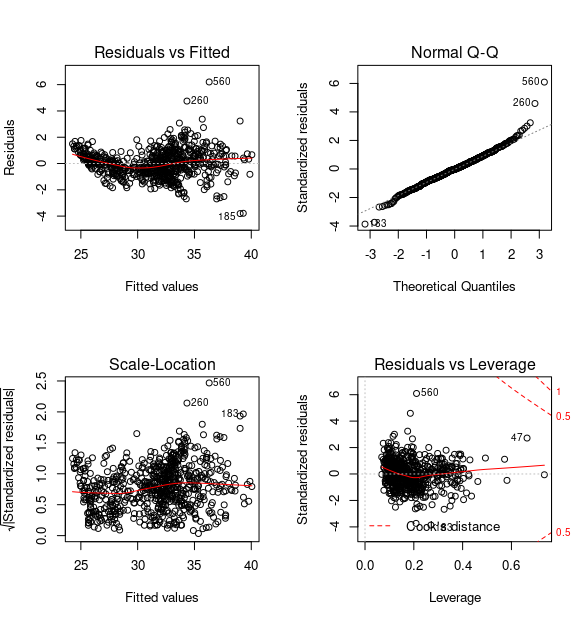
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.147 on 552 degrees of freedom

Multiple R-squared: 0.9194, Adjusted R-squared: 0.901

F-statistic: 50 on 126 and 552 DF, p-value: < 2.2e-16

As can be seen from the length of the summary, it includes many regressors. The following residual plots were produced.

The Residuals vs Fitted plot shows the residuals distributed about zero but it also shows that they tend to be more spread out for larger fitted values, which suggests that the variance is not constant, though this is not well shown by the Scale-Location plot which only shows a slight increase in variance. The Normal Q-Q plot shows that a small number of the largest residuals deviate from the straight line, as well as a couple of the smallest ones, but most observations fit the normal assumption quite well. No residual is beyond the 0.5 Cook’s distance curve in the Residuals vs Leverage plot.

According to the Shapiro-Wilk test, the hypothesis of normally distributed residuals is to be rejected, with a p-value much less than 0.05.

Shapiro-Wilk normality test

data: resid(full\_model1)

W = 0.97834, p-value = 1.761e-08

The non-constant variance test rejects the hypothesis of constant variance with a p-value far less than 0.05.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 73.98748, Df = 1, p = < 2.22e-16

Also the Durbin-Watson test rejects the assumption of uncorrelated residuals, with a p-value approximately zero.

lag Autocorrelation D-W Statistic p-value

1 0.4905518 1.017713 0

Alternative hypothesis: rho != 0

This model clearly violates the assumptions of linear regression models.

##### Linear Regression Model 6

A second model was fitted, this time transforming the response, soil moisture, as the reciprocal of its square root, and not transforming the soil temperature. It was summarised by R as follows.

Residuals:

Min 1Q Median 3Q Max

-0.013618 -0.001528 0.000015 0.001625 0.009503

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 1.536e-02 2.198e-02 0.699 0.48485

`454` 2.377e-01 5.094e-02 4.667 3.84e-06 \*\*\*

`458` -1.525e-01 1.300e-01 -1.173 0.24130

`462` -9.166e-01 2.144e-01 -4.274 2.26e-05 \*\*\*

`466` -1.357e-01 2.829e-01 -0.480 0.63167

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rows skipped for brevity

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`938` -4.968e-01 3.319e-01 -1.497 0.13500

`942` -7.079e-01 3.531e-01 -2.005 0.04548 \*

`946` 9.287e-01 3.501e-01 2.653 0.00821 \*\*

`950` -2.340e-01 1.921e-01 -1.218 0.22367

absolute\_soil\_temperature 4.739e-04 7.149e-05 6.630 8.02e-11 \*\*\*

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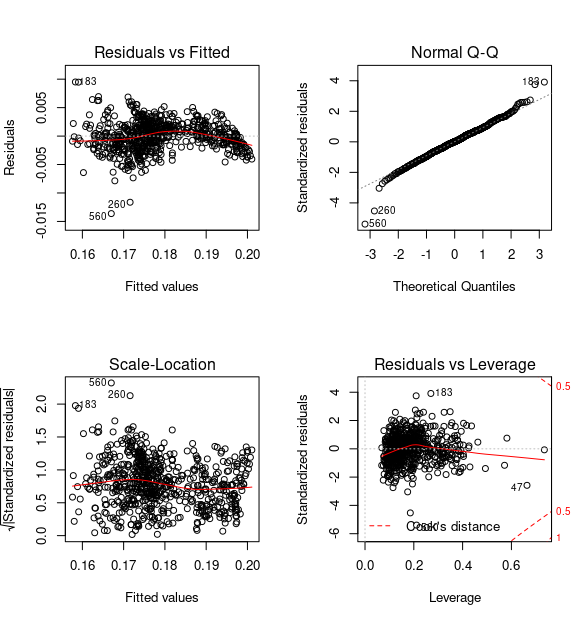
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.002844 on 552 degrees of freedom

Multiple R-squared: 0.9395, Adjusted R-squared: 0.9256

F-statistic: 67.98 on 126 and 552 DF, p-value: < 2.2e-16

Only a small sample of the hyperspectral predictors are shown to save space on this report. Anyone wishing to see the full summary can run the R code provided in the appendix. Plots of residuals are shown below, which indicate that this model also has problems but is superior to the previous model.



This model also displays non-constant variance, with the variance decreasing for larger fitted values. However the two plots on the left arguably show less heterodascity than the corresponding plots for the previous model. Furthermore, apart from four observations, the residuals fit a straight line on the Normal Q-Q plot very well. Three of these – observations 183, 260 and 560 – appear as unusual observations on the other residual plots also, so these may be outliers.

The Shapiro-Wilk test rejected the hypothesis of normally distributed residuals with a p-value of 3.686\*10-6, though this is exacerbated by the three observations identified before as possible outliers.

Shapiro-Wilk normality test

data: resid(full\_model2)

W = 0.98581, p-value = 3.686e-06

With the aforementioned observations removed, the result was very different.

Shapiro-Wilk normality test

data: resid(full\_model2)[c(1:182, 184:259, 261:559, 561:679)]

W = 0.99833, p-value = 0.7689

The non-constant variance test rejected the hypothesis of constant variance. Nevertheless, the p-value is larger than for the previous model, though still extremely low.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 54.21642, Df = 1, p = 1.7958e-13

Also the hypothesis of independent residuals is again rejected, the Durbin-Watson test yielding a p-value approximately zero.

lag Autocorrelation D-W Statistic p-value

1 0.4938877 1.011196 0

Alternative hypothesis: rho != 0

##### Linear Regression Model 7

A full model for soil moisture on both soil temperature and hyperspectral data with no transformations was also implemented. It was summarised by R as follows.

Residuals:

Min 1Q Median 3Q Max

-3.7816 -0.6501 -0.0298 0.5991 6.1957

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 84.3291 8.8539 9.525 < 2e-16 \*\*\*

`454` -95.8008 20.5225 -4.668 3.82e-06 \*\*\*

`458` 66.8321 52.3858 1.276 0.202574

`462` 326.7702 86.3924 3.782 0.000172 \*\*\*

`466` 86.5597 113.9558 0.760 0.447824

`470` -319.9693 130.0882 -2.460 0.014213 \*

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rows skipped for brevity

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`938` 201.5142 133.7151 1.507 0.132372

`942` 283.1241 142.2605 1.990 0.047064 \*

`946` -366.4030 141.0237 -2.598 0.009623 \*\*

`950` 90.0862 77.3904 1.164 0.244907

absolute\_soil\_temperature-0.1558 0.0288 -5.409 9.47e-08 \*\*\*

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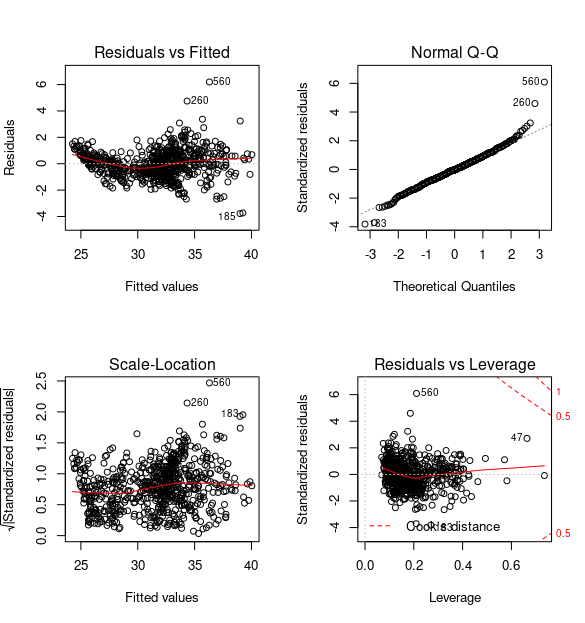
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.146 on 552 degrees of freedom

Multiple R-squared: 0.9196, Adjusted R-squared: 0.9012

F-statistic: 50.11 on 126 and 552 DF, p-value: < 2.2e-16

Its residuals are plotted below to assess the adequacy of the model.



The residual plots are similar to the first full model, which is understandable as in both models no transformation is applied to the response; the only difference being that in that model one predictor – temperature – is left not transformed here whereas it was transformed in that model. The results of the statistical tests are given below.

Shapiro-Wilk normality test

data: resid(full\_model3)

W = 0.97846, p-value = 1.909e-08

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 73.52163, Df = 1, p = < 2.22e-16

lag Autocorrelation D-W Statistic p-value

1 0.4916525 1.015513 0

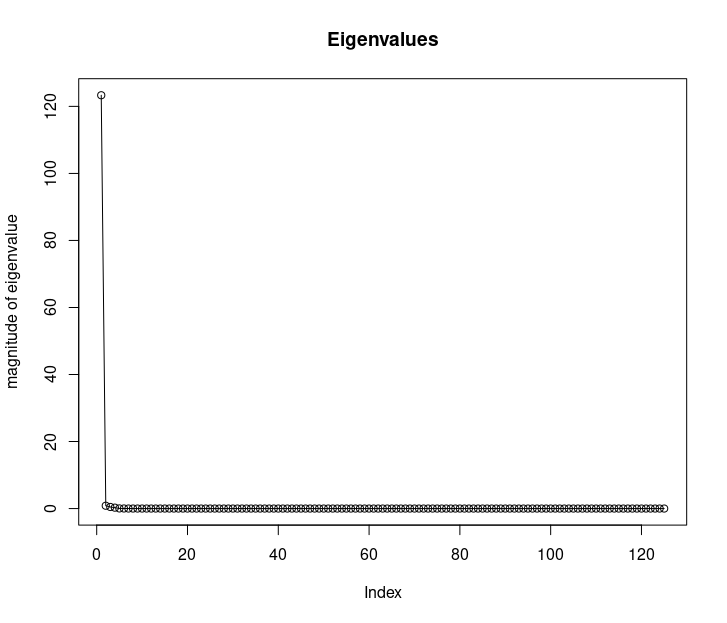
Alternative hypothesis: rho != 0

Again this model does not accord with the assumptions of the linear regression model. The variance is not constant and the residuals exhibit correlation.

These three full models violated the assumptions of the linear model. Of the three, the second model appeared better than the other two. In this model the response is transformed as the reciprocal of its square root. This means that once the inverse transformation is applied to predictions to obtain the soil moisture, it will be a positive number, which fits with the physical situation being modelled, soil moisture never being negative!

#### Taking principal components of hyperspectral image variables

As there are many hyperspectral variables, it would be preferable to compress the information contained therein into few variables. One way to do this is through principal component analysis. By taking the most significant principal components, the variation between observations can sometimes be adequately represented with only a small fraction of the original variables. Therefore, principal components of the 125 hyperspectral variables were obtained. The variance of the data in the direction of the nth principal component is proportional to the size of the nth eigenvalue. As can be seen from the plot below, one eigenvalue is much larger than the others. Therefore most of the variance in the hyperspectral data is along the first principal component.



##### Linear Regression Model 8

Subsequently a model was fitted of the same form as the second full model but also including the first principle component. That is, the model was of the form

where x\_1 and x\_2 were the soil temperature and the first principal component of the hyperspectral attributes respectively.

The following summary was produced.

Residuals:

Min 1Q Median 3Q Max

-0.017560 -0.003275 0.000181 0.003537 0.010987

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) -2.011e-01 1.471e-02 -13.68 <2e-16 \*\*\*

absolute\_soil\_temperature1.155e-03 4.922e-05 23.46 <2e-16 \*\*\*

PC1 -1.339e-02 6.176e-04 -21.68 <2e-16 \*\*\*

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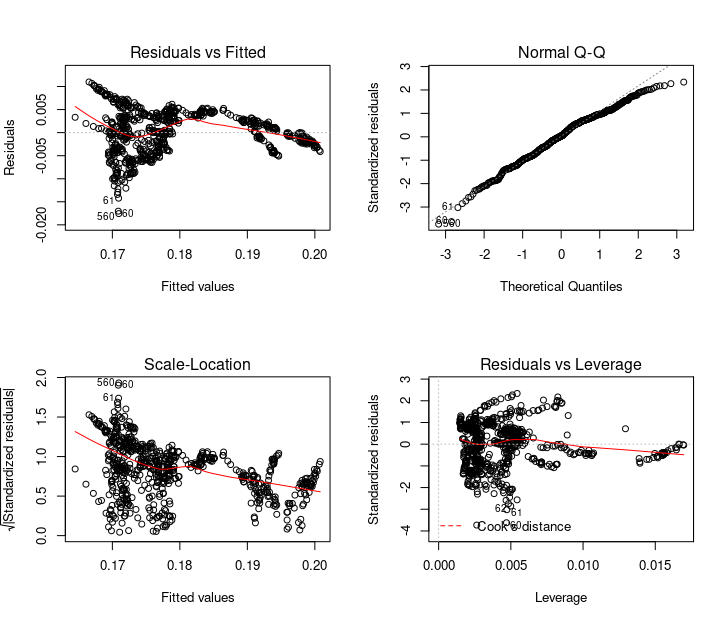
Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.004715 on 676 degrees of freedom

Multiple R-squared: 0.7962, Adjusted R-squared: 0.7955

F-statistic: 1320 on 2 and 676 DF, p-value: < 2.2e-16

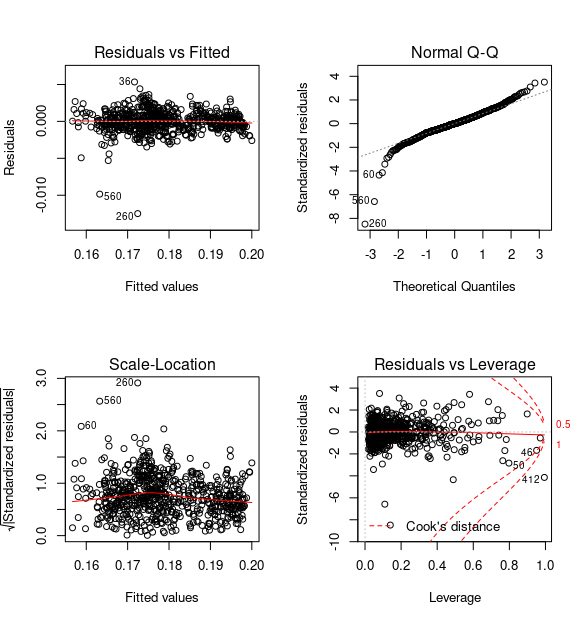
However, the linear regression model assumptions were not satisfied as shown by this plot.



Clearly, the residuals are not randomly distributed about zero, and this model can be discarded.

##### Linear Regression Model 9

By adding some more principal components, and including interaction terms, both between the principle components of the hyperspectral features themselves and between these principle components and the soil temperature, a better model was produced. Its residual plots are as follows.



There is possibly a slight trend downward for the largest residuals and the Normal Q-Q plot shows some deviation from a straight line at either end. The Scale-Location plot shows roughly constant variance, and the Residuals vs Leverage plot indicates that observations 412 and 46 exert significant influence on the model fit. Some feature selection had been used, including using AIC and F values to remove terms that did not significantly improve the model fit. This was important to prevent overfitting, as there are only 679 observations in total, and the number of predictors should ideally be much smaller than the number of observations.

As can be seen, above, observations 260 and 560 appear to be somewhat unusual so these may be outliers. These had a large impact on the Shapiro-Wilk test. With these observations included, the p-value was basically zero.

Shapiro-Wilk normality test

data: resid(reduced\_model23)

W = 0.92891, p-value < 2.2e-16

But with these removed, the p-value was much larger, though still smaller than 0.05.

Shapiro-Wilk normality test

data: resid(reduced\_model23)[c(1:259, 261:559, 561:679)]

W = 0.9935, p-value = 0.005016

The non-constant variance test rejected the hypothesis of constant variance.

Non-constant Variance Score Test

Variance formula: ~ fitted.values

Chisquare = 32.75391, Df = 1, p = 1.046e-08

Also the Durbin-Watson test rejected the hypothesis of uncorrelated residuals.

lag Autocorrelation D-W Statistic p-value

1 0.1667436 1.662287 0

Alternative hypothesis: rho != 0

This model violates the assumptions of linear models at the 5% significance level. Yet of the models fitted on the whole set of 679 observations, this was closest to being adequate.

The coefficients and the significance thereof are summarised by the following R output.

Residuals:

Min 1Q Median 3Q Max

-0.0112711 -0.0007216 0.0000144 0.0007910 0.0047620

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept) 2.552e+00 7.342e-01 3.476 0.000549 \*\*\*

absolute\_soil\_temperature -3.363e-03 2.529e-03 -1.330 0.184121

PC1 -5.340e-01 5.906e-01 -0.904 0.366373

PC2 -1.287e+01 2.146e+00 -5.998 3.62e-09 \*\*\*

PC3 7.676e+00 1.824e+00 4.209 3.00e-05 \*\*\*

PC4 2.642e+01 1.311e+01 2.015 0.044392 \*

PC5 1.834e+02 1.956e+01 9.377 < 2e-16 \*\*\*

PC6 -1.583e+01 6.687e+00 -2.367 0.018281 \*

PC7 4.109e+01 4.680e+01 0.878 0.380313

PC8 3.147e+01 1.226e+01 2.566 0.010541 \*

PC9 -8.176e+02 3.243e+02 -2.521 0.011969 \*

PC10 -1.071e+02 6.757e+01 -1.585 0.113641

absolute\_soil\_temperature:PC16.859e-03 2.000e-03 3.430 0.000649 \*\*\*

absolute\_soil\_temperature:PC2 3.608e-02 7.469e-03 4.831 1.77e-06 \*\*\*

absolute\_soil\_temperature:PC3 -3.442e-02 4.990e-03 -6.897 1.47e-11 \*\*\*

absolute\_soil\_temperature:PC4 5.140e-03 4.668e-02 0.110 0.912374

absolute\_soil\_temperature:PC5 -5.887e-01 6.354e-02 -9.265 < 2e-16 \*\*\*

absolute\_soil\_temperature:PC6 4.696e-02 2.027e-02 2.317 0.020865 \*

absolute\_soil\_temperature:PC7 -1.188e-01 1.532e-01 -0.776 0.438328

absolute\_soil\_temperature:PC8 2.457e-03 1.698e-02 0.145 0.885008

absolute\_soil\_temperature:PC9 2.475e+00 1.093e+00 2.264 0.023937 \*

absolute\_soil\_temperature:PC10 3.345e-01 2.229e-01 1.501 0.134027

PC1:PC2 -2.170e+00 2.907e-01 -7.464 3.30e-13 \*\*\*

PC1:PC3 -5.198e+00 5.617e-01 -9.255 < 2e-16 \*\*\*

PC1:PC4 -7.774e+01 1.159e+01 -6.705 5.00e-11 \*\*\*

PC1:PC5 1.110e+02 1.260e+01 8.808 < 2e-16 \*\*\*

PC1:PC6 -7.960e+00 1.701e+00 -4.681 3.61e-06 \*\*\*

PC1:PC7 -1.105e+01 1.732e+00 -6.381 3.75e-10 \*\*\*

PC1:PC8 1.796e+01 8.168e+00 2.198 0.028349 \*

PC1:PC9 -1.605e+02 3.131e+01 -5.125 4.13e-07 \*\*\*

PC1:PC10 1.521e+02 6.040e+01 2.518 0.012077 \*

PC2:PC3 7.713e+00 2.563e+00 3.009 0.002739 \*\*

PC2:PC4 -3.841e+02 4.170e+01 -9.210 < 2e-16 \*\*\*

PC2:PC5 8.317e+00 2.934e+00 2.835 0.004758 \*\*

PC2:PC6 -5.858e+00 2.196e+00 -2.667 0.007871 \*\*

PC2:PC7 -4.715e+00 5.610e+00 -0.841 0.400989

PC2:PC8 -1.061e+01 6.935e+00 -1.529 0.126769

PC2:PC9 -4.613e+02 9.491e+01 -4.860 1.53e-06 \*\*\*

PC2:PC10 8.836e+02 2.619e+02 3.373 0.000795 \*\*\*

PC3:PC4 -9.222e+01 2.014e+01 -4.580 5.75e-06 \*\*\*

PC3:PC5 -1.088e+01 2.444e+00 -4.453 1.02e-05 \*\*\*

PC3:PC6 -6.637e+01 1.242e+01 -5.345 1.33e-07 \*\*\*

PC3:PC7 2.267e+01 9.677e+00 2.343 0.019479 \*

PC3:PC8 -7.088e+01 2.220e+01 -3.192 0.001494 \*\*

PC3:PC9 1.992e+02 5.870e+01 3.394 0.000739 \*\*\*

PC3:PC10 -1.517e+02 4.241e+01 -3.577 0.000378 \*\*\*

PC4:PC5 4.727e+01 1.816e+01 2.603 0.009501 \*\*

PC4:PC6 -2.864e+01 2.726e+01 -1.050 0.293969

PC4:PC7 2.833e+02 4.280e+01 6.619 8.60e-11 \*\*\*

PC4:PC8 6.537e+02 2.089e+02 3.129 0.001845 \*\*

PC4:PC9 6.160e+02 3.727e+02 1.653 0.098935 .

PC4:PC10 1.224e+02 4.802e+01 2.548 0.011100 \*

PC5:PC6 1.843e+00 5.035e+00 0.366 0.714395

PC5:PC7 -1.650e+03 3.913e+02 -4.216 2.91e-05 \*\*\*

PC5:PC8 -2.513e+01 8.735e+00 -2.877 0.004176 \*\*

PC5:PC9 1.827e+02 9.124e+01 2.003 0.045674 \*

PC5:PC10 -2.320e+04 3.074e+03 -7.545 1.88e-13 \*\*\*

PC6:PC7 -2.396e+02 9.809e+02 -0.244 0.807109

PC6:PC8 -6.888e+02 1.953e+02 -3.527 0.000455 \*\*\*

PC6:PC9 1.929e+04 7.016e+03 2.750 0.006159 \*\*

PC6:PC10 8.692e+01 9.095e+01 0.956 0.339632

PC7:PC8 6.932e+02 1.996e+02 3.473 0.000555 \*\*\*

PC7:PC9 1.936e+05 8.077e+04 2.397 0.016854 \*

PC7:PC10 3.983e+02 1.788e+02 2.227 0.026338 \*

PC8:PC10 1.136e+03 3.036e+02 3.741 0.000203 \*\*\*

PC9:PC10 -6.850e+03 1.675e+03 -4.090 4.96e-05 \*\*\*

absolute\_soil\_temperature:PC1:PC4 3.404e-01 3.832e-02 8.883 < 2e-16 \*\*\*

absolute\_soil\_temperature:PC1:PC5 -3.507e-01 4.078e-02 -8.601 < 2e-16 \*\*\*

absolute\_soil\_temperature:PC1:PC10 -5.290e-01 1.976e-01 -2.677 0.007655 \*\*

absolute\_soil\_temperature:PC2:PC4 1.087e+00 1.442e-01 7.535 2.02e-13 \*\*\*

absolute\_soil\_temperature:PC2:PC10 -2.692e+00 8.665e-01 -3.107 0.001989 \*\*

absolute\_soil\_temperature:PC5:PC7 6.287e+00 1.337e+00 4.702 3.27e-06 \*\*\*

absolute\_soil\_temperature:PC5:PC10 7.549e+01 9.877e+00 7.644 9.47e-14 \*\*\*

absolute\_soil\_temperature:PC6:PC7 2.731e-01 3.219e+00 0.085 0.932415

absolute\_soil\_temperature:PC6:PC9 -5.760e+01 2.345e+01 -2.457 0.014336 \*

absolute\_soil\_temperature:PC7:PC9 -6.686e+02 2.649e+02 -2.524 0.011871 \*

PC1:PC2:PC3 8.990e+00 1.029e+00 8.740 < 2e-16 \*\*\*

PC1:PC2:PC4 -4.307e+01 6.172e+00 -6.979 8.61e-12 \*\*\*

PC1:PC2:PC7 1.126e+01 2.721e+00 4.140 4.01e-05 \*\*\*

PC1:PC2:PC8 -9.225e+00 3.822e+00 -2.414 0.016117 \*

PC1:PC3:PC4 -1.050e+02 1.192e+01 -8.815 < 2e-16 \*\*\*

PC1:PC3:PC10 -9.118e+01 2.453e+01 -3.718 0.000222 \*\*\*

PC1:PC4:PC5 7.537e+01 2.108e+01 3.576 0.000380 \*\*\*

PC1:PC4:PC6 -1.127e+02 2.885e+01 -3.907 0.000105 \*\*\*

PC1:PC4:PC8 3.893e+02 1.560e+02 2.495 0.012884 \*

PC1:PC4:PC9 -2.221e+03 4.877e+02 -4.553 6.51e-06 \*\*\*

PC1:PC4:PC10 6.656e+01 3.339e+01 1.993 0.046716 \*

PC1:PC5:PC10 -1.471e+04 1.952e+03 -7.537 2.00e-13 \*\*\*

PC1:PC6:PC8 -5.167e+02 1.386e+02 -3.728 0.000213 \*\*\*

PC1:PC6:PC9 1.264e+03 3.694e+02 3.422 0.000668 \*\*\*

PC1:PC6:PC10 4.620e+02 1.165e+02 3.966 8.28e-05 \*\*\*

PC1:PC7:PC9 2.167e+03 8.064e+02 2.687 0.007417 \*\*

PC1:PC7:PC10 -4.959e+02 1.564e+02 -3.171 0.001602 \*\*

PC1:PC8:PC10 1.077e+03 2.645e+02 4.070 5.39e-05 \*\*\*

PC1:PC9:PC10 1.041e+04 1.887e+03 5.514 5.41e-08 \*\*\*

PC2:PC3:PC4 2.008e+02 4.763e+01 4.215 2.92e-05 \*\*\*

PC2:PC3:PC6 3.686e+01 1.427e+01 2.582 0.010070 \*

PC2:PC3:PC10 -4.414e+02 1.205e+02 -3.663 0.000273 \*\*\*

PC2:PC4:PC5 1.519e+02 5.981e+01 2.539 0.011392 \*

PC2:PC4:PC9 -8.474e+03 2.043e+03 -4.147 3.89e-05 \*\*\*

PC2:PC5:PC7 -7.395e+02 1.039e+02 -7.115 3.51e-12 \*\*\*

PC2:PC5:PC10 -3.490e+03 3.612e+02 -9.662 < 2e-16 \*\*\*

PC2:PC7:PC9 1.318e+04 4.171e+03 3.161 0.001658 \*\*

PC2:PC7:PC10 -2.725e+03 5.630e+02 -4.841 1.68e-06 \*\*\*

PC2:PC9:PC10 5.252e+04 9.771e+03 5.375 1.14e-07 \*\*\*

PC3:PC4:PC6 -7.908e+02 1.597e+02 -4.951 9.86e-07 \*\*\*

PC3:PC4:PC8 -1.136e+03 3.828e+02 -2.969 0.003116 \*\*

PC3:PC6:PC7 -8.429e+02 1.851e+02 -4.554 6.48e-06 \*\*\*

PC3:PC6:PC10 3.535e+03 7.570e+02 4.670 3.80e-06 \*\*\*

PC3:PC7:PC8 -1.187e+03 3.641e+02 -3.260 0.001184 \*\*

PC3:PC7:PC10 -1.454e+03 5.684e+02 -2.558 0.010784 \*

PC3:PC8:PC10 3.337e+03 1.245e+03 2.681 0.007563 \*\*

PC4:PC6:PC7 -5.741e+03 8.849e+02 -6.487 1.95e-10 \*\*\*

PC4:PC6:PC8 -1.622e+04 4.324e+03 -3.752 0.000194 \*\*\*

PC4:PC6:PC9 -6.135e+03 5.046e+03 -1.216 0.224517

PC4:PC7:PC8 1.614e+04 5.032e+03 3.208 0.001416 \*\*

PC4:PC7:PC9 -2.312e+05 7.372e+04 -3.137 0.001801 \*\*

PC4:PC8:PC10 1.664e+04 6.466e+03 2.573 0.010353 \*

PC6:PC7:PC8 -1.225e+04 3.702e+03 -3.309 0.000998 \*\*\*

PC6:PC7:PC9 -4.613e+06 1.690e+06 -2.729 0.006546 \*\*

PC6:PC7:PC10 5.210e+03 3.611e+03 1.443 0.149704

PC7:PC8:PC10 1.795e+04 5.416e+03 3.314 0.000979 \*\*\*

absolute\_soil\_temperature:PC1:PC5:PC10 4.480e+01 6.205e+00 7.220 1.74e-12 \*\*\*

absolute\_soil\_temperature:PC6:PC7:PC9 1.560e+04 5.538e+03 2.816 0.005037 \*\*

PC1:PC2:PC3:PC4 1.837e+02 2.260e+01 8.128 2.90e-15 \*\*\*

PC1:PC4:PC6:PC8 -1.216e+04 3.039e+03 -4.002 7.14e-05 \*\*\*

PC1:PC4:PC8:PC10 9.899e+03 4.307e+03 2.298 0.021918 \*

PC4:PC6:PC7:PC8 -3.550e+05 9.976e+04 -3.558 0.000406 \*\*\*

PC4:PC6:PC7:PC9 4.534e+06 1.489e+06 3.045 0.002440 \*\*

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.001481 on 550 degrees of freedom

Multiple R-squared: 0.9836, Adjusted R-squared: 0.9798

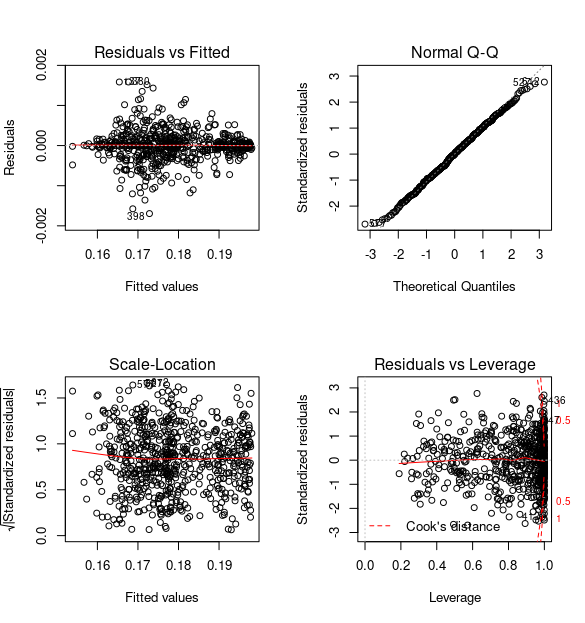
F-statistic: 258.4 on 128 and 550 DF, p-value: < 2.2e-16

This model included 128 predictors which is more than ideal, given that there are only 679 observations. There had been 561 predictors in the model before some were removed during feature selection, which is far too many. While the model with 561 predictors did not have autocorrelated residuals on the first lag according to the Durbin-Watson test, it also had many points with far too much leverage according to the Residuals vs Leverage plot. This showed that the model overfit the data. This is a problem because such a model would not generalise to other data. The Durbin-Watson test result and the residuals plots of this overfitted model are shown below.

lag Autocorrelation D-W Statistic p-value

1 -0.02676456 2.05321 0.34

Alternative hypothesis: rho != 0



It can be seen that there are many observations beyond Cook’s distance. These exert undue influence on the fitted parameters. It was necessary to remove terms to create a simpler model that would generalise better. Therefore, the reduced model is to be preferred, even though it has a Durbin-Watson statistic less than two and consequently the hypothesis of no correlation between consecutive residuals was rejected.

##### Logistic Regression Model 1

The logistic regression model predicting whether soil was between 30% and 40% included the soil temperature and the first ten principal components of the hyperspectral variables as predictors. It logit link to predict the probability that the soil moisture would be in this range. That is, the model was of the form

log(π/(1 – π)) = soil temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10

where π is the probability that the soil moisture is between 30% and 40%.

The Analysis of Deviance table showed that this model was significant.

Analysis of Deviance Table

Model 1: `30\_to\_40` ~ 1

Model 2: `30\_to\_40` ~ (absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 +

PC5 + PC6 + PC7 + PC8 + PC9 + PC10)

Resid. Df Resid. Dev Df Deviance Pr(>Chi)

1 678 863.92

2 667 86.18 11 777.74 < 2.2e-16 \*\*\*

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

It was decided that if the probability π was 0.5 or greater, than soil moisture would be predicted to be in the range 30% to 40% but if the probability π was less than 0.5 the soil moisture would be predicted to not be in this range. Using this model to predict the soil moisture, 97.94% of observations in the data set were correctly classified. The total number of samples in the data set with soil moisture between 30% and 40% was 66.72% so a model which always predicted the soil moisture to be in this range would have an accuracy of 66.72%. The model created is much better than this baseline, which indicates it is a reasonable model. However it would need to be tested on data not used to build the model to obtain an unbiased estimate of its accuracy. A summary of the model is shown below.

Deviance Residuals:

Min 1Q Median 3Q Max

-3.9964 0.0000 0.0030 0.0384 1.8024

Coefficients:

Estimate Std. Error z value Pr(>|z|)

(Intercept) 220.0563 122.3785 1.798 0.07215 .

absolute\_soil\_temperature -0.5201 0.3816 -1.363 0.17290

PC1 41.3459 22.1306 1.868 0.06172 .

PC2 76.4596 62.6664 1.220 0.22243

PC3 61.4430 41.2499 1.490 0.13635

PC4 506.5639 120.0864 4.218 2.46e-05 \*\*\*

PC5 367.6972 127.6207 2.881 0.00396 \*\*

PC6 -191.3726 129.6471 -1.476 0.13992

PC7 860.0738 209.9633 4.096 4.20e-05 \*\*\*

PC8 0.7474 165.6412 0.005 0.99640

PC9 1596.8895 1558.1976 1.025 0.30544

PC10 -1432.4696 355.6035 -4.028 5.62e-05 \*\*\*

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 863.92 on 678 degrees of freedom

Residual deviance: 86.18 on 667 degrees of freedom

AIC: 110.18

Number of Fisher Scoring iterations: 11

The Wald estimates show that not all terms are significant. Confidence intervals for the intercept and coefficients are shown below.

2.5 % 97.5 %

(Intercept) 25.366499 491.9810756

absolute\_soil\_temperature -1.355559 0.1045375

PC1 3.592374 90.0315833

PC2 -33.789850 212.1206287

PC3 -11.977170 151.3286498

PC4 299.497140 776.4174733

PC5 135.205384 644.4485926

PC6 -468.216962 49.5063365

PC7 494.037493 1335.3597140

PC8 -335.120706 324.4881161

PC9 -1416.228354 4776.9155147

PC10 -2228.657454 -815.1701793

##### Logistic Regression Model 2

The second logistic model predicted whether soil moisture was greater than 38%. There were only 24 observations in which the soil moisture was greater than 38%. This model was similar to the previous logistic model, but it only included the first seven principal components. It was of the form

log(π/(1 – π)) = soil temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7

where π is the probability that the soil moisture is over 38%.

Analysis of deviance showed this model was significant.

Analysis of Deviance Table

Model 1: `>38` ~ 1

Model 2: `>38` ~ absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 +

PC6 + PC7

Resid. Df Resid. Dev Df Deviance Pr(>Chi)

1 678 207.585

2 670 54.875 8 152.71 < 2.2e-16 \*\*\*

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

If the probability π was greater or equal to 0.5, then a soil moisture greater than 38% was predicted. This resulted in 98.82% of samples being correctly predicted as either having soil moisture greater than 38% or not. As the data is unbalanced, with only 24 of 679 observations having soil moisture greater than 38%, a model that always made a negative prediction – that is having *less* than 38%, would also have very high accuracy. So a more thorough analysis was carried out. It was found that of the 18 samples that were predicted to have soil moisture greater than 38%, 17 of these indeed had soil moisture greater than 38%. This gives a precision of 94.44%. With 17 of 24 samples being correctly identified as having greater than 38%, the recall was 70.83%. This model seems to be quite good at discriminating between samples with high soil moisture greater than 38% and other samples. Its principal component terms are all significant, as seen in the summary below.

Deviance Residuals:

Min 1Q Median 3Q Max

-1.86005 -0.03092 -0.00758 -0.00001 2.70310

Coefficients:

Estimate Std. Error z value Pr(>|z|)

(Intercept) 159.3989 132.9330 1.199 0.230492

absolute\_soil\_temperature -0.5542 0.4430 -1.251 0.210901

PC1 -62.6762 16.7869 -3.734 0.000189 \*\*\*

PC2 -242.2168 59.5504 -4.067 4.75e-05 \*\*\*

PC3 -212.5866 54.7876 -3.880 0.000104 \*\*\*

PC4 -195.0687 68.2587 -2.858 0.004266 \*\*

PC5 465.6496 117.3679 3.967 7.27e-05 \*\*\*

PC6 710.6193 211.1720 3.365 0.000765 \*\*\*

PC7 -1205.2162 320.3557 -3.762 0.000168 \*\*\*

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 207.585 on 678 degrees of freedom

Residual deviance: 54.875 on 670 degrees of freedom

AIC: 72.875

Number of Fisher Scoring iterations: 12

Only the intercept and the soil temperature are not significant. Interestingly, temperature was not considered significant in the previous logistic model either. This suggests that predicting whether or not soil moisture is within certain ranges can be done using only leading principal components of the hyperspectral data.

### Predictions

Some made-up data (both temperature and hyperspectral) was generated to predict soil moisture using various fitted models.

**Predictions from Linear Regression Models**

Using linear regression model 3, the predictions made were all within the range of soil moisture in original data. When linear regression model 6, the full model with the transformed response variable was used, some predictions were of similar scale to the original data but some were very different. One even had a soil moisture reading of over 400 thousand percent! When the model (linear regression model 9) including soil temperature, the first 10 principal components and interactions was used for prediction, most predictions were quite different to original data, some being of a small order of magnitude less than one. However, when a model including just temperature and the first principal component was used for prediction, the predictions were all within the numerical range of the original data. This model, when applied to some of the actual data, produced results quite close to the actual values of soil moisture.

Logistic regresson model 1 predicted five of ten of the generated samples to be between 30% and 40% soil moisture. Logistic regresson model 2 predicted two of ten samples to be above 38% soil moisture.

## Discussion

In the linear regression models, the residuals were autocorrelated because the data is time dependent. There are limitations of this modelling approach. Time series models such as an ARIMA model may be appropriate. Unsurprisingly, soil moisture readings taken two minutes apart are highly correlated. Modelling soil moisture in terms of soil temperature alone on data aggregated over a longer period, namely one hour, reduced this autocorrelation and allowed a plausible model to be fitted for the relationship between soil temperature and soil moisture.

Interestingly, a fitted model predicting soil moisture from just soil temperature and the first principal component produced decent predictions. The first principal component was seen to contain most of the variance in the hyperspectral imaging data. A time series model using the first principal component of the hyperspectral data and the soil temperature is of serious merit and should be considered for further research.

## Conclusion

The hyperspectral data was analysed and most of the variance can be expressed with one principal component. Because of the autocorrelation in the data, time series modelling would be more appropriate.

## References

Queensland Government. (2013). *Environment, land and water: Soil colour.* https://www.qld.gov.au/environment/land/management/soil/soil-properties/colour

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## Appendix: R code

# Load required packages

library(readr)

library(car)

library(ggplot2)

library(olsrr)

library(dplyr)

soil <- read\_csv("soilmoisture\_dataset.csv")

head(soil)

nrow(soil)

ncol(soil)

# The index column is not useful for predicting soil moisture

soil.clean <- soil %>% select(-index)

head(soil.clean)

# Measure temperature in terms of absolute temperature, i.e. in the Kelvin scale

soil.clean$absolute\_soil\_temperature = soil.clean$soil\_temperature + 273.15

soil.clean = soil.clean %>% select(-soil\_temperature)

# Overview of data

ggplot(data = soil.clean, mapping = aes(soil\_moisture)) + geom\_histogram() + ggtitle("Histogram of respose: soil moisture") + xlab("Soil Moisture (%)")

ggplot(data = soil.clean, mapping = aes(soil\_moisture)) + geom\_boxplot() + ggtitle("Boxplot of respose: soil moisture") + xlab("Soil Moisture (%)")

ggplot(data = soil.clean, mapping = aes(absolute\_soil\_temperature)) + geom\_histogram() + ggtitle("Histogram of a predictor: soil temperature") + xlab("Soil Temperature (K)")

ggplot(data = soil.clean, mapping = aes(absolute\_soil\_temperature)) + geom\_boxplot() + ggtitle("Boxplot of a predictor: soil temperature") + xlab("Soil Temperature (K)")

ggplot(data = soil.clean, mapping = aes(absolute\_soil\_temperature, soil\_moisture)) + geom\_point() + ggtitle("Soil moisture vs soil temperature") + xlab("Soil Temperature (K)") + ylab("Soil Moisture (%)")

ggplot(data = soil.clean, mapping = aes(`454`)) + geom\_histogram() + ggtitle("Histogram of a predictor: hyperspectral band 454") + xlab("hyperspectral band 454")

ggplot(data = soil.clean, mapping = aes(`454`)) + geom\_boxplot() + ggtitle("Boxplot of a predictor: hyperspectral band 454") + xlab("hyperspectral band 454")

ggplot(data = soil.clean, mapping = aes(`950`)) + geom\_histogram() + ggtitle("Histogram of a predictor: hyperspectral band 950") + xlab("hyperspectral band 950")

ggplot(data = soil.clean, mapping = aes(`950`)) + geom\_boxplot() + ggtitle("Boxplot of a predictor: hyperspectral band 950") + xlab("hyperspectral band 950")

# Firstly, a simple linear regression model will be fit

linear\_model1 = lm(soil\_moisture ~ absolute\_soil\_temperature, data = soil.clean)

summary(linear\_model1)

# This model appears significant with ANOVA giving F-statistic of 1143 on 1 and 677 d.f. leading to a p-value of 2.2e-16 or less

# Check whether assumptions of linear regression model are satisfied

par(mfrow = c(2,2))

plot(linear\_model1)

# The plot of residuals against fitted values does NOT show random noise about 0, instead, there are multiple strands of tightly bunched residuals exhibiting a downward trend against the fitted values. There is also two comparatively large positive residuals for fitted values between 34 and 36.

# The Scale-Location plot indicates possible increasing variance. The Normal Q-Q plot shows that the residuals display some non-Gaussian behaviour, diverging from the Q-Q line at either end.

# The Residuals vs Leverage plot does not indicate there are any influential outliers, which is good.

# Overall this model appears not to satisfy the assumptions of the linear regression model, with non-normal residuals and non-constant variance, as well as some clear trends on display in the Residuals vs Fitted plot

# These issues can also be assessed with formal statistical tests.

# Assess normality of residuals

shapiro.test(resid(linear\_model1))

# Assess non-constant variance

ncvTest(linear\_model1)

# The Shapiro-Wilk test indicates non-normality and the non-constant test indicates non-constant variance.

# Linear regression model also assumes uncorrelated residuals. This can be tested for the first lag with the Durbin-Watson test.

durbinWatsonTest(linear\_model1)

# There is evidently some correlation on the first lag with a p-value of 0.

# Multiple assumptions of a linear regression model are violated. The assumption of independent, normally distributed residuals with constant variance is violated. The residuals are not independent, identically distributed and normally distributed.

# Applying transformations to the data may help.

# To work out which transformation(s) would be appropriate, the distribution of both the independent and dependent variable will be considered.

ggplot(data = soil.clean, mapping = aes(absolute\_soil\_temperature)) + geom\_histogram()

ggplot(data = soil.clean, mapping = aes(soil\_moisture)) + geom\_histogram()

# The response variable is not normally distributed and should be transformed.

# Consider possible transformations

ggplot(data = soil.clean, mapping = aes(log(soil\_moisture))) + geom\_histogram()

ggplot(data = soil.clean, mapping = aes(soil\_moisture^(-0.5))) + geom\_histogram()

# Consider Box-Cox transformation

par(mfrow=c(1,1))

a=boxCox(linear\_model1)

a$x

a$y

a$x[a$y==max(a$y)]

par(mfrow=c(2,2))

ggplot(data = soil.clean, mapping = aes(soil\_moisture^(-0.828))) + geom\_histogram()

linear\_model2 = lm(soil\_moisture^(-0.828)~absolute\_soil\_temperature, data = soil.clean)

summary(linear\_model2)

# The linear model of the transformed data is significant, with a p-value less than or equal to 2.2e-16.

# Consider adequacy of model

plot(linear\_model2)

shapiro.test(resid(linear\_model2))

ncvTest(linear\_model2)

durbinWatsonTest(linear\_model2)

# The same problems exist with this model.

# Try transforming the independent variable

ggplot(data = soil.clean, mapping = aes(absolute\_soil\_temperature^2)) + geom\_histogram()

temp.squared = soil.clean$absolute\_soil\_temperature^2

linear\_model3 = lm(soil\_moisture^(-0.828)~temp.squared, data = soil.clean)

summary(linear\_model3)

plot(linear\_model3)

# Again the same problems are apparent.

# Try another transformation

ggplot(data = soil.clean, mapping = aes(1/absolute\_soil\_temperature)) + geom\_histogram()

temp.reciprocal = 1/soil.clean$absolute\_soil\_temperature

linear\_model4 = lm(soil\_moisture^(-0.828)~temp.reciprocal, data = soil.clean)

summary(linear\_model4)

plot(linear\_model4)

shapiro.test(resid(linear\_model4))

ncvTest(linear\_model4)

durbinWatsonTest(linear\_model4)

temp.log.reciprocal = log(temp.reciprocal)

linear\_model5 = lm(soil\_moisture^(-0.828)~temp.log.reciprocal, data = soil.clean)

plot(linear\_model5)

shapiro.test(resid(linear\_model5))

ncvTest(linear\_model5)

durbinWatsonTest(linear\_model5)

temp.reciprocal.sqrt = 1/(sqrt(soil.clean$absolute\_soil\_temperature))

linear\_model6 = lm(soil\_moisture^(-0.828)~temp.reciprocal.sqrt, data = soil.clean)

plot(linear\_model6)

temp.squared.reciprocal = 1/temp.squared

linear\_model7 = lm(soil\_moisture^(-0.828)~temp.squared.reciprocal, data = soil.clean)

summary(linear\_model7)

plot(linear\_model7)

shapiro.test(resid(linear\_model7))

par(mfrow=c(1,1))

hist(log(temp.squared.reciprocal))

par(mfrow=c(2,2))

temp.log.squared.reciprocal = log(temp.squared.reciprocal)

linear\_model8 = lm(soil\_moisture^(-0.828)~temp.log.squared.reciprocal, data = soil.clean)

summary(linear\_model8)

plot(linear\_model8)

shapiro.test(resid(linear\_model8))

ncvTest(linear\_model8)

durbinWatsonTest(linear\_model8)

# No matter which transformation is used, it will not erase the trends in the residuals plot.

# A simple linear regression model of soil moisture - or a transformation of it - against the soil temperature - or a transformation of it - will not suffice.

# Try multiple linear regression including multiple polynomial terms

linear\_model9 = lm(soil\_moisture ~ absolute\_soil\_temperature + temp.squared, data = soil.clean)

plot(linear\_model9)

shapiro.test(resid(linear\_model9))

ncvTest(linear\_model9)

durbinWatsonTest(linear\_model9)

# Try adding more terms

temp.cubed = soil.clean$absolute\_soil\_temperature^3

temp.4 = soil.clean$absolute\_soil\_temperature^4

linear\_model10 = lm(soil\_moisture ~ absolute\_soil\_temperature + temp.squared + temp.cubed + temp.4, data = soil.clean)

summary(linear\_model10)

anova(linear\_model9, linear\_model10)

plot(linear\_model10)

shapiro.test(resid(linear\_model10))

ncvTest(linear\_model10)

durbinWatsonTest(linear\_model10)

AIC(linear\_model10)

BIC(linear\_model10)

#This is looking better. A couple more may also help.

temp.5 = soil.clean$absolute\_soil\_temperature^5

temp.6 = soil.clean$absolute\_soil\_temperature^6

linear\_model11 = lm(soil\_moisture ~ absolute\_soil\_temperature + temp.squared + temp.cubed + temp.4 + temp.5 + temp.6, data = soil.clean)

summary(linear\_model11)

plot(linear\_model11)

shapiro.test(resid(linear\_model11))

ncvTest(linear\_model11)

durbinWatsonTest(linear\_model11)

# Check whether this is superior to the previous model

anova(linear\_model10, linear\_model11)

AIC(linear\_model11)

BIC(linear\_model11)

logLik(linear\_model11)-logLik(linear\_model10)

pchisq(logLik(linear\_model11)-logLik(linear\_model10), df = 2, lower.tail = F)

# Using likelihood ratio test, fail to reject hypothesis that simpler model is adequate at 5% significance level

# Try removing sample 183 which is an influential possible outlier

soil.clean.filtered = soil.clean[c(1:182,184:679),]

linear\_model12 = lm(soil\_moisture ~ absolute\_soil\_temperature + temp.squared[c(1:182,184:679)] + temp.cubed[c(1:182,184:679)] + temp.4[c(1:182,184:679)], data = soil.clean.filtered)

summary(linear\_model12)

plot(linear\_model12)

shapiro.test(resid(linear\_model12))

ncvTest(linear\_model12)

durbinWatsonTest(linear\_model12)

# Adding additional terms does not deal with the autocorrelation problem that has persisted in all models so far.

# Consistently the Durbin-Watson test has returned a p-value of 0, correct to the number of decimal places offered by this test.

# There is a lot of data collected across time, with one sample collected 2 minutes after another.

# It is unsurprising then that the data is likely to be highly autocorrelated. Soil moisture in the area will not change much in two minutes.

# To alleviate this problem to some extent, a decision was made to take the average hourly soil temperature and moisture levels and model these.

soil.clean$date = lubridate::date(soil.clean$datetime)

soil.clean$hour = lubridate::hour(soil.clean$datetime)

simplified = soil.clean %>% group\_by(date, hour) %>% summarise(moisture = mean(soil\_moisture), temperature = mean(absolute\_soil\_temperature))

simple\_model1 = lm(moisture ~ temperature, data = simplified)

summary(simple\_model1)

plot(simple\_model1)

shapiro.test(resid(simple\_model1))

ncvTest(simple\_model1)

durbinWatsonTest(simple\_model1)

# This model looks much better.

# There is still a concern that there is non-constant variance. A Box-Cox transformation may deal with this violation of the model's assumptions.

par(mfrow = c(1,1))

hist(simplified$moisture, main = "Histogram of aggregated soil moisture", xlab = "Soil moisture", breaks = 20)

hist(simplified$temperature, main = "Histogram of aggregated soil temperature", xlab ="Soil moisture", breaks = 20)

b=boxCox(simple\_model1)

b$x[b$y==max(b$y)]

hist((simplified$moisture)^(-1.2727), main = "Histogram of Box-Cox transformation \n of aggregated soil moisture", xlab = "Soil moisture^(-1.2727)", breaks = 20)

par(mfrow=c(2,2))

simple\_model2 = lm(moisture^(-1.2727) ~ temperature, data = simplified)

summary(simple\_model2)

plot(simple\_model2)

shapiro.test(resid(simple\_model2))

ncvTest(simple\_model2)

# Now the non-constant variance test fails to reject the hypothesis of constant variance (p-value = 0.3746)

durbinWatsonTest(simple\_model2)

# This model shows some autocorrelation at the first lag (p-value approx. 01)

# The reciprocal of the square root transformations can be applied, as the Scale-Location plot for the model of the non-transformed data showed some cubic behaviour.

simple\_model3 = lm(moisture^(-0.5) ~ temperature, data = simplified)

summary(simple\_model3)

plot(simple\_model3)

shapiro.test(resid(simple\_model3))

ncvTest(simple\_model3)

durbinWatsonTest(simple\_model3)

# There will probably always be some autocorrelation as these data are taken across time, and the averaged recordings from one hour will likely be correlated with the average recordings taken in the previous hour.

# There is no trend in the Residuals vs Fitted plot and the Normal Q-Q plot is consistent with the assumption of nornally distributed residuals.

# Furthermore, the Shapiro-Wilk test failed to reject the normally distributed residuals hypothesis (p-value = 0.9164) and the non-constant variance test failed to reject the constant variance hypothesis (p-value = 0.1708).

# This last model relates the reciprocal of the square root of soil moisture with the soil temperature, and finds that there is a positive linear association between the two, with p-value 1.30e-08.

# This means that there is a positive linear association between soil moisture and the reciprocal of the square of the soil temperature i.e soil\_moisture = A/(absolute\_soil\_temperature^2), for some positive constant A.

# This makes sense as this implies that for increasing temperatures, the soil moisture will be reduced, but will never get below zero, which is physically impossible.

# At higher temperatures, the soil will dry out more.

# Now models predicting soil moisture from the hyperspectral data as well as soil temperature will be built.

# As the soil moisture appears to be linearly associated with the reciprocal of the square of soil temperature, this term can replace soil temperature in the model.

# Alternatively, the transformed model predicting soil\_moisture^(-0.5) rather than soil\_moisture can be used.

par(mfrow=c(1,1))

hist(soil.clean$soil\_moisture, main = "Histogram of aggregated soil moisture", xlab = "Soil moisture", breaks = 30)

hist(soil.clean$soil\_moisture^(-0.5), main = "Histogram of reciprocal of the square root \n of aggregated soil moisture", xlab = "Reciprocal of square root of soil moisture", breaks = 30)

par(mfrow = c(2,2))

# Both approaches will be tried.

# First, a model will be created for raw soil\_moisture data in terms of the hyperspectral data and the reciprocal of the square of absolute\_soil\_temperature.

soil.final = soil.clean %>% select(-c(datetime, date, hour))

full\_model1 = lm(soil\_moisture ~ . - absolute\_soil\_temperature + temp.squared.reciprocal, data = soil.final)

summary(full\_model1)

# Consider adequacy of model

plot(full\_model1)

shapiro.test(resid(full\_model1))

ncvTest(full\_model1)

durbinWatsonTest(full\_model1)

# Second, the model for soil\_moisture^(-0.5) in terms of the hyperspectral data and the absolute\_soil\_temperature will be created.

full\_model2 = lm((soil\_moisture)^(-0.5) ~ ., data = soil.final)

summary(full\_model2)

# Consider adequacy of model

plot(full\_model2)

shapiro.test(resid(full\_model2))

ncvTest(full\_model2)

durbinWatsonTest(full\_model2)

# The second model appears superior with a larger adjusted R-squared value and also a larger F-statistic on the same number of degrees of freedom.

# Also consider model of soil\_measure against hyperspectral data and soil\_temperature with no transformations

full\_model3 = lm(soil\_moisture ~., data = soil.final)

summary(full\_model3)

plot(full\_model3)

shapiro.test(resid(full\_model3))

ncvTest(full\_model3)

durbinWatsonTest(full\_model3)

# full\_model2 appears best

# However, this model has issues with non-constant variance (as do the other two models).

# As with the other two models, the hypothesis of normally distributed residuals was rejected by the Shapiro-Wilk test.

# However this was largely because of a few outliers. If two of these are removed, then the Shapiro-Wilk test does not the normality hypothesis.

shapiro.test(resid(full\_model2)[c(1:259,261:559,561:679)])

# All the models have correlated first lags of residuals.

# There are a very large number of predictors. Consider modifying full\_model2 by removing insignificant predictors.

# Remove insignificant predictors using a backward stepwise algorithm

null\_model = lm((soil\_moisture)^(-0.5) ~ 1, data = soil.final)

reduced\_model1 = step(full\_model2, direction = "backward")

summary(reduced\_model1)

plot(reduced\_model1)

shapiro.test(resid(reduced\_model1))

ncvTest(reduced\_model1)

durbinWatsonTest(reduced\_model1)

# Also try forward selection algorithm

reduced\_model2 = step(null\_model, scope = list(lower = null\_model, upper = full\_model2), direction = "forward")

summary(reduced\_model2)

plot(reduced\_model2)

shapiro.test(resid(reduced\_model2))

ncvTest(reduced\_model2)

durbinWatsonTest(reduced\_model2)

# There is still a problem with the model adequacy.

# All of these full and reduced models fail the Shapiro-Wilk test and the non-constant variance test, that is, they reject respectively the hypotheses of normally distributed residuals and constant variance.

# We may need to add an additional term to the model.

soil.clean$temp.sqrt = sqrt(soil.clean$absolute\_soil\_temperature)

soil.final$temp.sqrt = soil.clean$temp.sqrt

full\_model4 = lm((soil\_moisture)^(-0.5) ~ ., data = soil.final)

summary(full\_model4)

# Consider adequacy of model

plot(full\_model4)

shapiro.test(resid(full\_model4))

ncvTest(full\_model4)

durbinWatsonTest(full\_model4)

# This modification increases the p-value slightly for both Shapiro-Wilk test and non-constant variance test, which is good.

# Consider the data set again

head(soil.final)

ncol(soil.final)

soil.final[1:4, 125:128]

# Consider taking principle components of the hyperspectral data

eigenvalues = soil.final[1:nrow(soil.final), 2:126] %>% cor() %>% eigen()

eigenvalues$values

par(mfrow = c(1,1))

plot(eigenvalues$values, type = 'o', main = "Eigenvalues", ylab = "magnitude of eigenvalue")

par(mfrow = c(2,2))

# Clearly the first principle component accounts for most of the variation amongst the hyperspectral variables.

e1 = eigenvalues$vectors[,1]

PC1 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC1[i] = sum(soil.final[i, 2:126]\*e1)

}

soil.final$PC1 = PC1

# Consider using this variable instead of all 125 hyperspectral features

reduced\_model4 = lm(soil\_moisture^(-0.5) ~ absolute\_soil\_temperature + PC1, soil.final)

summary(reduced\_model4)

plot(reduced\_model4)

# The linearity assumption is clearly violated.

shapiro.test(resid(reduced\_model4))

# We still do not have normally distributed residuals.

ncvTest(reduced\_model4)

# The variance is not constant.

# Adding additional principle components should improve the model as PC1 is inadequate.

e2 = eigenvalues$vectors[,2]

PC2 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC2[i] = sum(soil.final[i, 2:126]\*e2)

}

soil.final$PC2 = PC2

e3 = eigenvalues$vectors[,3]

PC3 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC3[i] = sum(soil.final[i, 2:126]\*e3)

}

soil.final$PC3 = PC3

e4 = eigenvalues$vectors[,4]

PC4 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC4[i] = sum(soil.final[i, 2:126]\*e4)

}

soil.final$PC4 = PC4

e5 = eigenvalues$vectors[,5]

PC5 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC5[i] = sum(soil.final[i, 2:126]\*e5)

}

soil.final$PC5 = PC5

e6 = eigenvalues$vectors[,6]

PC6 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC6[i] = sum(soil.final[i, 2:126]\*e6)

}

soil.final$PC6 = PC6

e7 = eigenvalues$vectors[,7]

PC7 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC7[i] = sum(soil.final[i, 2:126]\*e7)

}

soil.final$PC7 = PC7

e8 = eigenvalues$vectors[,8]

PC8 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC8[i] = sum(soil.final[i, 2:126]\*e8)

}

soil.final$PC8 = PC8

e9 = eigenvalues$vectors[,96]

PC9 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC9[i] = sum(soil.final[i, 2:126]\*e9)

}

soil.final$PC9 = PC9

e10 = eigenvalues$vectors[,10]

PC10 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC10[i] = sum(soil.final[i, 2:126]\*e10)

}

soil.final$PC10 = PC10

e11 = eigenvalues$vectors[,11]

PC11 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC11[i] = sum(soil.final[i, 2:126]\*e11)

}

soil.final$PC11 = PC11

e12 = eigenvalues$vectors[,12]

PC12 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC12[i] = sum(soil.final[i, 2:126]\*e12)

}

soil.final$PC12 = PC12

e13 = eigenvalues$vectors[,13]

PC13 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC13[i] = sum(soil.final[i, 2:126]\*e13)

}

soil.final$PC13 = PC13

e14 = eigenvalues$vectors[,14]

PC14 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC14[i] = sum(soil.final[i, 2:126]\*e14)

}

soil.final$PC14 = PC14

e15 = eigenvalues$vectors[,15]

PC15 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC15[i] = sum(soil.final[i, 2:126]\*e15)

}

soil.final$PC15 = PC15

e16 = eigenvalues$vectors[,16]

PC16 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC16[i] = sum(soil.final[i, 2:126]\*e16)

}

soil.final$PC16 = PC16

e17 = eigenvalues$vectors[,17]

PC17 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC17[i] = sum(soil.final[i, 2:126]\*e17)

}

soil.final$PC17 = PC17

e18 = eigenvalues$vectors[,18]

PC18 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC18[i] = sum(soil.final[i, 2:126]\*e18)

}

soil.final$PC18 = PC18

e19 = eigenvalues$vectors[,19]

PC19 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC19[i] = sum(soil.final[i, 2:126]\*e19)

}

soil.final$PC19 = PC19

e20 = eigenvalues$vectors[,20]

PC20 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC20[i] = sum(soil.final[i, 2:126]\*e20)

}

soil.final$PC20 = PC20

e21 = eigenvalues$vectors[,21]

PC21 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC21[i] = sum(soil.final[i, 2:126]\*e21)

}

soil.final$PC21 = PC21

e22 = eigenvalues$vectors[,22]

PC22 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC22[i] = sum(soil.final[i, 2:126]\*e22)

}

soil.final$PC22 = PC22

e23 = eigenvalues$vectors[,23]

PC23 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC23[i] = sum(soil.final[i, 2:126]\*e23)

}

soil.final$PC23 = PC23

e24 = eigenvalues$vectors[,24]

PC24 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC24[i] = sum(soil.final[i, 2:126]\*e24)

}

soil.final$PC24 = PC24

e25 = eigenvalues$vectors[,25]

PC25 = numeric(nrow(soil.final))

for (i in 1:nrow(soil.final)) {

PC25[i] = sum(soil.final[i, 2:126]\*e25)

}

soil.final$PC25 = PC25

reduced\_model5 = lm(soil\_moisture^(-0.5) ~ absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10, soil.final)

summary(reduced\_model5)

plot(reduced\_model5)

# The linearity assumption is violated.

shapiro.test(resid(reduced\_model5))

# We still do not have normally distributed residuals.

ncvTest(reduced\_model5)

reduced\_model6 = lm(soil\_moisture^(-0.5) ~ absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 + PC11 + PC12 + PC13 + PC14 + PC15, soil.final)

summary(reduced\_model6)

plot(reduced\_model6)

# The linearity assumption is violated.

shapiro.test(resid(reduced\_model6))

# We still do not have normally distributed residuals.

ncvTest(reduced\_model6)

reduced\_model7 = lm(soil\_moisture^(-0.5) ~ absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10

+ PC11 + PC12 + PC13 + PC14 + PC15 + PC16 + PC17 + PC18 + PC19 + PC20, soil.final)

summary(reduced\_model7)

plot(reduced\_model7)

# The linearity assumption is violated.

shapiro.test(resid(reduced\_model7))

# We still do not have normally distributed residuals.

ncvTest(reduced\_model7)

reduced\_model8 = lm(soil\_moisture^(-0.5) ~ absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10

+ PC11 + PC12 + PC13 + PC14 + PC15 + PC16 + PC17 + PC18 + PC19 + PC20 + PC21 + PC22 + PC23 + PC24 + PC25, soil.final)

summary(reduced\_model8)

plot(reduced\_model8)

# The linearity assumption is violated.

shapiro.test(resid(reduced\_model8))

# We still do not have normally distributed residuals, though this is due to just a few extreme observations as the following shows.

shapiro.test(resid(reduced\_model8)[c(1:182,184:259,261:559,561:679)])

ncvTest(reduced\_model8)

# Include the square root of temperature

reduced\_model9 = lm(soil\_moisture^(-0.5) ~ absolute\_soil\_temperature + temp.sqrt + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10

+ PC11 + PC12 + PC13 + PC14 + PC15 + PC16 + PC17 + PC18 + PC19 + PC20 + PC21 + PC22 + PC23 + PC24 + PC25, soil.final)

# Consider subsets of this model

subset = ols\_step\_best\_subset(reduced\_model9, metric = "adjr")

# Modify model of aggregated data to include first principle component

simplified2 = soil.final %>% full\_join(soil.clean) %>% group\_by(date, hour) %>% summarise(soil\_moisture=mean(soil\_moisture), soil\_temperature=mean(absolute\_soil\_temperature), PC1=mean(PC1))

temperature\_PC1 = lm(soil\_moisture^(-0.5) ~ soil\_temperature + PC1, data = simplified2)

plot(temperature\_PC1)

shapiro.test(resid(temperature\_PC1))

ncvTest(temperature\_PC1)

durbinWatsonTest(temperature\_PC1)

# Include the first five PCs

simplified2 = soil.final %>% full\_join(soil.clean) %>% group\_by(date, hour) %>% summarise(soil\_moisture=mean(soil\_moisture), soil\_temperature=mean(absolute\_soil\_temperature), PC1=mean(PC1), PC2=mean(PC2), PC3=mean(PC3), PC4=mean(PC4),PC5=mean(PC5))

temperature\_PC1 = lm(soil\_moisture^(-0.5) ~ soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5, data = simplified2)

summary(temperature\_PC1)

plot(temperature\_PC1)

shapiro.test(resid(temperature\_PC1))

ncvTest(temperature\_PC1)

durbinWatsonTest(temperature\_PC1)

sum(temperature\_PC1$residuals^2)

sum(simple\_model2$residuals^2)

# The sum of square errors is larger in the model that includes the principle components.

# Consider a model including temperature and PC1 as well as the interaction

interaction\_model1 = lm(soil\_moisture ~ (absolute\_soil\_temperature + PC1)^2 , data = soil.final)

summary(interaction\_model1)

plot(interaction\_model1)

# Consider similar models but with more principle components

interaction\_model2 = lm(soil\_moisture^(-0.5) ~ (absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10)^2, data = soil.final)

summary(interaction\_model2)

plot(interaction\_model2)

shapiro.test(resid(interaction\_model2))

ncvTest(interaction\_model2)

reduced\_model10 = step(interaction\_model2, direction = "backward")

summary(reduced\_model10)

plot(reduced\_model10)

shapiro.test(resid(reduced\_model10))

ncvTest(reduced\_model10)

reduced\_model11 = step(null\_model,scope = list(lower = null\_model, upper = interaction\_model2), direction = "forward")

summary(reduced\_model11)

plot(reduced\_model11)

shapiro.test(resid(reduced\_model11))

ncvTest(reduced\_model11)

reduced\_model12 = step(null\_model,scope = list(lower = null\_model, upper = interaction\_model2), direction = "both")

summary(reduced\_model12)

plot(reduced\_model12)

shapiro.test(resid(reduced\_model12))

ncvTest(reduced\_model12)

interaction\_model3 = lm(soil\_moisture^(-0.5) ~ (absolute\_soil\_temperature + PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10)^4, data = soil.final)

summary(interaction\_model3)

plot(interaction\_model3)

# There is a serious problem of observations with high leverage.

# This model is overfitted because there are too many terms included. Some - preferably many - terms will have to be removed.

shapiro.test(resid(interaction\_model3))

ncvTest(interaction\_model3)

durbinWatsonTest(interaction\_model3)

reduced\_model14 = step(null\_model,scope = list(lower = null\_model, upper = interaction\_model3), direction = "forward")

summary(reduced\_model14)

plot(reduced\_model14)

shapiro.test(resid(reduced\_model14))

ncvTest(reduced\_model14)

# This model is not adequate.

reduced\_model15 = step(interaction\_model3, direction = "backward")

summary(reduced\_model15)

plot(reduced\_model15)

# There is still a serious problem of observations with high leverage.

shapiro.test(resid(reduced\_model15))

# Reject null hypothesis of normally distributed residuals

ncvTest(reduced\_model15)

# Reject hypothesis of constant variance

durbinWatsonTest(reduced\_model15)

# Fail to reject hypothesis of no first lag residual correlation

# There is still a problem of many influential points beyond Cook's distance in the Residuals vs Leverage plot.

# There are still too many terms in this model

term1 = drop1(reduced\_model15, test = "F")

class(term1)

terms = term1 %>% filter(`F value` < 4)%>% select(Df)%>% row.names()

terms

reduced\_model15$call

reduced\_model16 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

absolute\_soil\_temperature:PC1 + absolute\_soil\_temperature:PC2 +

absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

absolute\_soil\_temperature:PC9 + absolute\_soil\_temperature:PC10 +

PC1:PC2 + PC1:PC3 + PC1:PC4 + PC1:PC5 + PC1:PC6 + PC1:PC7 +

PC1:PC8 + PC1:PC9 + PC1:PC10 + PC2:PC3 + PC2:PC4 + PC2:PC5 +

PC2:PC6 + PC2:PC7 + PC2:PC8 + PC2:PC9 + PC2:PC10 + PC3:PC4 +

PC3:PC5 + PC3:PC6 + PC3:PC7 + PC3:PC8 + PC3:PC9 + PC3:PC10 +

PC4:PC5 + PC4:PC6 + PC4:PC7 + PC4:PC8 + PC4:PC9 + PC4:PC10 +

PC5:PC6 + PC5:PC7 + PC5:PC8 + PC5:PC9 + PC5:PC10 + PC6:PC7 +

PC6:PC8 + PC6:PC9 + PC6:PC10 + PC7:PC8 + PC7:PC9 + PC7:PC10 +

PC8:PC9 + PC8:PC10 + PC9:PC10 + absolute\_soil\_temperature:PC1:PC2 +

absolute\_soil\_temperature:PC1:PC3 + absolute\_soil\_temperature:PC1:PC4 +

absolute\_soil\_temperature:PC1:PC5 + absolute\_soil\_temperature:PC1:PC6 +

absolute\_soil\_temperature:PC1:PC7 + absolute\_soil\_temperature:PC1:PC8 +

absolute\_soil\_temperature:PC1:PC9 + absolute\_soil\_temperature:PC1:PC10 +

absolute\_soil\_temperature:PC2:PC3 + absolute\_soil\_temperature:PC2:PC4 +

absolute\_soil\_temperature:PC2:PC5 + absolute\_soil\_temperature:PC2:PC6 +

absolute\_soil\_temperature:PC2:PC7 + absolute\_soil\_temperature:PC2:PC8 +

absolute\_soil\_temperature:PC2:PC9 + absolute\_soil\_temperature:PC2:PC10 +

absolute\_soil\_temperature:PC3:PC4 + absolute\_soil\_temperature:PC3:PC5 +

absolute\_soil\_temperature:PC3:PC6 + absolute\_soil\_temperature:PC3:PC7 +

absolute\_soil\_temperature:PC3:PC8 + absolute\_soil\_temperature:PC3:PC9 +

absolute\_soil\_temperature:PC3:PC10 + absolute\_soil\_temperature:PC4:PC5 +

absolute\_soil\_temperature:PC4:PC6 + absolute\_soil\_temperature:PC4:PC7 +

absolute\_soil\_temperature:PC4:PC8 + absolute\_soil\_temperature:PC4:PC9 +

absolute\_soil\_temperature:PC4:PC10 + absolute\_soil\_temperature:PC5:PC6 +

absolute\_soil\_temperature:PC5:PC7 + absolute\_soil\_temperature:PC5:PC8 +

absolute\_soil\_temperature:PC5:PC9 + absolute\_soil\_temperature:PC5:PC10 +

absolute\_soil\_temperature:PC6:PC7 + absolute\_soil\_temperature:PC6:PC8 +

absolute\_soil\_temperature:PC6:PC9 + absolute\_soil\_temperature:PC6:PC10 +

absolute\_soil\_temperature:PC7:PC8 + absolute\_soil\_temperature:PC7:PC9 +

absolute\_soil\_temperature:PC7:PC10 + absolute\_soil\_temperature:PC8:PC9 +

absolute\_soil\_temperature:PC8:PC10 + absolute\_soil\_temperature:PC9:PC10 +

PC1:PC2:PC3 + PC1:PC2:PC4 + PC1:PC2:PC5 + PC1:PC2:PC6 + PC1:PC2:PC7 +

PC1:PC2:PC8 + PC1:PC2:PC9 + PC1:PC2:PC10 + PC1:PC3:PC4 +

PC1:PC3:PC5 + PC1:PC3:PC6 + PC1:PC3:PC7 + PC1:PC3:PC8 + PC1:PC3:PC9 +

PC1:PC3:PC10 + PC1:PC4:PC5 + PC1:PC4:PC6 + PC1:PC4:PC7 +

PC1:PC4:PC8 + PC1:PC4:PC9 + PC1:PC4:PC10 + PC1:PC5:PC6 +

PC1:PC5:PC7 + PC1:PC5:PC8 + PC1:PC5:PC9 + PC1:PC5:PC10 +

PC1:PC6:PC7 + PC1:PC6:PC8 + PC1:PC6:PC9 + PC1:PC6:PC10 +

PC1:PC7:PC8 + PC1:PC7:PC9 + PC1:PC7:PC10 + PC1:PC8:PC9 +

PC1:PC8:PC10 + PC1:PC9:PC10 + PC2:PC3:PC4 + PC2:PC3:PC5 +

PC2:PC3:PC6 + PC2:PC3:PC7 + PC2:PC3:PC8 + PC2:PC3:PC9 + PC2:PC3:PC10 +

PC2:PC4:PC5 + PC2:PC4:PC6 + PC2:PC4:PC7 + PC2:PC4:PC8 + PC2:PC4:PC9 +

PC2:PC4:PC10 + PC2:PC5:PC6 + PC2:PC5:PC7 + PC2:PC5:PC8 +

PC2:PC5:PC9 + PC2:PC5:PC10 + PC2:PC6:PC7 + PC2:PC6:PC8 +

PC2:PC6:PC9 + PC2:PC6:PC10 + PC2:PC7:PC8 + PC2:PC7:PC9 +

PC2:PC7:PC10 + PC2:PC8:PC9 + PC2:PC8:PC10 + PC2:PC9:PC10 +

PC3:PC4:PC5 + PC3:PC4:PC6 + PC3:PC4:PC7 + PC3:PC4:PC8 + PC3:PC4:PC9 +

PC3:PC4:PC10 + PC3:PC5:PC6 + PC3:PC5:PC7 + PC3:PC5:PC8 +

PC3:PC5:PC9 + PC3:PC5:PC10 + PC3:PC6:PC7 + PC3:PC6:PC8 +

PC3:PC6:PC9 + PC3:PC6:PC10 + PC3:PC7:PC8 + PC3:PC7:PC9 +

PC3:PC7:PC10 + PC3:PC8:PC9 + PC3:PC8:PC10 + PC3:PC9:PC10 +

PC4:PC5:PC6 + PC4:PC5:PC7 + PC4:PC5:PC8 + PC4:PC5:PC9 + PC4:PC5:PC10 +

PC4:PC6:PC7 + PC4:PC6:PC8 + PC4:PC6:PC9 + PC4:PC6:PC10 +

PC4:PC7:PC8 + PC4:PC7:PC9 + PC4:PC7:PC10 + PC4:PC8:PC9 +

PC4:PC8:PC10 + PC4:PC9:PC10 + PC5:PC6:PC7 + PC5:PC6:PC8 +

PC5:PC6:PC9 + PC5:PC6:PC10 + PC5:PC7:PC8 + PC5:PC7:PC9 +

PC5:PC7:PC10 + PC5:PC8:PC9 + PC5:PC8:PC10 + PC5:PC9:PC10 +

PC6:PC7:PC8 + PC6:PC7:PC9 + PC6:PC7:PC10 + PC6:PC8:PC9 +

PC6:PC8:PC10 + PC6:PC9:PC10 + PC7:PC8:PC9 + PC7:PC8:PC10 +

PC7:PC9:PC10 + PC8:PC9:PC10 + absolute\_soil\_temperature:PC1:PC2:PC3 +

absolute\_soil\_temperature:PC1:PC2:PC4 + absolute\_soil\_temperature:PC1:PC2:PC7 +

absolute\_soil\_temperature:PC1:PC2:PC8 + absolute\_soil\_temperature:PC1:PC3:PC5 +

absolute\_soil\_temperature:PC1:PC3:PC6 + absolute\_soil\_temperature:PC1:PC3:PC7 +

absolute\_soil\_temperature:PC1:PC3:PC8 + absolute\_soil\_temperature:PC1:PC3:PC10 +

absolute\_soil\_temperature:PC1:PC4:PC6 + absolute\_soil\_temperature:PC1:PC4:PC7 +

absolute\_soil\_temperature:PC1:PC4:PC10 + absolute\_soil\_temperature:PC1:PC5:PC6 +

absolute\_soil\_temperature:PC1:PC5:PC7 + absolute\_soil\_temperature:PC1:PC5:PC8 +

absolute\_soil\_temperature:PC1:PC5:PC9 + absolute\_soil\_temperature:PC1:PC5:PC10 +

absolute\_soil\_temperature:PC1:PC6:PC7 + absolute\_soil\_temperature:PC1:PC6:PC9 +

absolute\_soil\_temperature:PC1:PC6:PC10 + absolute\_soil\_temperature:PC1:PC7:PC8 +

absolute\_soil\_temperature:PC1:PC7:PC10 + absolute\_soil\_temperature:PC1:PC8:PC9 +

absolute\_soil\_temperature:PC1:PC8:PC10 + absolute\_soil\_temperature:PC2:PC3:PC4 +

absolute\_soil\_temperature:PC2:PC3:PC5 + absolute\_soil\_temperature:PC2:PC3:PC6 +

absolute\_soil\_temperature:PC2:PC3:PC7 + absolute\_soil\_temperature:PC2:PC3:PC8 +

absolute\_soil\_temperature:PC2:PC3:PC9 + absolute\_soil\_temperature:PC2:PC4:PC5 +

absolute\_soil\_temperature:PC2:PC4:PC7 + absolute\_soil\_temperature:PC2:PC4:PC9 +

absolute\_soil\_temperature:PC2:PC5:PC6 + absolute\_soil\_temperature:PC2:PC5:PC7 +

absolute\_soil\_temperature:PC2:PC5:PC10 + absolute\_soil\_temperature:PC2:PC6:PC7 +

absolute\_soil\_temperature:PC2:PC6:PC8 + absolute\_soil\_temperature:PC2:PC6:PC9 +

absolute\_soil\_temperature:PC2:PC6:PC10 + absolute\_soil\_temperature:PC2:PC7:PC8 +

absolute\_soil\_temperature:PC2:PC7:PC9 + absolute\_soil\_temperature:PC2:PC8:PC10 +

absolute\_soil\_temperature:PC2:PC9:PC10 + absolute\_soil\_temperature:PC3:PC4:PC5 +

absolute\_soil\_temperature:PC3:PC4:PC6 + absolute\_soil\_temperature:PC3:PC4:PC7 +

absolute\_soil\_temperature:PC3:PC4:PC9 + absolute\_soil\_temperature:PC3:PC4:PC10 +

absolute\_soil\_temperature:PC3:PC5:PC7 + absolute\_soil\_temperature:PC3:PC5:PC8 +

absolute\_soil\_temperature:PC3:PC5:PC9 + absolute\_soil\_temperature:PC3:PC5:PC10 +

absolute\_soil\_temperature:PC3:PC6:PC7 + absolute\_soil\_temperature:PC3:PC6:PC8 +

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absolute\_soil\_temperature:PC4:PC5:PC7 + absolute\_soil\_temperature:PC4:PC5:PC9 +

absolute\_soil\_temperature:PC4:PC5:PC10 + absolute\_soil\_temperature:PC4:PC6:PC7 +

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PC1:PC2:PC4:PC7 + PC1:PC2:PC4:PC8 + PC1:PC2:PC4:PC9 + PC1:PC2:PC4:PC10 +

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PC1:PC3:PC6:PC10 + PC1:PC3:PC7:PC8 + PC1:PC3:PC7:PC9 + PC1:PC3:PC7:PC10 +

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PC2:PC4:PC6:PC10 + PC2:PC4:PC7:PC8 + PC2:PC4:PC7:PC9 + PC2:PC4:PC8:PC9 +

PC2:PC4:PC8:PC10 + PC2:PC5:PC6:PC7 + PC2:PC5:PC6:PC8 + PC2:PC5:PC6:PC9 +

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PC2:PC8:PC9:PC10 + PC3:PC4:PC5:PC7 + PC3:PC4:PC5:PC9 + PC3:PC4:PC5:PC10 +

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PC3:PC4:PC7:PC8 + PC3:PC4:PC7:PC9 + PC3:PC4:PC7:PC10 + PC3:PC4:PC8:PC9 +

PC3:PC4:PC8:PC10 + PC3:PC4:PC9:PC10 + PC3:PC5:PC6:PC7 + PC3:PC5:PC6:PC8 +

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PC3:PC7:PC8:PC10 + PC3:PC7:PC9:PC10 + PC4:PC5:PC6:PC7 + PC4:PC5:PC6:PC8 +

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PC5:PC6:PC7:PC8 + PC5:PC6:PC7:PC9 + PC5:PC6:PC7:PC10 + PC5:PC6:PC8:PC9 +

PC5:PC6:PC9:PC10 + PC5:PC7:PC8:PC9 + PC5:PC7:PC8:PC10 + PC5:PC7:PC9:PC10 +

PC6:PC7:PC8:PC10 + PC6:PC7:PC9:PC10 + PC6:PC8:PC9:PC10 +

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absolute\_soil\_temperature:PC1:PC4:PC10 - absolute\_soil\_temperature:PC1:PC6:PC10 -

absolute\_soil\_temperature:PC2:PC3:PC8 - absolute\_soil\_temperature:PC2:PC3:PC9 -

absolute\_soil\_temperature:PC2:PC5:PC7 - absolute\_soil\_temperature:PC2:PC5:PC10 -

absolute\_soil\_temperature:PC2:PC6:PC9 - absolute\_soil\_temperature:PC3:PC4:PC9 -

absolute\_soil\_temperature:PC3:PC6:PC8 - absolute\_soil\_temperature:PC4:PC5:PC6 -

absolute\_soil\_temperature:PC4:PC7:PC9 - absolute\_soil\_temperature:PC5:PC6:PC10 -

absolute\_soil\_temperature:PC5:PC8:PC10 - absolute\_soil\_temperature:PC6:PC8:PC10 -

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PC1:PC2:PC5:PC6 - PC1:PC2:PC5:PC7 - PC1:PC2:PC5:PC8 - PC1:PC2:PC5:PC9 -

PC1:PC2:PC6:PC10 - PC1:PC3:PC5:PC9 - PC1:PC3:PC8:PC9 - PC1:PC3:PC8:PC10 -

PC1:PC4:PC8:PC9 - PC1:PC5:PC7:PC10 - PC2:PC3:PC4:PC8 - PC2:PC3:PC6:PC9 -

PC2:PC4:PC7:PC8 - PC2:PC5:PC6:PC8 - PC3:PC4:PC6:PC7 - PC3:PC4:PC9:PC10 -

PC3:PC5:PC7:PC9 - PC4:PC5:PC6:PC9 - PC4:PC5:PC7:PC8 - PC4:PC5:PC7:PC9 -

PC4:PC5:PC8:PC9 - PC5:PC6:PC9:PC10 - PC5:PC7:PC8:PC10 - PC7:PC8:PC9:PC10, data = soil.final)

summary(reduced\_model16)

plot(reduced\_model16)

durbinWatsonTest(reduced\_model16)

coef(reduced\_model16)%>% length()

# There are still too many terms. There are 679 observations and so 448 terms is far more than desirable. There are far too many observations with high leverage.

terms2 = drop1(reduced\_model16, test = "F")

terms2 %>% filter(`F value`<4)%>%select(Df)%>% row.names()

reduced\_model16$call

reduced\_model17 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

absolute\_soil\_temperature:PC1 + absolute\_soil\_temperature:PC2 +

absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

absolute\_soil\_temperature:PC9 + absolute\_soil\_temperature:PC10 +

PC1:PC2 + PC1:PC3 + PC1:PC4 + PC1:PC5 + PC1:PC6 + PC1:PC7 +

PC1:PC8 + PC1:PC9 + PC1:PC10 + PC2:PC3 + PC2:PC4 + PC2:PC5 +

PC2:PC6 + PC2:PC7 + PC2:PC8 + PC2:PC9 + PC2:PC10 + PC3:PC4 +

PC3:PC5 + PC3:PC6 + PC3:PC7 + PC3:PC8 + PC3:PC9 + PC3:PC10 +

PC4:PC5 + PC4:PC6 + PC4:PC7 + PC4:PC8 + PC4:PC9 + PC4:PC10 +

PC5:PC6 + PC5:PC7 + PC5:PC8 + PC5:PC9 + PC5:PC10 + PC6:PC7 +

PC6:PC8 + PC6:PC9 + PC6:PC10 + PC7:PC8 + PC7:PC9 + PC7:PC10 +

PC8:PC9 + PC8:PC10 + PC9:PC10 + absolute\_soil\_temperature:PC1:PC2 +

absolute\_soil\_temperature:PC1:PC3 + absolute\_soil\_temperature:PC1:PC4 +

absolute\_soil\_temperature:PC1:PC5 + absolute\_soil\_temperature:PC1:PC6 +

absolute\_soil\_temperature:PC1:PC7 + absolute\_soil\_temperature:PC1:PC8 +

absolute\_soil\_temperature:PC1:PC9 + absolute\_soil\_temperature:PC1:PC10 +

absolute\_soil\_temperature:PC2:PC3 + absolute\_soil\_temperature:PC2:PC4 +

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absolute\_soil\_temperature:PC2:PC9 + absolute\_soil\_temperature:PC2:PC10 +

absolute\_soil\_temperature:PC3:PC4 + absolute\_soil\_temperature:PC3:PC5 +

absolute\_soil\_temperature:PC3:PC6 + absolute\_soil\_temperature:PC3:PC7 +

absolute\_soil\_temperature:PC3:PC8 + absolute\_soil\_temperature:PC3:PC9 +

absolute\_soil\_temperature:PC3:PC10 + absolute\_soil\_temperature:PC4:PC5 +

absolute\_soil\_temperature:PC4:PC6 + absolute\_soil\_temperature:PC4:PC7 +

absolute\_soil\_temperature:PC4:PC8 + absolute\_soil\_temperature:PC4:PC9 +

absolute\_soil\_temperature:PC4:PC10 + absolute\_soil\_temperature:PC5:PC6 +

absolute\_soil\_temperature:PC5:PC7 + absolute\_soil\_temperature:PC5:PC8 +

absolute\_soil\_temperature:PC5:PC9 + absolute\_soil\_temperature:PC5:PC10 +

absolute\_soil\_temperature:PC6:PC7 + absolute\_soil\_temperature:PC6:PC8 +

absolute\_soil\_temperature:PC6:PC9 + absolute\_soil\_temperature:PC6:PC10 +

absolute\_soil\_temperature:PC7:PC8 + absolute\_soil\_temperature:PC7:PC9 +

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PC4:PC8:PC10 + PC4:PC9:PC10 + PC5:PC6:PC7 + PC5:PC6:PC8 +

PC5:PC6:PC9 + PC5:PC6:PC10 + PC5:PC7:PC8 + PC5:PC7:PC9 +

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PC6:PC7:PC8 + PC6:PC7:PC9 + PC6:PC7:PC10 + PC6:PC8:PC9 +

PC6:PC8:PC10 + PC6:PC9:PC10 + PC7:PC8:PC9 + PC7:PC8:PC10 +

PC7:PC9:PC10 + PC8:PC9:PC10 + absolute\_soil\_temperature:PC1:PC2:PC3 +

absolute\_soil\_temperature:PC1:PC2:PC4 + absolute\_soil\_temperature:PC1:PC2:PC7 +

absolute\_soil\_temperature:PC1:PC2:PC8 + absolute\_soil\_temperature:PC1:PC3:PC5 +

absolute\_soil\_temperature:PC1:PC3:PC6 + absolute\_soil\_temperature:PC1:PC3:PC7 +

absolute\_soil\_temperature:PC1:PC3:PC8 + absolute\_soil\_temperature:PC1:PC3:PC10 +

absolute\_soil\_temperature:PC1:PC4:PC6 + absolute\_soil\_temperature:PC1:PC4:PC7 +

absolute\_soil\_temperature:PC1:PC4:PC10 + absolute\_soil\_temperature:PC1:PC5:PC6 +

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absolute\_soil\_temperature:PC1:PC6:PC7 + absolute\_soil\_temperature:PC1:PC6:PC9 +

absolute\_soil\_temperature:PC1:PC6:PC10 + absolute\_soil\_temperature:PC1:PC7:PC8 +

absolute\_soil\_temperature:PC1:PC7:PC10 + absolute\_soil\_temperature:PC1:PC8:PC9 +

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absolute\_soil\_temperature:PC2:PC3:PC9 + absolute\_soil\_temperature:PC2:PC4:PC5 +

absolute\_soil\_temperature:PC2:PC4:PC7 + absolute\_soil\_temperature:PC2:PC4:PC9 +

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absolute\_soil\_temperature:PC3:PC5:PC7 + absolute\_soil\_temperature:PC3:PC5:PC8 +

absolute\_soil\_temperature:PC3:PC5:PC9 + absolute\_soil\_temperature:PC3:PC5:PC10 +

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absolute\_soil\_temperature:PC3:PC7:PC9 + absolute\_soil\_temperature:PC3:PC7:PC10 +

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absolute\_soil\_temperature:PC3:PC9:PC10 + absolute\_soil\_temperature:PC4:PC5:PC6 +

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PC1:PC2:PC3:PC4 + PC1:PC2:PC3:PC5 + PC1:PC2:PC3:PC6 + PC1:PC2:PC3:PC7 +

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PC1:PC2:PC4:PC7 + PC1:PC2:PC4:PC8 + PC1:PC2:PC4:PC9 + PC1:PC2:PC4:PC10 +

PC1:PC2:PC5:PC6 + PC1:PC2:PC5:PC7 + PC1:PC2:PC5:PC8 + PC1:PC2:PC5:PC9 +

PC1:PC2:PC6:PC7 + PC1:PC2:PC6:PC8 + PC1:PC2:PC6:PC9 + PC1:PC2:PC6:PC10 +

PC1:PC2:PC7:PC8 + PC1:PC2:PC8:PC9 + PC1:PC2:PC8:PC10 + PC1:PC2:PC9:PC10 +

PC1:PC3:PC4:PC5 + PC1:PC3:PC4:PC6 + PC1:PC3:PC4:PC7 + PC1:PC3:PC4:PC8 +

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PC1:PC3:PC5:PC9 + PC1:PC3:PC5:PC10 + PC1:PC3:PC6:PC8 + PC1:PC3:PC6:PC9 +

PC1:PC3:PC6:PC10 + PC1:PC3:PC7:PC8 + PC1:PC3:PC7:PC9 + PC1:PC3:PC7:PC10 +

PC1:PC3:PC8:PC9 + PC1:PC3:PC8:PC10 + PC1:PC3:PC9:PC10 + PC1:PC4:PC5:PC6 +

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PC4:PC7:PC9:PC10 - PC5:PC6:PC7:PC8 - PC5:PC6:PC7:PC10 - PC5:PC6:PC8:PC9 -

PC5:PC7:PC8:PC9 - PC5:PC7:PC9:PC10 - PC6:PC7:PC8:PC10 - PC6:PC8:PC9:PC10, data = soil.final)

summary(reduced\_model17)

plot(reduced\_model17)

term3 = drop1(reduced\_model17, test = "F")

term3 %>% filter(`F value` < 4) %>% select(Df)%>% row.names()

reduced\_model17$call

reduced\_model18 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

absolute\_soil\_temperature:PC1 + absolute\_soil\_temperature:PC2 +

absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

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PC7:PC9:PC10 + PC8:PC9:PC10 + absolute\_soil\_temperature:PC1:PC2:PC3 +

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PC3:PC5:PC7:PC8 - PC3:PC6:PC8:PC10 - PC3:PC7:PC8:PC10 - PC4:PC5:PC6:PC10 - PC4:PC5:PC8:PC10, data = soil.final)

summary(reduced\_model18)

plot(reduced\_model18)

# The number of observations with high leverage has diminished somewhat but needs to be reduced further.

terms4 = drop1(reduced\_model18, test = "F")

terms4 %>% filter(`F value` < 4) %>% select(Df) %>% row.names()

reduced\_model18$call

reduced\_model19 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

absolute\_soil\_temperature:PC1 + absolute\_soil\_temperature:PC2 +

absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

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absolute\_soil\_temperature:PC1:PC9 + absolute\_soil\_temperature:PC1:PC10 +

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absolute\_soil\_temperature:PC5:PC7 + absolute\_soil\_temperature:PC5:PC8 +

absolute\_soil\_temperature:PC5:PC9 + absolute\_soil\_temperature:PC5:PC10 +

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absolute\_soil\_temperature:PC3:PC7 - absolute\_soil\_temperature:PC3:PC8 - absolute\_soil\_temperature:PC3:PC9 - absolute\_soil\_temperature:PC4:PC5 -

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PC3:PC4:PC5:PC9 - PC3:PC5:PC7:PC10 - PC3:PC5:PC8:PC9 - PC3:PC6:PC9:PC10 - PC4:PC6:PC7:PC10 - PC4:PC6:PC9:PC10 - PC6:PC7:PC9:PC10, data = soil.final)

summary(reduced\_model19)

plot(reduced\_model19)

# This is looking better but more variables still need to be removed.

terms5 = drop1(reduced\_model19, test = "F")

terms5 %>% filter(`F value`<4) %>% select(Df) %>% row.names()

reduced\_model19$call

reduced\_model20 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

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PC2:PC6 + PC2:PC7 + PC2:PC8 + PC2:PC9 + PC2:PC10 + PC3:PC4 +

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PC5:PC6:PC10 - PC5:PC7:PC8 - PC5:PC8:PC10 - PC5:PC9:PC10 -

PC6:PC8:PC10 - PC7:PC8:PC9 - absolute\_soil\_temperature:PC4:PC7:PC10 -

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PC4:PC5:PC9 - PC4:PC6:PC10 - PC5:PC7:PC10 - PC5:PC8:PC9 - PC6:PC9:PC10 - PC7:PC9:PC10 -

PC8:PC9:PC10 - absolute\_soil\_temperature:PC2:PC6:PC8 - absolute\_soil\_temperature:PC2:PC8:PC10 - PC3:PC6:PC7:PC9 - PC4:PC7:PC8:PC10, data = soil.final)

summary(reduced\_model20)

plot(reduced\_model20)

coef(reduced\_model20)%>%length()

# This is looking much better as there are only a few points now beyond Cook's distance exerting large influence on the model.

# The number of predictors has been reduced to 160, but it would be better to reduce it further to avoid overfitting.

terms6 = drop1(reduced\_model20, test = "F")

terms6 %>% filter(`F value` < 4) %>% row.names()

reduced\_model21 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

absolute\_soil\_temperature:PC1 + absolute\_soil\_temperature:PC2 +

absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

absolute\_soil\_temperature:PC9 + absolute\_soil\_temperature:PC10 +

PC1:PC2 + PC1:PC3 + PC1:PC4 + PC1:PC5 + PC1:PC6 + PC1:PC7 +

PC1:PC8 + PC1:PC9 + PC1:PC10 + PC2:PC3 + PC2:PC4 + PC2:PC5 +

PC2:PC6 + PC2:PC7 + PC2:PC8 + PC2:PC9 + PC2:PC10 + PC3:PC4 +

PC3:PC5 + PC3:PC6 + PC3:PC7 + PC3:PC8 + PC3:PC9 + PC3:PC10 +

PC4:PC5 + PC4:PC6 + PC4:PC7 + PC4:PC8 + PC4:PC9 + PC4:PC10 +

PC5:PC6 + PC5:PC7 + PC5:PC8 + PC5:PC9 + PC5:PC10 + PC6:PC7 +

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PC8:PC9 + PC8:PC10 + PC9:PC10 + absolute\_soil\_temperature:PC1:PC2 +

absolute\_soil\_temperature:PC1:PC3 + absolute\_soil\_temperature:PC1:PC4 +

absolute\_soil\_temperature:PC1:PC5 + absolute\_soil\_temperature:PC1:PC6 +

absolute\_soil\_temperature:PC1:PC7 + absolute\_soil\_temperature:PC1:PC8 +

absolute\_soil\_temperature:PC1:PC9 + absolute\_soil\_temperature:PC1:PC10 +

absolute\_soil\_temperature:PC2:PC3 + absolute\_soil\_temperature:PC2:PC4 +

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absolute\_soil\_temperature:PC3:PC4 + absolute\_soil\_temperature:PC3:PC5 +

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absolute\_soil\_temperature:PC3:PC8 + absolute\_soil\_temperature:PC3:PC9 +

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absolute\_soil\_temperature:PC4:PC10 + absolute\_soil\_temperature:PC5:PC6 +

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PC8:PC9 - absolute\_soil\_temperature:PC7:PC10 - absolute\_soil\_temperature:PC8:PC10 -

PC1:PC7:PC8 - PC2:PC3:PC8 - PC2:PC8:PC10 - PC3:PC4:PC5 - PC4:PC7:PC10 - PC3:PC4:PC6:PC8, data = soil.final)

summary(reduced\_model21)

plot(reduced\_model21)

# Still some high leverage observations

# Try removing a few more features

terms7 = drop1(reduced\_model21, test = "F")

terms7 %>% filter(`F value`<8) %>% row.names()

reduced\_model22 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

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absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

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PC3:PC7:PC9 - PC4:PC5:PC10 - absolute\_soil\_temperature:PC4:PC6:PC8 -

PC3:PC4:PC8:PC10 - PC5:PC6:PC7:PC9, data = soil.final)

summary(reduced\_model22)

plot(reduced\_model22)

# This model is looking much better.

# There is a problem however, with the residuals not being normally distributed.

# Observations 560 and 260 have extreme residuals, and there are also some other residuals at either end of the Normal Q-Q plot straying from the line.

# Check variance

ncvTest(reduced\_model22)

# There still is heterodascity based on the test.

durbinWatsonTest(reduced\_model22)

# There is also now a problem with residuals being correlated.

# Check number of terms.

coef(reduced\_model22)%>%length()

# 139 terms is still a rather large number of terms

terms8 = drop1(reduced\_model22, test = "F")

terms8 %>% filter(`F value`< 4) %>% row.names()

reduced\_model23 = lm(formula = soil\_moisture^(-0.5) ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10 +

absolute\_soil\_temperature:PC1 + absolute\_soil\_temperature:PC2 +

absolute\_soil\_temperature:PC3 + absolute\_soil\_temperature:PC4 +

absolute\_soil\_temperature:PC5 + absolute\_soil\_temperature:PC6 +

absolute\_soil\_temperature:PC7 + absolute\_soil\_temperature:PC8 +

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PC3:PC5 + PC3:PC6 + PC3:PC7 + PC3:PC8 + PC3:PC9 + PC3:PC10 +

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PC8:PC9 - absolute\_soil\_temperature:PC7:PC10 - absolute\_soil\_temperature:PC8:PC10 -

PC1:PC7:PC8 - PC2:PC3:PC8 - PC2:PC8:PC10 - PC3:PC4:PC5 - PC4:PC7:PC10 - PC3:PC4:PC6:PC8 -

absolute\_soil\_temperature:PC2:PC6 - absolute\_soil\_temperature:PC2:PC7 - absolute\_soil\_temperature:PC2:PC8 - absolute\_soil\_temperature:PC4:PC7 -

PC1:PC3:PC7 - PC2:PC6:PC8 - PC3:PC4:PC9 - PC3:PC6:PC8 -

PC3:PC7:PC9 - PC4:PC5:PC10 - absolute\_soil\_temperature:PC4:PC6:PC8 -

PC3:PC4:PC8:PC10 - PC5:PC6:PC7:PC9 - absolute\_soil\_temperature:PC4:PC6-absolute\_soil\_temperature:PC4:PC8-

absolute\_soil\_temperature:PC6:PC8-PC3:PC4:PC10 - PC3:PC6:PC9 - PC4:PC5:PC6 - PC4:PC9:PC10 - PC5:PC6:PC7 -

PC5:PC6:PC9-PC5:PC7:PC9 -absolute\_soil\_temperature:PC4:PC6-absolute\_soil\_temperature:PC4:PC8-absolute\_soil\_temperature:PC6:PC8-PC3:PC4:PC10 -

PC3:PC6:PC9 - PC4:PC5:PC6 - PC4:PC9:PC10-PC5:PC6:PC7 - PC5:PC6:PC9-PC5:PC7:PC9, data = soil.final)

summary(reduced\_model23)

shapiro.test(resid(reduced\_model23))

shapiro.test(resid(reduced\_model23)[c(1:259,261:559,561:679)])

ncvTest(reduced\_model23)

durbinWatsonTest(reduced\_model23)

coef(reduced\_model23)%>% length()

# Consider fitting a logistic model predicting whether soil moisture will be between 30% and 40%.

soil.final$`30\_to\_40` = 0

soil.final$`30\_to\_40`[soil.final$soil\_moisture < 40 & soil.final$soil\_moisture > 30]=1

soil.final$`30\_to\_40`[1:100]

# Fit a logistic model predicting whether the soil moisture will be between 30% and 40%

logistic\_model1 = glm(formula = `30\_to\_40` ~ (absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7 + PC8 + PC9 + PC10), data = soil.final, family = "binomial")

summary.glm(logistic\_model1)

pchisq(logistic\_model1$deviance, logistic\_model1$df.residual, lower.tail = FALSE)

null2 = glm(formula = `30\_to\_40` ~ 1, data = soil.final, family = "binomial")

anova(null2, logistic\_model1, test ="Chisq")

logit\_pred = predict(logistic\_model1, newdata = soil.final)

1/(1+ exp(-logit\_pred[1:5]))

predictions=numeric(679)

for (i in 1:679) {

if (1/(1+ exp(-logit\_pred[i])) < 0.5) {

predictions[i]=0

}

else

predictions[i]=1

}

# Find confidence intervals for all terms

confint(logistic\_model1)

# Find accuracy of logistic predictor

sum(predictions==soil.final$`30\_to\_40`)/nrow(soil.final)

# Almost 98% of the predictions were correct.

# This looks impressive, but the total number of samples having soil moisture in this range is large.

sum(soil.final$`30\_to\_40`)/nrow(soil.final)

# Two thirds of the observations have soil moisture within this range.

# The model seems quite good.

# A more challenging goal is to predict soil moisture being larger than 38%.

soil.final$`>38`=0

soil.final$`>38`[soil.final$soil\_moisture>38] = 1

sum(soil.final$`>38`)

# There are only 24 cases of soil moisture being greater than 38%.

logistic\_model2 = glm(formula = `>38` ~ absolute\_soil\_temperature +

PC1 + PC2 + PC3 + PC4 + PC5 + PC6 + PC7,

data = soil.final, family = "binomial")

summary.glm(logistic\_model2)

pchisq(logistic\_model2$deviance, logistic\_model2$df.residual, lower.tail = FALSE)

null3 = logistic\_model2 = glm(formula = `>38` ~ 1, data = soil.final, family = "binomial")

anova(null3, logistic\_model2, test = "Chisq")

logit\_pred2 = predict(logistic\_model2, newdata = soil.final)

1/(1+ exp(-logit\_pred2[1:5]))

predictions2=numeric(679)

for (i in 1:679) {

if (1/(1+ exp(-logit\_pred2[i])) < 0.5) {

predictions2[i]=0

}

else

predictions2[i]=1

}

# Calculations to determine accuracy of the model

sum(predictions2==soil.final$`>38`&predictions2==1)

sum(predictions2==soil.final$`>38`&predictions2==0)

sum(predictions2==1)

sum(predictions2==soil.final$`>38`)

671/679

# Calculate recall and precision

17/24

17/18

# Predictions: create 10 predictions based on new data

# Define 10 new temperatures

absolute\_soil\_temperature = data.frame(273.15 + c(30, 27, 35, 40, 45, 42, 33, 32, 36, 37))

names(absolute\_soil\_temperature)= "absolute\_soil\_temperature"

# For the 125 hyperspectral variables, create new samples by adding Gaussian noise to the mean of each.

hyperspec = numeric(125)

for ( i in 2:126) {

hyperspec[(i-1)]=colnames(soil.final)[i]

}

hyperspec = as.character(hyperspec)

generated = matrix(0,nrow = 10, ncol = 125)

for (i in 2:126) {

generated[1:10,(i-1)]=rnorm(10, soil.final[,i]%>%as.matrix()%>%as.vector()%>%mean(), soil.final[1:679,i]%>%as.matrix()%>%as.vector()%>%sd())

}

hyperspectral\_random\_data = data.frame(generated)

names(hyperspectral\_random\_data)= hyperspec

head(hyperspectral\_random\_data)

newdata = cbind(absolute\_soil\_temperature, hyperspectral\_random\_data)

# 10 new samples are defined including temperature and hyperspectral data

# Predictions Using Linear Regression Models

# Predict using only temperature using the simple model generated from aggregated data

# The response, soil moisture, was transformed in the model by raising it to the power -0.5.

# Hence the inverse operation, i.e. raising to the power -2, needs to be applied to the output of the model to get a prediction for soil moisture

linear\_pred1 = (predict(simple\_model3, newdata = newdata %>% mutate(temperature = absolute\_soil\_temperature)))^(-2)

linear\_pred1

# Predict using the model including temperature and all hyperspectral variables, with a transformed response, soil\_moisture^(-0.5).

# Again the inverse transformation must be applied to get a prediction for soil moisture.

linear\_pred2 = (predict(full\_model2, newdata = newdata))^(-2)

linear\_pred2

# Some of these predictions are well outside the range of the actual data, and physically impossible.

# It does not make sense for there to be soil moisture greater than 100%, yet one sample is predicted to have soil moisture of over 480 000% !

# However, there are some values at or near the magnitude of the original data.

# There is one sample predicted to have soil moisture of 31.56%, and there were indeed recordings of soil moisture at this level.

# Four other samples were predicted to have soil moisture readings between 18 and 23, which is lower than the samples in the original data, but still of the same order of magnitude.

# Predict using the final linear regression model including temperature and principal components of hyperspectral variables and their interactions, with a transformed response, soil\_moisture^(-0.5).

# Derive principle components for the generated data

newdata$PC1 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC1[i] = sum(newdata[i, 2:126]\*e1)

}

newdata$PC2 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC2[i] = sum(newdata[i, 2:126]\*e2)

}

newdata$PC3 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC3[i] = sum(newdata[i, 2:126]\*e3)

}

newdata$PC4 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC4[i] = sum(newdata[i, 2:126]\*e4)

}

newdata$PC5 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC5[i] = sum(newdata[i, 2:126]\*e5)

}

newdata$PC6 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC6[i] = sum(newdata[i, 2:126]\*e6)

}

newdata$PC7 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC7[i] = sum(newdata[i, 2:126]\*e7)

}

newdata$PC8 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC8[i] = sum(newdata[i, 2:126]\*e8)

}

newdata$PC9 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC9[i] = sum(newdata[i, 2:126]\*e9)

}

newdata$PC10 = numeric(nrow(newdata))

for (i in 1:nrow(newdata)) {

newdata$PC10[i] = sum(newdata[i, 2:126]\*e10)

}

linear\_pred3 = (predict(reduced\_model23, newdata = newdata))^(-2)

linear\_pred3

# This model some predicts values not on the same scale as the original data. Three values are between 0 and 1. Another value is over 3000.

# Only one prediction, of 21.18 is close to the values in the original data.

# However the models with only the temperature and one to ten principal components produce more reasonable predictions.

linear\_pred4 = predict(reduced\_model4, newdata = newdata)^(-2)

linear\_pred4

linear\_pred5 = predict(reduced\_model5, newdata = newdata)^(-2)

linear\_pred5

# The model including only one principal component produces very reasonable looking predictions.

# Compare this model's accuracy to that of the simple model only using temperature on six observations in the original data set.

predict(reduced\_model4, soil.final[c(30,48,146,228,405,581),])^(-2)

predict(simple\_model3, (soil.final %>% mutate(temperature = absolute\_soil\_temperature))[c(30,48,146,228,405,581),])^(-2)

# The actual values are given by the following code

soil.final$soil\_moisture[c(30,48,146,228,405,581)]

# Both these models with few terms appear reasonably accurate. Perhaps a simpler model is best after all!

# Predictions Using Logistic Models

# First predict whether the soil moisture is between 30% and 40%

logit\_pred3 = predict.glm(logistic\_model1, newdata = newdata)

predictions3 = numeric(length(logit\_pred3))

for (i in 1:length(logit\_pred3)) {

if (1/(1+exp(-logit\_pred3[i]))>=0.5)

predictions3[i] = 1

}

predictions3

# Five of ten samples are predicted to have soil moisture between 30% and 40%

# Now predict whether soil moisture is above 38%

logit\_pred4 = predict.glm(logistic\_model2, newdata = newdata)

predictions4 = numeric(length(logit\_pred4))

for (i in 1:length(logit\_pred4)) {

if (1/(1+exp(-logit\_pred4[i]))>=0.5)

predictions4[i] = 1

}

predictions4

# Two of ten samples are predicted to have soil moisture above 38%