Introduction

In a previous assignment, a team I was a part of analysed data about the growth measurements of Tammar Wallabies in Australia (originally provided by the CSIRO Biometrics Unit INRE in Canberra, this version cleaned and corrected by Professor Heike Hofmann, Department of Statistics at Iowa State University in 2008, publicly available from the Statistic Science domain http://www.statsci.org/data/oz/wallaby.html).

The data consists of 1463 measurements of 77 wallabies at different ages across fourteen locations. There are twelve variables, summarised below:

Attributes	Description	Format	Variable Type
Anim	Unique Animal Identifier	Number	Numeric
Sex	1= male, 2 = female	Binary Number	Categorical
Loca	Location of animal	Alphanumeric Text (two characters)	Categorical
Leng	Length of animal	Number (tenths of a millimetre)	Numeric
Head	Length of head	Number (tenths of a millimetre)	Numeric
Ear	Length of ear	Number (tenths of a millimetre)	Numeric
Arm	Length of arm	Number (tenths of a millimetre)	Numeric
Leg	Length of leg	Number (tenths of a millimetre)	Numeric
Pes	Length of foot (pes)	Number (tenths of a millimetre)	Numeric
Tail	Length of tail	Number (tenths of a millimetre)	Numeric
Weight	Weight	Number (tenths of a gram)	Numeric
Age	Days from birth	Number	Numeric

A plot of the data shows how highly correlated the physical measurements are:

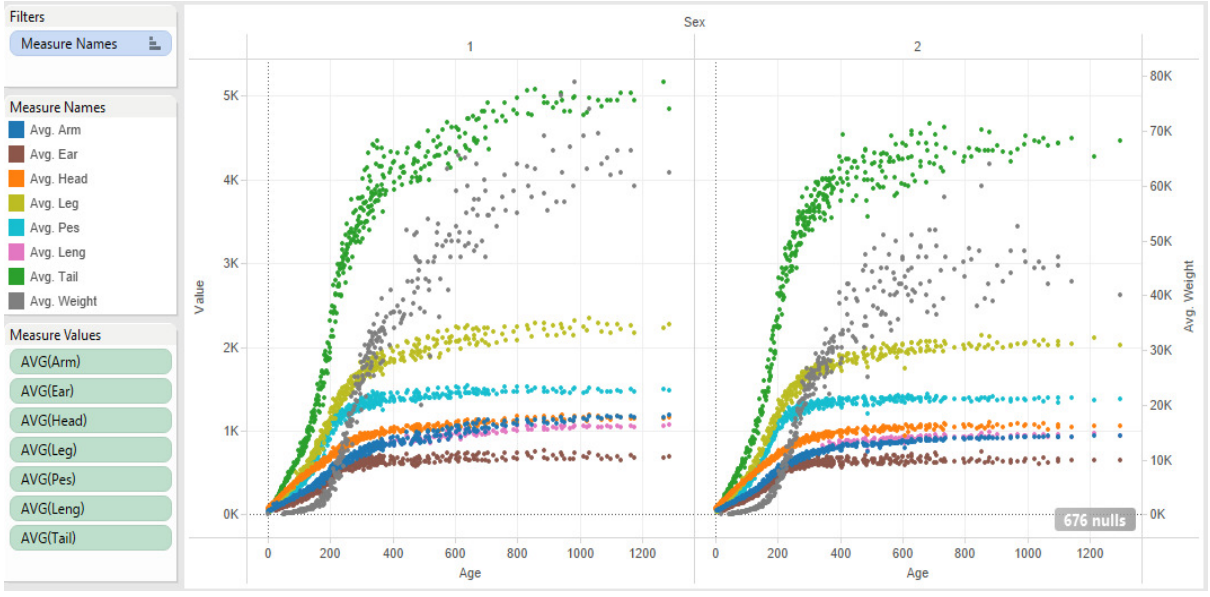

Figure1: Measurements by age and sex – with weight on separate axis

Previously, the team originally gave consideration to using Weight as the dependant variable, with some of the body part measurements as explanatory variables, in addition to age, location and gender. However, the high correlation meant that using all the variables wasn't appropriate in a regression, and did not improve a linear mixed model (LMM). Therefore, it was decided to use just

one of the body size variables. Head size was chosen instead of weight, due to there being no missing values for head.

In this assignment, a Principal Components Analysis (PCA) will be performed on the highly correlated variables. The component(s) will then be included in the LMM to see whether there is an improvement. Weight will be used instead of Head as the dependent variable. Length will still be excluded, as it is missing 1183 of the 1463 measurements. When the rows with data missing from the other variables are removed, there are 1182 of the original 1463 measurements left in the data set. A correlation matrix of the remaining variables is shown below:

```
          Weight      Head       Ear       Arm       Leg       Pes      Tail
Weight 1.0000000 0.8890429 0.8246763 0.9283592 0.8935956 0.8039926 0.9018297
Head   0.8890429 1.0000000 0.9778606 0.9878897 0.9961650 0.9798736 0.9879802
Ear    0.8246763 0.9778606 1.0000000 0.9609295 0.9837529 0.9892665 0.9788041
Arm    0.9283592 0.9878897 0.9609295 1.0000000 0.9908630 0.9604538 0.9871019
Leg    0.8935956 0.9961650 0.9837529 0.9908630 1.0000000 0.9834162 0.9943633
Pes    0.8039926 0.9798736 0.9892665 0.9604538 0.9834162 1.0000000 0.9740589
Tail   0.9018297 0.9879802 0.9788041 0.9871019 0.9943633 0.9740589 1.0000000
```

It appears from the graphs above that the weight does not differ significantly between male and female wallabies until approximately 400 days. Therefore, two k-means cluster analyses will also be run on the weight of wallabies older than 400 days. The first will create two clusters to see whether it separates the wallabies into male and female groups. The second will create three clusters to see whether they are grouped by location.

Method

A similar process will be followed as was performed in Assignment 2, where a linear regression was run and then a LMM. Although it was found that a linear regression was not appropriate due to some of the four assumptions of independence, linearity, normality and homoscedasticity not being met, it will set a baseline to measure any improvement offered by the LMM. A PCA will then be run and the number of major component(s) identified. The models will then be run again, including the component(s), to see whether there is an improvement, and whether location and / or sex have a statistically significant impact on the weight of the wallabies.

The dataset was named wallaby_na and the variables were assigned as follows:

```
H <- wallaby_na$Head
W <- wallaby_na$Weight
A <- wallaby_na$Age
L <- wallaby_na$Loca
An <- wallaby_na$Anim
S <- wallaby_na$Sex
```

A simple linear regression was run first with Age and Location as the explanatory variables:

```
lm1 <- lm(W ~ A + L)
```

As in assignment 2, the Box-Cox procedure was used to see whether the model could be improved by raising age to a power other than one, to better fit the curved shape of the graph.

```
a <- lm(W ~ A)
bc<-boxcox(a)
which.max(bc$y)
lambda<-bc$x[which.max(bc$y)]
lambda
```

This produced a value of 0.4646. This was included in the model as an extra variable:

```
A2 <- A^lambda
lm2 <- lm(W ~ A2 + A + L)
```

A third linear regression was run, including the Sex variable:

```
lm3 <- lm(W ~ A2 + A + L + S)
```

Two linear mixed models were then run, using Animal as the random effect:

```
lme1<-lme(W ~ A + A2 + L, data = wallaby_na, random = ~ 1 | An, correlation = corAR1(.5))
```

```
lme2<-lme(W ~ A + A2 + L + S, data = wallaby_na, random = ~ 1 | An, correlation = corAR1(.5))
```

Having created these models as a baseline, the PCA was then performed. The variables Head, Ear, Arm, Leg, Pes and Tail were included. The data was scaled first, so that larger values did not contribute inordinately to the result.

```
std_wall <- as.data.frame(scale(wallaby_na[5:10]))
wall.pca <- prcomp(std_wall)
```

A summary of the result showed that the first principal component accounted for 98.52% of the variance in the variables. This is an indication of how highly correlated the variables are. Each variable is weighted almost identically in the component.

```
summary(wall.pca)
```

```
Importance of components:
                          PC1     PC2    PC3     PC4     PC5     PC6
Standard deviation     2.4313 0.23915 0.1224 0.08910 0.08552 0.03920
Proportion of Variance 0.9852 0.00953 0.0025 0.00132 0.00122 0.00026
Cumulative Proportion  0.9852 0.99470 0.9972 0.99852 0.99974 1.00000
```

```
wall.pca$rotation[,1]
```

```
     Head       Ear       Arm       Leg       Pes      Tail
0.4095505 0.4068342 0.4066142 0.4108468 0.4065887 0.4090351
```

The first principal component was assigned to a variable:

```
H_PC1 <- wall.pca$x[,1]
```

The five models were then run again, this time including the component.

```
lm1_PC <- lm(W ~ H_PC1 + A + L)
lm2_PC <- lm(W ~ H_PC1 + A2 + A + L)
lm3_PC <- lm(W ~ H_PC1 + A2 + A + L + S)
lme1_PC <-lme(W ~ H_PC1 + A + A2 + L, data = wallaby_na, random = ~ 1 | An, correlation =
corAR1(.5))
lme2_PC <-lme(W ~ H_PC1 + A + A2 + L + S, data = wallaby_na, random = ~ 1 | An, correlation =
corAR1(.5))
```

A new data set was then created including only measurements for wallabies aged 400 days and over. The variables Weight, Head, Ear, Arm, Leg, Pes, Tail and Age were standardised and then the kmeans function run, splitting the data into two clusters. The cluster numbers were added to the dataset and then a table created to show how many of the measurements for male and female wallabies were added to each cluster.

```
wallaby_400 <- wallaby_na[wallaby_na$Age > 399, ]
std_wall <- as.data.frame(scale(wallaby_400[5:11]))

wall_400_fit <- kmeans(std_wall, 2)
wall_400_clust <- data.frame(wallaby_400, wall_400_fit$cluster)
table(wall_400_clust$Sex, wall_400_clust$wall_400_fit.cluster)

wall_400_fit <- kmeans(std_wall, 3)
wall_400_clust <- data.frame(wallaby_400, wall_400_fit$cluster)
table(wall_400_clust$Loca, wall_400_clust$wall_400_fit.cluster)
```

Results

The R-squared and AIC results for each model were as follows:

Model	R-squared	AIC
lm1	0.8569	24290.77
lm2	0.8947	23929.81
lm3	0.8975	23900.54
lme1		21162.07
lme2		21146.92
lm1_PC	0.9066	23788.18
lm2_PC	0.9088	23762.46
lm3_PC	0.9105	23741.47
lme1_PC		21107.99
lme2_PC		21092.88

As was found in Assignment 2, the linear mixed model performed better than the linear regression, and there was a slight improvement when the Sex variable was included. There was also a slight improvement when the principal component from the PCA was included.

The full output of the final model (lme2_PC) is shown below, without the correlation:

```
Linear mixed-effects model fit by REML
 Data: wallaby_na
       AIC      BIC    logLik
  21092.88 21199.13 -10525.44

Random effects:
 Formula: ~1 | An
        (Intercept) Residual
StdDev:    36.52957 7482.269

Correlation Structure: AR(1)
 Formula: ~1 | An
 Parameter estimate(s):
      Phi
0.9677602
Fixed effects: W ~ H_PC1 + A + A2 + L + S
                 Value Std.Error   DF   t-value p-value
(Intercept) 10282.244  3504.346 1108  2.934140  0.0034
H_PC1        1658.086   250.089 1108  6.629984  0.0000
A              72.029     5.769 1108 12.485557  0.0000
A2          -1200.373   354.768 1108 -3.383549  0.0007
LH1          6450.106  3171.598 1108  2.033709  0.0422
LH11          234.509  7625.976   56  0.030751  0.9756
LH12        -4026.850  7732.140   56 -0.520794  0.6046
LH2          2396.833  4311.366   56  0.555933  0.5805
LH3           715.509  3583.607   56  0.199662  0.8425
LH5           -53.002  7625.518   56 -0.006951  0.9945
LH7           125.018  5554.311   56  0.022508  0.9821
LH8          7230.287  6717.310   56  1.076366  0.2864
LH9           -98.646  4571.908   56 -0.021577  0.9829
LHa          2202.233  2113.623 1108  1.041923  0.2977
LHb          4493.989  3033.729   56  1.481342  0.1441
LK           6831.046  4668.793   56  1.463129  0.1490
LW           3484.987  4126.075   56  0.844625  0.4019
S2           -760.293  1923.655 1108 -0.395233  0.6927


Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-4.5577260 -0.6839594 -0.1932880  0.7431471  3.2799308

Number of Observations: 1182
Number of Groups: 68
```

The principal component was found to be significant. However, only location H1 has a p-value less than 0.05, showing that it is the only location likely to be a significant factor in the difference in Weight from location G. In addition, the sex does not contribute significantly to the weight of the wallaby.

However, the k-means cluster analysis seemed to indicate that sex could be significant to the weight of the wallaby once it is older than 400 days. To make the results clearer, the Sex variable was changed from 1 and 2 to M and F for male and female. The table showing the clusters and Sex is as follows:

```
    1   2
F   2 117
M  68  43
```

Nearly all the female wallaby measurements are in the same cluster, which would seem to indicate that, above 400 days of age, the weight of a wallaby is affected by the sex.

The result of segregating the data into three clusters and then comparing them by location is as follows:

	1	2	3
G	25	43	55
H1	0	2	0
H2	0	2	1
H8	0	0	1
Ha	0	20	17
Hb	26	1	12
K	0	7	14
W	0	4	0

Restricting the dataset has meant that there are only four locations with more than four measurements. This result would seem to support what was found above in the linear mixed model, that location is not a significant factor in the weight of a wallaby, as there is no clear cluster for each location.

Conclusion

As with Assignment 2, neither the Principal Components Analysis nor k-means clustering indicated that the location of a wallaby is a significant factor in its size. The PCA also didn't show that the sex of the wallaby is significant. However, when restricting the data to measurements of wallabies 400 days and older, the k-means cluster analysis seemed to show that sex was significant to some extent, with nearly all the measurements of females included in the one cluster, and 61% of male measurements in the other. As was concluded in Assignment 2, a larger and more comprehensive data set would be required before the effect of location and sex could be determined more confidently.

References

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Department of Primary Industries, Parks, Water and Environment, 2012, 'Pest risk assessment – Tammar Wallaby', viewed 1st of May 2015, <http://dpipwe.tas.gov.au/Documents/Tammar-Wallaby_Risk-Assessment.pdf>

Wood, J, CSIRO Biometrics Unit INRE, Canberra, 1994,'Growth of Tammar Wallabies', *OzDazl* data set, viewed 05May <http://www.statsci.org/data/oz/wallaby.html>

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West, B.T., Welch, K.B. & Galecki, A.T. 2007, *Linear mixed models- a practical guide using statistical software*, Taylor & Francis Group, Boca Raton.

Winter. B 2014, 'A very basic model for performing linear fixed effects analyses tutorial', *University of California*, viewed 15th of May 2016,<http//www.bodowinter.com/tutorial/bw_LME_tutorial.pdf>

Appendix

```
> summary(lm1)

Call:
lm(formula = W ~ A + L)

Residuals:
   Min     1Q Median     3Q    Max
-52820  -4264   -601   4830  19721

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -6135.5353   496.1502 -12.366  < 2e-16 ***
A              76.2958     0.9645  79.105  < 2e-16 ***
LH1           210.8395  1022.9554   0.206  0.83674
LH11         1553.9024  4948.6403   0.314  0.75357
LH12        -3441.0252  6979.4161  -0.493  0.62209
LH2          1991.8574  1065.8390   1.869  0.06190 .
LH3          1146.4857  1084.8781   1.057  0.29083
LH5          1285.5715  4948.3876   0.260  0.79507
LH7           875.4615  2878.4291   0.304  0.76107
LH8          1388.0238  1568.5448   0.885  0.37639
LH9           745.0874  2144.6253   0.347  0.72834
LHa          1607.7999   531.2692   3.026  0.00253 **
LHb          5468.6693   686.2803   7.969 3.79e-15 ***
LK           5131.3350   915.7019   5.604 2.62e-08 ***
LW            223.9549  1028.8996   0.218  0.82773
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 6969 on 1167 degrees of freedom
Multiple R-squared:  0.8569,   Adjusted R-squared:  0.8551
F-statistic:   499 on 14 and 1167 DF,  p-value: < 2.2e-16
```

```
> summary(lm2)

Call:
lm(formula = W ~ A2 + A + L)

Residuals:
   Min     1Q Median     3Q    Max
-35093  -4488     20   4348  18669

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -32730.975   1367.078 -23.942  < 2e-16 ***
A2            3687.548    180.125  20.472  < 2e-16 ***
A                3.661      3.643   1.005   0.3152
LH1           -190.216    877.952  -0.217   0.8285
LH11          7541.113   4256.175   1.772   0.0767 .
LH12         -5504.183   5989.443  -0.919   0.3583
LH2           1268.352    915.212   1.386   0.1661
LH3           -191.279    933.156  -0.205   0.8376
LH5           6758.432   4254.306   1.589   0.1124
LH7           5211.773   2478.864   2.102   0.0357 *
LH8            729.873   1346.253   0.542   0.5878
LH9           4089.705   1847.405   2.214   0.0270 *
LHa            347.377    459.987   0.755   0.4503
LHb           4788.447    589.790   8.119 1.19e-15 ***
LK            3932.095    787.887   4.991 6.93e-07 ***
LW            -928.221    884.626  -1.049   0.2943
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5979 on 1166 degrees of freedom
Multiple R-squared:  0.8947,   Adjusted R-squared:  0.8934
F-statistic: 660.5 on 15 and 1166 DF,  p-value: < 2.2e-16
```

```
summary(lm3)

Call:
lm(formula = W ~ A2 + A + L + S)

Residuals:
   Min     1Q Median     3Q    Max
-33827  -4297    328   4196  18190

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -32099.552   1354.414 -23.700  < 2e-16 ***
A2            3734.327    178.031  20.976  < 2e-16 ***
A                2.948      3.599   0.819  0.41288
LH1           1073.493    895.798   1.198  0.23102
LH11          6635.125   4205.177   1.578  0.11487
LH12         -4260.563   5917.463  -0.720  0.47167
LH2           2526.408    931.194   2.713  0.00676 **
LH3          -1221.812    939.563  -1.300  0.19372
LH5           5844.980   4203.384   1.391  0.16463
LH7           6558.544   2459.178   2.667  0.00776 **
LH8           -289.109   1341.582  -0.215  0.82942
LH9           3141.092   1831.794   1.715  0.08665 .
LHa            722.154    459.063   1.573  0.11597
LHb           4149.570    593.406   6.993 4.53e-12 ***
LK            5160.131    808.310   6.384 2.49e-10 ***
LW            -925.029    873.376  -1.059  0.28975
S2           -2279.890    407.965  -5.588 2.85e-08 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5903 on 1165 degrees of freedom
Multiple R-squared:  0.8975,   Adjusted R-squared:  0.896
F-statistic: 637.2 on 16 and 1165 DF,  p-value: < 2.2e-16
```

```
> summary(lme1)
Linear mixed-effects model fit by REML
 Data: wallaby_na
       AIC      BIC    logLik
  21162.07 21258.23 -10562.03

Random effects:
 Formula: ~1 | An
        (Intercept) Residual
StdDev:    1.759212 7650.424

Correlation Structure: AR(1)
 Formula: ~1 | An
 Parameter estimate(s):
      Phi
0.9680672
Fixed effects: W ~ A + A2 + L
                 Value Std.Error   DF   t-value p-value
(Intercept) -8731.627  1948.987 1110 -4.480084  0.0000
A              46.919     4.434 1110 10.580602  0.0000
A2            796.187   191.146 1110  4.165324  0.0000
LH1          7357.876  2604.875 1110  2.824656  0.0048
LH11          563.143  7757.392   56  0.072594  0.9424
LH12        -4321.281  7817.226   56 -0.552790  0.5826
LH2          2009.634  4253.292   56  0.472489  0.6384
LH3          1126.338  3580.442   56  0.314581  0.7542
LH5           245.380  7757.020   56  0.031633  0.9749
LH7           -10.326  5557.635   56 -0.001858  0.9985
LH8          7815.879  6830.178   56  1.144316  0.2574
LH9           656.107  4607.732   56  0.142393  0.8873
LHa          1869.890  2156.169 1110  0.867228  0.3860
LHb          4847.464  3097.153   56  1.565136  0.1232
LK           6393.817  4637.430   56  1.378742  0.1735
LW           3134.887  4221.916   56  0.742527  0.4609
 Correlation:
     (Intr) A      A2     LH1    LH11   LH12   LH2    LH3    LH5    LH7
LH8
A     0.425
A2   -0.546 -0.938
LH1  -0.522 -0.003  0.037
LH11 -0.175  0.015  0.003  0.125
LH12 -0.141  0.050 -0.044  0.120  0.041
LH2  -0.280  0.045 -0.037  0.220  0.075  0.075
LH3  -0.329  0.077 -0.061  0.263  0.090  0.091  0.163
LH5  -0.173  0.018 -0.001  0.125  0.043  0.041  0.075  0.090
LH7  -0.233  0.032 -0.012  0.173  0.059  0.058  0.105  0.126  0.059
LH8  -0.174  0.026 -0.022  0.137  0.047  0.047  0.085  0.102  0.047  0.065
LH9  -0.275  0.043 -0.022  0.208  0.071  0.070  0.127  0.152  0.071  0.099
0.079
LHa  -0.536  0.106 -0.097  0.734  0.147  0.149  0.270  0.323  0.147  0.206
0.168
LHb  -0.394  0.023 -0.020  0.301  0.102  0.101  0.185  0.221  0.102  0.142
0.115
LK   -0.262 -0.012  0.002  0.198  0.066  0.066  0.122  0.144  0.066  0.092
0.076
LW   -0.282  0.045 -0.037  0.222  0.076  0.076  0.137  0.165  0.076  0.106
0.085
     LH9    LHa    LHb    LK
A
A2
LH1
LH11
```

```
LH12
LH2
LH3
LH5
LH7
LH8
LH9
LHa   0.249
LHb   0.171  0.366
LK    0.112  0.241  0.169
LW    0.128  0.272  0.187  0.123

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-4.4935658 -0.7469041 -0.1961872  0.7675400  3.2870492

Number of Observations: 1182
Number of Groups: 68
```

```
> summary(lme2)
Linear mixed-effects model fit by REML
 Data: wallaby_na
       AIC      BIC    logLik
  21146.92 21248.13 -10553.46

Random effects:
 Formula: ~1 | An
        (Intercept) Residual
StdDev:    2.000707 7695.118

Correlation Structure: AR(1)
 Formula: ~1 | An
 Parameter estimate(s):
      Phi
0.9684354
Fixed effects: W ~ A + A2 + L + S
                Value Std.Error   DF   t-value p-value
(Intercept) -8423.534  2131.745 1109 -3.951473  0.0001
A              47.006     4.442 1109 10.581127  0.0000
A2            791.862   191.419 1109  4.136810  0.0000
LH1          8071.509  3255.166 1109  2.479600  0.0133
LH11          279.102  7844.902   56  0.035578  0.9717
LH12        -3889.787  7953.152   56 -0.489087  0.6267
LH2          2438.322  4443.857   56  0.548695  0.5854
LH3           849.336  3691.047   56  0.230107  0.8188
LH5           -38.065  7844.444   56 -0.004853  0.9961
LH7           414.209  5715.438   56  0.072472  0.9425
LH8          7558.445  6926.258   56  1.091274  0.2798
LH9           375.787  4704.630   56  0.079876  0.9366
LHa          1937.508  2178.115 1109  0.889534  0.3739
LHb          4766.190  3128.354   56  1.523546  0.1332
LK           6819.767  4818.759   56  1.415254  0.1625
LW           3119.330  4252.819   56  0.733474  0.4663
S2           -706.338  1982.986 1109 -0.356199  0.7218
 Correlation:
     (Intr) A      A2     LH1    LH11   LH12   LH2    LH3    LH5    LH7
LH8
A     0.405
A2   -0.514 -0.938
LH1  -0.152  0.023  0.006
LH11 -0.200  0.011  0.007  0.039
LH12 -0.070  0.055 -0.049  0.185  0.025
LH2  -0.143  0.055 -0.046  0.330  0.045  0.112
LH3  -0.381  0.066 -0.051  0.079  0.110  0.055  0.096
LH5  -0.199  0.013  0.003  0.039  0.053  0.025  0.045  0.110
LH7  -0.128  0.040 -0.020  0.259  0.037  0.087  0.154  0.076  0.037
LH8  -0.205  0.021 -0.017  0.041  0.058  0.029  0.050  0.123  0.058  0.039
LH9  -0.317  0.035 -0.015  0.064  0.087  0.043  0.075  0.183  0.087  0.060
0.097
LHa  -0.462  0.108 -0.099  0.637  0.138  0.159  0.280  0.298  0.138  0.218
0.157
LHb  -0.391  0.020 -0.017  0.199  0.108  0.089  0.159  0.231  0.108  0.124
0.123
LK   -0.138 -0.001 -0.008  0.300  0.039  0.100  0.179  0.084  0.039  0.138
0.045
LW   -0.268  0.044 -0.036  0.167  0.077  0.072  0.127  0.165  0.077  0.099
0.087
S2   -0.395 -0.043  0.040 -0.594  0.102 -0.150 -0.266  0.216  0.102 -0.207
0.115
     LH9    LHa    LHb    LK     LW
A
```

```
A2
LH1
LH11
LH12
LH2
LH3
LH5
LH7
LH8
LH9
LHa   0.232
LHb   0.181  0.358
LK    0.065  0.252  0.145
LW    0.129  0.269  0.188  0.114
S2    0.170 -0.078  0.073 -0.243  0.020

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-4.4146665 -0.7368546 -0.1921411  0.7751787  3.2426531

Number of Observations: 1182
Number of Groups: 68
```

```
> summary(lm1_PC)

Call:
lm(formula = W ~ H_PC1 + A + L)

Residuals:
   Min     1Q Median     3Q    Max
-35460  -4306    247   4010  18476

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  2623.886    533.243   4.921 9.87e-07 ***
H_PC1        2938.514    117.930  24.917  < 2e-16 ***
A              49.719      1.321  37.636  < 2e-16 ***
LH1          -687.106    827.479  -0.830   0.4065
LH11         6221.572   4003.593   1.554   0.1205
LH12        -6554.759   5641.749  -1.162   0.2455
LH2            98.774    864.694   0.114   0.9091
LH3          -442.861    879.054  -0.504   0.6145
LH5          5519.529   4002.612   1.379   0.1682
LH7          3821.746   2329.185   1.641   0.1011
LH8           -25.887   1268.878  -0.020   0.9837
LH9          3101.082   1735.741   1.787   0.0743 .
LHa          -233.881    435.657  -0.537   0.5915
LHb          3610.418    559.604   6.452 1.62e-10 ***
LK           3072.321    744.617   4.126 3.95e-05 ***
LW           -766.068    832.447  -0.920   0.3576
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5632 on 1166 degrees of freedom
Multiple R-squared:  0.9066,   Adjusted R-squared:  0.9054
F-statistic: 754.5 on 15 and 1166 DF,  p-value: < 2.2e-16
```

```
> summary(lm2_PC)

Call:
lm(formula = W ~ H_PC1 + A2 + A + L)

Residuals:
   Min     1Q Median     3Q    Max
-37929  -4025    546   3924  18494

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 26751.425   4619.205   5.791 8.97e-09 ***
H_PC1        4662.835    348.075  13.396  < 2e-16 ***
A2          -2632.682    500.731  -5.258 1.73e-07 ***
A              85.980      7.019  12.249  < 2e-16 ***
LH1          -927.691    819.463  -1.132 0.257837
LH11         4686.064   3969.380   1.181 0.238021
LH12        -6908.933   5578.783  -1.238 0.215806
LH2          -495.551    862.422  -0.575 0.565670
LH3          -420.409    869.190  -0.484 0.628704
LH5          4096.733   3966.893   1.033 0.301944
LH7          2454.769   2317.651   1.059 0.289745
LH8          -385.692   1256.490  -0.307 0.758929
LH9          2095.730   1726.863   1.214 0.225144
LHa          -414.717    432.134  -0.960 0.337408
LHb          3005.631    565.148   5.318 1.25e-07 ***
LK           2720.274    739.292   3.680 0.000244 ***
LW           -524.432    824.378  -0.636 0.524801
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5568 on 1165 degrees of freedom
Multiple R-squared:  0.9088,   Adjusted R-squared:  0.9075
F-statistic: 725.2 on 16 and 1165 DF,  p-value: < 2.2e-16
```

```
> summary(lm3_PC)

Call:
lm(formula = W ~ H_PC1 + A2 + A + L + S)

Residuals:
   Min     1Q Median     3Q    Max
-36822  -4085    678   3866  18115

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 25356.806   4585.735   5.529 3.96e-08 ***
H_PC1        4513.767    346.260  13.036  < 2e-16 ***
A2          -2393.067    498.621  -4.799 1.80e-06 ***
A              82.776      6.987  11.848  < 2e-16 ***
LH1           110.580    840.409   0.132    0.895
LH11         4049.875   3934.891   1.029    0.304
LH12        -5865.458   5531.455  -1.060    0.289
LH2           570.997    883.068   0.647    0.518
LH3         -1240.550    878.057  -1.413    0.158
LH5          3448.369   3932.515   0.877    0.381
LH7          3624.299   2309.188   1.570    0.117
LH8         -1168.220   1255.569  -0.930    0.352
LH9          1397.788   1717.094   0.814    0.416
LHa           -89.427    433.505  -0.206    0.837
LHb          2549.640    567.979   4.489 7.87e-06 ***
LK           3745.067    763.155   4.907 1.05e-06 ***
LW           -534.777    816.751  -0.655    0.513
S2          -1830.637    382.813  -4.782 1.96e-06 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5517 on 1164 degrees of freedom
Multiple R-squared:  0.9105,   Adjusted R-squared:  0.9092
F-statistic: 696.7 on 17 and 1164 DF,  p-value: < 2.2e-16
```

```
> summary(lme1_PC)
Linear mixed-effects model fit by REML
 Data: wallaby_na
       AIC     BIC    logLik
  21107.99 21209.2 -10533.99

Random effects:
 Formula: ~1 | An
        (Intercept) Residual
StdDev:     2.37582 7439.118

Correlation Structure: AR(1)
 Formula: ~1 | An
 Parameter estimate(s):
     Phi
0.967386
Fixed effects: W ~ H_PC1 + A + A2 + L
                 Value Std.Error   DF   t-value p-value
(Intercept)  9955.540  3399.657 1109  2.928396  0.0035
H_PC1        1658.545   250.066 1109  6.632436  0.0000
A              71.939     5.762 1109 12.485077  0.0000
A2          -1196.129   354.554 1109 -3.373617  0.0008
LH1          5688.070  2547.516 1109  2.232791  0.0258
LH11          539.731  7541.227   56  0.071571  0.9432
LH12        -4492.099  7600.658   56 -0.591014  0.5569
LH2          1934.484  4126.695   56  0.468773  0.6411
LH3          1013.678  3476.321   56  0.291595  0.7717
LH5           251.570  7540.854   56  0.033361  0.9735
LH7          -332.483  5401.661   56 -0.061552  0.9511
LH8          7509.119  6624.097   56  1.133607  0.2618
LH9           202.771  4477.971   56  0.045282  0.9640
LHa          2127.947  2092.279 1109  1.017047  0.3094
LHb          4580.843  3003.351   56  1.525244  0.1328
LK           6371.617  4492.912   56  1.418148  0.1617
LW           3501.863  4096.154   56  0.854915  0.3962
 Correlation:
      (Intr) H_PC1  A      A2     LH1    LH11   LH12   LH2    LH3    LH5
H_PC1  0.829
A      0.725  0.656
A2    -0.866 -0.848 -0.931
LH1   -0.368 -0.096 -0.065  0.101
LH11  -0.097  0.000  0.011  0.002  0.124
LH12  -0.081 -0.003  0.036 -0.021  0.119  0.041
LH2   -0.157 -0.002  0.033 -0.018  0.219  0.075  0.075
LH3   -0.186 -0.004  0.056 -0.029  0.261  0.090  0.091  0.163
LH5   -0.096  0.000  0.014  0.000  0.123  0.043  0.041  0.075  0.090
LH7   -0.137 -0.009  0.018  0.001  0.172  0.059  0.058  0.105  0.126  0.05
9
LH8   -0.102 -0.006  0.016 -0.007  0.136  0.046  0.047  0.085  0.101  0.04
7
LH9   -0.165 -0.015  0.023  0.001  0.207  0.071  0.070  0.126  0.152  0.07
1
LHa   -0.281  0.020  0.094 -0.068  0.725  0.147  0.149  0.269  0.322  0.14
7
LHb   -0.230 -0.013  0.009  0.001  0.300  0.101  0.101  0.185  0.221  0.10
1
LK    -0.146  0.000 -0.009  0.001  0.197  0.066  0.066  0.122  0.144  0.06
6
LW    -0.144  0.015  0.044 -0.032  0.219  0.075  0.076  0.137  0.164  0.07
5
      LH7    LH8    LH9    LHa    LHb    LK
H_PC1
```

```
A
A2
LH1
LH11
LH12
LH2
LH3
LH5
LH7
LH8    0.065
LH9    0.099  0.079
LHa    0.206  0.167  0.248
LHb    0.142  0.115  0.171  0.365
LK     0.092  0.076  0.111  0.241  0.169
LW     0.105  0.085  0.127  0.272  0.186  0.123

Standardized Within-Group Residuals:
      Min        Q1       Med        Q3       Max
-4.642937 -0.667319 -0.193920  0.709247  3.327137

Number of Observations: 1182
Number of Groups: 68
```

```
> summary(lme2_PC)
Linear mixed-effects model fit by REML
 Data: wallaby_na
       AIC      BIC    logLik
  21092.88 21199.13 -10525.44

Random effects:
 Formula: ~1 | An
        (Intercept) Residual
StdDev:    36.52957 7482.269

Correlation Structure: AR(1)
 Formula: ~1 | An
 Parameter estimate(s):
      Phi
0.9677602
Fixed effects: W ~ H_PC1 + A + A2 + L + S
                 Value Std.Error   DF   t-value p-value
(Intercept) 10282.244  3504.346 1108  2.934140  0.0034
H_PC1        1658.086   250.089 1108  6.629984  0.0000
A              72.029     5.769 1108 12.485557  0.0000
A2          -1200.373   354.768 1108 -3.383549  0.0007
LH1          6450.106  3171.598 1108  2.033709  0.0422
LH11          234.509  7625.976   56  0.030751  0.9756
LH12        -4026.850  7732.140   56 -0.520794  0.6046
LH2          2396.833  4311.366   56  0.555933  0.5805
LH3           715.509  3583.607   56  0.199662  0.8425
LH5           -53.002  7625.518   56 -0.006951  0.9945
LH7           125.018  5554.311   56  0.022508  0.9821
LH8          7230.287  6717.310   56  1.076366  0.2864
LH9           -98.646  4571.908   56 -0.021577  0.9829
LHa          2202.233  2113.623 1108  1.041923  0.2977
LHb          4493.989  3033.729   56  1.481342  0.1441
LK           6831.046  4668.793   56  1.463129  0.1490
LW           3484.987  4126.075   56  0.844625  0.4019
S2           -760.293  1923.655 1108 -0.395233  0.6927
 Correlation:
      (Intr) H_PC1  A      A2     LH1    LH11   LH12   LH2    LH3    LH5
H_PC1  0.806
A      0.711  0.655
A2    -0.846 -0.848 -0.931
LH1   -0.150 -0.075 -0.032  0.067
LH11  -0.119 -0.001  0.008  0.004  0.039
LH12  -0.043 -0.002  0.040 -0.024  0.183  0.025
LH2   -0.085 -0.001  0.041 -0.024  0.328  0.045  0.112
LH3   -0.229 -0.005  0.047 -0.023  0.079  0.109  0.055  0.096
LH5   -0.117  0.000  0.010  0.002  0.039  0.053  0.025  0.045  0.110
LH7   -0.082 -0.008  0.025 -0.004  0.258  0.037  0.087  0.154  0.076  0.03
7
LH8   -0.126 -0.006  0.012 -0.004  0.042  0.058  0.029  0.050  0.123  0.05
8
LH9   -0.199 -0.015  0.017  0.005  0.065  0.087  0.043  0.075  0.183  0.08
7
LHa   -0.256  0.020  0.096 -0.070  0.632  0.138  0.159  0.280  0.297  0.13
8
LHb   -0.242 -0.013  0.006  0.002  0.199  0.108  0.089  0.159  0.231  0.10
8
LK    -0.081  0.001  0.000 -0.005  0.298  0.039  0.100  0.179  0.084  0.03
9
LW    -0.146  0.014  0.043 -0.032  0.165  0.077  0.072  0.127  0.165  0.07
7
```

```
S2    -0.237 -0.004 -0.035  0.024 -0.590  0.102 -0.150 -0.266  0.215  0.10
2
      LH7    LH8    LH9    LHa    LHb    LK     LW
H_PC1
A
A2
LH1
LH11
LH12
LH2
LH3
LH5
LH7
LH8    0.039
LH9    0.060  0.097
LHa    0.217  0.157  0.231
LHb    0.123  0.123  0.181  0.358
LK     0.138  0.045  0.065  0.252  0.145
LW     0.099  0.087  0.129  0.269  0.187  0.114
S2    -0.207  0.116  0.170 -0.079  0.074 -0.244  0.020

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-4.5577260 -0.6839594 -0.1932880  0.7431471  3.2799308

Number of Observations: 1182
Number of Groups: 68
```