Lecture 7
Multiple Linear Regression
Reading: Chapter 12

STAT 8020 Statistical Methods II
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Notes

Agenda

Multiple Linear Regression
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Species Diversity on the Galapagos Islands
Multiple Linear Regression in Matrix Form
Estimation
Inference
Coefficient of Determination R^2

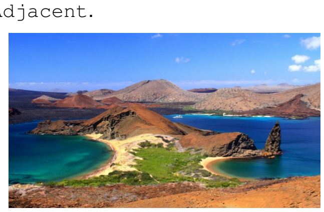
Notes

Multiple Linear Regression

Goal: To model the relationship between two or more explanatory variables (X's) and a response variable (Y) by fitting a **linear equation** to observed data:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{p-1} X_{p-1} + \varepsilon_i, \quad \varepsilon_i \overset{i.i.d.}{\sim} \mathrm{N}(0, \sigma^2)$$

Example: Species diversity on the Galapagos Islands.
We are interested in studying the relationship between the number of plant species (`Species`) and the following geographic variables: `Area`, `Elevation`, `Nearest`, `Scruz`, `Adjacent`.



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Data: Species Diversity on the Galapagos Islands

	Species	Endemics	Area	Elevation	Nearest	Scruz	Adjacent
Baltra	58	23	25.09	346	0.6	0.6	1.84
Bartolome	31	21	1.24	109	0.6	26.3	572.33
Caldwell	3	3	0.21	114	2.8	58.7	0.78
Champion	25	9	0.10	46	1.9	47.4	0.18
Coamano	2	1	0.05	77	1.9	1.9	903.82
Daphne.Major	18	11	0.34	119	8.0	8.0	1.84
Daphne.Minor	24	0	0.08	93	6.0	12.0	0.34
Darwin	10	7	2.33	168	34.1	290.2	2.85
Eden	8	4	0.03	71	0.4	0.4	17.95
Enderby	2	2	0.18	112	2.6	50.2	0.10
Espanola	97	26	58.27	198	1.1	88.3	0.57
Fernandina	93	35	634.49	1494	4.3	95.3	4669.32
Gardner1	58	17	0.57	49	1.1	93.1	58.27
Gardner2	5	4	0.78	227	4.6	62.2	0.21
Genovesa	40	19	17.35	76	47.4	92.2	129.49
Isabela	347	89	4669.32	1707	0.7	28.1	634.49
Marchena	51	23	129.49	343	29.1	85.9	59.56
Onslow	2	2	0.01	25	3.3	45.9	0.10
Pinta	104	37	59.56	777	29.1	119.6	129.49
Pinzon	108	33	17.95	458	10.7	10.7	0.03
Las.Plazas	12	9	0.23	94	0.5	0.6	25.09
Rabida	70	30	4.89	367	4.4	24.4	572.33
SanCristobal	280	65	551.62	716	45.2	66.6	0.57
SanSalvador	237	81	572.33	906	0.2	19.8	4.89
SantaCruz	444	95	903.82	864	0.6	0.0	0.52
SantaFe	62	28	24.08	259	16.5	16.5	0.52
SantaMaria	285	73	170.92	640	2.6	49.2	0.10
Seymour	44	16	1.84	147	0.6	9.6	25.09
Tortuga	16	8	1.24	186	6.8	50.9	17.95
Wolf	21	12	2.85	253	34.1	254.7	2.33

Notes

Let's Take a Look at the Correlation Matrix

```
> round(cor(gala[, -2]), 3)
          Species   Area Elevation Nearest  Scruz Adjacent
Species     1.000  0.618     0.738  -0.014 -0.171    0.026
Area        0.618  1.000     0.754  -0.111 -0.101    0.180
Elevation   0.738  0.754     1.000  -0.011 -0.015    0.536
Nearest    -0.014 -0.111    -0.011   1.000  0.615   -0.116
Scruz      -0.171 -0.101    -0.015   0.615  1.000    0.052
Adjacent    0.026  0.180     0.536  -0.116  0.052    1.000
```


Notes

Model 1: `Species` ∼ `Elevation`

```
Call:
lm(formula = Species ~ Elevation, data = gala)

Residuals:
     Min       1Q   Median       3Q      Max
-218.319  -30.721  -14.690    4.634  259.180

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 11.33511   19.20529   0.590     0.56
Elevation    0.20079    0.03465   5.795 3.18e-06 ***
---
Signif. codes:
0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 78.66 on 28 degrees of freedom
Multiple R-squared:  0.5454,	Adjusted R-squared:  0.5291
F-statistic: 33.59 on 1 and 28 DF,  p-value: 3.177e-06
```


Notes

Model 2: `Species ~ Elevation + Area`

```
Call:
lm(formula = Species ~ Elevation + Area, data = gala)

Residuals:
     Min       1Q   Median       3Q      Max
-192.619  -33.534  -19.199    7.541  261.514

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 17.10519   20.94211   0.817  0.42120
Elevation    0.17174    0.05317   3.230  0.00325 **
Area         0.01880    0.02594   0.725  0.47478
---
Signif. codes:
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 79.34 on 27 degrees of freedom
Multiple R-squared:  0.554,     Adjusted R-squared:  0.521
F-statistic: 16.77 on 2 and 27 DF,  p-value: 1.843e-05
```


Notes

Model 3: `Species ~ Elevation + Area + Adjacent`

```
Call:
lm(formula = Species ~ Elevation + Area + Adjacent, data = gala)

Residuals:
     Min       1Q   Median       3Q      Max
-124.064  -34.283   -8.733   27.972  195.973

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -5.71893   16.90706  -0.338  0.73789
Elevation    0.31498    0.05211   6.044  2.2e-06 ***
Area        -0.02031    0.02181  -0.931  0.36034
Adjacent    -0.07528    0.01698  -4.434  0.00015 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 61.01 on 26 degrees of freedom
Multiple R-squared:  0.746,     Adjusted R-squared:  0.7167
F-statistic: 25.46 on 3 and 26 DF,  p-value: 6.683e-08
```

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“Full Model”

```
lm(formula = Species ~ Area + Elevation + Nearest + Scruz + Adjacent,
    data = gala)

Residuals:
     Min       1Q   Median       3Q      Max
-111.679  -34.898   -7.862   33.460  182.584

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  7.068221  19.154198   0.369 0.715351
Area        -0.023938   0.022422  -1.068 0.296318
Elevation    0.319465   0.053663   5.953 3.82e-06
Nearest      0.009144   1.054136   0.009 0.993151
Scruz       -0.240524   0.215402  -1.117 0.275208
Adjacent    -0.074805   0.017700  -4.226 0.000297

(Intercept)
Area
Elevation   ***
Nearest
Scruz
Adjacent    ***
---
Signif. codes:
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 60.98 on 24 degrees of freedom
Multiple R-squared:  0.7658,    Adjusted R-squared:  0.7171
F-statistic:  15.7 on 5 and 24 DF,  p-value: 6.838e-07
```

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Multiple Linear Regression in Matrix Notation

Multiple Linear Regression (MLR):

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix} = \begin{pmatrix} 1 & X_{1,1} & X_{2,1} & \cdots & X_{p-1,1} \\ 1 & X_{1,2} & X_{2,2} & \cdots & X_{p-1,2} \\ \vdots & \cdots & \ddots & \vdots & \vdots \\ 1 & X_{1,n} & X_{2,n} & \cdots & X_{p-1,n} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_{p-1} \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}$$

We can express MLR as

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

Error Sum of Squares (SSE) $= \sum_{i=1}^{n}(Y_i - \beta_0 - \sum_{j=1}^{p-1}\beta_j X_j)^2$ can be expressed in matrix notation as:

$$(\boldsymbol{Y} - \boldsymbol{X}\boldsymbol{\beta})^T(\boldsymbol{Y} - \boldsymbol{X}\boldsymbol{\beta})$$

Again, we are going to find $\hat{\beta}$ to minimize SSE as our estimate for β

Notes

Estimation of Regression Coefficients

- The resulting least squares estimate is

$$\hat{\boldsymbol{\beta}} = \left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1}\boldsymbol{X}^T\boldsymbol{Y}$$

- Fitted values:

$$\hat{\boldsymbol{Y}} = \boldsymbol{X}\hat{\boldsymbol{\beta}} = \boldsymbol{X}\left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1}\boldsymbol{X}^T\boldsymbol{Y} = \boldsymbol{H}\boldsymbol{Y}$$

- Residuals:

$$\boldsymbol{e} = \boldsymbol{Y} - \hat{\boldsymbol{Y}} = (\boldsymbol{I} - \boldsymbol{H})\boldsymbol{Y}$$

Notes

Estimation of σ^2

- Similar approach as we did in SLR

$$\begin{aligned} \hat{\sigma}^2 &= \frac{\boldsymbol{e}^T\boldsymbol{e}}{n-p} \\ &= \frac{(\boldsymbol{Y} - \boldsymbol{X}\hat{\boldsymbol{\beta}})^T(\boldsymbol{Y} - \boldsymbol{X}\hat{\boldsymbol{\beta}})}{n-p} \\ &= \frac{\text{SSE}}{n-p} \\ &= \text{MSE} \end{aligned}$$

Notes

ANOVA Table

Source	df	SS	MS	F Value
Model	$p-1$	SSR	MSR = SSR/$(p-1)$	MSR/MSE
Error	$n-p$	SSE	MSE = SSE/(n-p)	
Total	$n-1$	SST		

- F Test: Tests if the predictors $\{X_1, \cdots, X_{p-1}\}$ collectively help explain the variation in Y
  - $H_0 : \beta_1 = \beta_2 = \cdots = \beta_{p-1} = 0$
  - $H_a :$ at least one $\beta_k \neq 0, \quad 1 \leq k \leq p-1$
  - $F^* = \frac{\text{MSR}}{\text{MSE}} = \frac{\text{SSR}/(p-1)}{\text{SSE}/(n-p)} \overset{H_0}{\sim} F(p-1, n-p)$
  - Reject H_0 if $F^* > F(1-\alpha, p-1, n-p)$

Notes

Testing Individual Predictor

- We can show that $\hat{\boldsymbol{\beta}} \sim \mathrm{N}_p\left(\boldsymbol{\beta}, \sigma^2\left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1}\right) \Rightarrow \hat{\beta}_k \sim \mathrm{N}(\beta_k, \sigma^2_{\hat{\beta}_k})$
- Perform **t test**:
  - $H_0 : \beta_k = 0$ vs. $H_a : \beta_k \neq 0$
  - $\frac{b\hat{e}ta_k - \beta_k}{\hat{\sigma}_{\hat{\beta}_k}} \sim t_{n-p} \Rightarrow t^* = \frac{\hat{\beta}_k}{\hat{\sigma}_{\hat{\beta}_k}} \overset{H_0}{\sim} t_{n-p}$
  - Reject H_0 if $|t^*| > t_{1-\alpha/2, n-p}$
- Confidence interval for β_k: $\hat{\beta}_k \pm t_{1-\alpha/2, n-p}\hat{\sigma}_{\hat{\beta}_k}$

Notes

Coefficient of Multiple Determination

- Coefficient of Determination R^2 describes proportional reduction in total variation associated with the full set of predictor variables

$$R^2 = \frac{\text{SSR}}{\text{SST}} = 1 - \frac{\text{SSE}}{\text{SSR}}, \quad 0 \leq R^2 \leq 1$$

- R^2 usually increases with the increasing p, the number of the predictors
  - Adjusted R^2, denoted by $R^2_{\text{adj}} = \frac{\text{SSR}/(n-p)}{\text{SST}/(n-1)}$ attempts to account for p

Notes