Linear models for temperature effect

Sasha D. Hafner

14 January, 2025 Jan:01

```
library(lme4)
```

Main subset all micromet

Subset with air temperature.

```
dd <- df[!is.na(AirTemperature), ]
```

```
dfsumm(df[, .(Ref, NH3loss, AirTemperature, FertiliserType)])
```

```
##
##   244 rows and 4 columns
##   243 unique rows
##                                   Ref NH3loss AirTemperature
## Class                          factor numeric        numeric
## Minimum          Bacon and Freney 1989       0             -5
## Maximum          Nikolajsen et al. 2020      60           27.7
## Mean          Sanz-Cobena et al. 2008       13           12.4
## Unique (excld. NA)                 38     165             81
## Missing values                      0       0             42
## Sorted                          FALSE   FALSE          FALSE
##
##                  FertiliserType
## Class                    factor
## Minimum                      AS
## Maximum                    Urea
## Mean                       Urea
## Unique (excld. NA)            3
## Missing values                0
## Sorted                    FALSE
##
```

```
dfsumm(dd[, .(Ref, NH3loss, AirTemperature, FertiliserType)])
```

```
##
##   202 rows and 4 columns
##   201 unique rows
##                                   Ref NH3loss AirTemperature FertiliserType
```

```
## Class                             factor numeric        numeric        factor
## Minimum             Bacon and Freney 1989       0             -5            AS
## Maximum           Nikolajsen et al. 2020      60           27.7          Urea
## Mean               Salazar et al. 2012      12.7           12.4          Urea
## Unique (excld. NA)                   31     143             81             3
## Missing values                       0       0              0             0
## Sorted                           FALSE   FALSE          FALSE         FALSE
##
```

```r
ggplot(dd, aes(AirTemperature, NH3loss, color = FertiliserType, shape = Application)) + geom_point()
```
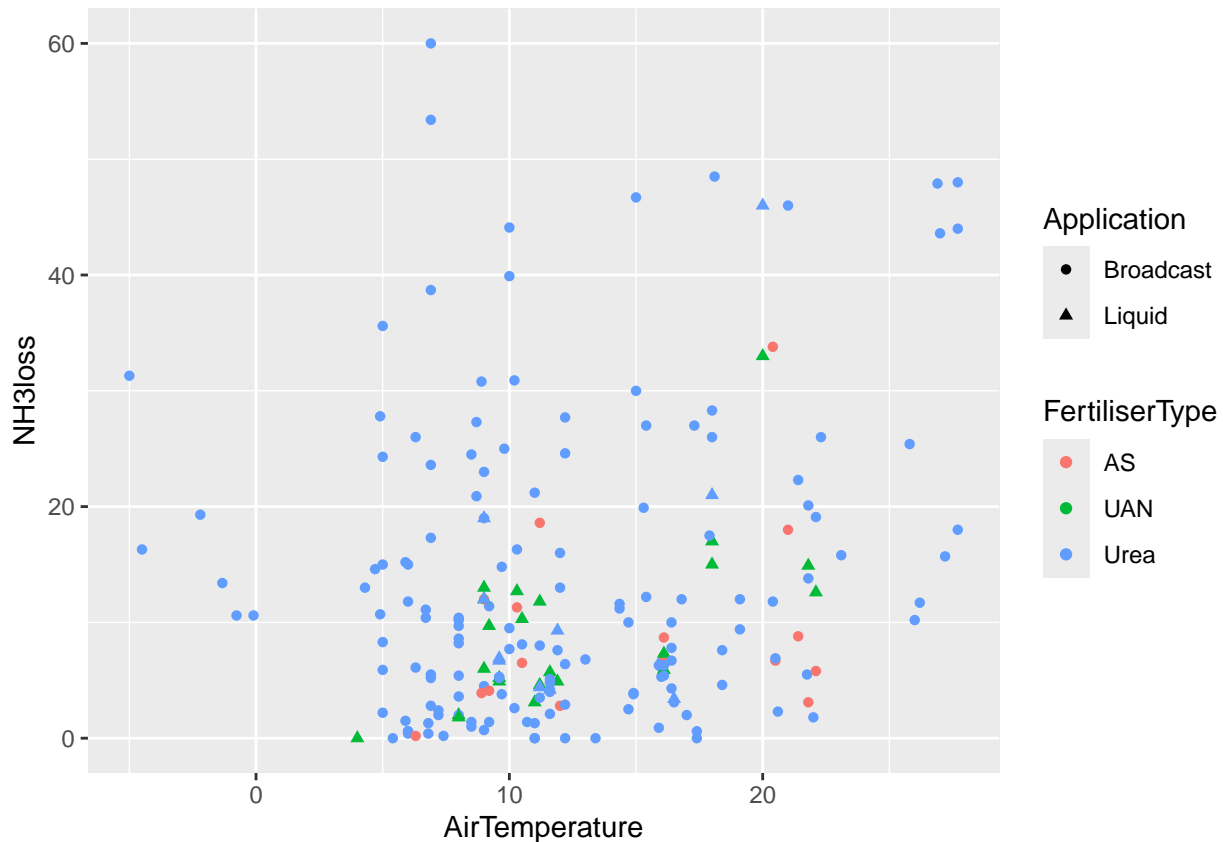


```r
m1 <- lm(NH3loss ~ AirTemperature * FertiliserType, data = dd)
summary(m1)
```

```
##
## Call:
## lm(formula = NH3loss ~ AirTemperature * FertiliserType, data = dd)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -15.389  -8.717  -3.187   5.214  48.371
##
## Coefficients:
##                              Estimate Std. Error t value Pr(>|t|)
## (Intercept)                    3.0030     8.5946   0.349    0.727
## AirTemperature                 0.4365     0.5444   0.802    0.424
```

2

```
## FertiliserTypeUAN                       -5.3640     11.0875   -0.484     0.629
## FertiliserTypeUrea                        6.1545      8.8215    0.698     0.486
## AirTemperature:FertiliserTypeUAN          0.5022      0.7583    0.662     0.509
## AirTemperature:FertiliserTypeUrea        -0.0783      0.5633   -0.139     0.890
##
## Residual standard error: 11.97 on 196 degrees of freedom
## Multiple R-squared:  0.06538,    Adjusted R-squared:  0.04154
## F-statistic: 2.742 on 5 and 196 DF,  p-value: 0.02028
```

```r
m2 <- lmer(NH3loss ~ AirTemperature * FertiliserType + (1|Ref), data = dd)
summary(m2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ AirTemperature * FertiliserType + (1 | Ref)
##    Data: dd
##
## REML criterion at convergence: 1515.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.5311 -0.6154 -0.2251  0.4305  3.4102
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 79.48    8.915
##  Residual             92.69    9.628
## Number of obs: 202, groups:  Ref, 31
##
## Fixed effects:
##                                    Estimate Std. Error t value
## (Intercept)                         9.00086    7.63585   1.179
## AirTemperature                      0.34497    0.46584   0.741
## FertiliserTypeUAN                  -7.92291    9.33865  -0.848
## FertiliserTypeUrea                  2.94923    7.74981   0.381
## AirTemperature:FertiliserTypeUAN    0.59366    0.63037   0.942
## AirTemperature:FertiliserTypeUrea   0.03453    0.48668   0.071
##
## Correlation of Fixed Effects:
##             (Intr) ArTmpr FrTUAN FrtlTU AT:FTUA
## AirTempertr -0.901
## FrtlsrTyUAN -0.755  0.733
## FrtlsrTypUr -0.930  0.889  0.744
## ArTmp:FTUAN  0.659 -0.725 -0.931 -0.650
## ArTmprt:FTU  0.854 -0.950 -0.700 -0.927  0.692
```

```r
m3 <- lmer(NH3loss ~ AirTemperature + FertiliserType + (1|Ref), data = dd)
m3n <- update(m3, ~ . - AirTemperature)
summary(m3)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ AirTemperature + FertiliserType + (1 | Ref)
##    Data: dd
##
```

```
## REML criterion at convergence: 1517.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.5324 -0.6309 -0.2409  0.4669  3.4201
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 80.31    8.962
##  Residual             92.34    9.609
## Number of obs: 202, groups:  Ref, 31
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)         7.6494     3.9022   1.960
## AirTemperature      0.4308     0.1384   3.113
## FertiliserTypeUAN  -0.3130     3.3337  -0.094
## FertiliserTypeUrea  3.5602     2.8938   1.230
##
## Correlation of Fixed Effects:
##             (Intr) ArTmpr FrTUAN
## AirTempertr -0.529
## FrtlsrTyUAN -0.543  0.097
## FrtlsrTypUr -0.715  0.066  0.664
```

`summary(m3n)`

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ FertiliserType + (1 | Ref)
##    Data: dd
##
## REML criterion at convergence: 1524.8
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.5062 -0.6142 -0.2266  0.3869  3.3022
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 79.09    8.893
##  Residual             96.98    9.848
## Number of obs: 202, groups:  Ref, 31
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)         14.048      3.364   4.176
## FertiliserTypeUAN   -1.329      3.397  -0.391
## FertiliserTypeUrea   2.979      2.955   1.008
##
## Correlation of Fixed Effects:
##             (Intr) FrTUAN
## FrtlsrTyUAN -0.587
## FrtlsrTypUr -0.809  0.663
```

4

```
anova(m3, m3n)
```

```
## refitting model(s) with ML (instead of REML)
```

```
## Data: dd
## Models:
## m3n: NH3loss ~ FertiliserType + (1 | Ref)
## m3: NH3loss ~ AirTemperature + FertiliserType + (1 | Ref)
##      npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## m3n     5 1545.6 1562.2 -767.82   1535.6
## m3      6 1538.0 1557.9 -763.02   1526.0 9.5929  1   0.001953 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
confint(m3)
```

```
## Computing profile confidence intervals ...
```

```
##                         2.5 %      97.5 %
## .sig01             5.8785646 12.6565771
## .sigma             8.6077293 10.6412386
## (Intercept)        0.0529258 15.2452450
## AirTemperature     0.1596608  0.7002022
## FertiliserTypeUAN -6.8356328  6.1908339
## FertiliserTypeUrea -2.0813099  9.2245520
```

```
coef(m3)
```

```
## $Ref
##                        (Intercept) AirTemperature FertiliserTypeUAN
## Bacon and Freney 1989    -1.4977280      0.4307774        -0.3129982
## Ferrar et al. 2014       -1.1362037      0.4307774        -0.3129982
## Kemmann et al. 2025       0.2708660      0.4307774        -0.3129982
## Recio et al. 2020         0.6350375      0.4307774        -0.3129982
## Ni et al. 2015           -1.0996264      0.4307774        -0.3129982
## Abalos et al. 2012        2.9931462      0.4307774        -0.3129982
## Schwenke 2014             1.5553552      0.4307774        -0.3129982
## Pedersen et al. 2018      2.8972478      0.4307774        -0.3129982
## Tuner et al. 2010         4.8502762      0.4307774        -0.3129982
## Salazar et al. 2012       3.8241834      0.4307774        -0.3129982
## Sanz-Cobena et al. 2008   1.9697136      0.4307774        -0.3129982
## Engel et al. 2017         5.5528993      0.4307774        -0.3129982
## Lam et al. 2019           3.8451057      0.4307774        -0.3129982
## Engel 2011               25.2733471      0.4307774        -0.3129982
## Huckaby 2012              3.1856755      0.4307774        -0.3129982
## Lam et al. 2018           5.1558102      0.4307774        -0.3129982
## Suter et al. 2013         5.4541504      0.4307774        -0.3129982
## Tuner et al. 2012         5.7845208      0.4307774        -0.3129982
## Cai et al. 2002           9.7643529      0.4307774        -0.3129982
## Vaio et al. 2008         12.3018771      0.4307774        -0.3129982
## Black et al. 1989        10.0924281      0.4307774        -0.3129982
```

```
## Horneck 2013              12.1005540      0.4307774         -0.3129982
## Pacholski 2006            16.1706628      0.4307774         -0.3129982
## Yang et al. 2013          10.9225586      0.4307774         -0.3129982
## Holcomb 2011              20.6020811      0.4307774         -0.3129982
## Black et al. 1985         11.9924594      0.4307774         -0.3129982
## Ryden and Lockyer 1985    19.5958913      0.4307774         -0.3129982
## Del Moro et al. 2017      16.2369102      0.4307774         -0.3129982
## Krol et al. 2020          21.1528247      0.4307774         -0.3129982
## Hayashi et al. 2011        2.9217015      0.4307774         -0.3129982
## Nikolajsen et al. 2020     3.7636439      0.4307774         -0.3129982
##                           FertiliserTypeUrea
## Bacon and Freney 1989               3.560205
## Ferrar et al. 2014                  3.560205
## Kemmann et al. 2025                 3.560205
## Recio et al. 2020                   3.560205
## Ni et al. 2015                      3.560205
## Abalos et al. 2012                  3.560205
## Schwenke 2014                       3.560205
## Pedersen et al. 2018                3.560205
## Tuner et al. 2010                   3.560205
## Salazar et al. 2012                 3.560205
## Sanz-Cobena et al. 2008             3.560205
## Engel et al. 2017                   3.560205
## Lam et al. 2019                     3.560205
## Engel 2011                          3.560205
## Huckaby 2012                        3.560205
## Lam et al. 2018                     3.560205
## Suter et al. 2013                   3.560205
## Tuner et al. 2012                   3.560205
## Cai et al. 2002                     3.560205
## Vaio et al. 2008                    3.560205
## Black et al. 1989                   3.560205
## Horneck 2013                        3.560205
## Pacholski 2006                      3.560205
## Yang et al. 2013                    3.560205
## Holcomb 2011                        3.560205
## Black et al. 1985                   3.560205
## Ryden and Lockyer 1985              3.560205
## Del Moro et al. 2017                3.560205
## Krol et al. 2020                    3.560205
## Hayashi et al. 2011                 3.560205
## Nikolajsen et al. 2020              3.560205
##
## attr(,"class")
## [1] "coef.mer"
```

Try without new German data.

```
dnd <- dd[!grepl('Kemmann', Ref), ]
m3 <- lmer(NH3loss ~ AirTemperature + FertiliserType + (1|Ref), data = dnd)
m3n <- update(m3, ~ . - AirTemperature)
summary(m3)
```

```
## Linear mixed model fit by REML ['lmerMod']
```

6

```
## Formula: NH3loss ~ AirTemperature + FertiliserType + (1 | Ref)
##    Data: dnd
##
## REML criterion at convergence: 1138.6
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.5443 -0.5966 -0.1712  0.4444  3.4287
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 87.64    9.362
##  Residual             91.71    9.576
## Number of obs: 151, groups:  Ref, 30
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)         4.7670     4.1163   1.158
## AirTemperature      0.6446     0.1575   4.092
## FertiliserTypeUAN   0.1932     3.3322   0.058
## FertiliserTypeUrea  3.8950     2.8924   1.347
##
## Correlation of Fixed Effects:
##             (Intr) ArTmpr FrTUAN
## AirTempertr -0.575
## FrtlsrTyUAN -0.528  0.111
## FrtlsrTypUr -0.684  0.075  0.664
```

summary(m3n)

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ FertiliserType + (1 | Ref)
##    Data: dnd
##
## REML criterion at convergence: 1152.3
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.4020 -0.5746 -0.1840  0.4237  3.1898
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept)  77.07    8.779
##  Residual             104.64   10.229
## Number of obs: 151, groups:  Ref, 30
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)         14.360      3.468   4.140
## FertiliserTypeUAN   -1.344      3.522  -0.382
## FertiliserTypeUrea   3.085      3.064   1.007
##
## Correlation of Fixed Effects:
##             (Intr) FrTUAN
```

```
## FrtlsrTyUAN -0.592
## FrtlsrTypUr -0.810  0.664
```

anova(m3, m3n)

```
## refitting model(s) with ML (instead of REML)
```

```
## Data: dnd
## Models:
## m3n: NH3loss ~ FertiliserType + (1 | Ref)
## m3: NH3loss ~ AirTemperature + FertiliserType + (1 | Ref)
##     npar    AIC    BIC  logLik deviance Chisq Df Pr(>Chisq)
## m3n    5 1173.4 1188.5 -581.69   1163.4
## m3     6 1159.5 1177.7 -573.78   1147.5 15.82  1  6.966e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

confint(m3)

```
## Computing profile confidence intervals ...
```

```
##                      2.5 %      97.5 %
## .sig01            6.0283922 13.3168812
## .sigma            8.3907750 10.8098499
## (Intercept)      -3.2792667 12.7995165
## AirTemperature    0.3310988  0.9535421
## FertiliserTypeUAN -6.3336055  6.6820140
## FertiliserTypeUrea -1.7394873  9.5515433
```

coef(m3)

```
## $Ref
##                        (Intercept) AirTemperature FertiliserTypeUAN
## Bacon and Freney 1989   -3.8203146      0.6446248         0.1931692
## Ferrar et al. 2014      -5.5164266      0.6446248         0.1931692
## Recio et al. 2020       -3.6295907      0.6446248         0.1931692
## Ni et al. 2015          -4.8534344      0.6446248         0.1931692
## Abalos et al. 2012      -0.2379843      0.6446248         0.1931692
## Schwenke 2014           -1.7439242      0.6446248         0.1931692
## Pedersen et al. 2018     0.9711005      0.6446248         0.1931692
## Tuner et al. 2010        2.0264567      0.6446248         0.1931692
## Salazar et al. 2012      0.6241657      0.6446248         0.1931692
## Sanz-Cobena et al. 2008 -2.6716266      0.6446248         0.1931692
## Engel et al. 2017        4.4523026      0.6446248         0.1931692
## Lam et al. 2019          0.4915491      0.6446248         0.1931692
## Engel 2011              23.9148124      0.6446248         0.1931692
## Huckaby 2012            -1.8961616      0.6446248         0.1931692
## Lam et al. 2018          0.9784601      0.6446248         0.1931692
## Suter et al. 2013        2.7238349      0.6446248         0.1931692
## Tuner et al. 2012        3.3245855      0.6446248         0.1931692
## Cai et al. 2002          5.5535446      0.6446248         0.1931692
```

```
## Vaio et al. 2008          9.0022471     0.6446248     0.1931692
## Black et al. 1989         7.4289006     0.6446248     0.1931692
## Horneck 2013              9.6638628     0.6446248     0.1931692
## Pacholski 2006           12.0145281     0.6446248     0.1931692
## Yang et al. 2013          7.5694555     0.6446248     0.1931692
## Holcomb 2011             18.8225974     0.6446248     0.1931692
## Black et al. 1985         8.6933993     0.6446248     0.1931692
## Ryden and Lockyer 1985   16.6644603     0.6446248     0.1931692
## Del Moro et al. 2017     12.4800777     0.6446248     0.1931692
## Krol et al. 2020         18.6299787     0.6446248     0.1931692
## Hayashi et al. 2011       0.5506999     0.6446248     0.1931692
## Nikolajsen et al. 2020    0.7997164     0.6446248     0.1931692
##                          FertiliserTypeUrea
## Bacon and Freney 1989              3.89495
## Ferrar et al. 2014                 3.89495
## Recio et al. 2020                  3.89495
## Ni et al. 2015                     3.89495
## Abalos et al. 2012                 3.89495
## Schwenke 2014                      3.89495
## Pedersen et al. 2018               3.89495
## Tuner et al. 2010                  3.89495
## Salazar et al. 2012                3.89495
## Sanz-Cobena et al. 2008            3.89495
## Engel et al. 2017                  3.89495
## Lam et al. 2019                    3.89495
## Engel 2011                         3.89495
## Huckaby 2012                       3.89495
## Lam et al. 2018                    3.89495
## Suter et al. 2013                  3.89495
## Tuner et al. 2012                  3.89495
## Cai et al. 2002                    3.89495
## Vaio et al. 2008                   3.89495
## Black et al. 1989                  3.89495
## Horneck 2013                       3.89495
## Pacholski 2006                     3.89495
## Yang et al. 2013                   3.89495
## Holcomb 2011                       3.89495
## Black et al. 1985                  3.89495
## Ryden and Lockyer 1985             3.89495
## Del Moro et al. 2017               3.89495
## Krol et al. 2020                   3.89495
## Hayashi et al. 2011                3.89495
## Nikolajsen et al. 2020             3.89495
##
## attr(,"class")
## [1] "coef.mer"
```

DK smaller subset

```
dds <- droplevels(df.sub[!is.na(AirTemperature), ])
```

```
dfsumm(dds[, .(Ref, NH3loss, AirTemperature, FertiliserType)])
```

```
##
##  69 rows and 4 columns
##  69 unique rows
##                                   Ref NH3loss AirTemperature FertiliserType
## Class                          factor numeric        numeric         factor
## Minimum         Kemmann et al. 2025       0              4            UAN
## Maximum      Nikolajsen et al. 2020     48.5           20.6           Urea
## Mean                  Ni et al. 2015    9.89           11.4           Urea
## Unique (excld. NA)                 6      61             33              2
## Missing values                     0       0              0              0
## Sorted                         FALSE   FALSE          FALSE          FALSE
##
```

```
ggplot(dds, aes(AirTemperature, NH3loss, color = FertiliserType, shape = Application)) + geom_point()
```
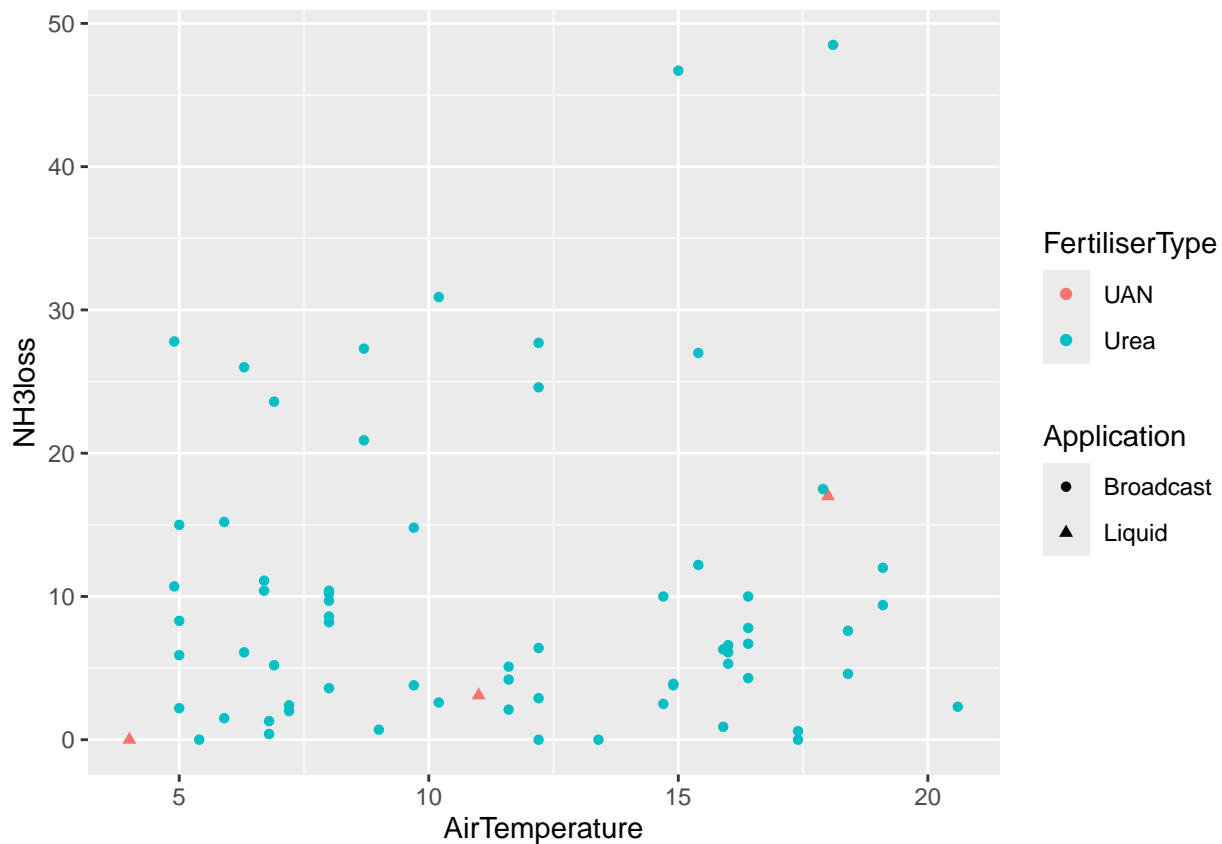


```
m1 <- lm(NH3loss ~ AirTemperature * FertiliserType, data = dds)
summary(m1)
```

```
##
## Call:
## lm(formula = NH3loss ~ AirTemperature * FertiliserType, data = dds)
##
## Residuals:
```

```
##     Min      1Q  Median      3Q     Max
## -10.253  -7.164  -3.600   1.800  38.221
##
## Coefficients:
##                                 Estimate Std. Error t value Pr(>|t|)
## (Intercept)                       -6.657     13.193  -0.505    0.616
## AirTemperature                     1.214      1.064   1.141    0.258
## FertiliserTypeUrea                16.277     13.637   1.194    0.237
## AirTemperature:FertiliserTypeUrea -1.178      1.100  -1.070    0.288
##
## Residual standard error: 10.54 on 65 degrees of freedom
## Multiple R-squared:  0.02412,    Adjusted R-squared:  -0.02092
## F-statistic: 0.5355 on 3 and 65 DF,  p-value: 0.6596
```

```r
m2 <- lmer(NH3loss ~ AirTemperature * FertiliserType + (1|Ref), data = dds)
summary(m2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ AirTemperature * FertiliserType + (1 | Ref)
##    Data: dds
##
## REML criterion at convergence: 489.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.3007 -0.6951 -0.1393  0.2488  2.6026
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 316.44   17.789
##  Residual              70.02    8.368
## Number of obs: 69, groups:  Ref, 6
##
## Fixed effects:
##                                 Estimate Std. Error t value
## (Intercept)                      -6.6571    20.6454  -0.322
## AirTemperature                    1.2143     0.8453   1.437
## FertiliserTypeUrea               29.5748    22.4704   1.316
## AirTemperature:FertiliserTypeUrea -1.4169    0.8815  -1.607
##
## Correlation of Fixed Effects:
##            (Intr) ArTmpr FrtlTU
## AirTempertr -0.450
## FrtlsrTypUr -0.919  0.414
## ArTmprt:FTU  0.432 -0.959 -0.437
```

```r
m3 <- lmer(NH3loss ~ AirTemperature + FertiliserType + (1|Ref), data = dds)
m3n <- update(m3, ~ . - AirTemperature)
summary(m3)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ AirTemperature + FertiliserType + (1 | Ref)
##    Data: dds
```

```
##
## REML criterion at convergence: 493.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.2350 -0.7130 -0.2023  0.2187  2.5892
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 306.26   17.500
##  Residual             71.93     8.481
## Number of obs: 69, groups:  Ref, 6
##
## Fixed effects:
##                    Estimate Std. Error t value
## (Intercept)         7.65966   18.36820   0.417
## AirTemperature     -0.08724    0.24309  -0.359
## FertiliserTypeUrea 13.72772   19.92423   0.689
##
## Correlation of Fixed Effects:
##            (Intr) ArTmpr
## AirTempertr -0.146
## FrtlsrTypUr -0.899 -0.022
```

```r
summary(m3n)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ FertiliserType + (1 | Ref)
##    Data: dds
##
## REML criterion at convergence: 492.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.2132 -0.7475 -0.2492  0.2729  2.6221
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 299.74   17.313
##  Residual             71.03     8.428
## Number of obs: 69, groups:  Ref, 6
##
## Fixed effects:
##                    Estimate Std. Error t value
## (Intercept)           6.70      17.98   0.373
## FertiliserTypeUrea   13.56      19.71   0.688
##
## Correlation of Fixed Effects:
##            (Intr)
## FrtlsrTypUr -0.912
```

```r
anova(m3, m3n)
```

```
## refitting model(s) with ML (instead of REML)
```

12

```
## Data: dds
## Models:
## m3n: NH3loss ~ FertiliserType + (1 | Ref)
## m3: NH3loss ~ AirTemperature + FertiliserType + (1 | Ref)
##     npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## m3n    4 513.65 522.58 -252.82   505.65
## m3     5 515.55 526.72 -252.78   505.55 0.0931  1     0.7603
```

For clay, larger dataset

```r
dd <- df[!is.na(Clay), ]
```

```r
dfsumm(df[, .(Ref, NH3loss, Clay, FertiliserType)])
```

```
##
##   244 rows and 4 columns
##   242 unique rows
##                               Ref NH3loss    Clay FertiliserType
## Class                      factor numeric numeric         factor
## Minimum       Bacon and Freney 1989       0       4             AS
## Maximum       Nikolajsen et al. 2020      60      68           Urea
## Mean          Sanz-Cobena et al. 2008     13    26.9           Urea
## Unique (excld. NA)             38     165      59              3
## Missing values                  0       0      28              0
## Sorted                      FALSE   FALSE   FALSE          FALSE
##
```

```r
dfsumm(dd[, .(Ref, NH3loss, Clay, FertiliserType)])
```

```
##
##   216 rows and 4 columns
##   215 unique rows
##                               Ref NH3loss    Clay FertiliserType
## Class                      factor numeric numeric         factor
## Minimum       Bacon and Freney 1989       0       4             AS
## Maximum       Nikolajsen et al. 2020    48.5      68           Urea
## Mean          Sanz-Cobena et al. 2008   12.7    26.9           Urea
## Unique (excld. NA)             33     152      59              3
## Missing values                  0       0       0              0
## Sorted                      FALSE   FALSE   FALSE          FALSE
##
```

```r
ggplot(dd, aes(Clay, NH3loss, color = FertiliserType, shape = Application)) + geom_point()
```
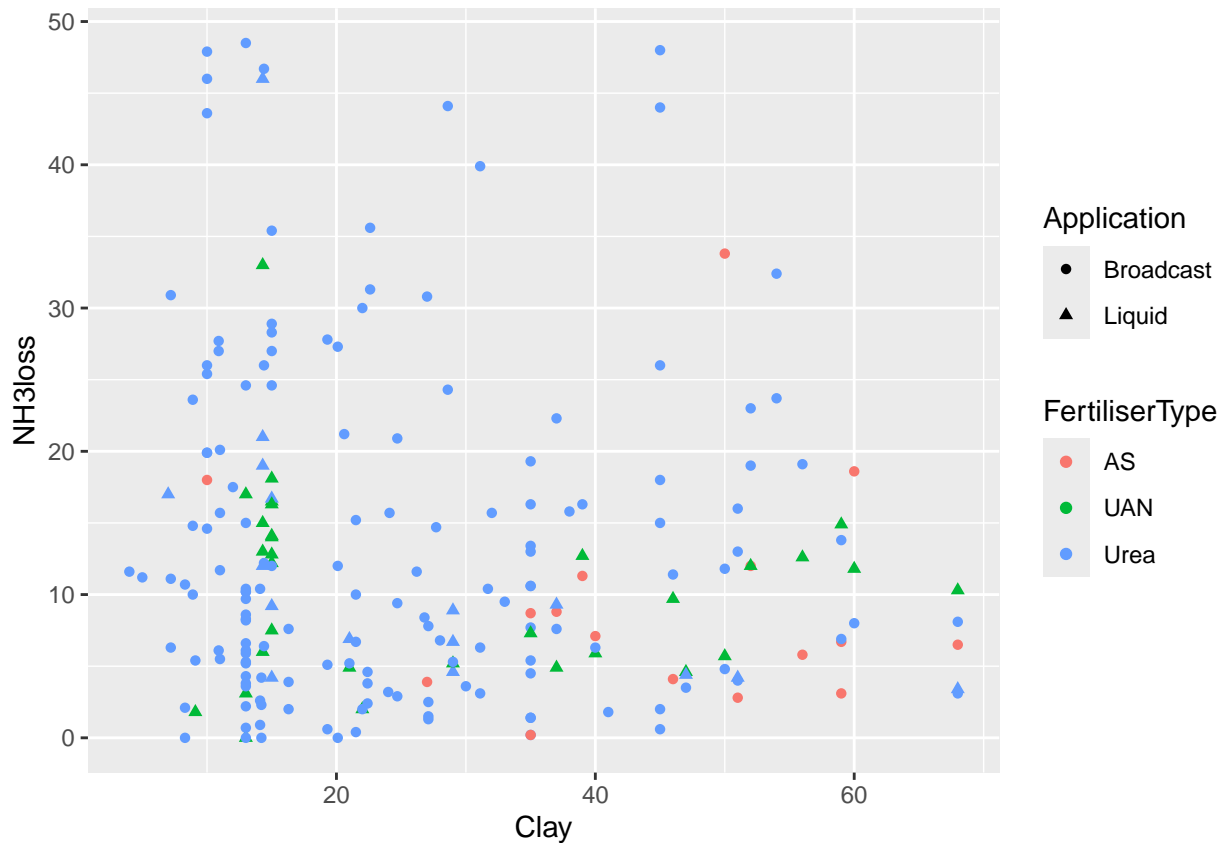
```r
m1 <- lm(NH3loss ~ Clay * FertiliserType, data = dd)
summary(m1)
```

```
##
## Call:
## lm(formula = NH3loss ~ Clay * FertiliserType, data = dd)
##
## Residuals:
##     Min     1Q  Median     3Q     Max
## -14.537  -7.904  -3.196   4.972  35.849
##
## Coefficients:
##                        Estimate Std. Error t value Pr(>|t|)
## (Intercept)           10.817495   9.170351   1.180    0.239
## Clay                  -0.029945   0.193296  -0.155    0.877
## FertiliserTypeUAN      0.693949   9.911076   0.070    0.944
## FertiliserTypeUrea     4.259251   9.317176   0.457    0.648
## Clay:FertiliserTypeUAN -0.006109   0.223296  -0.027    0.978
## Clay:FertiliserTypeUrea -0.035077   0.201464  -0.174    0.862
##
## Residual standard error: 11.02 on 210 degrees of freedom
## Multiple R-squared:  0.02269,    Adjusted R-squared:  -0.0005751
## F-statistic: 0.9753 on 5 and 210 DF,  p-value: 0.4338
```

```r
m2 <- lmer(NH3loss ~ Clay * FertiliserType + (1|Ref), data = dd)
summary(m2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ Clay * FertiliserType + (1 | Ref)
##    Data: dd
##
## REML criterion at convergence: 1607.1
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.1091 -0.5740 -0.1970  0.3273  2.9575
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 48.11    6.936
##  Residual             87.52    9.355
## Number of obs: 216, groups:  Ref, 33
##
## Fixed effects:
##                         Estimate Std. Error t value
## (Intercept)              7.31176    8.45623   0.865
## Clay                     0.11094    0.17656   0.628
## FertiliserTypeUAN       -0.60893    9.37416  -0.065
## FertiliserTypeUrea      11.88964    8.69725   1.367
## Clay:FertiliserTypeUAN   0.02288    0.20615   0.111
## Clay:FertiliserTypeUrea -0.22362    0.18432  -1.213
##
## Correlation of Fixed Effects:
##             (Intr) Clay   FrTUAN FrtlTU C:FTUA
## Clay        -0.924
## FrtlsrTyUAN -0.897  0.835
## FrtlsrTypUr -0.962  0.890  0.888
## Cly:FrtTUAN  0.815 -0.825 -0.936 -0.807
## Cly:FrtlsTU  0.900 -0.919 -0.830 -0.946  0.819
```

```r
m3 <- lmer(NH3loss ~ Clay + FertiliserType + (1|Ref), data = dd)
m3n <- update(m3, ~ . - Clay)
summary(m3)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ Clay + FertiliserType + (1 | Ref)
##    Data: dd
##
## REML criterion at convergence: 1608.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.0844 -0.6549 -0.2119  0.3772  2.9139
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
```

```
##  Ref      (Intercept) 42.57     6.524
##  Residual              89.93     9.483
## Number of obs: 216, groups:  Ref, 33
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)       14.36755    3.50809   4.096
## Clay              -0.04593    0.06591  -0.697
## FertiliserTypeUAN -1.98746    3.15756  -0.629
## FertiliserTypeUrea 2.84284    2.81123   1.011
##
## Correlation of Fixed Effects:
##            (Intr) Clay   FrTUAN
## Clay       -0.517
## FrtlsrTyUAN -0.651  0.132
## FrtlsrTypUr -0.789  0.113  0.730
```

```r
summary(m3n)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ FertiliserType + (1 | Ref)
##    Data: dd
##
## REML criterion at convergence: 1605.1
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.1204 -0.6477 -0.1985  0.3658  2.8928
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 44.1     6.641
##  Residual             89.4     9.455
## Number of obs: 216, groups:  Ref, 33
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)        13.116      3.006   4.363
## FertiliserTypeUAN  -1.705      3.123  -0.546
## FertiliserTypeUrea  3.063      2.787   1.099
##
## Correlation of Fixed Effects:
##            (Intr) FrTUAN
## FrtlsrTyUAN -0.685
## FrtlsrTypUr -0.856  0.725
```

```r
anova(m3, m3n)
```

```
## refitting model(s) with ML (instead of REML)
```

```
## Data: dd
## Models:
```

```
## m3n: NH3loss ~ FertiliserType + (1 | Ref)
## m3: NH3loss ~ Clay + FertiliserType + (1 | Ref)
##     npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## m3n    5 1625.0 1641.9 -807.50   1615.0
## m3     6 1626.5 1646.7 -807.24   1614.5 0.5171  1     0.4721
```

```
confint(m3)
```

```
## Computing profile confidence intervals ...
```

```
##                        2.5 %      97.5 %
## .sig01             3.7813566   9.64871114
## .sigma             8.5316191  10.48022071
## (Intercept)        7.5473754  21.21193211
## Clay              -0.1757978   0.08303743
## FertiliserTypeUAN -8.1554641   4.18618559
## FertiliserTypeUrea -2.6585991  8.32862789
```

```
coef(m3)
```

```
## $Ref
##                          (Intercept)       Clay FertiliserTypeUAN
## Ferrar et al. 2014          10.021891 -0.0459337         -1.987457
## Kemmann et al. 2025          6.955928 -0.0459337         -1.987457
## Recio et al. 2020           10.767844 -0.0459337         -1.987457
## Ni et al. 2015               8.140074 -0.0459337         -1.987457
## Abalos et al. 2012          11.436336 -0.0459337         -1.987457
## Schwenke 2014               10.516408 -0.0459337         -1.987457
## Pedersen et al. 2018         7.976780 -0.0459337         -1.987457
## McInnes et al. 1986         10.818511 -0.0459337         -1.987457
## Ferguson et al. 1988        11.717910 -0.0459337         -1.987457
## Tuner et al. 2010           12.377509 -0.0459337         -1.987457
## Salazar et al. 2012         11.725844 -0.0459337         -1.987457
## Sanz-Cobena et al. 2008     12.307259 -0.0459337         -1.987457
## Engel et al. 2017            9.767048 -0.0459337         -1.987457
## Lam et al. 2019             11.642543 -0.0459337         -1.987457
## Engel 2011                  18.203399 -0.0459337         -1.987457
## Huckaby 2012                13.856019 -0.0459337         -1.987457
## Perin et al. 2020           14.572701 -0.0459337         -1.987457
## Lam et al. 2018             14.475202 -0.0459337         -1.987457
## Suter et al. 2013           12.456802 -0.0459337         -1.987457
## Tuner et al. 2012           12.826157 -0.0459337         -1.987457
## Cai et al. 2002             19.590585 -0.0459337         -1.987457
## Pacholski 2008              15.379170 -0.0459337         -1.987457
## Vaio et al. 2008            19.498964 -0.0459337         -1.987457
## Black et al. 1989           15.953220 -0.0459337         -1.987457
## Pacholski 2006              23.877853 -0.0459337         -1.987457
## Yang et al. 2013            17.338829 -0.0459337         -1.987457
## Black et al. 1985           18.151500 -0.0459337         -1.987457
## Fox et al. 1996             19.468821 -0.0459337         -1.987457
## Ryden and Lockyer 1985      24.062563 -0.0459337         -1.987457
## Del Moro et al. 2017        22.474159 -0.0459337         -1.987457
```

```
## Krol et al. 2020          24.053751 -0.0459337          -1.987457
## Hayashi et al. 2011        10.332622 -0.0459337          -1.987457
## Nikolajsen et al. 2020     11.385054 -0.0459337          -1.987457
##                          FertiliserTypeUrea
## Ferrar et al. 2014                  2.84284
## Kemmann et al. 2025                 2.84284
## Recio et al. 2020                   2.84284
## Ni et al. 2015                      2.84284
## Abalos et al. 2012                  2.84284
## Schwenke 2014                       2.84284
## Pedersen et al. 2018                2.84284
## McInnes et al. 1986                 2.84284
## Ferguson et al. 1988                2.84284
## Tuner et al. 2010                   2.84284
## Salazar et al. 2012                 2.84284
## Sanz-Cobena et al. 2008             2.84284
## Engel et al. 2017                   2.84284
## Lam et al. 2019                     2.84284
## Engel 2011                          2.84284
## Huckaby 2012                        2.84284
## Perin et al. 2020                   2.84284
## Lam et al. 2018                     2.84284
## Suter et al. 2013                   2.84284
## Tuner et al. 2012                   2.84284
## Cai et al. 2002                     2.84284
## Pacholski 2008                      2.84284
## Vaio et al. 2008                    2.84284
## Black et al. 1989                   2.84284
## Pacholski 2006                      2.84284
## Yang et al. 2013                    2.84284
## Black et al. 1985                   2.84284
## Fox et al. 1996                     2.84284
## Ryden and Lockyer 1985              2.84284
## Del Moro et al. 2017                2.84284
## Krol et al. 2020                    2.84284
## Hayashi et al. 2011                 2.84284
## Nikolajsen et al. 2020              2.84284
##
## attr(,"class")
## [1] "coef.mer"
```

DK smaller subset, clay

```
dds <- droplevels(df.sub[!is.na(Clay), ])
```

```
dfsumm(dds[, .(Ref, NH3loss, Clay, FertiliserType)])
```

```
##
##  69 rows and 4 columns
##  69 unique rows
##                                  Ref NH3loss    Clay FertiliserType
```

```
## Class                                factor numeric numeric       factor
## Minimum              Kemmann et al. 2025       0     7.2          UAN
## Maximum         Nikolajsen et al. 2020    48.5    27.1         Urea
## Mean                     Ni et al. 2015    9.89    15.4         Urea
## Unique (excld. NA)                       6      61      16            2
## Missing values                           0       0       0            0
## Sorted                            FALSE   FALSE   FALSE        FALSE
##
```

```r
ggplot(dds, aes(Clay, NH3loss, color = FertiliserType, shape = Application)) + geom_point()
```
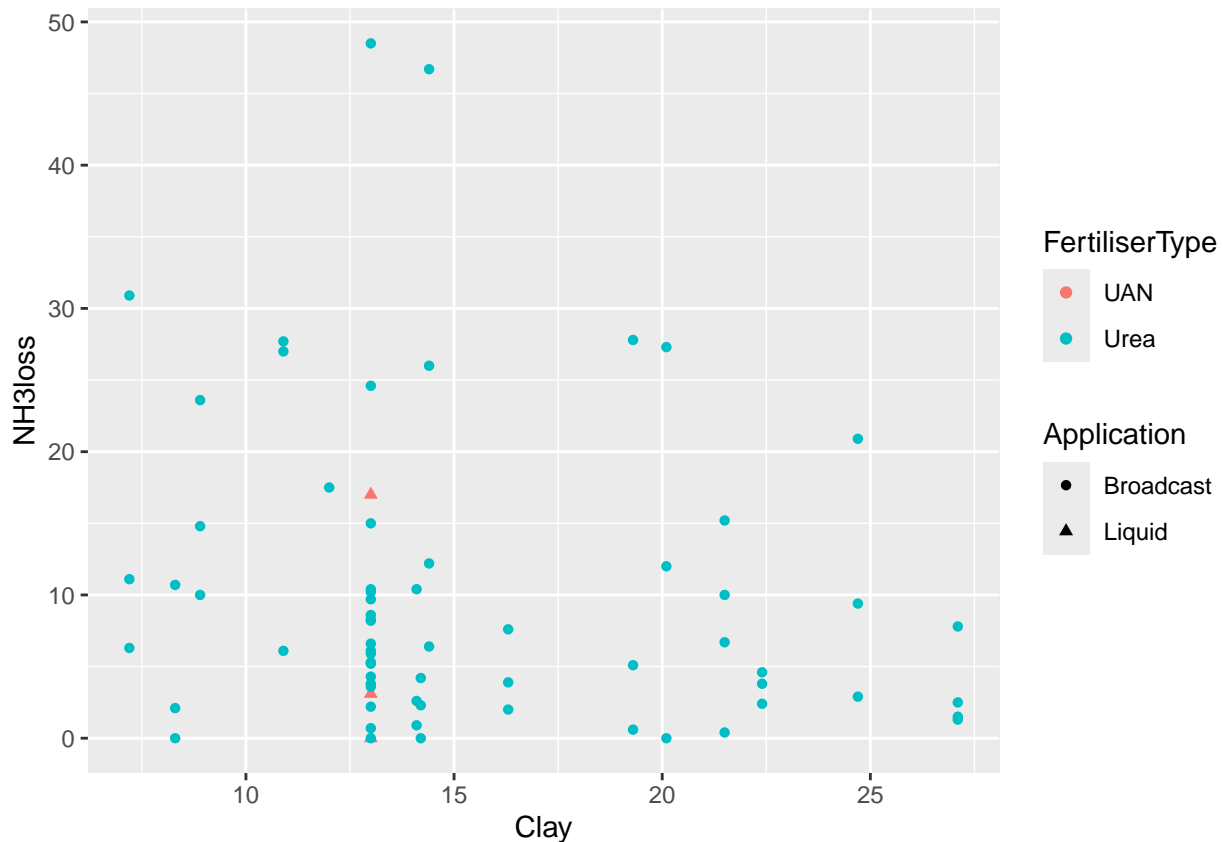


```r
m1 <- lm(NH3loss ~ Clay * FertiliserType, data = dds)
summary(m1)
```

```
##
## Call:
## lm(formula = NH3loss ~ Clay * FertiliserType, data = dds)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -12.721  -6.669  -3.213   2.302  37.531
##
## Coefficients: (1 not defined because of singularities)
##                      Estimate Std. Error t value Pr(>|t|)
## (Intercept)           11.5459     6.7402   1.713   0.0914 .
## Clay                  -0.3728     0.2381  -1.566   0.1222
```

19

```
## FertiliserTypeUrea          4.2694      6.1510    0.694    0.4901
## Clay:FertiliserTypeUrea          NA          NA      NA        NA
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 10.37 on 66 degrees of freedom
## Multiple R-squared:  0.03997,    Adjusted R-squared:  0.01088
## F-statistic: 1.374 on 2 and 66 DF,  p-value: 0.2602
```

```r
m2 <- lmer(NH3loss ~ Clay * FertiliserType + (1|Ref), data = dds)
```

```
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```r
summary(m2)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ Clay * FertiliserType + (1 | Ref)
##    Data: dds
##
## REML criterion at convergence: 491.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.3474 -0.6580 -0.2094  0.3415  2.3941
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 299.67   17.311
##  Residual              69.47    8.335
## Number of obs: 69, groups:  Ref, 6
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)        10.6990    18.1496   0.589
## Clay               -0.3076     0.1973  -1.559
## FertiliserTypeUrea 13.8747    19.6956   0.704
##
## Correlation of Fixed Effects:
##            (Intr) Clay
## Clay       -0.141
## FrtlsrTypUr -0.902 -0.009
## fit warnings:
## fixed-effect model matrix is rank deficient so dropping 1 column / coefficient
```

```r
m3 <- lmer(NH3loss ~ Clay + FertiliserType + (1|Ref), data = dds)
m3n <- update(m3, ~ . - Clay)
summary(m3)
```

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ Clay + FertiliserType + (1 | Ref)
##    Data: dds
##
```

```
## REML criterion at convergence: 491.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.3474 -0.6580 -0.2094  0.3415  2.3941
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 299.67   17.311
##  Residual             69.47     8.335
## Number of obs: 69, groups:  Ref, 6
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)        10.6990    18.1496   0.589
## Clay               -0.3076     0.1973  -1.559
## FertiliserTypeUrea 13.8747    19.6956   0.704
##
## Correlation of Fixed Effects:
##            (Intr) Clay
## Clay       -0.141
## FrtlsrTypUr -0.902 -0.009
```

summary(m3n)

```
## Linear mixed model fit by REML ['lmerMod']
## Formula: NH3loss ~ FertiliserType + (1 | Ref)
##    Data: dds
##
## REML criterion at convergence: 492.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.2132 -0.7475 -0.2492  0.2729  2.6221
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  Ref      (Intercept) 299.74   17.313
##  Residual             71.03     8.428
## Number of obs: 69, groups:  Ref, 6
##
## Fixed effects:
##                   Estimate Std. Error t value
## (Intercept)           6.70      17.98   0.373
## FertiliserTypeUrea   13.56      19.71   0.688
##
## Correlation of Fixed Effects:
##            (Intr)
## FrtlsrTypUr -0.912
```

anova(m3, m3n)

```
## refitting model(s) with ML (instead of REML)
```

```
## Data: dds
## Models:
## m3n: NH3loss ~ FertiliserType + (1 | Ref)
## m3: NH3loss ~ Clay + FertiliserType + (1 | Ref)
##     npar    AIC    BIC  logLik deviance  Chisq Df Pr(>Chisq)
## m3n    4 513.65 522.58 -252.82   505.65
## m3     5 513.22 524.39 -251.61   503.22 2.4233  1     0.1195
```