

# Contents

PREFACE .....	V
ACKNOWLEDGEMENTS.....	V
DATASETS AND R CODE USED IN THIS BOOK .....	VI
CHAPTER 1 OF ZUUR ET AL. (2012A) AND ZUUR (2012B) .....	VI
COVER ART .....	VI
CONTRIBUTORS .....	XII

## 1 INTRODUCTION TO GENERALIZED LINEAR MODELS .....1

1.1 LINEAR REGRESSION APPLIED ON FISHERIES DATA.....	1
1.2 POISSON GLM.....	7
<i>1.2.1 Poisson distribution for count data</i> .....	7
<i>1.2.2 Predictor function</i> .....	8
<i>1.2.3 Linking the mean and the predictor function</i> .....	9
<i>1.2.4 Maximum likelihood to estimate the parameters</i> .....	9
<i>1.2.5 Application of Poisson GLM on the fisheries data</i> .....	11
<i>1.2.6 Overdispersion</i> .....	19
<i>1.2.7 Adding covariates</i> .....	23
<i>1.2.8 Using the offset</i> .....	24
1.3 NEGATIVE BINOMIAL GLM .....	26
<i>1.3.1 Negative binomial distribution for count data</i> .....	26
<i>1.3.2 Example of Negative binomial regression</i> .....	28
<i>1.3.3 Heterogeneous Negative binomial regression</i> .....	34
<i>1.3.4 A note on modelling under-dispersion</i> .....	36
1.4 BINOMIAL GLM FOR BINARY DATA .....	36
<i>1.4.1 Parasites in honeybee larvae</i> .....	36
<i>1.4.2 Visualizing the data</i> .....	36
<i>1.4.3 Defining the three steps of a binomial GLM</i> .....	38
<i>1.4.4 Results for the bee data</i> .....	40
<i>1.4.5 Likelihood function for a binomial GLM</i> .....	42
<i>1.4.6 Other link functions</i> .....	42
1.5 BINOMIAL GLM FOR PROPORTIONAL DATA .....	43
<i>1.5.1 Binomial distribution</i> .....	43
<i>1.5.2 Predictor function</i> .....	45
<i>1.5.3 Link function</i> .....	45
<i>1.5.4 Fitting the model in R</i> .....	45
1.6 OTHER DISTRIBUTIONS .....	47

## 2 GENERALIZED LINEAR MODELLING APPLIED TO RED SQUIRREL DATA .....49

2.1 RED SQUIRRELS .....	49
2.2 IMPORTING THE DATA .....	50
2.3 DATA EXPLORATION .....	51
<i>2.3.1 Outliers</i> .....	51
<i>2.3.2 Collinearity</i> .....	52

<i>2.3.3 Relationships</i> .....	54
<b>2.4 FITTING THE POISSON GLM IN R</b> .....	55
<i>2.4.1 Specifying the model</i> .....	55
<i>2.4.2 Execute the Poisson GLM in R</i> .....	55
<i>2.4.3 Model validation</i> .....	57
<b>2.5 FITTING THE NEGATIVE BINOMIAL GLM IN R</b> .....	60
<i>2.5.1 Using the glm.nb function</i> .....	60
<i>2.5.2 Heterogeneous negative binomial GLM</i> .....	63
<b>2.6 BAYESIAN APPROACH – RUNNING THE POISSON GLM</b> .....	66
<i>2.6.1 Obtaining and installing JAGS</i> .....	66
<i>2.6.2 Specifying the data for JAGS</i> .....	67
<i>2.6.3 Specifying the model for JAGS</i> .....	68
<i>2.6.4 Specifying the initial values</i> .....	69
<i>2.6.5 Parameters to store</i> .....	69
<i>2.6.6 Running JAGS via R</i> .....	69
<i>2.6.7 Generalizing the JAGS modelling code</i> .....	72
<b>2.7 ASSESSING MIXING OF CHAINS</b> .....	73
<i>2.7.1 Assess mixing of chains if R2jags is used</i> .....	74
<b>2.8 MODEL VALIDATION</b> .....	76
<i>2.8.1 Checking for overdispersion</i> .....	76
<i>2.8.2 Obtaining Pearson residuals</i> .....	77
<b>2.9 APPLYING A NEGATIVE BINOMIAL GLM IN JAGS</b> .....	79
<b>2.10 MIXING OF CHAINS</b> .....	81
<b>2.11 MODEL VALIDATION</b> .....	83
<b>2.12 MODEL INTERPRETATION</b> .....	84
<b>2.13 DISCUSSION</b> .....	87
<b>2.14 WHAT TO PRESENT IN A PAPER</b> .....	87
<b>3 GLM APPLIED TO PRESENCE-ABSENCE POLYCHAETA DATA</b> .....	89
<i>3.1 MARINE BENTHIC DATA</i> .....	89
<i>3.2 IMPORTING THE DATA AND HOUSEKEEPING</i> .....	90
<i>3.3 DATA EXPLORATION</i> .....	91
<i>3.4 BINARY GLM; A FREQUENTIST APPROACH</i> .....	94
<i>3.4.1 Specifying the distribution and link function</i> .....	94
<i>3.4.2 Specifying the predictor function</i> .....	95
<i>3.4.3 Running the glm function</i> .....	96
<i>3.4.4 Results of the glm function</i> .....	96
<i>3.4.5 Model selection</i> .....	97
<i>3.4.6 Results of the optimal model</i> .....	100
<i>3.4.7 Model validation</i> .....	101
<i>3.4.8 Visualizing the model</i> .....	102
<i>3.5 FITTING A BERNOULLI GLM IN JAGS</i> .....	103
<i>3.5.1 Specifying the data for JAGS</i> .....	103
<i>3.5.2 JAGS modelling code</i> .....	104
<i>3.5.3 Initial values and parameters to save</i> .....	105
<i>3.5.4 Running JAGS from R</i> .....	105

3.5.5 JAGS results presented within R .....	105
3.6 MODEL SELECTION USING AIC, DIC AND BIC IN JAGS .....	106
3.7 MODEL INTERPRETATION .....	110
3.8 DISCUSSION.....	113
3.9 WHAT TO PRESENT IN A PAPER .....	114

## **4 INTRODUCTION TO MIXED EFFECTS MODELS.....115**

4.1 SPIDERS .....	115
4.2 LINEAR REGRESSION APPLIED ON THE SPIDER DATA .....	115
4.3 LINEAR MIXED EFFECTS MODELS .....	118
<i>4.3.1 Model formulation and interpretation.....</i>	118
<i>4.3.2 Fitting a linear mixed effects model using lmer .....</i>	119
<i>4.3.3 Analysis using lmer .....</i>	122
4.4 FITTING A LINEAR MIXED EFFECTS MODEL IN JAGS .....	128
4.5 USING A VARIABLE AS A FIXED OR RANDOM TERM?.....	131
4.6 RANDOM INTERCEPT AND SLOPE MODEL.....	131
4.7 GENERALIZED LINEAR MIXED EFFECTS MODELS .....	132

## **5 GLMM APPLIED ON HONEYBEE POLLINATION DATA .....133**

5.1 HONEYBEES AND DANDELION POLLEN .....	133
5.2 DATA DESCRIPTION AND IMPORTING THE DATA .....	134
5.3 DATA EXPLORATION .....	135
5.4 BUILDING UP A MODEL .....	136
5.5 POISSON GLMM USING GLMER .....	137
5.6 POISSON GLMM USING JAGS .....	140
<i>5.6.1 Data for JAGS .....</i>	140
<i>5.6.2 JAGS modelling code .....</i>	141
<i>5.6.3 Likelihood .....</i>	142
<i>5.6.4 Priors.....</i>	142
<i>5.6.5 Initial values .....</i>	144
<i>5.6.6 Parameters to save .....</i>	144
<i>5.6.7 Executing JAGS and obtaining results .....</i>	145
5.7 NEGATIVE BINOMIAL GLMM USING GLMMADMB .....	146
5.8 NEGATIVE BINOMIAL GLMM USING JAGS .....	147
<i>5.8.1 Data for JAGS .....</i>	147
<i>5.8.2 JAGS modelling code .....</i>	147
<i>5.8.3 Initial values .....</i>	148
<i>5.8.4 Parameters to save .....</i>	149
<i>5.8.5 Executing JAGS and obtaining results .....</i>	149
<i>5.8.6 Mixing of chains .....</i>	150
<i>5.8.7 Model validation .....</i>	150
<i>5.8.8 Model interpretation .....</i>	152
5.9 GLMM WITH AUTO-REGRESSIVE CORRELATION .....	154
<i>5.9.1 Simulate temporal correlated counts .....</i>	155
<i>5.9.2 JAGS to estimate the Poisson GLM with AR correlation...158</i>	158
<i>5.9.3 Multiple Poisson time series .....</i>	161
<i>5.9.4 Poisson GLMM with AR correlation.....161</i>	161
5.10 WHAT TO PRESENT IN A PAPER .....	164

<b>6 GLMM FOR STRICTLY POSITIVE DATA: BIOMASS OF RAINFOREST TREES .....</b>	<b>165</b>
6.1 RAINFOREST TREE SPECIES .....	165
6.2 IMPORTING THE DATA AND HOUSEKEEPING .....	167
6.3 DATA EXPLORATION .....	168
6.3.1 <i>Outliers</i> .....	168
6.3.2 <i>Collinearity</i> .....	169
6.3.3 <i>Relationships</i> .....	170
6.4 MULTIPLE LINEAR REGRESSION: A FREQUENTIST APPROACH .....	173
6.5 GAMMA GLM USING A FREQUENTIST APPROACH .....	175
6.5.1. <i>Formulating the gamma GLM</i> .....	175
6.5.2 <i>Scale and shape</i> .....	176
6.5.3 <i>Visualizing the gamma distribution</i> .....	176
6.5.4 <i>Different link functions</i> .....	178
6.5.5 <i>Running the Gamma GLM using the glm function</i> .....	179
6.5.6 <i>Scale confusion</i> .....	179
6.5.7 <i>Identity link and inverse link function</i> .....	182
6.6 FITTING A GAMMA GLM USING JAGS .....	183
6.6.1 <i>Specifying the data for JAGS</i> .....	183
6.6.2 <i>JAGS modelling code</i> .....	185
6.6.3 <i>Priors</i> .....	185
6.6.4 <i>Likelihood function</i> .....	185
6.6.5 <i>Initial values and parameters to save</i> .....	186
6.6.6 <i>Running JAGS from R</i> .....	186
6.6.7 <i>JAGS results presented within R</i> .....	187
6.6.8 <i>Model interpretation</i> .....	190
6.6.9 <i>Model validation</i> .....	193
6.7 ADDING MORE COVARIATES TO THE GAMMA GLM IN JAGS .....	195
6.8 GAMMA GLMM .....	195
6.8.1 <i>R code for a gamma GLMM in JAGS</i> .....	196
6.8.2 <i>Results from JAGS for the gamma GLMM</i> .....	198
6.9 TRUNCATED GAUSSIAN LINEAR REGRESSION .....	199
6.9.1 <i>Zero trick to fit any statistical distribution in JAGS</i> .....	199
6.9.2 <i>Multiple linear regression in JAGS with the zero trick</i> .....	200
6.9.3 <i>Tobit model in JAGS</i> .....	203
6.9.4 <i>Tobit model with random effects in JAGS</i> .....	205
6.10 DISCUSSION .....	205
6.11 WHAT TO PRESENT IN A PAPER .....	206
<b>7 BINOMIAL, BETA-BINOMIAL, AND BETA GLMM APPLIED TO CHEETAH DATA .....</b>	<b>207</b>
7.1 STEREOTYPIC BEHAVIOURS IN CAPTIVE CHEETAHS .....	207
7.2 IMPORTING THE DATA .....	209
7.3 DATA EXPLORATION .....	209
7.3.1 <i>Outliers</i> .....	209
7.3.2 <i>Collinearity</i> .....	210
7.4 BINOMIAL GLMM USING A FREQUENTIST APPROACH .....	212

7.4.1 Standardizing covariates .....	212
7.4.2 Binomial GLMM with random intercept <i>zoo</i> .....	213
7.4.3 Executing the GLMM using the <i>glmer</i> function .....	213
7.4.4 Overdispersion .....	215
7.4.5 Binomial GLMM with observation level random intercept	216
7.4.6 Visualization of results .....	220
<b>7.5 BINOMIAL GLMM WITH RANDOM INTERCEPT ZOO IN JAGS .....</b>	<b>223</b>
7.5.1 Data for JAGS .....	223
7.5.2 JAGS modelling code for a binomial GLMM.....	224
7.5.3 Results for the binomial GLMM.....	226
7.5.4 Overdispersion .....	226
<b>7.6 BETA-BINOMIAL GLMM IN JAGS .....</b>	<b>228</b>
7.6.1 The Beta distribution .....	228
7.6.2 From beta to beta-binomial distribution .....	229
7.6.3 JAGS code for beta-binomial GLMM .....	230
7.6.4 Beta-binomial GLMM results.....	232
7.6.5 Model validation of the beta-binomial GLMM .....	232
<b>7.7 USING A BETA GLMM FOR PROPORTIONS .....</b>	<b>234</b>
<b>7.8 COMPARING ESTIMATED PARAMETERS FROM ALL MODELS.....</b>	<b>237</b>
<b>7.9 MODEL SELECTION FROM A FREQUENTIST POINT OF VIEW .....</b>	<b>239</b>
<b>7.10 MODEL SELECTION FROM A BAYESIAN POINT OF VIEW .....</b>	<b>241</b>
7.10.1 Using the DIC, AIC and BIC .....	242
7.10.2 Inclusion probabilities.....	245
<b>7.11 WHAT TO PRESENT IN A PAPER .....</b>	<b>246</b>
<b>REFERENCES .....</b>	<b>247</b>
<b>INDEX .....</b>	<b>251</b>
<b>BOOKS BY HIGHLAND STATISTICS .....</b>	<b>255</b>
UPCOMING BOOKS IN 2013 AND 2014 .....	256