THE COSTS OF FOX PREDATION TO AGRICULTURE IN BRITAIN

Thesis submitted for the Degree of
Doctor of Philosophy
in
Environmental Economics and Environmental Management

by
Rebecca L. Moberly

University of York
Environment Department

June 2002

ABSTRACT

Foxes (*Vulpes vulpes*) are considered to be a pest in many parts of the world because of their predation on livestock, poultry and game. Predation poses costs to farmers in terms of loss of stock and measures taken to prevent losses. This thesis aimed to assess the costs of fox predation in Britain and the factors that influence them. Such research is an important step towards the effective and efficient management of fox predation.

Questionnaire surveys of sheep farmers, free-range poultry producers, outdoor pig producers and game interests were carried out to collect data on the perceptions of stock losses to foxes, along with information on farm characteristics, husbandry and fox control. Regression analyses were used to determine what factors influenced the incidence and level of fox predation. Economic models were developed to assess the farmers' costs of predation and identify financially efficient management strategies.

For all producer types, reported fox predation losses were low on the majority of holdings, although high predation levels were reported on a few individual farms. Variation in fox predation between holdings was associated with regional location, flock or herd size and the level of fox control on farms. Fox population density was only associated with predation losses in the case of sheep.

Effective measures for preventing fox predation were identified for two producer types: indoor lambing for sheep and electric fencing for pig producers. Financial analysis indicated that the optimal strategy for a sheep farmer, in terms of minimising total costs of predation, was to house all ewes and lambs for less than a day. According to the analysis, housing ewes was a more cost-effective strategy than additional fox control. Expenditure on fencing solely to prevent fox predation was only worthwhile for some pig producers. In both cases, analyses indicated that, to meet cost-minimising objectives, some predation losses should be tolerated.

The economic framework developed here can be used for future evaluations of livestock predation and management strategies from the farmer's point of view. In addition, identification of the factors influencing fox predation should help target research and strategies to manage the problem.

CONTENTS

Page

ABSTRACT 2

LIST OF TABLES 9

LIST OF FIGURES 15

ACKNOWLEDGEMENTS 20

AUTHOR'S DECLARATION 22

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW 23
- 1.1 Introduction 23
- 1.2 Analysis of vertebrate pest management 24
  - 1.2.1 Applications of economics to vertebrate pest management 25
  - 1.2.2 Valuing predation losses 27
  - 1.2.3 Approaches relevant to the economic analysis of predation losses 29
  - 1.2.4 Pest abundance and pest damage 33
- 1.3 Fox distribution and pest status worldwide 33
- 1.4 Status of foxes in Britain 35
  - 1.4.1 Population estimates for the whole of Britain 35
  - 1.4.2 Local and regional fox population estimates 36
- 1.5 Management of fox populations in Britain 38
  - 1.5.1 Reasons for management of fox populations 38
  - 1.5.2 Methods used to manage fox populations and published information on fox population management 39
    - 1.5.2.1 Hunting with dogs
    - 1.5.2.2 Management by parties other than organised hunts
  - 1.5.3 Effectiveness of fox population management 43
  - 1.5.4 Other factors influencing fox population densities 46
- 1.6 Foxes and agriculture in Britain 48
  - 1.6.1 The fox as a pest 48
  - 1.6.2 Collection of data on livestock predation 49
- 1.7 Aims and outline of thesis 50

CHAPTER 2: FACTORS INFLUENCING PERCEIVED FOX PREDATION OF LAMBS ON SHEEP FARMS 52
- 2.1 Introduction 52
- 2.2 Methods 57
  - 2.2.1 Questionnaire survey of sheep farmers 57
  - 2.2.2 Regional representativeness of sample 57
  - 2.2.3 Relative fox population density estimates 57
  - 2.2.4 Analyses 62
  - 2.2.5 Reliability ratings 63

2.3 Results 64
  2.3.1 Relative fox population density estimates 67
  2.3.2 Factors related to the occurrence of perceived fox predation of lambs 69
    2.3.2.1 Farm location
    2.3.2.2 Farm size, lambing rates and stocking densities
    2.3.2.3 Land uses surrounding farms
    2.3.2.4 Lambing indoors and multiple births
    2.3.2.5 Timing of lambing
    2.3.2.6 Sheep breed
    2.3.2.7 Lamb mortality due to causes other than predation
    2.3.2.8 Fox control and relative fox population density
  2.3.3 Model relating the occurrence of perceived fox predation of lambs to farm characteristics 73
  2.3.4 Factors related to the scale of perceived fox predation of lambs 75
    2.3.4.1 Surrounding land-uses and farm location
    2.3.4.2 Farm size, lambing rates and stocking densities
    2.3.4.3 Lambing indoors and multiple births
    2.3.4.4 Timing of lambing
    2.3.4.5 Sheep breed
    2.3.4.6 Lamb mortality due to causes other than predation
    2.3.4.7 Fox control and relative fox population density
  2.3.5 Model relating the scale of perceived fox predation of lambs to farm characteristics 77
  2.3.6 Associations between respondent reliability ratings for lamb losses and perceived fox predation of lambs 79
2.4 Discussion 85
  2.4.1 Data reliability 85
    2.4.1.1 Accuracy of lamb loss figures
    2.4.1.2 Sample bias and comparison with the literature
    2.4.1.3 Respondent reliability ratings
  2.4.2 Farm characteristics influencing the occurrence and scale of perceived fox predation of lambs 89
    2.4.2.1 Farm location and the influence of farm size
    2.4.2.2 Relative fox abundance and fox control
    2.4.2.3 Surrounding land-uses
    2.4.2.4 Husbandry techniques
2.5 Conclusions 95
2.6 Summary 96

CHAPTER 3: FINANCIAL ANALYSIS OF FOX PREDATION AND PREVENTIVE MEASURES ON SHEEP FARMS 104
3.1 Introduction 104
3.2 Theoretical model 105
3.3 Empirical analysis 111
  3.3.1 Fox population density estimates 111

3.3.2 Monetary valuation of lamb losses 112
3.3.3 Expenditure on indoor housing 114
3.3.4 Specification of model relating expected lamb losses to expenditure on indoor housing 116
3.4 Model output 120
3.5 Discussion 122
3.5.1 Data reliability 122
3.5.2 Model criticism 123
3.5.3 Model output 125
3.6 Conclusions 128
3.7 Summary 129

CHAPTER 4: STATIC FINANCIAL ANALYSIS OF FOX CONTROL ON SHEEP FARMS 137
4.1 Introduction 137
4.2 Theoretical background 139
4.3 Empirical analysis 143
4.3.1 Costs of fox control 144
4.4 Model output 146
4.4.1 Modelling the total costs of lamb losses, preventive measures and fox control 148
4.5 Discussion 150
4.5.1 Model criticism 150
4.5.2 Model output 151
4.5.3 Assumptions and realism of analysis 152
4.5.3.1 Fox population density and lamb losses
4.5.3.2 Ecological considerations
4.5.3.3 Costs of fox control
4.5.3.3 Applicability of analysis
4.6 Conclusions 157
4.7 Summary 159

CHAPTER 5: IMPACT OF FOXES ON FREE-RANGE POULTRY PRODUCTION 168
5.1 Introduction 168
5.2 Methods 171
5.2.1 Questionnaire surveys 171
5.2.1.1 Chicken producers
5.2.1.2 Turkey producers
5.2.1.3 Egg producers
5.2.1.4 Goose producers
5.2.2 Relative fox density estimates 172
5.2.3 Analyses 173
5.2.3.1 Temporal distribution of predation
5.2.3.2 Effectiveness of fencing
5.2.3.3 Factors influencing reported fox predation of chickens
5.2.4 Modelling the farmers' costs of poultry predation by foxes 174

- 5.2.4.1 Theoretical model
- 5.2.4.2 Valuation of costs of poultry predation by foxes
- 5.2.4.3 Valuation of expenditure on fencing
- 5.2.4.4 Empirical estimation of model

- 5.3 Results 180
  - 5.3.1 Relative fox population density estimates 191
  - 5.3.2 Temporal distribution of predation 193
  - 5.3.3 Effectiveness of fencing 193
    - 5.3.3.1 Effectiveness at preventing entry of foxes
    - 5.3.3.2 Effectiveness at preventing entry of unwanted animals
    - 5.3.3.3 Effectiveness at preventing escapees
  - 5.3.4 Factors influencing reported fox predation of chickens 202
    - 5.3.4.1 Univariate analyses
    - 5.3.4.2 Overall logistic regression model
  - 5.3.5 Modelling the farmers' costs of poultry predation by foxes 204
    - 5.3.5.1 Empirical estimation of model
- 5.4 Discussion 210
  - 5.4.1 Data reliability 210
  - 5.4.2 Reported fox predation of poultry 211
  - 5.4.3 Effectiveness of fencing 213
  - 5.4.4 Costs of poultry predation by foxes 214
- 5.5 Conclusions 216
- 5.6 Summary 217

CHAPTER 6: IMPACT OF FOXES ON OUTDOOR PIG PRODUCTION 226

- 6.1 Introduction 226
- 6.2 Methods 227
  - 6.2.1 Questionnaire survey of outdoor pig producers 227
  - 6.2.2 Relative fox population density estimates 228
  - 6.2.3 Factors influencing reported fox predation of piglets 228
  - 6.2.4 Costs of piglet predation by foxes 229
    - 6.2.4.1 Theoretical model
    - 6.2.4.2 Valuation of piglet losses due to fox predation and expenditure on boundary fencing
    - 6.2.4.3 Empirical estimation of the model
- 6.3 Results 233
  - 6.3.1 Relative fox population density estimates 234
  - 6.3.2 Factors influencing reported fox predation of piglets 239
  - 6.3.3 Costs of piglet predation by foxes 240
    - 6.3.3.1 Empirical estimation of the model
- 6.4 Discussion 247
  - 6.4.1 Data reliability 247
  - 6.4.2 Reported piglet predation by foxes 248
  - 6.4.3 Costs of piglet predation by foxes 249
  - 6.4.4 Model criticism 251
- 6.5 Conclusions 252

6.6 Summary 253

CHAPTER 7: IMPACT OF FOXES ON GAME INTERESTS: PREDATION OF RELEASED PHEASANTS 261
7.1 Introduction 261
7.2 Methods 265
  7.2.1 Questionnaire survey of gamekeepers and estates 265
  7.2.2 Relative fox population density estimates 266
  7.2.3 Factors influencing reported fox predation of pheasants from release pens 267
  7.2.4 Costs of pheasant predation by foxes from release pens
    7.2.4.1 Theoretical model
    7.2.4.2 Valuation of pheasant losses due to fox predation from release pens
    7.2.4.3 Expenditure on fox control by gamekeepers
    7.2.4.4 Expenditure on release pens and associated preventive measures
    7.2.4.5 Empirical estimation of the model
  7.2.5 Fox control and estimated relative fox density 272
7.3 Results 273
  7.3.1 Relative fox population density estimates 277
  7.3.2 Factors influencing fox predation of pheasants from release pens 277
  7.3.3 Costs of pheasant predation by foxes from release pens 280
    7.3.3.1 Empirical estimation of the model
  7.3.4 Fox control and estimated relative fox density 283
7.4 Discussion 284
  7.4.1 Data reliability 284
  7.4.2 Reported fox predation of pheasants from release pens 285
  7.4.3 Costs of fox predation of pheasants from release pens 287
  7.4.4 Fox control and fox density 289
7.5 Conclusions 289
7.6 Summary 291

CHAPTER 8: OVERALL DISCUSSION AND CONCLUSIONS 299
8.1 Predation losses to foxes 299
  8.1.1 Factors influencing fox predation 299
  8.1.2 Fox control, abundance and predation 301
8.2 Costs of fox predation 303
8.3 Data reliability 305
  8.3.1 Questionnaire survey data 305
  8.3.2 Fox population density estimates 306
8.4 Wider economic impacts of fox predation 306
8.5 Future work 308

APPENDICES 312
Appendix A: Questionnaire form for sheep producer survey 312

Appendix B: Summary of the variables and codes used in Chapters 2, 3 and 4 analyses 314
Appendix C: Questionnaire forms for free-range poultry producer surveys 318
Appendix D: Summary of the variables and codes used in Chapter 5 logistic regression analyses for chicken and egg producer data 323
Appendix E: Questionnaire form for outdoor pig producer survey 325
Appendix F: Summary of the variables and codes used in Chapter 6 regression analyses 327
Appendix G: Questionnaire form for survey of game interests 330
Appendix H: Summary of the variables and codes used in Chapter 7 regression analyses 332

REFERENCES 335

LIST OF TABLES

Page

CHAPTER 2

Table 2.1: Allocations of postcodes to regions using Royal Mail System 59

Table 2.2: Regions defined by postcode and their MAFF census counterparts 59

Table 2.3: Regions used to calculate relative fox density estimates (Webbon 2002) 60

Table 2.4: Land class groups used to calculate relative fox density estimates (Webbon 2002) 61

Table 2.5: Survey returns and data from 1999 MAFF and Scottish Executive June Censuses on sheep holdings by region 65

Table 2.6: Reported losses of lambs between birth and weaning to fox predation, all predation and other causes 66

Table 2.7: Relative fox densities based on regions (Webbon 2002) 68

Table 2.8: Relative fox densities based on land class groups (Webbon 2002) 68

Table 2.9: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by country within UK 69

Table 2.10: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by postcode-derived region 69

Table 2.11: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by farm type 70

Table 2.12: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by month lambing took place 72

Table 2.13: Parameter estimates and significance test statistics for overall logistic regression model describing variation in the occurrence of perceived fox predation of lambs between farms 74

Table 2.14: Parameter estimates and t-test statistics for univariate regression analyses relating location variables to the scale of perceived fox predation of lambs 75

Table 2.15: Parameter estimates and t-test statistics for overall multiple linear regression model explaining variation in the scale of perceived fox predation of lambs 78

Table 2.16: Mean rank in Kruskal-Wallis analysis of variance of number of lambs reported killed by foxes for each loss reliability rating 81

Table 2.17: Median, mean, standard deviation and number in sample of lambs reported killed by foxes or each loss reliability rating 81

Table 2.18: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs and loss reliability rating 81

Table 2.19: Overall model fit, parameter estimates and significance tests for variables in multiple logistic regression model explaining variation in occurrence of perceived fox predation of lambs, including dummy variables coding for reliability ratings of 3 and 4 82

Table 2.20: Overall model fit, parameter estimates and significance tests for variables in multiple logistic regression model explaining variation in occurrence of perceived fox predation of lambs, including dummy variables coding for reliability ratings of 3 and 5 82

Table 2.21: Overall model fit, parameter estimates and significance tests for variables in multiple logistic regression model explaining variation in occurrence of perceived fox predation of lambs, including dummy variables coding for reliability ratings of 4 and 5 83

Table 2.22: Mean rank in Kruskal-Wallis analysis of variance of logged number of lambs perceived killed by foxes per ewe for each loss reliability rating 83

Table 2.23: Overall model fit, parameter estimates and significance test statistics for variables in linear regression model explaining variation in perceived scale of fox predation of lambs, including dummy variables coding for reliability ratings of 3 and 5 84

Table 2.24: Overall model fit, parameter estimates and significance test statistics for variables in linear regression model explaining variation in perceived scale of fox predation of lambs, including dummy variables coding for reliability ratings of 4 and 5 84

CHAPTER 3

Table 3.1: Predicted association between the probability of lamb predation occurring and expenditure on indoor housing 108

Table 3.2: Pay-off matrix indicating lamb loss due to fox predation outcomes according to expenditure on indoor housing 110

Table 3.3: Absolute fox density estimates based on regions 112

Table 3.4: Summary statistics for the cost of lamb losses to foxes per ewe and expenditure on indoor housing for the sample 116

Table 3.5: Coefficient estimates and significance test statistics for logistic regression model describing variation in the likelihood of fox predation of lambs ($\ln[p_i/(1-p_i)]$) 118

Table 3.6: Coefficient estimates and significance test statistics for linear regression model describing variation in the costs of lamb losses to fox predation on farms where predation occurred (L_i) 119

CHAPTER 4

Table 4.1: Coefficient estimates and significance test statistics for linear regression model describing variation in the costs of fox control (K_i) 145

Table 4.2: Pay-off matrix illustrating the expected outcomes of fox control in terms of lamb losses for a farm of 200 hectares with 800 ewes in the Southwest region, with game rearing in its surroundings and 7 foxes on its land, where all ewes are lambed indoors and kept inside for one day 146

Table 4.3: Output of model giving total and marginal benefits and costs of fox control according to number of foxes left and number of foxes killed for a 200 hectare farm with 800 ewes in the Southwest, with game rearing in its surroundings, where all ewes are lambed indoors and kept inside for one day 147

CHAPTER 5

Table 5.1: Reported losses of turkeys in 1998 to fox predation, all predation, other causes and in total 183

Table 5.2: Reported losses of geese in 1999 to fox predation, all predation, other causes and in total 184

Table 5.3: Reported losses of table chickens during last growing cycle to fox predation, all predation, other causes and in total 185

Table 5.4: Reported losses of laying hens during last laying cycle to fox predation, all predation, other causes and in total 186

Table 5.5: Percentage of poultry producer respondents with various factor levels for husbandry, fencing, farm surroundings, farm location, fox control and fox predation factors by producer type 187

Table 5.6: Summary statistics on flock size and foxes killed for poultry producers by producer type 190

Table 5.7: Spearman's rank correlation associations between land class and regional fox density and the percentage and number of birds reported killed by foxes and the number of foxes killed on farms in the last year by poultry producer type 192

Table 5.8: Observed and expected frequencies of fence effectiveness ratings for preventing foxes from entering areas where birds were kept for tested fence types and chi-square statistics for associations between frequencies, with equal expected frequencies for each rating 196

Table 5.9: Observed and expected frequencies of fence effectiveness ratings for preventing foxes from entering areas where birds were kept for tested fence types and chi-square statistics for associations between frequencies, with expected frequencies for each rating proportionate to those of the sample 197

Table 5.10: Observed and expected frequencies of fence effectiveness ratings for preventing all unwanted animals from entering areas where birds were kept for tested fence types and chi-square statistics for associations between frequencies, with equal expected frequencies for each rating 198

Table 5.11: Observed and expected frequencies of fence effectiveness ratings for preventing all unwanted animals from entering areas where birds were kept for tested fence types and chi-square statistics for associations between frequencies, with expected frequencies for each rating proportionate to those of the sample 199

Table 5.12: Observed and expected frequencies of fence effectiveness ratings for preventing birds from escaping for tested fence types and chi-square statistics for associations between frequencies, with equal expected frequencies for each rating 200

Table 5.13: Observed and expected frequencies of fence effectiveness ratings for preventing birds from escaping for tested fence types and chi-square statistics for associations between frequencies, with expected frequencies for each rating proportionate to those of the sample 201

Table 5.14: Coefficient estimates and significance test statistics for variables that were significantly related to the occurrence of reported fox predation of chickens in univariate logistic regression analyses 202

Table 5.15: Coefficient estimates and significance test statistics for overall logistic regression model describing variation in the occurrence of reported fox predation of chickens between farms 203

Table 5.16: Summary statistics for the reported costs of fox kills, stress and the reported value of one bird killed by a fox and for estimated output losses due to fox predation for each poultry producer type 206

Table 5.17: Summary statistics for expenditure on fencing per bird per year and for expenditure on fence maintenance per bird per year for each poultry producer type 207

Table 5.18: Coefficient estimates and adjusted R^2 values for regression models estimated for relationship between poultry losses to foxes and expenditure on fencing 209

CHAPTER 6

Table 6.1: Characteristics of pig producer sample in terms of use of possible anti-predation measures, fencing, fox predation. farm surroundings and location and reported fox predation 235

Table 6.2: Summary statistics on reported losses of piglets to fox predation, all predation and all causes between birth and weaning. 237

Table 6.3: Summary statistics for numbers of sows, piglets born and fox control 238

Table 6.4: Coefficient estimates and significance test results for multivariate logistic regression model 1 explaining variation in the occurrence of reported fox predation of piglets 239

Table 6.5: Coefficient estimates and significance test results for multivariate logistic regression model 2 explaining variation in the occurrence of reported fox predation of piglets 240

Table 6.6: Summary statistics of estimated and reported costs of piglet losses to foxes per sow per year 241

Table 6.7: Summary statistics of expenditure on fence maintenance and total expenditure on fencing per sow per year 241

Table 6.8: Model output for regression models with piglet losses to foxes per sow as the dependent variable $La_{i1} = f(MF_{i1})$ 243

Table 6.9: Coefficient estimates and significance test results for multiple linear regression model with piglet loss to foxes per sow as the dependent variable 244

Table 6.10: Variation in optimal expenditure on fence maintenance per sow per year (MF_i*) and optimal losses of piglets the farmer should accept per sow per year (La_i*) with the values of V_i, Eas_i, Mid_i and EL_i 246

CHAPTER 7

Table 7.1: Characteristics of game interest sample in terms of use of various release pen preventive measures, land uses surrounding shoots, location and reported fox predation of pheasants in release pens 274

Table 7.2: Summary statistics on reported losses of pheasants from release pens due to fox predation, all predation and other causes 276

Table 7.3: Summary statistics for pheasants released, shoot area, foxes killed on shoot and losses to foxes as percentages out of totals 276

Table 7.4: Coefficient estimates and significance test statistic for logistic regression model with best accuracy for predicting the likelihood of reported fox predation of pheasants 278

Table 7.5: Coefficient estimates and t-test statistics for best-fit linear regression model explaining variation in the scale of reported fox predation of pheasants 279

Table 7.6: Coefficient estimates and t-test statistics for linear regression model of pheasant bag against total income per shoot day 280

Table 7.7: Summary statistics of values of pheasant losses and expenditure on keeper fox control and release pens and preventive measures 280

Table 7.8: Model output for regression models with pheasant losses to foxes (plus 0.01) as the dependent variable, $Lc_{i1} = f(MF_i)$ 282

Table 7.9: Estimated coefficients and t-test statistics for relationship between regional fox density (log-transformed) and expenditure on keeper fox control per fox killed (log-transformed) 284

LIST OF FIGURES

Page

CHAPTER 1

Figure 1.1a: The disease-loss expenditure frontier (from McInerney *et al.* 1992 and McInerney 1996) 32

Figure 1.1b: Marginal cost (MC) and marginal benefit (MB) curves for control of stock mortality, illustrating the optimal point where curves intersect (E_M/L_M) 32

CHAPTER 2

Figure 2.1: Location of the farms of sheep farmer questionnaire respondents by postcode-derived region 97

Figure 2.2: Pie-chart showing the percentage of hill, upland and lowland farms in sheep farm sample 98

Figure 2.3: Histogram of number of ewes per holding 99

Figure 2.4: Histogram of responses for reported lamb mortality due to foxes 100

Figure 2.5: Histogram of responses to question about changes in number of lambs killed by foxes over last five years 101

Figure 2.6: Histogram of reported number of foxes killed per hectare on sheep farms in the last year 102

Figure 2.7a: Scatter plot of the number of lambs reported killed by foxes against regional fox density 103

Figure 2.7b: Scatter plot of the percentage of lambs born reported killed by foxes against regional fox density 103

CHAPTER 3

Figure 3.1: Reported costs of lamb losses to foxes per ewe compared to estimated monetary lamb loss due to fox predation per ewe 130

Figure 3.2: Relationship between expected lamb loss (Z) and expenditure on indoor housing per ewe ($Y \cdot D$) for various values of dummy variables and N (lambing ewes) and two different levels of Y 131

Figure 3.3: Relationship between total costs of fox predation (housing plus lamb losses) (TC) and expenditure on indoor housing per ewe ($Y \cdot D$) for various values of dummy variables and N (lambing ewes) and two different levels of Y 132

Figure 3.4: Relationships between expenditure on indoor housing ($Y \cdot D$) and both expected lamb losses due to fox predation (Z) and total costs of fox predation (housing plus lamb losses) (TC), showing the optimal point where total costs are minimised, for a farm with 200 lambing ewes ($N = 200$), a fox density of 0.03 per hectare ($X = 0.03$) in Southwest England ($SW = 1$) 133

Figure 3.5: 3-D plot illustrating the relationship between expected lamb loss to foxes per ewe (Z) and both the number of days for which ewes and lambs are housed (D) and expenditure on indoor housing per ewe per day (Y) for the estimated model for a farm in the Southwest with 200 ewes and 0.03 foxes per hectare 134

Figure 3.6: 3-D plot illustrating the relationship between total costs of fox predation (indoor housing plus lamb loss) per ewe (TC) and both the number of days for which ewes and lambs are housed (D) and expenditure on indoor housing per ewe per day (Y) for the estimated model for a farm in the Southwest with 200 ewes and 0.03 foxes per hectare 135

Figure 3.7: Plot of standardised residuals against standardised predicted values from regression of ln-cost of lamb losses to foxes per ewe against 7 regressors 136

CHAPTER 4

Figure 4.1: Cost of killing the next fox per ewe in terms of number of foxes on the farm for various farm areas and number of lambing ewes according to estimated model 160

Figure 4.2: Total lamb loss due to fox predation, costs of fox control and costs of lamb losses plus control for each fox killed from a starting density of 0.035 foxes per hectare on a 200 hectare farm in the Southwest with 800 ewes, where all ewes are lambed indoors for one day and there is game rearing in the surroundings, showing the optimal point where the total costs of lamb losses plus fox control are minimised 161

Figure 4.3: Marginal lamb loss due to fox predation, cost of fox control and cost of lamb loss plus fox control for each fox killed from a starting density of 0.035 foxes per hectare on a 200 hectare farm in the Southwest with 800 ewes, where all ewes are lambed indoors for one day and there is game rearing in the surroundings, showing the optimal point where the total costs of lamb losses plus fox control are minimised 162

Figure 4.4: Marginal cost of lamb losses plus fox control for each fox killed on 200 hectare farms with a fox population starting density of 0.035 foxes per hectare and various characteristics 163

Figure 4.5a: Marginal cost of lamb loss plus fox control for each fox killed on farms with all ewes housed indoors for one day and 4 foxes in total ($Q = 4$) (densities, X, varying with area) and various size characteristics 164

Figure 4.5a: Marginal cost of lamb loss plus fox control for each fox killed on farms with all ewes housed indoors for one day ($Y = 0.15$, $D = 1$) and a fox population density of 0.04 foxes per hectare ($X = 0.04$) (total fox numbers, Q, varying with area) and various size characteristics 164

Figure 4.6: 3-D plots for expected lamb loss to foxes per ewe (Z) against both the number of days for which ewes and lambs are housed (D) and expenditure on indoor housing per ewe per day (Y) for seven different numbers of foxes on the farm (Q) from a starting density (Q_0) of 7 for a 200 hectare farm in the Southwest with 800 ewes and game rearing in the surroundings 165

Figure 4.7: 3-D plots for total costs of fox predation per ewe (TC) against both the number of days for which ewes and lambs are housed (D) and expenditure on indoor housing per ewe per day (Y) for seven different numbers of foxes on the farm (Q) from a starting density (Q_0) of 7 for a 200 hectare farm in the Southwest with 800 ewes and game rearing in the surroundings 166

Figure 4.8: Plot of standardised residuals against standardised predicted values for ln cost of killing the next fox per ewe (K_i) according to the model $\ln(K_i) = -2.80 + -0.478.\ln(Q_i) + 0.0011.S_i - 0.0008.N_i$ 167

CHAPTER 5

Figure 5.1: Histogram of percentage of flock reported killed by foxes by poultry producer type 218

Figure 5.2: Histogram of percentage of farms that reported fox predation according to poultry producer type 219

Figure 5.3: Histogram of producers reporting goose and turkey depredation by foxes per month 220

Figure 5.4: Reported costs of losses of turkeys to foxes per turkey compared to estimated output losses due to fox predation per turkey 221

Figure 5.5: Reported costs of losses of geese to foxes per goose compared to estimated output losses due to fox predation per goose 222

Figure 5.6: Reported costs of losses of laying hens to foxes per hen compared to estimated output losses at point-of-lay and mid-laying cycle due to fox predation per hen 223

Figure 5.7: Estimated output loss due to foxes per bird compared to expenditure on fencing per bird 224

Figure 5.8: Estimated output loss due to foxes per bird compared to expenditure on fence maintenance per bird 225

CHAPTER 6

Figure 6.1: Histogram of responses for reported piglet mortality due to fox predation 254

Figure 6.2: Reported costs of piglet losses to foxes per sow compared to estimated output loss due to fox predation per sow 255

Figure 6.3: Total costs of fencing per sow per year compared with output loss due to fox predation 256

Figure 6.4: Costs of fence maintenance per sow per year compared with output loss due to fox predation 257

Figure 6.5: Relationship between piglet losses to foxes and expenditure on fence maintenance with variation in farm characteristics, according to the model, $\ln(La_{i1}) = 2.04 - 1.17\cdot MF_i + 2.18\cdot V_i - 2.58\cdot Eas_i - 2.18\cdot Mid_i - 1.60\cdot EL_i$ 258

Figure 6.7: Relationship between total costs of fox predation and expenditure on fence maintenance with variation in farm characteristics, showing the point where total costs are minimised in each case 259

Figure 6.7: Histogram of the avoidable costs, or differences between actual and estimated optimal total costs, of fox predation to pig producers (including the costs of piglet losses and the costs of boundary fence maintenance) 260

CHAPTER 7

Figure 7.1: Histogram of responses for reported pheasant mortality due to fox predation 292

Figure 7.2: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on keeper fox control per bird released 293

Figure 7.3: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on release pens and preventive measures per bird released 294

Figure 7.4: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on pen preventive measures per bird released 295

Figure 7.5: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on keeper fox control plus release pens and preventive measures per bird released 296

Figure 7.6: Comparison of expenditure on the two preventive measures considered (pheasant pens and associated preventive measures and fox control) 297

Figure 7.7: Association between keeper control expenditure per fox killed and regional fox density both for actual data and relationship modelled with regression analysis 298

ACKNOWLEDGEMENTS

Firstly, I would like to thank my principal supervisor, Piran White, for his advice and support throughout the PhD process and for being a very helpful and speedy proof-reader and editor. I would also like to thank Steve Harris for valuable input as the thesis and research developed. Piran and Steve first proposed the project and obtained funding for it, without which I would not have started this PhD, so I am grateful to them both for this and for the fact that I was chosen to take up the studentship.

The research was funded by a grant from the Royal Society for the Prevention of Cruelty to Animals and I am grateful for their support.

Both Mette Termansen and Jim Smart provided me with invaluable guidance, additional brainpower and help. I am extremely grateful to them for the time they gave up in order to help me. I would like to thank Riccardo Scarpa for his comments on draft chapters and helpful advice and members of my Thesis Advisory Committee, Colin McClean, Jon Lovett and Ed Barbier, as well as Jeremy Kemp. Colin and Mette also provided useful comments on a previous draft of this thesis. Thanks also go to Lynda Rodwell, Deborah Kirby, Geraldine Newton-Cross and Mark Bulling for their input and support and to Jo Burgess for her early supervisory role, as well as to other Environment Department staff and students.

I am very grateful for the information and data on fox population densities provided by Charlotte Webbon at Bristol University and for additional help from Phil Baker in this respect. I would also like to thank Robbie McDonald for the information and advice he gave me at the start of the project.

I would like to thank all the producers, estates and shoots who so kindly supplied me with information for this study, without which it would not have been possible. I would also like to thank: the National Sheep Association, especially Helen Owen and Dyana Loach, for their help in the design and distribution of the sheep producer survey; the Blackface Sheep Breeders Association; the British Charollais Sheep Society; Richard

Kempsey, John Widdowson and members of the British Free Range Egg Producers Association; Penny Jones, Chris Frederick and members of the Traditional Farmfresh Turkey Association; John Walker and members of the British Goose Producers Association; Mike Kennardsmith of West Country Free Range, Lloyd Maunder Ltd.; John Parsons and Jonathan Birnie of the NFU; Malcolm Black and Derek Wells of Signet Livestock Business Consultancy; Andrew Sheppard at the University of Exeter; Jonathon Reynolds and Stephen Tapper of the Game Conservancy Trust; Jed Green, Head Keeper at Harewood House; the Soil Association; and all the other individuals that helped me design and distribute the surveys and provided me with contacts.

In addition to academic support, I would like to thank all my friends and family for helping me through the PhD. Special thanks go to: my brother, Thomas, as he was also prepared to proof-read some chapters; my dad, Bob, for being so interested, his helpful advice and for reading through reports and summaries; my mum, Tess, for always being on my side; my housemates, Gerry and Nola, for putting up with my madness; Sonja Teelucksingh for emotional support; Chris Schelten and Robert Rea for being fellow nearly-there-ers; and, of course, last but definitely not least, Tom for sticking with me and helping me relax.

AUTHOR'S DECLARATION

I declare that the work contained within this thesis is my own and has not been submitted previously for any degree or award, with the exception of data on relative fox population density estimates discussed in Chapter 2, Section 2.2.3, and on fox scat production in bait marking trials discussed in Chapter 3, Section 3.3.1, which were collected and compiled by Charlotte C. Webbon.

Rebecca L. Moberly

Rebecca L. Moberly

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. INTRODUCTION

This study is concerned with the red fox (*Vulpes vulpes*) and its management in rural Britain. It concentrates on the costs of foxes to agriculture in Britain, including prevention and control, and factors influencing these costs.

For as long as there has been settled agriculture in Britain, the red fox has impinged on people's activities and livelihoods (Kolb 1996). The situation regarding this species in the UK is complicated because it has interactions with many different economic sectors (agriculture, forestry, wildlife conservation and recreation), as well as ecologically, via its predation on small mammal and wild bird species. To some people the fox is unwelcome as a predator of poultry, lambs and game, while to others its predation on rodents and rabbits is beneficial. It is a hunting quarry, yet at the same time is treasured (Macdonald 1984), as Britain's largest native mammalian predator (Kolb 1996). This means that views on how fox populations should be managed vary, whilst fox control is frequently carried out with no clearly specified management objectives (Harris & Saunders 1993). The controversy surrounding fox management is primarily concerned with how important predation by foxes is for different interest groups, the effectiveness of culling and other remedial measures and the humaneness of culling methods (Heydon & Reynolds 2000a).

This study aims to address two of these issues, by investigating the costs of fox predation to four agricultural sectors: sheep farming, free-range poultry production, outdoor pig production and game bird shooting interests; and determining what preventive measures help limit these costs. These sectors were chosen because they are those for which the costs of foxes are most significant.

1.2. ANALYSIS OF VERTEBRATE PEST MANAGEMENT

Wildlife management implies the stewardship of a population and may be an attempt to make it increase, decrease or harvest it for a continuing yield (Caughley & Sinclair 1994). In the case of vertebrate pests, it is usually the second of these (or holding the population at a reduced level) that is the aim. The concept of a pest is difficult to define and the issues involved in deciding whether an animal is termed a pest are both scientific and social (Harris 1989; Hone 1994). A general definition is a species that conflicts with human interests, having implications for economic systems or human health (Conway 1981; Harris 1989; Putman 1989; Hone 1994). It is the damage that vertebrate pests cause that justifies their control (Hone 1994). However, pest management is frequently carried out in an *ad hoc* fashion and the appropriateness of management is rarely assessed (Shea *et al.* 2000).

One of the criteria for determining whether control is an appropriate management action is whether the benefit of carrying out control exceeds the cost and this should be determined before a control program is instigated (Conway 1981; Caughley & Sinclair 1994) in order to prevent unnecessary or uneconomic control actions. For this reason and the fact that there is generally a need to weigh-up a number of conflicting objectives or allocate scarce resources among competing needs, economic analysis is a useful tool for the analysis of pest management (Mumford & Norton 1984; Bicknell 1993). The use of economic analysis for the management of arthropod, fungal and plant pests is well established. However, its use in such decision-making for vertebrates has been neglected (Hone 1994), probably because they cause less damage than invertebrate organisms (Pimentel 1986; Van Vuren & Smallwood 1996). A number of economic techniques can be applied to vertebrate pest control analysis. Four are described by Hone (1994): marginal cost-benefit, cost-benefit and cost-effectiveness analyses and decision theory. Mumford and Norton (1984) recognise a further category of analysis in pest management: the behavioural decision model, which attempts to account for the influence of a farmer's perceptions, personal objectives and other behavioural characteristics on decision making. Examples of some applications of economic analysis to vertebrate pests are outlined below. Hone (1994) provides a number of further empirical examples, including a few applications of cost-effectiveness analysis to pest control, whilst also illustrating that much of the work has been theoretical or based on hypothetical situations.

The analysis of pest control is not only important in financial terms, but also needs to meet social and moral criteria. Any control strategy should take acceptability into account as well as effectiveness and efficiency (Reynolds & Tapper 1996; Andrew & Robottom 2001). This thesis does not consider the ethical issues surrounding fox culling and the different methods that are used to manage fox populations. However, these are a significant input to pest control decision-making, and decision processes should not neglect animal welfare.

In the resource economics literature, a distinction is often drawn between financial and economic analysis, generally with regard to cost-benefit analysis, e.g. Swanson and Barbier (1992). The definition of financial analysis used here is an analysis that determines the profitability (or returns) to a project or production system using actual market prices (Brent 1997). Therefore, financial analysis tends to assess the private costs of a project or action to a particular individual or firm and shareholders, for example (Hanley *et al.* 2001). Economic analysis, on the other hand, extends this to incorporate the hidden costs of externalities, adjusting market prices for distortions and including non-market costs and benefits to assess the implications of the project or action to society as a whole in terms of economic welfare (Barbier *et al.* 1997; Perry & Randolph 1999). The distinction is therefore drawn between the costs and benefits to an individual and the social gains and losses of an investment decision (Dasgupta & Pearce 1978; Pearce & Moran 1994).

1.2.1. Applications of economics to vertebrate pest management

Aubert (1999) evaluated the costs and benefits of wildlife rabies control in France, comparing the cumulative costs of the two main strategies for management of the disease within the wildlife reservoir, foxes: lethal control and oral vaccination. The study concluded that vaccination was the less costly of the two strategies. However, it appeared that the benefits did not outweigh the costs for either strategy and the use of a formal cost-benefit analysis framework in the study was not apparent. A more formal cost-benefit framework was used to assess five possible solutions to the problem of brent geese grazing on farm crops in Britain (Vickery *et al.* 1994). These authors pointed out that, whilst cost-benefit analyses have been carried out to evaluate the establishment of reserves and protection of wildlife areas, use of such analyses to evaluate the costs and benefits of different management options for single species have been neglected. Their analysis concentrated on the direct costs and benefits of brent goose management to farmers and society, considering farm profits and societal levels of taxation, and illustrated that the optimal solution from a cost-benefit analysis at the societal level may differ from that at the farm level. Although the authors were not able to consider all the benefits and costs of such management strategies both to farmers and society and to conservation and wild-fowling interests, their study highlights the difficulty in obtaining suitable data and deriving the values necessary for a full analysis of this type.

Collins *et al.* (1984) also used a cost-benefit approach to assess whether the control of black-tailed prairie dogs to increase livestock forage was economically feasible from both the U.S. Forest Service (assumed to be an agent for society) and rancher viewpoints. The ability of the control programs to recover initial costs depended on the percentage of annual maintenance control, but initial costs were only covered when an unrealistically low re-population rate was assumed. Therefore the authors concluded that control of prairie dogs was not worthwhile in economic terms. Their analysis neglected some of the benefits of control, as well as non-market benefits and costs, but indicates that pest control is frequently undertaken despite the fact that it is not worthwhile.

The benefits and costs of controlling coyotes to increase the hunting harvest of pronghorn in Arizona were studied by Smith, Neff and Woolsey (1986). They compared the predicted effects of eight different control strategies by computer simulation and estimated the net benefits ratio of each in comparison to the strategy of controlling in the first of ten years only. The strategy with the highest net benefits ratio was control every second year. However, further analysis of these data by Hone (1994) illustrates that their conclusions would have been different if the authors had assessed the cost-benefit ratios or costs of control only in order to decide which was the best strategy.

Choquenot and Hone (unpublished) incorporated bioeconomic models for the interactions between control operations, pig population density and lamb predation into a financial cost-benefit analysis comparing two methods of controlling feral pigs in Australia to reduce lamb predation by pigs. The authors were able to evaluate whether helicopter shooting was more cost-effective than 1080 poisoning and indications were that this depended on the standing pasture biomass. Models of increased complexity allowed the frequency with which control should be carried out for each strategy to be determined. The analyses illustrated that increasing the realism of models results in higher data requirements, but that simple models are often unable to address questions that are of much practical use.

1.2.2. Valuing predation losses

Rather than undertaking a full analysis of costs and benefits, various researchers have simply attempted to evaluate the costs of pest damage. There are several ways of valuing the costs of stock mortality. One approach is to use the 'output loss' or the value of the animal when it is lost (McInerney 1987). However, this value is likely to be difficult to estimate if the animal is not at point of sale, when the output loss is simply the market price (McInerney 1987). An alternative approach is to use the resource cost, which is the expenditure on the animal up to its point of death. However, this will underestimate the 'true' loss or cost (McInerney 1987). McInerney *et al.* (1992) argued that loss and cost should be defined as different from each other. Loss is the benefit taken away from the farmer (losses on the output side of production), whilst the cost (C) is the loss (L) plus expenditure (E) or the extra inputs due to mortality, which include the control and prevention costs (McInerney *et al.* 1992):

$$C = L + E$$

This approach was used by Bennett *et al.* (1999) to value the direct costs of endemic diseases in farm animals, where the costs of treatment and prevention were considered separately. These costs of treatment and prevention can be thought of as analogous to the costs of preventive measures and control in the case of livestock predation. It is important that these costs are considered in an assessment of wildlife damage, in addition to those of direct losses in output.

Studies estimating the costs of livestock predation by wildlife have generally estimated total costs to farmers based on the farm-gate or market price of an animal multiplied by the number of losses. These include Butler's (2000) assessment of the 'economic' costs of wildlife predation in Zimbabwe, with the aim of calculating the levels of compensation for local communities suffering livestock depredation under CAMPFIRE schemes. His valuations were in fact financial rather than economic losses and were based on questionnaire surveys of households with livestock. Further examples are the valuation of farm revenue losses due to fox predation of lambs on two Scottish hill farms (White *et al.* 2000b), losses of livestock to snow leopards in Nepal (Oli *et al.* 1994), total losses due to livestock predation in the United States (Conover *et al.* 1995) and annual damage by wolves to livestock in Spain (Blanco *et al.* 1992). Andelt and Hopper (2000) estimated the total amount that producers using guard dogs saved in terms of reduced sheep losses to predators. Other estimates of the costs of agricultural damage by pests have been based on the producers' own estimates of damage, e.g. Baines *et al.* (1995) and Moore *et al.* (1999).

A more sophisticated approach to valuing the financial costs of predation on livestock was developed by Mizutani (1999) for leopards on a Kenyan ranch. This involved estimating production models for sheep and cattle on the ranch with and without leopard predation and calculating the cost of leopards in terms of reduced income to the farm. Production models were used because the impact of predation one year was felt the next year, as the animals took more than an accounting year to mature.

Total cost estimates of wildlife damage allow us to put a value to damage and may enable assessment of whether the animal can be considered to be a pest (or in the case of Butler's (2000) study how much compensation payments should be). However, McInerney *et al.* (1992) argued that total costs have no particular significance because they do not allow us to make decisions about what should be done about the situation, i.e. they are of little use in guiding resource use decisions (McInerney 1996; Perry & Randolph 1999), especially if it is not possible, or will be hugely costly, to eliminate a disease or pest (McInerney & Kooij 1997). Therefore, total costs alone generally do not help us determine what management action(s) should be taken to help alleviate the problem.

1.2.3. Approaches relevant to the economic analysis of predation losses

The resources spent on preventing livestock losses to predators are likely to be traded off against the cost of these losses. Therefore it is not just the total cost of losses and preventive and treatment measures that should be considered in an economic analysis of predation, but how these relate to one another and therefore what is the most efficient point in terms of resource allocation. A number of approaches could be used to analyse the costs of predation in an economic framework, with the aim of aiding resource allocation decisions or efficient management.

One evaluation technique used for assessing pest control is decision theory. Generally, a farmer has to decide what strategy or level of pest control or preventive measures to use before the economic impact of the pest is known. If there is uncertainty about what level of pest attack will occur, but the probability of any particular level of attack occurring is known, the expected outcome of alternative strategies can be determined (Mumford & Norton 1984; Hone 1994). Mumford and Norton (1984) suggested knowledge of the probabilities could be based on past experience. It could incorporate quantifiable factors, such as farm characteristics, for example. The expected outcomes of various preventive or control strategies can be determined in monetary terms via a pay-off matrix (Norton 1976; Mumford & Norton 1984; Hone 1994).

An alternative to risk decision models is the use of marginal analysis, where the costs of preventive measures and/or control are compared with the benefits of reduced losses due to the control effort. Taylor *et al.* (1979) suggested that the production function approach should be used to estimate the optimum rates of predator control and the predator density, which is socially, economically and ecologically acceptable for predation of lambs by coyotes in Utah, by including predator density as an input in the function. The production function approach has been used by environmental economists to value environmental or resource quality for which there is no direct market value (Adams *et al.* 1982; Adams & McCarl 1985; Adams *et al.* 1986; Ellis & Fisher 1986; Mäler 1992; Freeman 1993; Narain & Fisher 1995; Acharya 1998). Whilst more direct market- or resource-based approaches (as discussed above) can be used for valuing livestock mortality due to predation, the approach illustrates how environmental resources can be included in production functions, which could then be used for more detailed analysis, including assessing optimal levels of use of preventive measures (as outlined theoretically for livestock disease by McInerney 1996).

As predation affects losses directly, we can also consider the cost- rather than the production-side of an operation. Fankhauser (1995) developed a cost function for sea-level rise, incorporating the costs of emission abatement, protection costs and the costs of damage due to sea level rise, which he used to find an optimal combination of abatement and protection levels, by minimising the cost function (minimising total costs).

An alternative is to model the impact of control expenditures on losses more directly. McInerney *et al.* (1992) and McInerney (1996) proposed the disease loss-expenditure frontier as a way of estimating the avoidable rather than total costs of livestock mortality caused by disease in economic analysis. McInerney (1996) argued that such a model was more readily applicable to disease control decisions than a production function approach in that it was simple and easily applied empirically. The loss-expenditure frontier gives the general relationship between disease losses (L) and control expenditures (E) at the minimum level of output loss due to disease technically obtainable for each specified level of expenditure; the line L'L" on Figure 1.1a. L' is the amount of losses if no control measures are undertaken and losses decline with progressive increases in expenditure, but at a declining rate because of diminishing marginal returns to disease control effort. In theory, a farmer could choose to accept losses of anywhere between L' and L", where livestock losses are reduced to an absolute minimum, but to minimise total costs in this situation the farmer should spend E_M on preventive measures and accept L_M losses. Point M defines this management strategy at which the lowest cost can be achieved in this situation or the economic optimum (where total costs $C_M = L_M + E_M$). This economically optimal position for disease control expenditure versus loss to disease is when an additional unit of currency spent earns exactly the same additional unit in return (McInerney *et al.* 1992). This defines the point at which the cost of the disease is minimised, if the cost is defined as the loss plus expenditures (McInerney 1996). At this point, the marginal costs of control (MC) equal the marginal benefits of control (MB), where the benefits are defined as the reduction in livestock losses due to control, as illustrated in Figure 1.1b. The optimal point, where the marginal cost and marginal benefit curves intersect, defines both the optimal level of expenditure on control (E_M) on the x-axis and the optimal level of losses the farmer should tolerate (L_M), if the x-axis variable is inverse losses (i.e. benefits) rather than expenditure.

The loss-expenditure frontiers for mastitis in the UK and Scotland have been estimated by McInerney *et al.* (1992) and Yalcin *et al.* (1999), respectively. Both sets of authors estimated the expenditures and output losses associated with specific control procedures and took the lower boundary of these points as the loss-expenditure frontier, the level of technically minimum-attainable revenue loss (technical efficiency) under different levels of mastitis-control expenditure. McInerney and Kooij (1997) used a similar total cost approach to evaluate alternative Aujeszky's disease (AD) control programmes. They considered the total costs of the disease to the economy as a whole and identified the most economic AD control strategy as the one with the lowest total costs. Their analysis indicates how, in addition to quantifying the avoidable costs of livestock mortality, the use of a loss-expenditure type approach could inform decisions on the allocation of resources to control expenditure and therefore identify efficient levels of control.

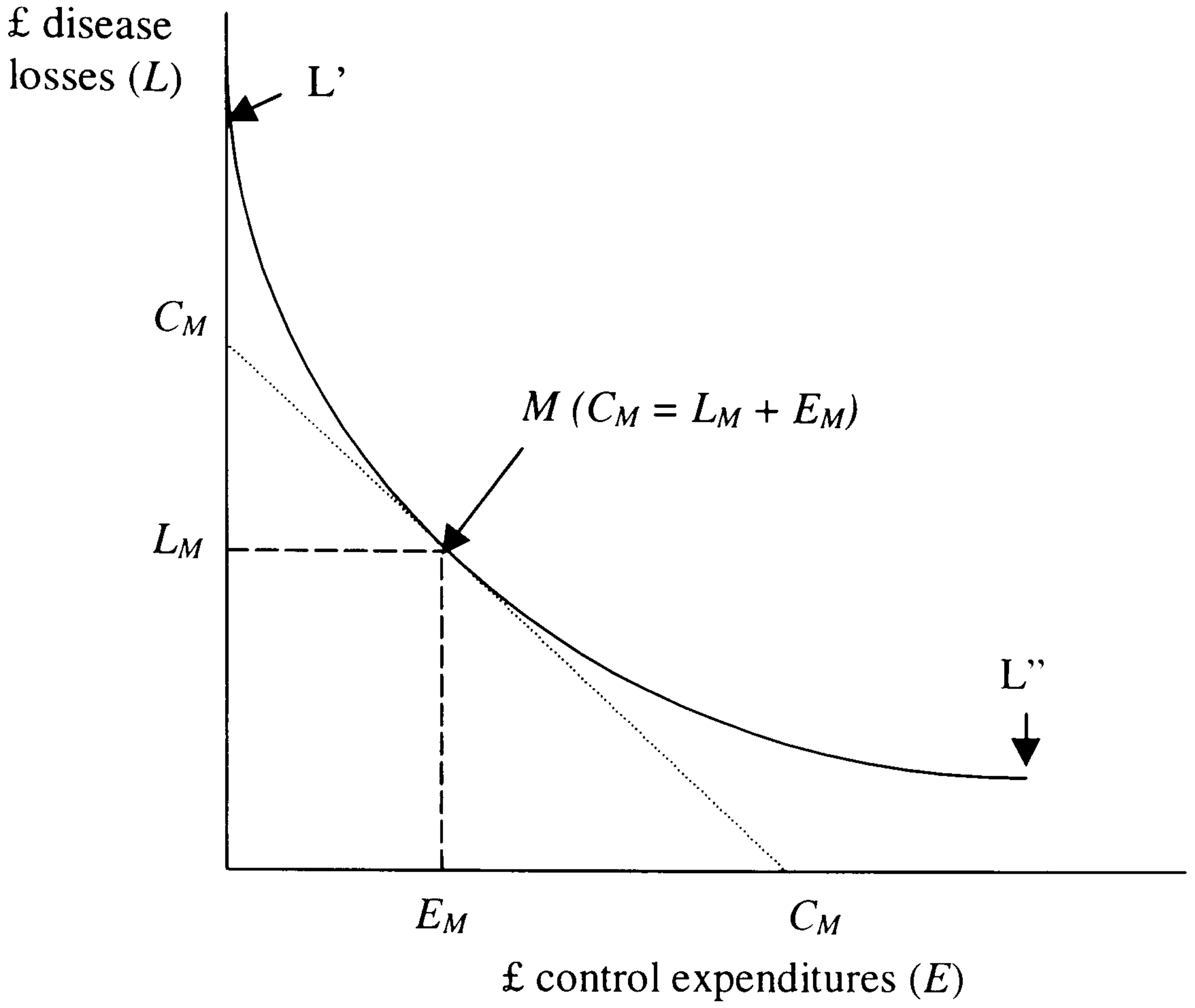


Figure 1.1a: The disease-loss expenditure frontier (from McInerney *et al.* 1992 and McInerney 1996)

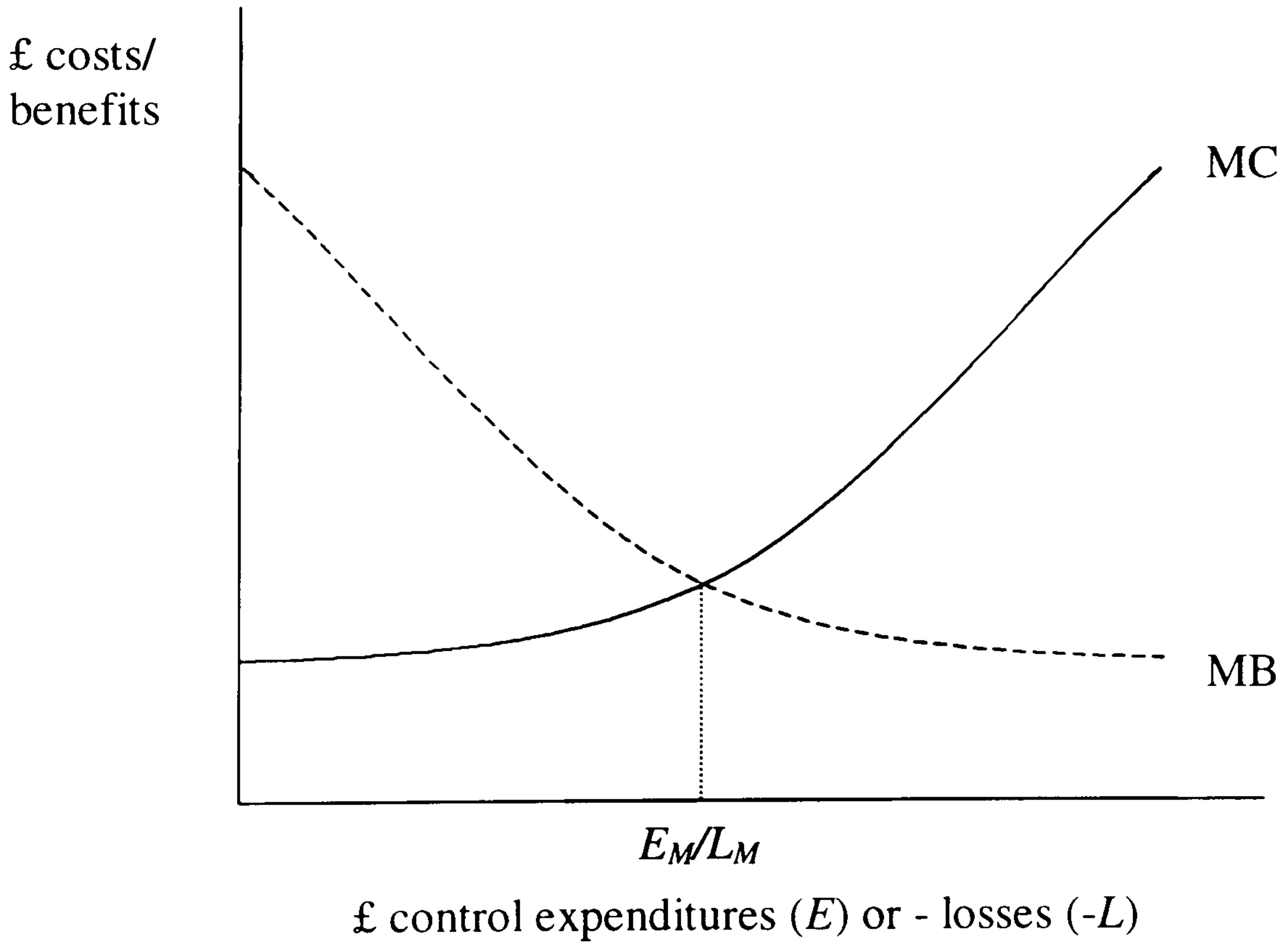


Figure 1.1b: Marginal cost (MC) and marginal benefit (MB) curves for control of stock mortality, illustrating optimal point where curves intersect (E_M/L_M)

1.2.4. Pest abundance and pest damage

The use of these types of analysis for the evaluation of pest management relies on the pest management action having an effect on pest damage. In order to assess this effect, the relationships between pest control and pest abundance and between pest abundance and pest damage need to be specified. Hone (1994) points out that a simple relationship between pest abundance and damage is unlikely and rare because the extent of damage depends on a number of variables other than the pest abundance. These include the destructive potential of each pest animal, which may vary with age, size, genotype and environment, the duration of exposure and the resistance of the object being attacked (Cherrett *et al.* 1971). Other factors may enhance susceptibility to pest damage, such as weather conditions, disease and the availability of alternative food sources. Consequently, direct estimates of damage functions tend to be difficult and expensive to obtain (Choquenot & Parkes 2001).

Choquenot *et al.* (1997) found a positive association between predator densities and predation of livestock for feral pigs and lambs in Australia. This relationship was modelled by Choquenot and Hone (unpublished) in their assessment of the benefits of control strategies to prevent predation by feral pigs. In another Australian study, fox control was associated with lower levels of fox predation on lambs, but not with lower fox abundance (Greentree *et al.* 2000). The results of other studies on vertebrate predators, such as those on sheep predation by other canid species, have been less conclusive (Robel *et al.* 1981; Landa *et al.* 1999). The general lack of data on associations between vertebrate predator populations, control and damage is not surprising given the fact that even linking pest population dynamics with damage or yield loss for invertebrates and weeds, upon which a good deal more research and theoretical modelling work has been carried out, has proved difficult because of the complexity of the systems involved (Kropff *et al.* 1995; Hone 1994).

1.3. FOX DISTRIBUTION AND PEST STATUS WORLDWIDE

The red fox is a widely distributed species and is found throughout most of the northern hemisphere from the Arctic Circle in the north to Sudan in the south (Harris & Lloyd

1991; Gefen & Macdonald 2001). It is native to Europe, Africa and Asia and was introduced to eastern United States in the 1700s from where it spread west- and southward. It is also present in Australia, where it was introduced around 1850 (Lever 1985).

The control of foxes to reduce the damage they cause as a pest takes place across much of their range. In continental Europe, the pest status of the fox is primarily a function of it being the wildlife reservoir for a number of diseases, of which the most significant is rabies (Macdonald 1980; Anderson *et al.* 1981; Smith & Harris 1991; Artois 1997; Romig *et al.* 1999; Chautan *et al.* 2000; Suppo *et al.* 2000; Artois *et al.* 2001). Foxes are also considered a pest in many countries due to their predation of game animals. Examples include gamebirds and hares in Scandinavia (Märcstrom *et al.* 1988; Lindström *et al.* 1994; Smedshaug *et al.* 1999; Kauhala *et al.* 2000; Kauhala 2001), gamebirds in Italy (Lovari & Parigi 1995) and pheasants and ducks in North America (Sargeant 1978; Sargeant *et al.* 1984; Sargeant *et al.* 1995; Schmitz & Clark 1999). Lamb and poultry predation by foxes also causes problems in countries other than Britain (Rowley 1970; Coman 1985; Brochier 1989; Saunders *et al.* 1997; Greentree *et al.* 2000).

Foxes are often a threat to endangered species (Harris & Saunders 1993; Reynolds & Tapper 1996), especially in those areas where they are not native, such as Australia (e.g. Kinnear *et al.* 1988; Abenspergtraun 1991; Cowan and Tyndale-Biscoe 1997; Risbey *et al.* 2000) and California (e.g. Harding *et al.* 2001). Introduced foxes have contributed to the decline and extinction of marsupial populations and adversely affected the range and distribution of many species in Australia (Kinnear *et al.* 1988; Dickman *et al.* 1993). In their natural range foxes also cause problems for species of conservation importance. Examples include passerine birds in Spain (Suarez *et al.* 1993), loggerhead turtles in Turkey (Yerli *et al.* 1997) and songbirds in Canada (Dion *et al.* 1999).

1.4. STATUS OF FOXES IN BRITAIN

1.4.1. Population estimates for the whole of Britain

Foxes are found throughout the British mainland. They were (until recently) absent from all the Scottish islands except Skye (Harris & Lloyd 1991; Harris *et al.* 1995), but appear to have been introduced recently to Harris in the Outer Hebrides (Harris *et al.* 1995). A population estimate for the whole of Britain of 252,000 adult foxes in the Spring, which could double by late summer with the inclusion of juveniles and itinerant adults, was made by Macdonald *et al.* (1981). To calculate this figure, fox density estimates were made for each square in a sample of 256 1km grid squares, then mean estimated densities were calculated for Institute of Terrestrial Ecology (ITE) land classes to obtain a map of densities across Britain.

However, this figure is unlikely to be wholly accurate (Harris *et al.* 1995) and an estimate, attempting to overcome these problems, puts the total pre-breeding population of foxes in Britain at 240,000 (195,000 in England, 23,000 in Scotland and 22,000 in Wales), including barren vixens and itinerant foxes (Harris *et al.* 1995). The total urban fox population is estimated at 33,000 (30,000 in England, 2,900 in Scotland and 100 in Wales), whilst, if a mean litter size of five is assumed, around 425,000 cubs are born each spring (Harris *et al.* 1995). Of these estimates, those of urban populations are likely to be more accurate because precise data (from the studies outlined below) are available, whereas estimates for rural areas are less reliable due to paucity of population data (Harris *et al.* 1995).

Rural population estimates were based on the few studies done in Britain (see below). These density estimates were assigned to land classes and mean densities estimated as the number of social groups per square kilometre. The number of foxes per social group was estimated from available data on the demography of rural foxes, but this is also very scarce (Harris *et al.* 1995). In addition, the use of land classes to extrapolate fox densities is questionable because it relies on the assumption that fox densities are mainly determined by landscape and habitat-related factors (Heydon *et al.* 2000). Heydon *et al.* (2000) found that predictions of fox densities based on landscape variables did not always fit in with estimates of fox densities obtained by alternative methods and hypothesised that another factor, such as culling by man, was influencing fox densities in some regions. Therefore, density estimates based on regional rather than landscape variables may be more reliable. However, it should be noted that the quality of the original data in Harris *et al.*'s (1995) estimate of fox density using landscape extrapolation was questioned by the authors themselves and these same data were used by Heydon *et al.* (2000) to compare with other estimation techniques.

The numbers of foxes killed by gamekeepers has been increasing since 1960 (Tapper 1992; Heydon & Reynolds 2000a), which suggests that fox numbers may be increasing (Tapper 1992; Harris *et al.* 1995). This increase may be due to any of several factors: an increased rabbit population and increase in other food supplies, such as reared pheasants; the presence of sheep carrion in upland areas; the exploitation of urban food resources; and the relaxation of control by man (Harris *et al.* 1995). However, the magnitude of any change in fox populations and the definite causes behind any change are unknown.

1.4.2. Local and regional fox population estimates

Several studies have been carried out investigating urban fox populations (Harris & Rayer 1986; Harris & Smith 1987a; Harris & Smith 1987b; Harris & Woollard 1988) and estimates have been made for the sizes and distribution of populations in Bath, Birmingham, Bournemouth, Bristol, Cheltenham, Coventry, Dudley, Gloucester, Leicester, Nottingham, Poole, Solihull, Walsall and Wolverhampton (Harris & Rayer 1986). These studies combined the results of a Spring count of the number of fox litters in an area of each city with the results of a sightings survey by school children; and fox densities were described using fox family group as the basic recording unit (Harris & Rayer 1986). From these data, predictive models for estimating mean fox density values from sociological data in urban areas were developed (Harris & Smith 1987b), meaning that population densities for any city in Britain can be estimated.

Estimating fox populations in cities, although difficult, is easier than in rural areas, and much of the study of fox ecology has been centred upon urban areas. This means that there are few data on rural fox populations. Hewson (1986) investigated the numbers and distribution of breeding dens in different habitats in Scotland to get an indication of fox numbers. He found an average of one den per 31.9 km^2 in deer forest; one per 23.3 km^2 grouse moorland; one per 20.2 km^2 on estates with a mix of agricultural land and moorland; and one per 10.1 km² on agricultural land (with game management). However it was not possible to relate the number of dens to the number of foxes, so a ratio, from Lloyd (1980), of 2.67 foxes to each litter found per km² was used to estimate density: 0.08 foxes per km² in deer forest, 0.11 per km² on grouse moorland, 0.13 per km² on a mix of agricultural land and moorland and 0.27 per km² on agricultural land (Hewson 1986).

In May 1974, the Forestry Commission carried out a survey of fox breeding dens in the New Forest to estimate the population density. The survey covered a 20 per cent sample of the forest and numbers were extrapolated to obtain a figure of 2.18 (+/- 0.45) foxes per km² for the 271 km² area of the New Forest (Insley 1977). However, this study will not have counted non-breeding or itinerant foxes and there is debate as to how reliable population estimates based on counting the number of breeding dens are (Insley 1977).

Local fox population numbers were estimated for two sites in southern England, on Salisbury Plain and Dorset for the three years 1985-87 (Reynolds *et al.* 1993). The adult breeding population was estimated, after the mean territory and mean breeding group sizes had been calculated via a radio-tracking study, and expected cub production was estimated using two models: 'minimum population model' and 'territory packing model'. However, the figures were used for a comparison with the numbers of foxes culled and to estimate impacts on the population, so no definitive numbers are estimated. Quoted figures for the expected number of adult foxes, calculated using the two models, range from between 14 and 30 for the 15.2km² Salisbury Plain area, and 10.1 to 27.5 for the Dorset 11.0km² area. These numbers did not, however, include itinerant foxes or immigrants that replaced culled foxes (Reynolds *et al.* 1993).

Hewson has carried out studies investigating changes in the numbers and distribution of foxes in Scotland using data on fox kills (assuming these provide a reliable index of population changes) (Hewson & Kolb 1973; Hewson 1984a). He found that overall more foxes were killed in 1971-78 than 1961-68, but that there were differences between regions in the direction of annual changes in kills (Hewson 1984a). The use of kill data enables trends in population numbers over time to be looked at if constant control effort can be assumed, but does not give true population estimates. Hewson

(1984a) associates changes in fox numbers with changes in the number of field voles available as food; as is the case in north-east and west Scotland (Kolb & Hewson 1980) and Lochaber (Hewson 1984a).

Heydon *et al.* (2000b) carried out a regional study of fox populations in three rural areas of Britain, in mid-Wales (Region A), east Midlands (Region B) and East Anglia (Region C), between 1995 and 1997, using line-transect survey techniques and censuses of fox breeding dens. The line-transect techniques gave estimates from 0.32 to 1.05 foxes per km^2 for Region A, from 0.79 to 2.76 per km^2 for Region B and from 0.14 to 0.60 per km^2 in Region C between Autumn 1995 and Spring 1997, the lowest estimates being for Spring. These estimates were based on counts in open habitat only, forested areas being excluded from analyses. Density estimates for 1996 of 0.64±0.26 foxes per km^2 for Region A (revised to 0.73±0.29 per km^2, on inclusion of a percentage of barren females as found by Lloyd (1980)), 1.06±0.24 per km^2 for Region B and 0.34±0.13 per km^2 for Region C were obtained by censusing breeding earths.

1.5. MANAGEMENT OF FOX POPULATIONS IN BRITAIN

1.5.1. Reasons for management of fox populations

The management of fox populations is taken to mean any deliberate interventions by man to manipulate the number, structure, distribution, and impact of foxes living in a defined area (Macdonald *et al.* 2000). Several studies have used surveys to determine the reasons why farmers and landowners in various regions of Britain undertake fox control (Macdonald 1984; Baines *et al.* 1995; Macdonald & Johnson 1996; Heydon & Reynolds 2000b; White *et al.* 2000a). The majority of farmers and landowners stated that their intention was to achieve several goals (Burns *et al.* 2000). Reasons given include reducing rates of predation on livestock and game, as well as on wildlife, reducing the spread of disease, for sport and as a good neighbour policy, with the most frequently cited reason in four of these studies (Macdonald 1984; Baines *et al.* 1995; Macdonald & Johnson 1996; White *et al.* 2000a) being to reduce fox abundance (Burns *et al.* 2000). Macdonald *et al.* (2000) suggest that a farmer's objectives are driven by the amount of damage it is perceived would occur in the absence of control.

There were regional differences in the reasons farmers and landowners gave for fox control and how these explanations were prioritised, which are related to a large extent to differences in farming practices and land-use between regions. There were also response differences with farm size (Burns *et al.* 2000). Control measures on larger farms seemed to be undertaken more as a preventive measure than as a reaction to recent experiences of fox predation (Burns *et al.* 2000; Heydon & Reynolds 2000b). In general, though, the studies suggest that recent experience of stock predation did influence a farmer's decision on whether to carry out fox control. In Heydon and Reynolds' (2000b) study of three regions in mid-Wales, east Midlands and East Anglia, 72 per cent of farmers that controlled foxes stated that they aimed to contribute to regional fox control, rather than just remove troublesome foxes or reduce the number on their land. One problem with all the above studies, however, is that they tend to be biased towards lowland farms in England.

1.5.2. Methods used to manage fox populations and published information on fox population management

As with the fox population data, there is little precise information on fox management across the country, with few individual studies of management practices. There is no nation-wide strategy of fox control or management, with individual parties carrying out management independently, often with no specific plan or goal. A variety of different methods are used to kill foxes in Britain: lamping with rifles, shooting by day, hunting with hounds (gun-packs, on foot and horseback), digging out with terriers, lamping with lurchers, snares, traps, poisoning and gassing (Burns *et al.* 2000), with the use of these methods varying regionally (White *et al.* 2000a). There is, however, very little information on the number of foxes deliberately killed each year or on which methods are used (Burns *et al.* 2000). It has been estimated that 185,000 foxes are deliberately killed by humans in Britain per year (Pye-Smith 1997), 80,000 being shot, 50,000 dug out with terriers, 30,000 snared, 15,000 killed by fox hunts and 10,000 killed by lurchers.

Insley (1977) states that 80 to 100 foxes were killed each season by hunts in the New Forest in 1974, while foxes were shot on neighbouring estates and farms (though no numbers were known, apart from a figure of over 40 annually for one estate). Lloyd (1968) provides a summary of fox control in Britain, but this is unlikely to be generally applicable now due to changes in practices in the last 30 years. (For example, changes in the enforcement of laws governing the use of snares and poisons and in the laws themselves, as well as in the provision of bounties for killing foxes.)

Hewson (1984a) used data from various sources on fox kills in Scotland and states that the Forestry Commission annually killed more foxes than any other organisation (mostly by snaring) and had records covering over 20 years. Foxes were also killed by fox destruction clubs and hunts (Hewson 1984a). The figures from this study provide a time series of fox kills in Scotland, as well as some idea of regional variation in the years 1971 to 1978, with previous data from 1948 to 1970 also being available (Hewson & Kolb 1973). In 1992, the Forestry Commission's policy on fox control was revised and now the emphasis is more on a 'quick and effective response to lamb killing by foxes on land adjacent to Forestry Commission forests' thus controlling only the specific individuals that cause problems (Chadwick *et al.* 1997).

1.5.2.1. Hunting with dogs

A study of fox hunting in Wiltshire (Baines *et al.* 1995) showed that farmers overestimated the number of foxes killed on their land by hunts, compared to the figures obtained from hunt Masters. In the 1994/5 hunting season (late summer to March or April), 0.11 foxes were killed per km², according to hunt Masters of the hunts active in Wiltshire. In addition, in this same year, a mean weighted density of 2.15 foxes per km² were shot by farmers. Shooting occurred year round, but in this year efforts were concentrated in March (Baines *et al.* 1995). A study looking at three regions of Britain (mid-Wales, east Midlands and East Anglia) also found that farmers significantly overestimated the number of foxes killed by mounted fox hunts and foot packs, with the scale of the overestimation being between seven and twelve times (Heydon & Reynolds 2000b). In a study of the impacts of fox-hunting in west Somerset and Exmoor (Manley *et al.* 1999), it is stated that fox hunts were willing to be and were called out to deal with specific 'problem' foxes. The study covered Exford and Stogursey and, in both places, fox control was mainly left to the local hunt. However, the numbers of foxes killed were not among the data collected.

Macdonald and Johnson (1996) carried out a survey of fox hunts across the country and found that hunts killed more foxes during 'cubhunting' than hunting proper and that hunting is less effective as the season progresses, also indicated by data discussed in Macdonald *et al.* (2000). Cubhunting takes place in September and October prior to the start of the fox hunting season in November and is intended to move foxes and encourage dispersal (Macdonald & Johnson 1996). Foot hunting packs in Welsh uplands were found to kill far more foxes than mounted hunts in the same region (at least an order of magnitude more). A mean density of 0.10 foxes were killed per km² by hunts between 1960 and 1980, which gives a figure of approximately 14,500 foxes killed annually by hunts during this period, in Britain. More foxes were killed per km² during the late 1980s (nearly 0.15), due to an increase in foxes killed by hunts in the South. There was regional variation in fox kills by hunts, with more killed in the South than the North. This was also the case with foxes killed by gamekeepers, though figures were highest in the Southwest, which is not true for hunting kills. Farmers were found to kill the most foxes per km² in the Wales and the West region and the least in the North (Macdonald & Johnson 1996).

Harris and Lloyd (1991) summarise available data, estimating that around 12,500 foxes are killed each year by hunts (a figure of 15,000 is estimated by Macdonald and Johnson, 1996), whilst, between 1965 and 1980, 22,000 foxes were killed annually by the Forestry Commission and the 221 fox destruction societies of England, Scotland and Wales (Lloyd 1980). More recent estimates put fox kills by Masters of Fox Hound Association (MFHA)-registered hunts at between 14,000 and 15,000 per year and kills by upland foot and gun packs at 7,000 to 10,000 (Burns *et al.* 2000). Heydon and Reynolds (2000b) collected data on fox kills by hunts and by gun packs. Hunt culling levels for the study regions as a whole were highest in the east Midlands region at 0.13 foxes per km^2, six times higher than in the East Anglian region where 0.02 foxes were killed overall per km^2. In the mid-Wales region, mounted hunts killed 0.09 foxes per km^2 overall, whilst foot packs killed 0.50 foxes per km^2. Hunts often keep fox cull records from which it is possible to obtain figures. However, the only feasible way to obtain information from other individuals carrying out fox control (such as farmers and gamekeepers) is by asking them after the control event (Heydon & Reynolds 2000b).

1.5.2.2. Management by parties other than organised hunts

Fox control, mainly shooting with rifles, by gamekeepers occurs on most game estates in Britain. Pye-Smith (1995) estimated that gamekeepers kill between 70,000 and

80,000 foxes a year in Britain, but Macdonald *et al.* (2000) believe this figure to be an over-estimate. Data from the Game Conservancy's National Game Bag Census (Tapper 1992) show that approximately 2.0 foxes per km² per year were killed by gamekeepers within shooting estates between 1980 and 1990. Reynolds *et al.* (1993), also quoting data from the National Game Bag Census, state that between 1970 and 1980, the regional average number of foxes killed per year could be as high as 5 per km² in some years, with more than 100 foxes killed per km² per year on occasion on some estates. The highest numbers of foxes were killed in southern England (Tapper 1992). By extrapolating figures from the National Game Bag Census, Macdonald *et al.* (2000) estimate figures of 38,000 foxes killed by gamekeepers in 1992 and 37,000 in 1998 in England and Wales. They also carried out a stratified analysis, dividing Britain into ten regions and came up with a figure of 39,000 foxes killed annually on shooting estates, including those with no gamekeepers, in England and Wales (Macdonald *et al.* 2000). However, the number of gamekeepers in Britain is not known precisely, nor is the number of individuals who actively cull foxes (Macdonald *et al.* 2000).

In a survey of farmers in ten regions representative of lowland agricultural landscapes in England (Macdonald 1984), 32.6 per cent of farmers said that they controlled foxes, while 44.4 per cent of farmers in a survey sample of 'midland' farmers (Oxfordshire, Buckinghamshire, Northamptonshire and Warwickshire) attempted fox control, half as a matter of annual routine and half only in response to sporadic damage (Macdonald 1984). Lloyd (1980) estimates that a reasonable figure for the total number of fox kills in 1978 was 100,000 minimum. A figure of 477,000 foxes killed across England and Wales in 1980, based on an average of 2.3 foxes killed per km^2 a year, is estimated by Macdonald *et al.* (2000), based on data from Macdonald and Johnson (1996), whilst in 1995 an average of 2.26 foxes were killed per km^2 in Wiltshire by farmers and hunt Masters (Macdonald *et al.* 2000).

In Heydon and Reynolds' (2000b) survey of farmers and landowners in study areas in mid-Wales, east Midlands and East Anglia, 88 per cent of respondents reported that fox culling occurred on their land, with variation in culling frequencies between regions, with farm size and farm type. Of the farmers that stated that fox culling occurred on their land, 44 per cent relied on the services of organised groups for this, but the overall numbers of foxes killed by organised groups relative to the overall cull were low (less than 10 per cent), with the exception of gun packs in mid-Wales. On average, farmers and landowners that practised culling killed 5.1 foxes per km^2 in the mid-Wales study region, 3.57 foxes per km^2 in the east Midlands region and 3.22 foxes per km^2 in the East Anglian region. Regional estimates, taking account of non-cullers, farm size and presence of a gamekeeper, were made, giving figures of 1.31 foxes killed per km^2 in the mid-Wales study region, 1.71 per km^2 in the east Midlands region and 2.63 per km^2 in the East Anglian region. A minimum likely cull, which took farmers' overestimates of hunt kills into account led to a decrease in these estimates with 0.11 foxes killed per km^2 in the mid-Wales study region, 0.24 per km^2 in the east Midlands region and 0.39 per km^2 in the East Anglian region. Data from this study also indicated that culling levels between 1992 and 1996 increased significantly in the mid-Wales and East Anglian study regions.

It should be noted that the frequency of culling indicated by Heydon and Reynolds' study is much higher than that found by other studies of this type. This may be, as the authors suggest, because the study was more comprehensive than previous ones with a greater sampling intensity of the regions covered. However, there could be alternative reasons for this difference. One reason is that there was a sampling bias, caused by self-selection, in that more farmers and landowners that culled foxes participated in the surveys. The authors did undertake a follow-up telephone survey of non-respondents to detect such bias, but 16 to 18 per cent of those followed up declined to participate, which could still mean that the study was affected by a self-selection bias.

1.5.3. Effectiveness of fox population management

A number of studies have addressed the effectiveness of fox management strategies. There is a problem, however, in that, in order to judge effectiveness, a clearly defined, quantifiable objective is needed, whilst in practice an objective for fox management is rarely explicitly stated (Caughley & Sinclair 1994; White *et al.* 2000a). The objective could be to reduce damage by foxes or increase production; or to reduce fox numbers. However, these objectives are not necessarily intrinsically linked: a reduction in fox numbers will not necessarily translate into a reduction in a perceived problem (Burns *et al.* 2000). In addition, the number of foxes and the significance of the damage they cause are difficult to assess, whilst the geographical scale of fox culling is variable, so culling efforts may be deemed successful or unsuccessful depending on the scale at which they are considered (Macdonald *et al.* 2000). In the main, studies have considered the effectiveness of fox control with regard to reducing fox numbers.

Based on average population demographics, it appears that fox culling levels need to be high to limit population growth (over 67 per cent removal in the absence of immigration and non-breeding subordinate individuals) (White *et al.* 2000a). Population models indicate that if sub-adults are culled, more moderate cull levels (30 per cent of sub-adults removed and 10 per cent of adults) may result in reductions in fox abundance (Macdonald *et al.* 2000). Modelling work indicates that dispersal and the timing of culling are important in determining the effectiveness of fox control (Macdonald *et al.* 2000; White *et al.* 2000a).

According to a study in Scotland (Hewson 1986), non-selective control of foxes (killing from October to the end of March, away from breeding dens) neither reduced the breeding population, though it may have prevented it from increasing; nor did it reduce complaints of lamb-killing. Kolb and Hewson (1980) conclude their study of fox populations in Scotland from 1971 to 1976 by stating that it was unlikely that the level of control at that time was limiting the fox population of Scotland as a whole. Therefore, a far greater expenditure and effort in control than was occurring would be necessary to reduce fox populations and maintain them at a low level over large areas (Kolb & Hewson 1980). However, destruction of foxes at dens often stops local instances of lamb killing and may even be effective if only cubs are killed, as has been the case with coyotes in America (Hewson 1986). Macdonald and Johnson (1996) argued that culling by hunting with hounds was ineffective in limiting regional fox populations.

Reynolds *et al.* (1993) conclude their study of two sites in Dorset and on Salisbury Plain by stating that fox control had a local impact only on fox numbers and the areas became 'sinks', with the effect of control being removed every year by immigration of juvenile animals. Harding *et al.* (2001) used data on native water bird populations and red fox control in California and population modelling to assess the effectiveness of control to protect bird populations. They found control to be effective in the short term, but suggested that long-term success may require efforts to control juvenile and immigrant foxes. It is often the case that more foxes are killed on an area of land than could possibly ever live on it because of immigration (White *et al.* 2000a). This is further illustrated by Jenkins *et al.*'s (1964) findings at Glen Esk in Angus between 1956 and 1961, where predator numbers (mainly foxes) were not primarily controlled by gamekeepers, as a similar number appeared every year despite predator destruction. In addition, culling will set density-dependent processes into action, which tend to compensate for the effects of lethal control (Caughley & Sinclair 1994) and may result in numbers higher than before control (Van Vuren & Smallwood 1996). Population control, therefore, may result in a short-term (and quick-acting) attenuation in the problems caused by a pest, but necessitates population reduction to be sustained year after year if this effect is to be maintained (Putman 1989).

In Heydon and Reynolds' (2000a) three-region study, the impact of culling on fox populations on a regional (rather than a local) scale was considered. The authors compared levels of culling relative to estimated productivity of the population in the study regions. They assessed evidence for female pre-natal reproductive suppression, believed to be evident only in fox populations at or near carrying capacity. They concluded that in the mid-Wales and East Anglian study regions, culling effectively reduced fox populations below the carrying capacity of the environment, as the culls in these regions were high relative to estimated productivity and they found little evidence of female reproductive suppression. In the east Midlands study region, however, the fox cull was low relative to estimated productivity and there was evidence of reproductive suppression in females. Estimated productivity differed significantly between regions. The difference between fox productivity and cull data was only statistically significant for the east Midlands region, however. Therefore, the authors' interpretation of these results must be treated with some caution. In addition, Heydon and Reynolds suggest that the East Anglian region was effectively a 'sink' for dispersing foxes from other nearby regions, which suggests that fox control is only effective if it is continuous in time (as studies of the effectiveness of fox control on a local scale have suggested).

Some control of urban fox populations has taken place in the past, but its effectiveness is questionable. In south and southeast London, in 1983, Local Authorities trapped and dug out litters of cubs, as well as undertaking some shooting and gassing. This led to no significant reduction in the number of family groups each Spring, but a reduction in total numbers of adult foxes (by 20 per cent) and cubs (by 12 per cent) in the population (i.e. a mean decrease in family group size) (Harris & Smith 1987a). There was no effect on the number of cubs born nor on the number of complaints received from householders, despite a cost of £70 per fox to kill 164 foxes (Harris & Saunders 1993).

Côté and Sutherland (1997) reviewed twenty studies in order to achieve an overall perspective on the effectiveness of predator removal in protecting bird populations. Although this study was not specifically about foxes, but predators in general, studies on fox control were included in the analysis. They found that predator control was often effective in fulfilling a game manager's goal of high post-breeding (autumn) population sizes, but less frequently achieved a conservationist's objective of keeping long-term breeding numbers high. In 75 per cent of declining populations, predator removal failed to stem the decline. Reynolds *et al.* (1998) came to a similar conclusion, judging that predators have a significant influence on game bird breeding production but effects on breeding density are usually less significant during the breeding season. An experimental reduction in predator abundance (foxes, carrion crows and magpies) during the nesting period of grey partridges led to a significant increase in the proportion of partridges that bred successfully, as well as in the average size of their broods, with effects continuing over several years with ongoing predator control (Tapper *et al.* 1996).

Côté and Sutherland (1997) found that it was difficult to eliminate the effects of emigration in judging whether a bird population had increased. Early avian mortality was reduced considerably and significantly by predator removal, but on the mainland, removal needed to be kept up in the long term in order to produce long-lasting effects. They concluded by suggesting that habitat improvement may be a more cost-effective way of spending resources. Removal of one predator species was not always effective because, in some cases, the empty niche left by one predator may have been filled by another. Therefore, control efforts should consider wider predator guild level and ecosystem effects, rather than single species alone.

1.5.4. Other factors influencing fox population densities

Fox mortality is believed to be caused mostly by humans (Harris & Smith 1987a; Harris & Lloyd 1991; Reynolds & Tapper 1995), either by deliberate killing or accidentally.

via road deaths and poisoning (Chautan *et al.* 2000). It has been estimated that 100,000 foxes are killed annually on roads in Britain (Pye-Smith 1997). In a study of fox mortality in urban Bristol, the most common cause of death for adult foxes was road accidents, whilst death by disease was also important (Harris & Smith 1987b). It is difficult to assess the importance of disease and parasitism in influencing fox populations, especially in the long-term (Chautan *et al.* 2000). Sarcoptic mange (*Sarcoptes scabei*) may be important in regulating fox populations, especially at high densities. The disease has had dramatic effects on Nordic fox populations, considerably reducing their abundance (Lindström *et al.* 1994; Forchhammer & Asferg 2000), whilst it has similarly reduced study populations in Bristol (Baker *et al.* 2000). It is likely that factors vary in the relative magnitude of their importance in influencing fox populations according to whether the foxes are in urban or rural areas (Chautan *et al.* 2000), with deliberate killing by humans being more important in the countryside than in towns.

Apart from human-induced death and disease, fox population numbers are mainly influenced by factors related to food supply. This association is illustrated by: the correlation between fox population numbers and numbers of field voles (Kolb & Hewson 1980; Hewson 1984a); the marked peak in the number of foxes killed in Scotland with the advent of myxomatosis in 1955/56 (when there were many ailing or dead rabbits), followed by a decrease over the next three years (Hewson & Kolb 1973); and the increase in reproductive success and/or cub survival in Scotland with increased amounts of carrion due to a severe winter (Hewson & Kolb 1973). It has also been suggested that afforestation may bring about local increases in fox numbers due to the increases in field vole numbers following ploughing and planting (Hewson 1986). The effect of prey availability on fox demographics seems to be more pronounced when food resource diversity is low, in winter and in northern regions (Chautan *et al.* 2000). It has been estimated that around 40 per cent of all fox mortality is due to natural factors (White *et al.* 2000a). However, as with information on foxes killed by man, data are lacking on the number of foxes dying due to non-human-induced causes.

Foxes are territorial animals and live in family groups (Harris & Lloyd 1991). The size of their territories varies with habitat type, as well as being dependent on food availability and the density of foxes (Lloyd 1980; Macdonald 1980; Harris & Lloyd 1991). Fox population numbers appear to be regulated by the number of territories a particular habitat can support, through changes in their litter sizes and the percentage of barren females in a family group (Kolb & Hewson 1980; Harris & Smith 1987b; Lindström 1989; Cavallini & Santini 1996; Chautan *et al.* 2000; Heydon & Reynolds 2000a). However, for their model of fox population dynamics, Suppo *et al.* (2000) assume that fox fecundity is not influenced by population density because according to them, there is a lack of variability in fertility rate across Europe, also supported by Harris and Smith (1987a)'s results for Bristol's fox population. The probability of dispersal is likely to be influenced by population density (Kolb & Hewson 1980), whilst mortality due to disease, fights with other animals and other causes has been shown to increase with increasing density (Lloyd 1980; Macdonald 1980; Harris & Smith 1987a). Therefore, fox populations are subject to some density-dependent processes that will tend to limit them at high densities and lead to population growth when densities are reduced.

1.6. FOXES AND AGRICULTURE IN BRITAIN

1.6.1. The fox as a pest

A survey by Baines *et al.* (1995) asked farmers in Wiltshire to quantify the costs of certain mammal species as pests to their farms. In general, the fox was quoted as being the fifth most expensive pest (after the public, badgers, rabbits and pigeons), with non-dairy farmers reporting losses that were on average second only to the public. Using the same data set, but interpreted in terms of the score farmers gave according to the financial damage inflicted by pests, foxes were third worst pest (after rabbits and badgers) overall and third after corvids and badgers for non-dairy farmers (Baker & Macdonald 2000). Of respondents to Macdonald's (1984) survey of farmers in lowland England, 30.2 per cent reported experiencing significant damage due to foxes. On average, gamekeepers in Wales and the Midlands considered foxes to be their most serious pest (Packer & Birks 1999). As discussed earlier, prevention of damage by foxes is a major reason why they are culled across Britain. It is the predation of newborn lambs, poultry and newborn piglets that brings foxes into conflict with farmers, whilst predation on game birds conflicts with game shooting interests. However, there is a lack of available information on these predation impacts and the factors that influence them, especially for predation on poultry and piglets, whilst there has been no assessment of their cost to farmers, producers and game interests. This study aims to address this lack of research.

The perception of foxes as carriers of disease also makes them a pest in many farmers' eyes. In a questionnaire survey of farms in nine regions of England, 45.8 per cent of farmers cited the fox's role in spreading disease as one of the reasons why fox control should be carried out (Macdonald 1984); whilst a third of farmers surveyed in a study in Wiltshire thought foxes should be controlled for this reason (Baker & Macdonald 2000) and 10.1 per cent of respondents overall in Heydon and Reynolds' (2000b) study gave this as a reason for culling. Thus farmers consider the spread of disease by foxes to be a fairly important problem, although in Macdonald's (1984) study, it was not one of the three most commonly stated reasons as most important for fox control. Foxes have been found to carry a variety of diseases, which they may pass on to livestock, but there is very little known about the transfer of parasites from foxes to other animals (Richards *et al.* 1995; Macdonald *et al.* 2000; White *et al.* 2000a). There is no clear evidence that foxes have been a significant contributory factor in any disease in Britain and fox control specifically to prevent disease transmission is considered unwarranted (White *et al.* 2000a). Because of this lack of evidence to suggest that disease transmission by foxes is significant and the lack of available data to assess the impact, it is not further investigated in this thesis.

1.6.2. Collection of data on livestock predation

There are three main ways of collecting information on predation: manipulative experiments, monitoring prey populations during changes in predator density and collecting data on the extent of predation in different situations (Reynolds & Tapper 1996). With regard to livestock predation, these methods can be subdivided and within the third category range from questionnaires, surveys and personal interviews through domestic animal claims and field post-mortem examinations to direct observation (Hone 1994). The accuracy and reliability of data increases along this list of methods, as does the resource cost (with direct observation of predation being especially difficult) (Knowlton *et al.* 1999), whilst the sample area under consideration is reduced. Therefore the decision of which method will be used to study predation requires a compromise between these three attributes. For this research, the questionnaire survey approach was considered the most appropriate, given that coverage of predation impacts on a national scale with limited resources was required. Data on livestock predation are therefore based on the perceptions of those surveyed and throughout the thesis the terms 'perceived' and 'reported' are used as qualifiers to predation loss data because they have not been verified as actual loss data. The analysis of perceived loss data can be justified by the fact that individuals tend to act on their perceptions, so any preventive or reactive actions are likely to be based on these rather than actual losses.

1.7. AIMS AND OUTLINE OF THESIS

The fundamental step to effective pest control is determining the pest status of an animal (Hone 1994) and there are a number of reasons why the losses caused by pests should be assessed (Judenko 1973). It is only by determining the extent and significance of damage caused by pests and its associated costs that the need for management can be assessed (Reynolds & Tapper 1996; Moore *et al.* 1999). To this end, this thesis aims to assess the problem of fox predation to agricultural interests and undertake analysis of population control with the aim of reducing these problems, where such analysis is possible.

In addition to assessing the extent and significance of damage caused by a pest, it is important to identify the factors that influence predation impacts. By doing so, husbandry and management techniques that may alleviate predation problems can be identified. This forms the basis for the implementation of effective preventive measures. It also allows targeting of future research into management options for damage limitation at the areas and situations where damage is most significant (Moore *et al.* 1999; Stahl *et al.* 2001; Tourenq *et al.* 2001). The methods used to effectively manage carnivore-livestock conflicts will differ depending on whether attacks are evenly distributed spatially or if they are concentrated on a small proportion of holdings and it is important to collect data in a variety of habitat and husbandry contexts (Stahl *et al.* 2001). Therefore, one of the aims of data collection for this research was to survey a wide range of such contexts wherever possible and to investigate what factors influence perceived predation by foxes across Britain.

Foxes are one of those animals that Putman (1989) points out are only pests in certain contexts and, as is often the case, how they are viewed depends on how individuals are personally affected by their actions (Messmer 2000). In addition to their costly impacts, foxes have a positive value to many in the British Isles. Therefore, it is not the aim of any pest control objective to reduce fox population abundances to zero and alternatives to lethal population control are to be preferred in many circumstances. Accordingly, this thesis also aims to identify non-lethal measures that aid prevention of fox predation through analysis of the husbandry and management factors that influence predation.

In this thesis, the impact of fox predation is quantified for four sectors of British agriculture: sheep farming, free-range poultry production, outdoor pig production and game interests. Data were collected through questionnaire surveys of these interest groups. The first three chapters of the thesis focus on sheep producers. In Chapter 2, the factors influencing fox predation of lambs are assessed, in order to determine those situations where the impact of damage is most significant and identify any preventive measures that might help reduce these impacts. Chapter 3 involves the development of a framework to evaluate the costs of fox predation to sheep farmers in terms of lamb losses and preventive measures, in this case indoor housing, based on the analyses of Chapter 2. This framework is developed from the theories outlined earlier in Section 1.3.2 and tested empirically using survey data. In Chapter 4, this analysis is furthered by including the costs of fox control.

Chapter 5 focuses on free-range poultry production and uses the analyses of Chapters 2 and 3 as a basis for assessing the impact of fox predation on poultry producers. The impacts of fox predation on outdoor pig producers and game interests are analysed in the same manner in Chapters 6 and 7, with Chapter 7 focusing on the predation of pheasants from release pens. In Chapter 8, the overall results of the study are discussed and conclusions drawn. Potential approaches for future research are also outlined.

CHAPTER 2

FACTORS INFLUENCING PERCEIVED FOX PREDATION OF LAMBS ON SHEEP FARMS

2.1. INTRODUCTION

One of the most significant perceived impacts of the fox in Britain is the predation of lambs from sheep farms. The Ministry of Agriculture, Fisheries and Food (MAFF 1996) attributed five per cent of lamb losses to 'predators/misadventure', stressing that this could include predation by dogs as well as other causes. Various studies in Britain involving surveys of sheep farmers have assessed the magnitude of this perceived problem (Macdonald 1984; Anon 1993; Macdonald & Johnson 1996; Baker & Macdonald 2000; Heydon & Reynolds 2000b). The proportions of farmers reporting lamb predation in these studies have varied from 16% of a sample of Wiltshire farmers to 60.5% of a sample of Welsh sheep farmers (Baker & Macdonald 2000; Heydon & Reynolds 2000b). Other studies have investigated fox predation on farms more directly by establishing how lambs have died through post-mortem analysis (Hewson 1984b; White *et al.* 2000b). One of the conclusions to be reached from the research is that, although losses of lambs to foxes are generally low, there seems to be a variation in losses between farms, with some experiencing fairly high losses.

Heydon and Reynolds (2000b) carried out a postal survey of farmers in three regions of Britain and asked them for information on lamb losses in the last 12 months. They found that both the occurrence and scale of perceived lamb losses to foxes were highly variable between farms. Average reported losses were between 0.0% and 0.6% for the three regions studied, with losses up to 5.2% in the Midlands, 14.5% in East Anglia and 28.6% in Wales. White *et al.* (2000a) suggest that fox predation of lambs may be a spatially and temporally concentrated problem, whilst Lloyd (1980) reported that heavy losses of lambs to foxes may occur on particular nights.

Various factors, including husbandry, where a farm is situated and the incidence of twin births among lambs, have been implicated in influencing differences between farms in the magnitude of fox predation on lambs. Lamb losses to foxes are likely to be reduced by lambing ewes indoors, which protects lambs during their vulnerable early days (Bryson 1984; White *et al.* 2000a). Lambs are most at risk from fox predation when less than five days old (Hewson 1984b). Warren *et al.* (2001) identified the age of the dam (mother) and the age of the lamb at release as the factors that best explained lamb mortality (including predation) in free-ranging flocks in northern Norway. The latter of these supports the assertion that lambs are less likely to be predated upon if kept indoors after birth. However, it should be noted that a suite of predators, not just foxes, was implicated in killing lambs in this study in Norway.

In Britain, a distinction can be drawn between hill, upland and lowland sheep farms. Hill farms tend to be characterised by poor land and a relatively harsh climate, with low sheep stocking rates, relatively large flocks and extensive systems of management. Lowland farms, on the other hand, tend to have fertile land, a milder climate, high sheep stocking rates, relatively small flocks and intensive systems of management, often in a mixed farm situation, whilst upland farms fit between the two in terms of the favourability of conditions (Cottle & Cottle 1998; MAFF 1999). Consequently, these farm types are associated with broad-scale differences in husbandry practices, which, in turn, may affect differences in perceptions of the importance of fox predation. For example, on lowland farms, where lambs are often born indoors, fox predation is generally considered less of a problem than on upland and hill farms (Harris & White 1994; McDonald *et al.* 1997; White *et al.* 2000a). It is unclear whether this is due to the difference in weather conditions or in husbandry techniques or whether both of these have an effect. In addition, many lowland farms lamb early, before the time that foxes start producing cubs (Macdonald 1987), which could mean the timing of lambing helps with avoidance of predation, if foxes are more likely to kill lambs when they have cubs to feed. However, this effect may be solely due to a coincidence of timing. It has also been suggested that forestry plantations in upland and hill areas tend to harbour foxes that forage in open hill and rough grazing areas (Lloyd 1980; Chadwick *et al.* 1997).

A further influence of husbandry is increasing winter feed available to ewes, which has been implicated in reducing the number of lambs reportedly killed by foxes (Burrows 1968). In a study of two hill farms by White *et al.* (2000b), the main difference between the farms was that on one farm, ewes with multiple lambs were housed when giving birth and received supplementary feeding, whereas on the other they were not. It was on the former that lamb mortality due to fox predation was lower. In their study, lambs born as twins or triplets were more susceptible to predation. Large litters may be more prone to predation because ewes are less vigilant per lamb and lambs tend to be smaller (Nash *et al.* 1996; White *et al.* 2000b). These results are supported by studies on overall lamb mortality (Stevens *et al.* 1982) and predation of lambs by feral pigs in Australia (Choquenot *et al.* 1997). However, Hewson (1984b) found that predators (both foxes and eagles) killed lambs that were slightly larger and in a better condition (estimated by fat deposits) than those of a similar age dying due to natural causes throughout the lambing season. There was no evidence of whether the predated lambs were diseased or not.

White *et al.* (2000a) compiled average figures from studies of lamb predation and pointed out that the number of lambs believed to have been lost to foxes tends to increase in parallel with the overall number of lambs lost, across the studies. This suggests the problem is one with the levels of losses generally, rather than predation specifically. These overall losses are likely to be a function of husbandry practices. However, individual studies have not investigated the relationship between lamb losses overall and losses to foxes and whether these two increase in parallel.

Few studies have considered the link between fox control and predation, probably because it is difficult to separate out the causes and effects involved: farmers may only control foxes when they feel there is a need, for example when a predation event has occurred; whilst it is difficult to set up field experiments to test for effects. A study in south-eastern Australia (Greentree *et al.* 2000), using factorial experimental design, found that, although fox control reduced the minimum percentage of lamb carcasses identified as killed by foxes, fox control had no influence on lamb production. Hewson (1990) observed no increase in the number of lambs lost to foxes when fox control was stopped, but there are a few flaws to his study (discussed by Macdonald *et al.*, 2000), including the fact that culling was still carried out in areas neighbouring the study site.

There has also been a lack of research assessing the link between fox population densities and lamb losses to foxes. The pattern of lamb losses among regions in Heydon and Reynolds' (2000b) study was not mirrored by fox abundance measured in the same three regions (Heydon *et al.* 2000a; Macdonald *et al.* 2000), but the degree of association between the two was not tested by the authors.

Studies that have collected data on lamb predation by foxes (or perceived predation) on a large scale (a number of farms across several regions), e.g. Heydon and Reynolds (2000b) and Macdonald and Johnson (1996), have shown that perceived levels of predation tend to vary between regions. Heydon and Reynolds (2000b) found a statistically significant difference between regions in the proportion of farmers reporting lamb losses to foxes, the highest proportion being in Wales and the lowest in East Anglia. There was also a difference in reported lamb losses (as a percentage of lambs), losses in Wales and the east Midlands being higher than in East Anglia. The authors detected a significant interaction between culling and region, there being higher lamb losses on farms where fox culling occurred in Wales and the east Midlands, but in the presence of a gamekeeper, losses tended to be lower. In a study of food remains at 396 fox dens in Scotland from mid-April to late-May 1973-7, lamb carcasses were found at dens in all parts of Scotland, but most often in the Highlands and Argyll (Hewson 1985). In Lochaber, where there were more fox dens with lamb remains than in other areas, there were many complaints of foxes killing lambs. However, a high proportion of these carcasses are likely to have been scavenged and there was no evidence that lamb remains at dens represented predated viable lambs (Hewson 1985).

In North America, fairly extensive research has been carried out on the problem of coyote predation of sheep. Coyote depredation rates are influenced by factors including the breed of sheep, husbandry practices (such as confinement and shed lambing), predator fences, frightening devices, guard animals, aspects of coyote behaviour, environmental factors and coyote control (Robel *et al.* 1981; Knowlton *et al.* 1999; Wagner & Conover 1999; Andelt & Hopper 2000; Meadows & Knowlton 2000). However, there are several important differences in the hunting behaviour of coyotes and red foxes, two being that coyotes can hunt in packs and that they can kill adult sheep, meaning that inferences from one to the other must be drawn with care.

Greentree *et al.* (2000) highlighted the fact that lamb losses to foxes can vary between individual flocks or areas in a country, reviewing a couple of studies carried out in Australia where high losses were associated with a particular sheep breed type and the proximity of optimal fox habitat (Moore *et al.* 1966; Coman 1985). They also drew attention to the limited evidence that suggests that individual foxes become habituated to the killing of lambs (Rowley 1970) and can cause serious losses in individual flocks (Turner 1965). It is commonly held belief that a small minority of foxes are responsible for lamb predation in Britain (Burns *et al.* 2000; White *et al.* 2000a), but although this could explain some of the variation between farms in lamb losses, there is scant scientific evidence to support the hypothesis.

Of the studies on fox predation of lambs mentioned above, the large-scale questionnaire surveys of farmers have tended to consider perceived predation of lambs only as part of a larger study and concentrated on the scale of perceived predation. Except for Heydon and Reynolds' (2000b) mention of the influence of region and fox control on perceived predation, studies have not addressed the factors that influence differences in perceived fox predation of lambs between farms. In addition, no study has assessed the problem of fox predation of lambs across Britain on a nation-wide scale and, with the exception of Anon (1993), studies have focused on regions with characteristics that are not necessarily representative of Britain as a whole. Smaller scale studies have examined the factors that influence lamb mortality in Britain, but only one (White *et al.* 2000b) has considered the problem of fox predation specifically. However, White *et al.*'s (2000b) study involved only two farms and was a comparison of the characteristics of the lambs that were assumed to have been killed by foxes and of those that did not die, rather than a comparison between farms.

This chapter aims to address the lack of information on factors associated with variation in fox predation of lambs between farms across Britain. Assessing the reasons behind the fox predation problem is an important part of the process of identifying appropriate strategies to manage it. A survey of sheep farmers across Britain was carried out to ascertain perceived levels of fox predation of lambs. The data collected from this survey were used to find out what factors influence perceived fox predation on sheep farms and, therefore, why there are differences between farms across Britain in the occurrence and scale of perceived fox predation. As several of these factors were likely to be inter-related, the study aimed to identify the most important factors behind the variation.

2.2. METHODS

2.2.1. Questionnaire survey of sheep farmers

In November 1999, questionnaires were sent out, with an explanatory letter and Freepost reply envelope, to 2000 members of the National Sheep Association. The questionnaire consisted of questions on land-uses surrounding farms, husbandry, losses to predation and other causes between birth and weaning at the most recent lambing, fox control, production of sheep and costs on the farm (Appendix A). The survey followed an earlier pilot survey of 55 Charollais and Blackface sheep farmers to assess the suitability of the questions, identify categories for answers, where appropriate, and assess the likely response rate.

2.2.2. Regional representativeness of sample

In order to check whether the data to be used were representative of the regional distribution of sheep farms in Britain, the distribution of sheep farms from the survey was compared to the distribution of holdings with sheep from the 1999 MAFF and Scottish Executive June Censuses using a chi-square goodness-of-fit test. Every response was allocated to a region according to its postcode. Regions were identified using a Royal Mail system for grouping by postcode into Scotland, Wales, Northeast, Northwest, Midlands, Anglia, Southeast, South and Southwest regions (Table 2.1). These regions were then matched up to those in the MAFF and Scottish Executive censuses (Table 2.2) and the total number of holdings with sheep calculated for each region.

2.2.3. Relative fox population density estimates

Relative fox densities were estimated using faecal counts in 444 1-km squares surveyed across Britain during 1999 and 2000 (Webbon 2002). Beltrán, Delibes and Rau (1991) and Cavallini (1994) discuss this technique of density estimation. Two walks of a selection of linear features were undertaken in each 1-km square each year. On the first walk, fox scats were removed from the linear features and on the second, two to six weeks later, the number of new scats counted. Relative densities were calculated as:

$$d_i = k_i n_i / w_i t_i$$

where:

d_i = relative density estimate for the *i*th 1-km square, in total number of scats per kilometre square per day

k_i = total number of kilometres of linear features in the *i*th square

n_i = number of scats found on the second walk along linear features in the *i*th square

w_i = number of kilometres of linear features walked in the *i*th square

t_i = number of days between walks for the *i*th square

Median relative densities were calculated based on nine regions (Table 2.3) and seven land class groups (Table 2.4). Land class groups were the same as those used for national brown hare and barn owl surveys (Hutchings & Harris 1996; Love *et al.* 2000), based on Bunce (1992). Medians were used due to the non-normal distribution of the data. Each farm returning a questionnaire was allocated both a region-based and a land class-based density estimate (from here on referred to as 'regional fox density' and 'land class fox density', respectively), depending on the region in which the farm was situated and the land class of the Ordnance Survey kilometre grid square (Barr *et al.* 1993) in which the central farm buildings were located (determined from their postcodes). Grid square references were identified for each farm with an available postcode using Matchcode 5 Webnet Demo (Capscan Ltd., London).

Spearman's rank correlations were used to test the associations between these density estimates and the number and percentage of lambs reported killed by foxes on farms, as well as the number of foxes killed by different control methods. Non-parametric correlation tests were deemed more appropriate for these data than parametric correlation as the data were non-normally distributed and because there is a lower likelihood of Type I error with non-parametric tests, especially for large sample sizes. The associations between the percentage of farms reporting fox predation and fox densities in each region and land class group were also tested using rank correlations.

Table 2.1: Allocations of postcodes to regions using Royal Mail system

Region	Postcode
Scotland	AB, DD, DG, EH, FK, IV, KA, KW, KY, ML, PA, PH, TD, ZE
Wales	CF, CH, LD, LL, NP, SA, SY
Northeast	BD, DH, D, DN, HG, HU, NE, TS, YO
Northwest	BB, CA, DY, L, LA, OL, SK, TF
Midlands	B, CV, DE, LE, NG, NN, ST, WV
Anglia	MK, NR, PE, SG
Southeast	BN, DA, KT, ME, RH, TN
South	GU, HP, OX, RG, SL, SN, SO, SP
Southwest	BA, BS, DT, EX, GL, HR, PL, TA, TQ, WR

Table 2.2: Regions defined by postcode and their MAFF census counterparts

Postcode-defined region	Government Office Regions/Counties
Scotland	Scotland
Wales	Wales and Shropshire
Northeast	North East and Yorkshire and the Humber
Northwest	North West
Midlands	East Midlands, Staffordshire, West Midlands (county), Warwickshire and Buckinghamshire
Anglia	Eastern
Southeast	London, Surrey, Kent, East Sussex and West Sussex
South	Oxfordshire, Berkshire, Hampshire, Isle of Wight and Wiltshire
Southwest	Herefordshire, Worcestershire and South West, except Wiltshire

Table 2.3: Regions used to calculate relative fox density estimates (Webbon 2002)

Region Code	Region	Counties
1	North Scotland	Aberdeenshire, incl. Aberdeen; Angus; Argyll and Bute; Clackmannanshire; Falkirk; Fife; Highlands; Moray; Perth and Kinross; Stirling
2	South Scotland	Dumfries and Galloway; East Ayrshire; East Dunbartonshire; East Lothian; East Renfrewshire; Edinburgh; Glasgow; Inverclyde; Mid Lothian; North Ayrshire; North Lanarkshire; Renfrewshire; Scottish Borders; South Ayrshire; South Lanarkshire; West Dunbartonshire; West Lothian
3	North England	Cheshire; Cleveland; Cumbria; Durham; Greater Manchester; Lancashire; Merseyside; North Yorkshire; Northumbria; South Yorkshire; Tyne and Wear; West Yorkshire
4	East England	Cambridgeshire; Essex; Humberside; Lincolnshire; Norfolk; Suffolk
5	Midlands	Derbyshire; Gloucestershire; Hereford and Worcester; Leicestershire; Nottinghamshire; Shropshire; Staffordshire; Warwickshire; West Midlands
6	Central England	Bedfordshire; Buckinghamshire; Greater London; Hertfordshire; Northamptonshire; Oxfordshire
7	Southwest England	Avon; Cornwall; Devon; Dorset; Somerset
8	South England	Berkshire; East Sussex; Hampshire; Isle of Wight; Kent; Surrey; West Sussex; Wiltshire
9	Wales	Anglesey; Clwyd; Dyfed; Gwent; Gwynedd; Mid Glamorgan; Powys; South Glamorgan; West Glamorgan

Table 2.4: Land class groups used to calculate relative fox density estimates (Webbon 2002)

Land class Group Code	Land class Group	Description
1	Arable I	Open, gently sloping, varied agriculture
2	Arable II	Flat, open, intensive agriculture
3	Arable III	Lowlands with mainly arable use
4	Pastoral IV	Undulating country, mainly pasture. Also coastal regions
5	Pastoral V	Mainly lowlands with mixed agriculture, predominantly pastoral
6	Marginal upland VI	Rounded hills, semi-improved pasture, moorlands
7	Upland VII	Upper mountain slopes, often moorland or bog covered

2.2.4. Analyses

Statistical analyses were used to identify both the factors influencing the occurrence of perceived fox predation and the factors influencing the scale of perceived fox predation (or the numbers of lambs reported killed by foxes). Appendix B summarises the variables used in these analyses. Independent variables were chosen due to a priori hypotheses that they were influences on the occurrence or scale of perceived fox predation of lambs and from examination of scatter plots of the data. Data were transformed where necessary to meet the assumptions of normality of error and homogeneity of variance for regression analysis.

Chi-square tests and logistic regression analyses were used to assess the associations between the occurrence of perceived fox predation on a farm and other factors. The dependent variable in all logistic regression models was a binary response variable (occurrence of perceived predation), coded zero for no reported fox predation of lambs on the farm and one for at least one lamb having been reported lost to foxes. This variable was also used in the chi-square tests. Univariate analyses were used to investigate preliminary relationships in the data and to identify the most significant variables for inclusion in a logistic regression model. Chi-square tests were used for all analyses involving one other categorical variable and logistic regression for analyses using a continuous independent variable or several dummy variables.

Variables were selected for the overall multiple logistic regression model based on decreases in the –2 log likelihood of the model and retention of a significant relationship with the occurrence of perceived fox predation, once the effects of other variables were included. Variables for which the effects did not show up in univariate analyses were also tested in this multivariate approach to ensure no necessary variables were left out of the overall model.

For the analyses on factors influencing the scale of perceived predation, data for farms that reported no lamb losses to foxes were removed, leaving 251 data points. The data on reported numbers of lambs killed by foxes were then converted to per ewe figures by dividing by the number of lambing ewes on the farm. As these data were right-skewed, with a variance that increased with the mean, they were log-transformed to reduce heterogeneity of variance and meet the assumptions of linear regression. This variable was used as the dependent variable in linear regression analyses identifying the factors affecting the perceived numbers of lambs lost to foxes per lambing ewe. Univariate regression analyses were used to examine relationships and identify independent variables for the overall multiple linear regression model. Independent variables were the same as those used in the logistic regression analyses (Appendix B). Only those variables that retained a statistically significant relationship with the dependent variable, when included with other variables, were kept in this overall model. Variables that it was considered might be important, but for which the effects may not have shown up in univariate analyses, were also tested in this multivariate approach to ensure no necessary variables were left out of the overall model. Partial correlation coefficients were used to assess these relationships. Variables were only considered necessary if there was an increase in the adjusted R^2 of the model on their inclusion and the resultant model met the assumptions of linear regression.

2.2.5. Reliability ratings

Respondents were asked to rate the reliability of their figures for lamb losses from one to five, one being a guess, three an estimate and five accurate figures. To assess how the respondents' assessment of the reliability of their figures for lamb losses affected the models estimated, the associations between these loss reliability ratings and the dependent variables measuring occurrence and scale of fox predation of lambs, as well as reported number of lambs killed by foxes, were tested. The loss reliability scores were also included in the overall multivariate models estimated. Those scores for which there were large enough samples (3, 4 and 5) were coded into dummy variables (a coding of one meaning this score had been given by the respondent) to allow for their inclusion in the models. It was hypothesised that there might be a link between given reliability ratings and the size of a farm, with farmers being able to keep track of the causes of lamb losses better with fewer sheep. The associations between two farm size variables, lambs born and lambing ewes, and reliability rating were therefore tested, via Kruskal-Wallis analyses of variance.

2.3. RESULTS

In total 543 questionnaires (27%) were returned: of these, 490 (25%) were used in the analyses, 48 were mistargeted and five respondents declined to participate. Mistargeted forms included those returned from Northern Ireland and from Scottish islands on which foxes are not found. Not all respondents answered all the questions on the survey form (due to lack of knowledge on the subject covered or unwillingness to supply the information asked for). Therefore the sample sizes differ between analyses. Sample sizes are indicated in square brackets in the text. All figures for statistics are quoted to 3 significant figures or 2 decimal places. Estimated Beta coefficients for independent variables in regression analyses are given as 'B'. Statistical significance was taken as being at or above the 95% level ($\alpha = 0.05$), i.e. $p \leq 0.05$.

The number of holdings with sheep from the MAFF and Scottish Executive 1999 June Census data and the number of questionnaire responses for each postcode-derived region were calculated from the available data (Table 2.5 and Figure 2.1). There was a statistically significant difference between the regional distribution of the survey sample and that of holdings with sheep in the censuses (chi-square goodness-of-fit test: $\chi^2 = 55.8$, d.f. = 8, $p < 0.001$ [n = 9]). There were more responses than expected from Scotland and Wales, with fewer than expected from Northeast England and the Midlands (Table 2.5).

The sample contained a fairly even number of hill, upland and lowland farms, lowland farms being the most numerous (Figure 2.2). There was a large range in the number of ewes per holding, from 4 to 4000, with the mean number of ewes per holding being 582 (S.E. = 28.5) and the median number, 400 (Figure 2.3).

The figures for reported losses of lambs to foxes, all predators (including foxes), other causes and in total between birth and weaning are summarised in Table 2.6. All figures are given based on untransformed data. Lamb mortality is given as the percentage of lambs said to have been lost to that cause out of the total number of lambs born alive on each farm. More than half the respondents (59.4% of 429) reported fox predation of lambs at their most recent lambing. The majority of farms reported that they experienced low (one per cent or less) mortality of lambs due to fox predation (Figure

2.4). However, the problem was perceived to be greater on some individual farms. On farms where fox predation was reported, the median percentage of lambs reported killed by foxes out of the total born was 1.39%, with a range from 0.06 to 15%. The majority of respondents (60.9%) thought the numbers of lambs lost to foxes had not changed over the past five years, whilst nearly a quarter of them (23.8%) thought these losses had increased (Figure 2.5).

The reported number of foxes killed per hectare on farms in the last year varied from none (on 31% of farms) to 1.07 killed per hectare on one farm (Figure 2.6).

Table 2.5: Survey returns and data from 1999 MAFF and Scottish Executive June Censuses on sheep holdings by region

Region	Number of survey responses from region	Number of holdings with sheep in region	Expected survey response based on June Census data
Scotland (excluding Shetland, Orkney and Eileanan an Iar)	116	11270	76
Wales	170	20962	142
Northeast	36	8672	59
Northwest	37	6878	47
Midlands	21	6610	45
Anglia	4	1804	12
Southeast	22	2934	20
South	13	2051	14
Southwest	68	10816	73
Nation-wide Total	487	60727	

Table 2.6: Reported losses of lambs between birth and weaning to fox predation, all predation and other causes

Cause of lamb mortality		Fox predation	All predation	Other causes	All causes
Number of lambs reported died per farm	Mean (S.E.)	8.32 (0.82)	9.79 (0.91)	26.11 (1.92)	35.37 (2.39)
	Median	2	4	15	22
	Range	0-150	0-200	0-520	0-650
	n	427	430	441	437
Number of lambs reported died per ewe	Mean (S.E.)	0.016 (0.001)	0.021 (0.002)	0.066 (0.003)	0.086 (0.004)
	Median	0.006	0.008	0.045	0.066
	Range	0-0.257	0-0.420	0-0.455	0-0.646
	n	426	429	440	436
Reported lamb mortality (%)	Mean (S.E.)	1.17 (0.104)	1.45 (0.119)	4.39 (0.208)	5.87 (0.26)
	Median	0.42	0.58	3.11	4.40
	Range	0-15.0	0-17.4	0-40.0	0-56.0
	n	422	424	440	435
Percentage of respondents reported no lambs lost		40.6 [n = 429]	37.7 [n = 430]	6.1 [n = 441]	5.3 [n = 437]
Percentage of respondents reported more than 10 lambs lost		22.7 [n = 427]	24.9 [n = 430]	54.6 [n = 441]	67.0 [n = 437]

2.3.1. Relative fox population density estimates

Relative fox density estimates calculated for each region and land class group varied from 0 to 1.52 scats per kilometre square per day (Table 2.7 and Table 2.8). It was not possible to allocate a regional density estimate to three farms, as location information was not available, whilst for 53 farms, no land class information was allocated, due to a lack of specific location data.

Land class fox density was not significantly associated with the number of lambs reported killed by foxes ($r_s = -0.081$, $p > 0.10$ [$n = 383$]), but regional fox density was positively correlated with the number of lambs reported killed by foxes ($r_s = 0.151$, $p = 0.002$ [$n = 424$]) (Figure 2.7a). The percentage of lambs born reported killed by foxes was also positively associated with regional fox density ($r_s = 0.108$, $p = 0.028$ [$n = 419$]) (Figure 2.7b), which was not the case when using Spearman's rank correlation with land class fox density ($r_s = -0.048$, $p > 0.10$ [$n = 380$]). Neither regional nor land class fox density were associated with the number of lambs reported killed by foxes per lambing ewe ($r_s = 0.091$, $p > 0.05$ [$n = 423$] and $r_s = -0.047$, $p > 0.10$ [$n = 382$], respectively). Regional fox density was positively correlated both with the number of foxes reported killed on a farm and with the number of foxes killed per hectare ($r_s = 0.150$, $p = 0.001$ [$n = 448$] and $r_s = 0.120$, $p = 0.011$ [$n = 448$] respectively). Land class fox density was not significantly associated with either of these variables ($r_s = 0.010$, $p > 0.05$ [$n = 402$] and $r_s = 0.064$, $p > 0.10$ [$n = 402$], respectively).

There was a significant association between the percentage of farms reporting fox predation in each region and regional fox density ($r_s = 0.800$, $p = 0.01$ [$n = 9$]), but not between the percentage of farms reporting fox predation in each land class group and land class fox density ($r_s = -0.036$, $p > 0.90$ [$n = 7$]).

Table 2.7: Relative fox densities based on regions (Webbon 2002)

Region Code	Region	N	Median relative density (scats per kilometre square per day)
1	North Scotland	56	0.461
2	South Scotland	36	0.930
3	North England	44	0.242
4	East England	50	0.199
5	Midlands	52	0.613
6	Central England	40	0.366
7	Southwest England	50	1.52
8	South England	71	0.460
9	Wales	45	0.639

Table 2.8: Relative fox densities based on land class groups (Webbon 2002)

Land class Code	Land class Group	N	Median relative density (scats per kilometre square per day)
1	Arable I	60	0.353
2	Arable II	113	0.448
3	Arable III	44	1.19
4	Pastoral IV	91	0.833
5	Pastoral V	56	0.775
6	Marginal upland VI	55	0.449
7	Upland VII	25	0

2.3.2. Factors related to the occurrence of perceived fox predation of lambs

2.3.2.1. Farm location

Chi-square tests were used to analyse the association between farm location and the occurrence of perceived fox predation of lambs. The effect of 'country' was found to be significant ($\chi^2 = 12.0$, d.f. = 2, p = 0.002 [n = 425]). Farms in Scotland and Wales experienced higher occurrences of reported fox predation than expected and farms in England had lower occurrences than expected, illustrated by the cross-tabulation of these two variables (Table 2.9). The effect of 'region' was also statistically significant ($\chi^2 = 19.9$, d.f. = 8, p = 0.011 [n = 425]). The Northwest and Northeast of England had lower than expected occurrences of perceived predation. The differences in frequencies of reported fox predation of lambs for each postcode region are given in Table 2.10.

Table 2.9: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by country within UK

Country	**Occurrence of perceived fox predation of lambs**		**N**
	No fox predation	**Fox predation reported**	
England	87	88	175
Wales	57	93	150
Scotland	29	71	100
All	173	252	425

Table 2.10: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by postcode-derived region

Region	**Occurrence of perceived fox predation of lambs**		**N**
	No fox predation	**Fox predation reported**	
Southwest	23	35	58
South	6	5	11
Southeast	10	12	22
Midlands	9	8	17
Wales	57	93	150
Northwest	17	14	31
Northeast	18	14	32
Anglia	4	0	4
Scotland	29	71	100
All	173	252	425

Table 2.11: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by farm type

Farm type	Occurrence of perceived fox predation of lambs		N
	No fox predation	Fox predation reported	
Lowland	90	85	175
Upland	57	87	144
Hill	26	82	108
All	173	254	427

The association between farm type and the occurrence of perceived predation was tested ($\chi^2 = 20.8$, d.f. = 2, $p < 0.001$ [n = 427]). The occurrence of reported fox predation on hill farms was higher than expected, whilst that on lowland farms was lower than expected, illustrated by the table of frequencies (Table 2.11).

2.3.2.2.Farm size, lambing rates and stocking densities

The total area of the farm was positively related to the reported occurrence of lamb predation by foxes (B = 0.004, Wald = 27.9, $p < 0.001$ [n = 426]), as was the area of land on the farm devoted to sheep farming (B = 0.01, Wald = 26.3, $p < 0.001$ [n = 421]). The number of lambs born and the number of lambing ewes on the farm (both ln-transformed) were also related to the occurrence of perceived fox predation (B = 0.910, Wald = 68.3, $p < 0.001$ [n = 416] and B = 0.980, Wald = 91.2, $p < 0.001$ [n = 427], respectively). So too were the number of lambs born per lambing ewe (B = -1.71,Wald = 23.1, $p < 0.001$ [n = 415]) and whether the farm had more than 250 ewes (B = 1.84, Wald = 71.5, $p < 0.001$ [n = 427]). Ewe stocking density was not related to the occurrence of perceived fox predation.

2.3.2.3.Land uses surrounding the farm

Respondents to the questionnaires were asked to rate various land uses according to how much of the land surrounding their farm was taken up by these land uses. The land-uses were 'arable', 'livestock', 'game-rearing', 'forestry', 'village', 'urban' and 'rough grazing' and were each rated from zero to five. A rating of zero meant that this land-use took up none of the surrounding land, and a rating of five that it took up all the surrounding land. Ratings rather than rankings were used for ease of response, to allow respondents to give the same rating to more than one land-use and to allow them to be included as covariates in analyses to account for some effect of scale. A category for 'other', allowing for specification of land-use types that did not fit in to the given categories, was also available. However, only 32 (of 477) respondents considered that they had any other land-use type in the land surrounding their farm and thirteen different types of land-use were given by these respondents, so the sample sizes were too small for inclusion in the analyses.

The rated land-use variables were included individually in regression models, both as covariates and as dummy variables coding for the presence or absence of the land-use type in surrounding land. Forestry and rough grazing in surrounding land were both positively related to the reported occurrence of lamb predation by foxes. These relationships were evident whether rated scores were used as the independent variables in the regression (forestry a: B = 0.231, Wald = 7.22, p = 0.007 [n = 415]; rough grazing a: B = 0.223, Wald = 11.6, p = 0.001 [n = 415]) or dummy variables coding for the presence or absence in surrounding land of the land-use type in question were used (forestry b: B = 0.610, Wald = 8.96, p = 0.003 [n = 415]; rough grazing b: B = 0.688, Wald = 11.1, p = 0.001 [n = 415]). Arable land in the surroundings was negatively related to the occurrence of reported lamb predation, when the rated score was included as a covariate (arable a: B = -0.141, Wald = 4.37, p = 0.037 [n = 415]).

2.3.2.4.Lambing indoors and multiple births

The percentage of ewes lambed indoors (arcsine-transformed to fit the assumptions of regression) was negatively related to the occurrence of perceived predation in a logistic regression (B = -0.819, Wald = 24.1, p < 0.001 [n = 420]), as was the percentage of ewes lambed in lambing pens (arcsine-transformed) (B = -0.339, Wald = 5.90, p = 0.015). The percentage of ewes with multiple births (also arcsine-transformed) was similarly negatively related to the dependent variable (B = -1.458, Wald = 16.7, p < 0.001 [n = 421]). A dummy variable coding for whether all ewes were lambed indoors also showed up the relationship between indoor lambing and occurrence of perceived predation (B = -1.166, Wald = 31.0, p < 0.001 [n = 428]). The number of days in after lambing was negatively related to the occurrence of perceived fox predation (B = -0.024, Wald = 10.6, p = 0.001 [n = 422]).

No association was found between ewes with multiple lambs being given supplementary feeding and the perceived occurrence of fox predation when tested using a chi-square test ($\chi^2 = 2.42$, d.f. = 1, $p > 0.05$ [n = 419]). However, of the farmers that gave information on supplementary feeding and lamb losses to foxes, less than ten per cent did not give ewes supplementary feed (38 out of 419).

2.3.2.5.Timing of lambing

The month in which lambing took place had an influence over the perceived occurrence of predation ($\chi^2 = 18.9$, d.f. = 5, $p = 0.002$ [n = 428]). March and April had higher than expected occurrences of reported fox predation, whilst those for all other months were lower than expected (Table 2.12).

Table 2.12: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs by month lambing took place

Month of lambing	**Occurrence of perceived predation of lambs**		**N**
	No fox predation	**Fox predation reported**	
January	29	24	53
February	37	35	72
March	62	119	181
April	26	60	86
May to November	7	8	15
December	13	8	21
All	174	254	428

2.3.2.6.Sheep breed

Dummy variables coding for each sheep breed type (Mountain and Moorland, Grass Hill, Longwool, Terminal Sire and Halfbred) were included in a multivariate logistic regression model ($\chi^2 = 23.0$, d.f. = 5, $p < 0.001$ [n = 428]). These variables coded for whether each type of sheep breed was on the farm, regardless of whether other types were also present. Only the variables coding for Mountain and Grass Hill breeds had statistically significant parameter estimates and farms with these breeds reported significantly higher occurrences of predation than those with other breeds (B = 0.795, Wald = 8.54, $p = 0.003$ and B = 0.635, Wald = 4.45, $p = 0.035$ respectively). A variable coding for whether the farm had Scottish Blackface sheep was included alone and this was also positively related to the occurrence of perceived predation (B = 1.024, Wald = 6.89, $p = 0.009$ [n = 422]).

2.3.2.7.Lamb mortality due to causes other than predation

The reported number of lambs lost to causes other than predation between birth and weaning, included as an independent variable in a logistic regression, was associated with the occurrence of perceived fox predation of lambs (B = 0.024, Wald = 23.2, $p < 0.001$ [n = 395]). In contrast, the reported number of lambs lost to causes other than predation per lambing ewe had a negative association with the dependent variable (B = -5.139, Wald = 9.146, $p < 0.001$ [n = 394]).

2.3.2.8.Fox control and relative fox population density

The number of foxes killed in the last year on the farm was positively associated with the occurrence of reported fox predation (B = 0.145, Wald = 35.0, $p < 0.001$ [n = 396]), as was a dummy variable coding for fox control being carried out (B = 1.98, Wald = 67.7, $p < 0.001$ [n =396]). The number of foxes killed per hectare was not related to the dependent variable. Regional fox density was significantly and positively related to the occurrence of reported fox predation (B = 0.781, Wald = 4.56, $p = 0.033$ [n = 425]), but land class fox density was not related to this dependent variable.

2.3.3. Model relating the occurrence of perceived fox predation of lambs to farm characteristics

The overall logistic regression model included four variables: whether all the ewes were lambed indoors; whether fox control was carried out on the farm; the number of lambing ewes (ln-transformed); and whether the farm was in Northwest England (Table 2.13). The initial –2 log likelihood or likelihood ratio χ^2 (LRχ^2) (for a model with the constant only) was 525.3 and for the fitted model, LRχ^2 was 347.9. The overall predictive accuracy of the model was 79.6% (χ^2 = 177.3, d.f. = 4, $p < 0.001$ [n = 392]). The model correctly predicted the occurrence of fox predation on 87.0% of farms where predation had occurred. Lambing all ewes indoors was associated with a lower likelihood of perceived fox predation, whilst farms where fox control was carried out tended to have higher occurrences of reported losses to foxes, as did farms with larger flocks. Perceived fox predation was less likely to have occurred in Northwest England.

Multicollinearity was not considered to be a problem in the model as there was no evidence of degradation in the fit, whilst estimated standard errors of coefficients were relatively low (Hosmer & Lemeshow 1989).

Table 2.13: Parameter estimates and significance test statistics for overall logistic regression model describing variation in the occurrence of perceived fox predation of lambs between farms

Variable	**B**	**Wald**	**p**
Indoor lambing	-1.28	20.1	<0.001
Fox control carried out	1.27	19.0	<0.001
Lambing ewes (ln-transformed)	0.896	54.8	<0.001
Northwest	-1.33	6.44	0.011
Constant	-4.41	45.7	<0.001

2.3.4. Factors related to the scale of perceived fox predation of lambs

Linear regression analyses were carried out only on data from farms that had reported at least one lamb killed by foxes [n = 251], with the logged number of lambs perceived killed by foxes per ewe as the dependent variable. Independent variables were the same as those used for analyses of the occurrence of perceived predation.

2.3.4.1.Surrounding land-uses and farm location

None of the surrounding land-use variables were statistically significantly related to the number of lambs perceived killed by foxes per ewe, neither when included in analyses as dummy variables nor as covariates. Some of the farm location variables were related to this dependent variable (Table 2.14).

Table 2.14: Parameter estimates and t-test statistics for univariate regression analyses relating location variables to the scale of perceived fox predation of lambs

Factor	B	t	p
England [n = 248]	0.364	2.68	0.008
Scotland [n = 248]	-0.509	-3.58	<0.001
Southwest [n = 248]	0.399	2.13	0.034
South [n = 248]	0.794	1.70	0.090
Hill [n = 250]	-0.247	-1.77	0.078
Upland [n = 250]	-0.245	-1.78	0.076
Lowland [n = 250]	0.491	3.61	<0.001

2.3.4.2.Farm size, lambing rates and stocking densities

The total area of the farm in hectares was negatively related to the number of lambs reported killed by foxes per ewe (B = -0.001, t = -4.13, p < 0.001 [n = 249]), as was the area of land on the farm used for sheep farming (B = -0.001, t = -3.68, p < 0.001 [n = 246]). The number of lambing ewes and the number of lambs born (both ln-transformed) were similarly related to the dependent variable (B = -0.478, t = -8.25, p < 0.001 [n = 251] and B = -0.499, t = -8.46, p < 0.001 [n = 244], respectively). Farms with more than 250 ewes were associated with lower numbers of lambs reported killed by foxes per ewe (B = -0.938, t = -6.76, p < 0.001 [n = 251]), but neither ewe stocking density nor the number of lambs born per ewe were related to the dependent variable.

2.3.4.3. Lambing indoors and multiple births

None of the lambing indoors or use of lambing pens variables were related to the scale of perceived fox predation. The percentage of ewes that had multiple births was also unrelated to the dependent variable, but the supplementary feeding of ewes with multiple lambs had an effect ($B = -0.579$, $t = -2.285$, $p = 0.023$ [$n = 244$]).

2.3.4.4. Timing of lambing

The month in which lambing took place, included as a fixed factor in a univariate analysis of variance, had a significant influence on the number of lambs reported killed by foxes per ewe ($F = 3.196$, d.f. = 5, 245, $p = 0.005$ [$n = 251$]). Lambings in January and February were associated with a significantly higher logged number of lambs perceived killed (means both = -3.83) than lambings in March and April (means = -4.22 and -4.33, respectively). Lambings in March and April were associated with a significantly lower logged number of lambs perceived killed than lambings in May to November and December (means = -3.45 and -3.33, respectively).

2.3.4.5. Sheep breed

The type of sheep breed on the farm had an influence on the number of lambs reported taken by foxes per ewe ($F = 2.29$, d.f. = 5, 245, $p = 0.047$ [$n= 251$]). Dummy variables coding for each breed type were included in a linear regression model. Only the coefficient for the variable coding for longwool breeds was significantly different from zero with a tendency for reported losses to foxes to be higher on farms with this breed type than on those without ($B = 0.497$, $t = 2.188$, $p = 0.030$). Whether farms had Scottish Blackface sheep did not influence perceived losses to foxes.

2.3.4.6. Lamb mortality due to causes other than predation

The reported number of lambs lost to causes other than predation between birth and weaning was negatively related to the scale of perceived fox predation ($B = - 0.003$, $t = -2.12$, $p = 0.035$ [$n = 224$]), but the reported number lost to causes other than predation per ewe was not significantly associated with the dependent variable.

2.3.4.7. Fox control and relative fox population density

The number of foxes killed on the farm in the last year was not significantly related to the number of lambs reported killed by foxes per ewe, but the number of foxes killed per hectare was (B = 2.523, t = 4.181, $p < 0.001$ [n = 239]). Fox control was not associated with the number of lambs reported killed by foxes per ewe. Neither regional nor land class fox density were related to the number of lambs perceived killed by foxes per ewe when included as independent variables in regression models. The same conclusion was reached when non-parametric correlation tests were used to analyse these associations.

2.3.5. Model relating the scale of perceived fox predation of lambs to farm characteristics

The most statistically significant variables explaining variation in the logged number of lambs reported taken by foxes per ewe were included in an overall linear regression model (Table 2.15) ($R^2 = 0.360$, Adjusted $R^2 = 0.340$, F = 18.1, d.f. = 7, 225, $p < 0.001$ [n = 233]). These variables were indoor lambing, number of foxes killed per hectare in last year, lambing ewes, whether there was land used for game rearing in the surroundings of the farm, whether the farm was in the Northeast region, whether the farm was in the Southwest region and whether the farm had longwool type sheep breeds.

Multicollinearity was not a problem in the model, the highest variance inflation factor (VIF) being 1.17 and the lowest tolerance 0.854. Lambing ewes indoors was associated with lower perceived lamb losses to foxes, whilst larger farms also experienced lower reported losses. The magnitude of fox culling was positively related to the scale of perceived predation, as were the presence of game rearing in the surroundings of the farm and longwool sheep breeds. Losses in Southwest England were higher than elsewhere and those in the Northeast lower.

Table 2.15: Parameter estimates and t-test statistics for overall multiple linear regression model explaining variation in the scale of perceived fox predation of lambs

Variable	**B**	**t**	**p**
Indoor lambing	-0.507	-4.21	<0.001
Number of foxes killed per hectare in last year	1.63	3.13	0.002
Lambing ewes (ln-transformed)	-0.470	-8.30	<0.001
Game rearing b	0.401	2.77	0.006
Northeast	-0.440	-1.80	0.074
Southwest	0.347	2.03	0.043
Longwool	0.451	2.32	0.021
Constant	-1.25	-3.35	0.001

2.3.6. Associations between respondent reliability ratings for lamb losses and perceived fox predation of lambs

Respondents rated the reliability of their figures for lamb losses from one to five, one being a guess, three an estimate and five accurate figures. Only 14 of 475 respondents rated their figures as being one or two in reliability score; 158 gave a score of three, 128 a score of four and 175 of five.

There was a significant difference in the reported number of lambs killed by foxes between loss reliability ratings, shown up by including loss reliability rating as the grouping variable in a Kruskal-Wallis analysis of variance (including all farms in the analysis) ($\chi^2 = 39.0$, d.f. = 4, $p < 0.001$ [n = 418]). Ratings of 5 had the lowest mean rank, indicating that respondents giving a rating of 5 tended to report lower numbers of lambs lost to foxes than respondents giving other ratings (Table 2.16). This is also shown up by the medians of the data on number of lambs reported killed by foxes for each reliability rating (Table 2.17). (The means of the data do not show this up because the distribution of the data distorts this figure, there being a few farms with large numbers of lambs reported lost to foxes for ratings of 3, 4 and 5.)

There was a statistically significant association between reliability ratings given by respondents and the occurrence of reported fox predation of lambs ($\chi^2 = 46.2$, d.f. = 2, $p < 0.001$). Only data with loss reliability ratings of 3 or above were included in this analysis, as contingency table cells for reliability ratings of 1 and 2 had expected values of less than five, which meant the chi-square statistic would be invalid. Ratings of 3 and 4 were associated with a higher than expected occurrence of reported fox predation and ratings of 5 with a lower than expected occurrence, which is shown by the frequencies in cells of a cross-tabulation of the two variables (Table 2.18).

Dummy variables coding for these three loss reliability scores (3, 4 and 5) (a coding of one meaning this score had been given by the respondent) were included in the overall multivariate logistic regression model estimated earlier in three paired combinations (Tables 2.19 to 2.21). Multicollinearity would have been a problem if they were all included together, as only eight data points did not have reliability scores of 3 or above. These analyses show the same relationships as shown up with the chi-squared analysis for ratings of 3 and 5, though neither were statistically significant at the 5% level when both were included in the model together. With the effects of other factors taken into account, ratings of 4 were associated with lower occurrences of predation (negative B in Table 2.21).

A Kruskal-Wallis test was used to analyse the association between loss reliability rating and the dependent variable used for analyses on the perceived scale of predation (logged number of lambs perceived killed by foxes per ewe on farms that reported at least one lamb killed). This showed that there was a significant difference between loss reliability ratings in terms of this variable ($\chi^2 = 14.1$, d.f. = 4, $p = 0.007$ [$n = 249$]), ratings of 4 and 5 having higher mean ranks than other ratings (Table 2.22). The dummy variables coding for reliability ratings of 3, 4 and 5 were included in the overall multivariate linear regression model for perceived scale of predation estimated above, in paired combinations. When included together, neither ratings of 3 nor 4 were statistically significant in the model. A rating of 3 had a negative relationship with the dependent variable that was just statistically significant at the 10% level, when included with a rating of 5 in the model (Table 2.23). Ratings of 4 and 5 were statistically significant, at the 5% and 10% levels respectively, and positively related to the dependent variable when they were included together (Table 2.24). These results indicate that the perceived scale of fox predation was greater for respondents giving either of these ratings than for those giving a rating of 3, but that the perceived scale of fox predation did not differ significantly between ratings of 4 and ratings of 5.

There was a significant association between loss reliability ratings 3 to 5 and the farm size variables, lambs born and lambing ewes, when all the data were included in a Kruskal-Wallis analysis of variance ($\chi^2 = 73.5$, d.f. = 2, $p < 0.001$ and $\chi^2 = 73.5$, d.f. = 2, $p < 0.001$, respectively), with a rating of 5 having a lower mean rank than ratings of 3 and 4, that of 4 being marginally lower than that of 3. When only data for farms where perceived fox predation of lambs occurred were included in the Kruskal-Wallis analysis, however, the association between lambs born and reliability rating was only just significant ($\chi^2 = 6.44$, d.f. = 2, $p = 0.040$) and that between lambing ewes and reliability rating statistically insignificant ($\chi^2 = 5.78$, d.f. = 2, $p > 0.05$). Once again, a reliability rating of 5 had the lowest mean rank, followed by a rating of 4.

Table 2.16: Mean rank in Kruskal-Wallis analysis of variance of number of lambs reported killed by foxes for each loss reliability rating, a higher rank indicating numbers of lambs reported killed by foxes were higher in this group

Loss reliability rating	N	Mean rank
1	3	288
2	5	199
3	131	235
4	114	241
5	165	166

Table 2.17: Median, mean, standard deviation and number in sample of number of lambs reported killed by foxes for each loss reliability rating

Loss reliability rating	Median	Mean	Standard deviation	N
1	8	8.67	6.03	3
2	2	2.20	1.10	5
3	5	8.73	16.0	131
4	5	13.3	24.1	114
5	0	5.01	10.6	165
All	3	8.44	17.1	418

Table 2.18: Cross-tabulation of frequencies of occurrence of perceived fox predation of lambs and loss reliability rating

Loss reliability rating	Occurrence of perceived fox predation of lambs		N
	No fox predation	Fox predation reported	
1	0	3	3
2	0	5	5
3	33	99	132
4	34	80	114
5	100	65	165
All	167	252	419

Table 2.19: Overall model fit, parameter estimates and significance tests for variables in multiple logistic regression model explaining variation in occurrence of perceived fox predation of lambs, including dummy variables coding for reliability ratings of 3 and 4

Overall fit: Initial $LR\chi^2 = 512.0$, $LR\chi^2$ for fitted model = 334.4, $\chi^2 = 177.5$, d.f. = 6, $p < 0.001$ [n = 384]

Variable	**B**	**Wald**	**p**
Indoor lambing	-1.32	19.9	<0.001
Fox control carried out	1.38	20.7	<0.001
Lambing ewes	0.782	35.8	<0.001
Northwest	-1.42	6.86	0.009
Loss reliability rating of 3	0.891	6.11	0.013
Loss reliability rating of 4	0.138	0.165	0.685
Constant	-4.10	38.5	<0.001

Table 2.20: Overall model fit, parameter estimates and significance tests for variables in multiple logistic regression model explaining variation in occurrence of perceived fox predation of lambs, including dummy variables coding for reliability ratings of 3 and 5

Overall fit: Initial $LR\chi^2 = 512.0$, $LR\chi^2$ for fitted model = 331.9, $\chi^2 = 180.1$, d.f. = 6, $p < 0.001$ [n = 384]

Variable	**B**	**Wald**	**p**
Indoor lambing	-1.30	19.4	<0.001
Fox control carried out	1.42	21.2	<0.001
Lambing ewes	0.735	31.7	<0.001
Northwest	-1.328	6.53	0.011
Loss reliability rating of 3	0.542	2.15	0.143
Loss reliability rating of 5	-0.562	2.76	0.097
Constant	-3.51	21.8	<0.001

Table 2.21: Overall model fit, parameter estimates and significance tests for variables in multiple logistic regression model explaining variation in occurrence of perceived fox predation of lambs, including dummy variables coding for reliability ratings of 4 and 5

Overall fit: Initial $LR\chi^2 = 512.0$, $LR\chi^2$ for fitted model = 327.1, $\chi^2 = 184.8$, d.f. = 6, $p < 0.001$ [n = 384]

Variable	**B**	**Wald**	**p**
Indoor lambing	-1.39	21.2	<0.001
Fox control carried out	1.48	22.4	<0.001
Lambing ewes	0.726	30.7	<0.001
Northwest	-1.46	7.09	0.008
Loss reliability rating of 4	-0.978	6.65	0.010
Loss reliability rating of 5	-1.32	12.9	<0.001
Constant	-2.70	11.8	0.001

Table 2.22: Mean rank in Kruskal-Wallis analysis of variance of logged number of lambs perceived killed by foxes per ewe for each loss reliability rating, a higher rank indicating logged numbers of lambs perceived killed by foxes per ewe were higher in this group

Loss reliability rating	**N**	**Mean rank**
1	3	112
2	5	87.4
3	97	106
4	80	135
5	64	144

Table 2.23: Overall fit, parameter estimates and significance test statistics for variables in linear regression model explaining variation in perceived scale of predation of lambs, including variables coding for reliability ratings of 3 and 5

$R^2 = 0.370$, Adjusted $R^2 = 0.344$, $F = 14.4$, d.f. = 9, 221, $p < 0.001$ [n = 231]

Variable	B	t	p
Indoor lambing	-0.468	-3.82	<0.001
Foxes killed per hectare	1.50	2.80	0.006
Lambing ewes	-0.458	-7.92	<0.001
Game rearing b	0.420	2.89	0.004
Northeast	-0.477	-1.94	0.054
Southwest	0.319	1.86	0.064
Longwool	0.428	2.19	0.030
Loss reliability rating of 3	-0.224	-1.69	0.092
Loss reliability rating of 5	-0.003	-0.002	0.999
Constant	-1.24	-3.17	0.002

Table 2.24: Overall fit, parameter estimates and significance test statistics for variables in linear regression model explaining variation in perceived scale of predation of lambs, including variables coding for reliability ratings of 4 and 5

$R^2 = 0.379$, Adjusted $R^2 = 0.354$, $F = 15.0$, d.f. = 9, 214, $p < 0.001$ [n = 225]

Variable	B	t	p
Indoor lambing	-0.449	-3.69	<0.001
Foxes killed per hectare	1.41	2.64	0.009
Lambing ewes	-0.462	-8.05	<0.001
Game rearing b	0.417	2.89	0.004
Northeast	-0.499	-2.04	0.043
Southwest	0.326	1.92	0.056
Longwool	0.417	2.15	0.033
Loss reliability rating of 4	0.336	2.53	0.012
Loss reliability rating of 5	0.264	1.86	0.064
Constant	-1.48	-3.82	<0.001

2.4. DISCUSSION

2.4.1. Data reliability

2.4.1.1. Accuracy of lamb loss figures

One of the problems with studying lamb predation by foxes in Britain is that accounts of foxes killing healthy lambs tend to be anecdotal (Macdonald & Johnson 1996). In a study in west Scotland, Hewson found no visual evidence of foxes killing sheep, eagles being seen killing sheep only very occasionally (Hewson 1984b). Diet studies, examining scat and stomach contents, have identified sheep as a component of fox diets (Lever 1959; Hewson & Leitch 1983), but it is not possible to distinguish between sheep carrion and sheep that have been killed by foxes from these remains (Kolb 1996). The presence of calliphorid maggots inside fox stomachs suggests at least some of the sheep in their diet are eaten as carrion, as does wool in stomachs from areas where there have been no complaints of sheep losses, thought to be wool discarded during shearing (Lever 1959). Richards (1977) identified the remains of sheep in fox scats and at feeding sites in south Devon, but was able to connect all these remains to animals that had been buried following natural deaths.

It is likely that there has been some over-estimation of the number of lambs killed by foxes and the occurrence of lamb predation by respondents to this survey, as has occurred in previous surveys of this kind (Knowlton *et al.* 1999; Macdonald *et al.* 2000; White *et al.* 2000a). The reasons for over-estimation of losses include incorrectly assigning carcasses found as fox kills (including those that have been scavenged by foxes after death) and assuming missing lambs have been killed when they have died of other causes (White *et al.* 2000a). However, because of resource constraints, a study on this scale has to rely on the farmers' judgement of the level of predation they experience, despite the likelihood of over-estimation (Macdonald *et al.* 2000).

It is not always possible to verify whether a lamb death was due to foxes or not, even in the field. Although foxes often exhibit a characteristic manner of killing and subsequent treatment of lambs (teeth marks over the shoulder and crushed cervical vertebrae, often with decapitation (Harris & Lloyd 1991)), it is not easy to ascertain whether a sheep has been scavenged or killed by a fox (Lloyd 1980). The use of the size of the gap between canines shown in bite marks does not distinguish between a fox and a medium-sized dog, so is not sufficient evidence to prove fox predation (Swire 1978; Harris & Lloyd 1991). In both Hewson (1984b) and White *et al.*'s (2000b) studies, which used post-mortem analyses to establish cause of death, a large number of lambs went missing so their cause of death was unknown and both sets of authors calculated a figure for maximum mortality due to predation, including these lambs. One could therefore assume that the figures for predation obtained in this study were maximum values of lamb losses to foxes.

2.4.1.2. Sample bias and comparison with the literature

The issue of self-selection, or non-response error, is invariably a problem with mail surveys because their response rates are typically low. Ideally, in order to minimise or identify sources of bias, one would carry out a follow-up of non-respondents to the questionnaire (McNeill 1990; Barnett 1991). Unfortunately this was not possible in this study, due to data confidentiality issues. Therefore, average figures from this study were compared with those in the literature, from both field-based and survey-based studies, to assess whether sample characteristics, including occurrence and scale of fox predation of lambs, were representative of the population of British sheep farmers as a whole.

The mean and median number of ewes in this survey sample were similar to the UK national average flock size of 529 ewes (Cottle & Cottle 1998). Figures from the literature on the percentage of lambs killed by foxes compare favourably with those from this study (Table 2.6). In Heydon and Reynolds' (2000b) three region study, reported lamb losses due to fox predation varied from a median of 0% mortality of lambs in East Anglia to a median of 0.6% in Wales, with a range of figures from 0 to 28.6% of lambs. In a survey of members of the National Sheep Association carried out in 1993 by the Field magazine (Anon 1993), the average percentage of lambs lost (out of the annual lambing) reported by these sheep farmers was 1%, but it was considered that some farmers suffered more severe losses.

Hewson (1984b) quantified lamb mortality due to fox predation in two areas of western Scotland between 1976 and 1979. Percentages of the estimated sheep crop confirmed to have been killed by foxes in that study were between 0.6 and 1.8% in any one year, with 24% dying from other causes. Lambs whose cause of death was unknown were included to obtain a maximum figure for predation (by both eagles and foxes) of 5.2% of the total crop, recorded in 1977. White *et al.* (2000b) collected data on the numbers of lambs killed by foxes, as well as deaths due to other causes, on two Scottish hill farms between 1993 and 1996. Rates of predation were between 0.6 and 1.8% on one farm and between 0.2 and 1.7% on the other.

There have also been a number of studies that have considered fox predation on lambs in Australia (Saunders *et al.* 1997; Greentree *et al.* 2000) and in Norway (Warren & Mysterud 1995; Warren *et al.* 2001). However, due to differences in husbandry measures and weather conditions, figures from these studies are unlikely to be applicable to the British situation. It should be noted from one of these studies that, although estimated losses due to primary fox predation were fairly low, at 1.3%, losses could have reached 33% if lambs that would have died anyway as a result of other factors had been included in the figures (Saunders *et al.* 1997).

Via a questionnaire survey of farmers, Macdonald and Johnson (1996) calculated the annual loss of lambs per sheep to quantify perceived damage to lambs by foxes. Losses varied amongst the four regions they considered: a mean of 0.0045 lambs per sheep in the Midlands and East (for three years' data), 0.0063 lambs per sheep in the North, 0.0037 in the South and 0.0196 in Wales and the West. It is assumed that these are per number of sheep in the flock rather than per ewe figures, so they are not directly comparable with those in this study. The mean absolute number of lambs taken per flock was lower than that from this study at 1.74 lambs, likely to be because mean flock sizes were also lower.

The proportion of farms out of the total surveyed that reported fox predation (59.3%) was higher than the average in the two other studies that give a comparable figure (Macdonald 1984; Heydon & Reynolds 2000b). In Macdonald's (1984) survey of ten regions of England, an average per year (over the years 1976 to 1978) of 31% of farms on which sheep were kept reported one or more lambs had been lost on their farm to foxes. In Heydon and Reynolds' (2000b) survey of farmers in three regions of Britain, the overall average was 44.5% of farmers reporting predation by foxes. The differences between these results may well be a function of regional differences. Macdonald's (1984) survey only encompassed lowland England, whilst Heydon and Reynolds'

(2000b) figures varied between the three regions under study, 60.5% of sheep farmers in Wales reporting fox predation. In any case, for a comparison of characteristics between farms where predation was perceived to have occurred and those where it was not, the analysis is valid as long as there are a substantial number of each type of farm in the sample, assuming that their other characteristics are representative of the overall population.

Higher than expected responses to the survey were received from Scotland and Wales. These were regions where perceived losses of lambs to foxes were more likely to have occurred than elsewhere, which probably reflects the fact that farmers were more likely to respond if they experienced a problem with fox predation. Because the survey was distributed to a random sample of members of a national association, the sample will reflect the regional distribution of members of this organisation, which may not be the same as that determined from government census statistics.

2.4.1.3. Respondent reliability ratings

Reliability ratings given by the respondents provide us with a measure of how closely perceptions are likely to match up with reality, if we assume that reliability was accurately reported by respondents. Different reliability ratings were associated with different levels of the occurrence and scale of perceived predation, which suggests that inaccuracy in the figures reported by farmers differs between farms in a fairly consistent manner.

Perceived fox predation was less likely to have occurred where figures for losses were considered to be most accurate by respondents (a reliability rating of 5). This can be explained by the fact that, given all the difficulties in ascertaining whether a lamb has been killed by a fox or not, the perceived cause and number of losses are likely to be less reliable where fox predation is thought to have occurred. Reliability ratings were also associated with farm size. On farms with fewer sheep, respondents tended to rate the reliability of their loss figures higher. These results support the hypothesis that a farmer is able to keep track of lamb losses to a greater extent if there are fewer sheep. There was a negative relationship between farm size and the scale of perceived predation, which explains why the scale of perceived predation was positively associated with the reliability ratings. Thus, the indication is that differences in the reliability (and therefore accuracy) of perceived loss figures are associated with variation in farm management systems and farm size.

2.4.2. Farm characteristics influencing the occurrence and scale of perceived fox predation of lambs

2.4.2.1. Farm location and the influence of farm size

The univariate analyses carried out enable confirmation (or disaffirmation) of relationships that have previously been hypothesised. This analysis shows that perceived predation by foxes was more likely to have occurred on hill farms, as has been suggested in reviews of the topic (Harris & White 1994; McDonald *et al.* 1997; White *et al.* 2000a). However, in this survey, on farms where fox predation was perceived to have occurred, reported losses to foxes were lower on upland and hill farms than on lowland farms. In addition, while perceived predation was more likely to have occurred in Scotland and Wales (where there are more hill farms), perceived numbers of lambs killed by foxes were lower in Scotland and higher on farms in England. The reasons for this can be determined from the multivariate analyses.

A number of variables were significantly related to the occurrence and scale of perceived fox predation in univariate analyses, with this no longer being the case when they were included with other variables in multivariate models. For some variables, such as the percentage of ewes lambed indoors, this was simply because an alternative variable that influenced variation in reported predation in the same way had a more statistically significant effect. In others, it was because the relationships were in fact due to the effects of other variables to which they were related. For example, on average there were more sheep on hill farms (mean number of ewes on hill farms = 881, mean number on non-hill farms = 476), so when the effect of number of ewes on variation in perceived predation was included in the models, the effects of being in a hill area and having mountain or grass hill sheep breeds were no longer statistically significant. The conclusion to be drawn from this is that the hypothesised relationship between a farm's location in terms of it being in a hill, upland or lowland area and perceived fox predation was a function of other variables, one being the size of the farm. The same appears to be true of lambing in March and April. Lambing at this time of year is associated with hill farms, which have larger numbers of sheep, and farms that lamb outdoors and the variables that represent both farm size and indoor lambing have greater effects on the dependent variable than the month of lambing does.

This fact can also be used to explain why some factors had effects in directions that appear counter-intuitive. One example is the influence of having Scottish Blackface sheep on a farm. Because of their mothering skills, one would possibly expect losses to Scottish Blackface ewes to be lower than to other breeds, whereas the opposite was the case. This is because Scottish Blackface is a hill breed. Unfortunately, due to the large number of different breeds and the fact that farms often had more than one breed of sheep, the sample size of each was not sufficient to consider breeds separately, which is why they were classed together as breed types. Farms with longwool breeds generally had higher perceived numbers of lambs taken by foxes than those with other breed types. Longwool breeds were traditionally bred for their wool and for producing mutton, but are now used for mainly used for crossing (Boatfield 1994; Cottle & Cottle 1998). They are large-bodied with a high twinning rate (Cottle & Cottle 1998) and are suited to good conditions (likely to be on lowland farms) (Boatfield 1994). In general, farms with longwool breeds in this sample had slightly smaller flocks. It may be that longwool breeds are more prone to predation for one or several of these reasons, or that farmers with these breeds perceive the impact of foxes to be greater than those without. Alternatively, an association with another variable may be obscuring the real reason behind this relationship.

These associations amongst variables also explain why the directions of relationships between farm location variables differed between the two dependent variables. Hill and upland farms and farms in Scotland and Wales, both in this survey sample and according to the literature (Cottle & Cottle 1998; MAFF 1999), tend to have larger numbers of sheep. All variables describing the size of the farm and the number of sheep on the farm were positively related to the occurrence of perceived fox predation but negatively related to the scale of perceived predation where it occurred. The number of lambs born on the farm was an important determinant of the occurrence and scale of perceived predation and included in the overall models explaining variation in these two variables. The location variables, therefore, just reflect this difference: perceived fox predation of lambs was more likely to occur on larger farms but fewer lambs were perceived to be lost per ewe when fox predation did occur on larger farms.

A couple of studies have highlighted the association between farm size and farmers' perceptions of foxes. Baines *et al.* (1995) found that farms owned by council tenants were significantly smaller than farms falling into other ownership categories and that council tenants perceived foxes to be a greater pest than did other groups. Produce Studies (1995) reported a similar relationship between perceptions of the fox and farm size. These results support the negative relationship found in the present study between farm size and the scale of perceived predation on farms where predation was reported to have occurred. One lamb lost to a fox on a small farm will represent a larger proportion per ewe than on a larger farm and this negative relationship shows that the perceived number of lambs lost overall to foxes per flock was not proportionally dependent on flock size. Landa *et al.* (1999), on the other hand, found a positive relationship between sheep lost to wolverines and overall numbers of sheep grazing in summer on the Snøhetta plateau in south central Norway over 15 years, losses increasing proportionally with sheep numbers.

That the occurrence of perceived predation was greater on farms where more lambs were born could be due to various reasons including foxes being more attracted to farms with more lambs or the level of care of individual lambs being lower when there are more lambs. Kenward *et al.* (2001) draw a distinction between the factors that encourage a predator to start hunting at a site (site attraction) and the mechanisms that make it more rewarding to kill prey there (prey vulnerability) in explaining the difference between factors determining the occurrence and scale of predation (in their case, for buzzards preying on pheasants). In consideration of the reasons behind the associations between farm size variables and the occurrence and scale of perceived fox predation, however, the inter-relatedness of farm size to other variables should not be forgotten. Thus the associations may not be wholly due to variation in farm size. In addition, as the figures are 'perceived' losses, differences may simply be a function of variation in perceptions.

The relationships between some of the location variables remained even with the inclusion of farm size variables in the model, meaning their effects were independent of farm size. Farms in the Northwest postal region of Britain were less likely to have reported an occurrence of fox predation than farms elsewhere, whilst farms in the

Northeast where perceived fox predation occurred generally reported losing fewer lambs than farms elsewhere. Farms in Southwest England generally reported losing more lambs to foxes. Macdonald and Johnson (1996) found variation between regions in the number of sheep farmers claiming to have seen foxes attacking lambs, with 53.2% of farmers in the South claiming to have seen an attack and only 17.7% in the North doing so. This variation in lamb losses to foxes between regions mirrors variation in fox population densities between regions, the highest relative fox density being in Southwest England and one of the lowest in North England (Table 2.7).

2.4.2.2. Relative fox abundance and fox control

Regional fox density was related to the occurrence of fox predation in univariate analyses. The relationship was as hypothesised: a higher likelihood of the occurrence of perceived fox predation where relative fox population density was higher. The scale of perceived predation was not related to relative fox density, although both the number and the percentage of lambs reported killed by foxes were related to regional fox density. The scale of perceived predation was positively related to the number of foxes killed on the farm per hectare and the occurrence of fox predation was positively related to the number of foxes killed on the farm. The reason for these associations could be that fox kills are an index of fox population density (Hewson & Kolb 1973; Hewson 1984a), but it also may be the case that more foxes were killed where they were perceived to be more of a problem (Heydon & Reynolds 2000b).

Determining the relative importance of these two hypotheses is not possible since preventive and reactive fox control can not be distinguished from the data collected. It should be noted that any interpretation of kill data as an index of fox numbers assumes constant culling effort (McDonald & Harris 1999). Unfortunately data on culling effort were not available for this data set, but the number of foxes killed on the farm and the number killed per hectare were both positively associated with regional fox density. That at least some of the fox control carried out was reactive rather than preventive is suggested by the positive influence of 'fox control carried out' on the occurrence of perceived fox predation. This variable was the most statistically significant of the variables relating to fox control and was included in the overall model explaining variation in the occurrence of perceived fox predation. Both Macdonald and Johnson (1996) and Heydon and Reynolds (2000b) identified a similar association between reported damage by foxes and fox control. Heydon and Reynolds (2000b) found that experience of predation in the previous year was associated with a higher culling frequency only for farms of less than two hundred hectares. This effect could not be tested with these data, but farm size could well be a factor affecting the incidence of preventive versus reactive control on these farms too.

2.4.2.3. Surrounding land-uses

Both forestry and rough grazing land-uses in farm surroundings were related to a higher likelihood of perceived fox predation and arable land-uses were associated with a lower likelihood of predation. This could be a function of the attractiveness of these habitats to foxes: forestry plantations in particular may provide harbourage for foxes in upland areas (Lloyd 1980; Chadwick *et al.* 1997). A more likely explanation of these relationships, however, given that they do not hold in the multivariate model, is that rough grazing and forestry land-uses are most often found in upland and hill areas, whilst arable land is more common in lowland regions.

The positive association between game rearing in the surroundings and the scale of perceived fox predation, with the effects of other factors taken into account, may relate in some way to fox management practices in the surroundings. Alternatively, it could be that higher numbers of pheasants and other gamebirds mean there is more available food for foxes, which encourages them into the area, or that the perceived impact of foxes is heightened with game interests nearby. Heydon and Reynolds (2000b) and White *et al.* (2000a) point out that farmers' perceptions of foxes are inherently linked to their farming practices. It could therefore be that farmers' perceptions are also linked to the practices of their neighbours. Other studies have considered land-uses on the farm in question rather than in its surroundings, so are not directly comparable to this one. These studies have found game rearing to have an opposite effect to that observed here. In Heydon and Reynolds' (2000b) study, perceived losses of lambs were approximately halved in the presence of a gamekeeper, whilst Baker and Macdonald (2000) found that game-shooting farms were generally less likely to consider the fox a pest.

2.4.2.4. Husbandry techniques

The percentage of ewes lambed in lambing pens, the percentage of ewes having multiple births and the number of lambs born per ewe were related to the occurrence of perceived fox predation only in univariate analyses. This was due to their association with indoor lambing. Using lambing pens was associated with lambing indoors, as were a higher percentage of ewes with multiple births and a higher number of lambs born per ewe. Generally a higher ewe output is associated with lambing indoors (Bryson 1984), as well as with lowland sheep farming (Cottle & Cottle 1998). It was not possible to assess whether twins or triplets were more prone to predation with this data set because it dealt with between-farm characteristics rather than those between lambs. Indoor lambing was important in explaining variation between farms both in terms of the occurrence and scale of perceived fox predation. As discussed in the Introduction, other authors have hypothesised that this factor is likely to be important (Bryson 1984; Burns *et al.* 2000), whilst coyote predation studies in the U.S. have also found indoor lambing to be important in preventing sheep losses, e.g. (Robel *et al.* 1981).

Supplementary feeding of ewes with multiple births also had an effect on the scale of perceived predation in univariate analyses. Lower numbers of lambs were perceived to have been killed by foxes on farms that gave their ewes supplementary feeding, as was also found to be the case by Burrows (1968). As discussed, the lack of an effect on the occurrence of perceived predation is likely to be due to the low numbers of farmers not giving supplementary feeding to ewes with multiple lambs. Supplementary feeding of ewes with multiple lambs will mean that their lambs tend to be stronger and therefore potentially less prone to predation by foxes. A number of other husbandry practices that were not considered here may also be associated with fox predation of lambs. These include electric fencing, the number of shepherds per head of sheep and the proximity of lambing fields to farm buildings. A further survey of sheep producers was planned to assess these and other factors, but was not possible due to the outbreak of foot and mouth disease (FMD) in February 2001.

2.5. CONCLUSIONS

The use of univariate analyses to identify factors explaining variation in both the occurrence and the scale of perceived fox predation enabled the testing of various hypotheses concerning whether specific factors have an influence on variation in perceived fox predation between farms. However, it was through multivariate analyses that the most important factors influencing the dependent variables could be identified. These multivariate analyses also enabled the inter-relationships amongst some factors to be determined.

The model explaining variation in the occurrence of perceived predation had a predictive accuracy of 80%, which is fairly high for this type of empirical data, but left one fifth of the data mis-classified. The model explaining variation in the scale of perceived predation also did not fully explain variation in the dependent variable, accounting for only 36% of the variation. Incorporation of the respondents' own reliability ratings enhanced the amount of variation explained by the models slightly, but because the data are based on perceptions, they are likely to be subject to a large number of factors, which may be very specific to individual farms and some of which may be impossible to measure. Therefore, although it has been possible to identify a number of factors that influence perceived fox predation of lambs, the reasons behind some of the variation between farms remain unexplained.

A factor that strongly influenced variation in perceived fox predation between farms was lambing indoors. The decisions of whether to lamb indoors and how long to keep ewes and lambs in after lambing are under the farmer's control and indoor housing can be considered to be a preventive measure against fox predation. However, there are costs to indoor housing. The balancing of the benefits of preventing fox predation with these costs is the subject of Chapter 3.

2.6. SUMMARY

Lamb predation is one of the most significant perceived impacts of the fox in Britain, but the degree to which lamb predation occurs is subject to variation between farms. An assessment of the reasons behind the fox predation problem is an important part of the process of managing it, but such an investigation has not previously been carried out in Britain.

This chapter aimed to identify factors associated with differences in the occurrence and scale of perceived fox predation on sheep farms across Britain. This was done via a questionnaire survey of sheep farmers and using field data on relative fox population densities on a broad-scale basis.

Factors associated with variation in the occurrence of perceived fox predation were identified using logistic regression analyses and those associated with variation in the scale of perceived fox predation via linear regression. The main factors influencing variation in both the occurrence and scale of perceived fox predation were generally similar. Flock size was an important determinant of perceived fox predation. Fox predation was more likely to have occurred on larger farms, but, when it did, fewer lambs were perceived lost per ewe. Indoor lambing was associated with a lower likelihood of fox predation occurring and lower levels of predation. Various other non-management characteristics, including regional location, had an influence on fox predation.

Fox control was positively related to both the scale and occurrence of predation. This may be due to a relationship between fox abundance and perceived predation or due to reactive behaviour by farmers or a consequence of both of these.

This study illustrates the importance of multivariate analyses in assessing what factors affect perceived fox predation. By identifying some of the causes of variation in perceived predation between farms, strategies to manage the predation problem can be identified and management can be more targeted.

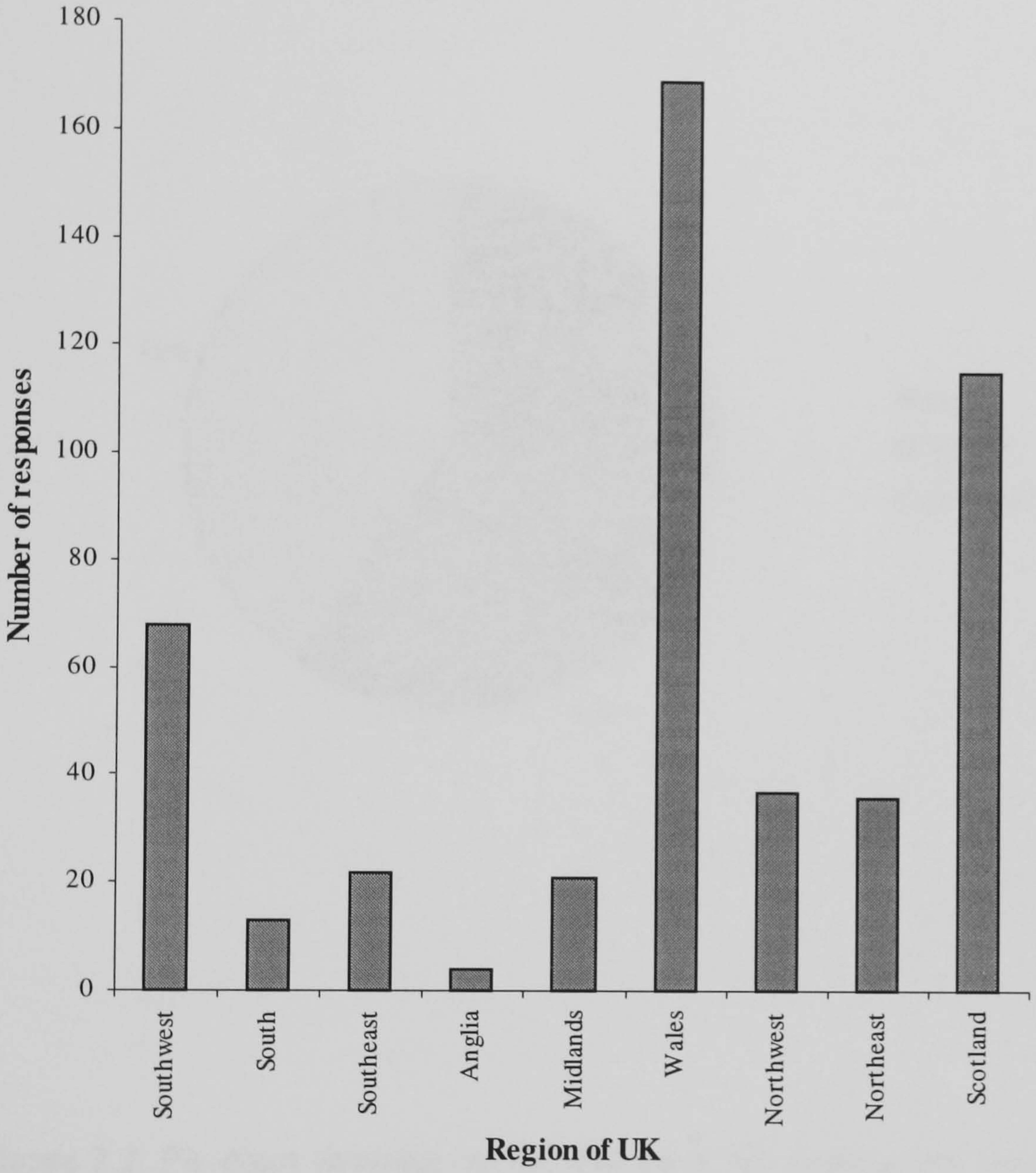


Figure 2.1: Location of the farms of sheep farmer questionnaire respondents by postcode-derived region [n = 487]

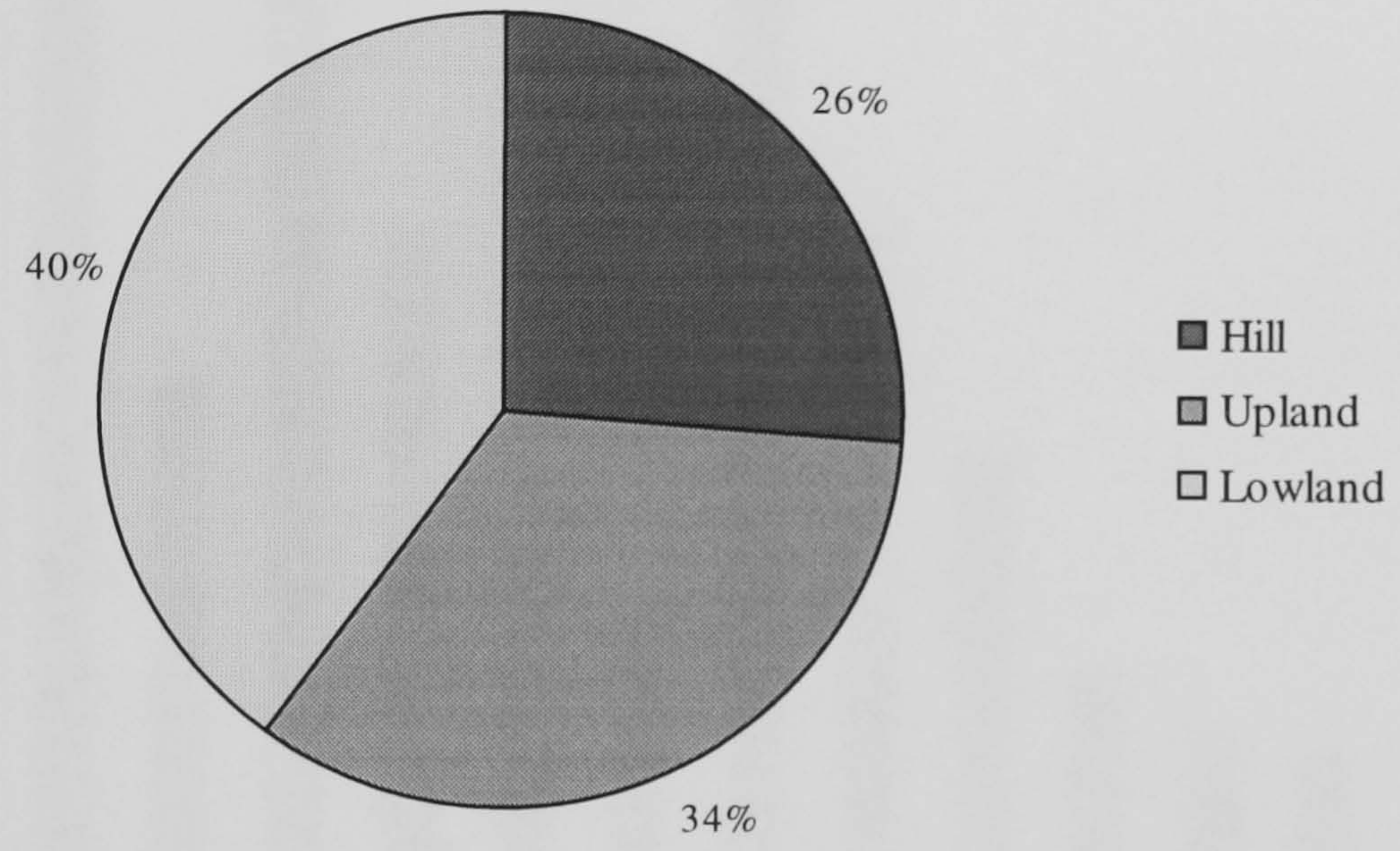


Figure 2.2: Pie-chart showing the percentage of hill, upland and lowland farms in sheep farm sample [n = 488]

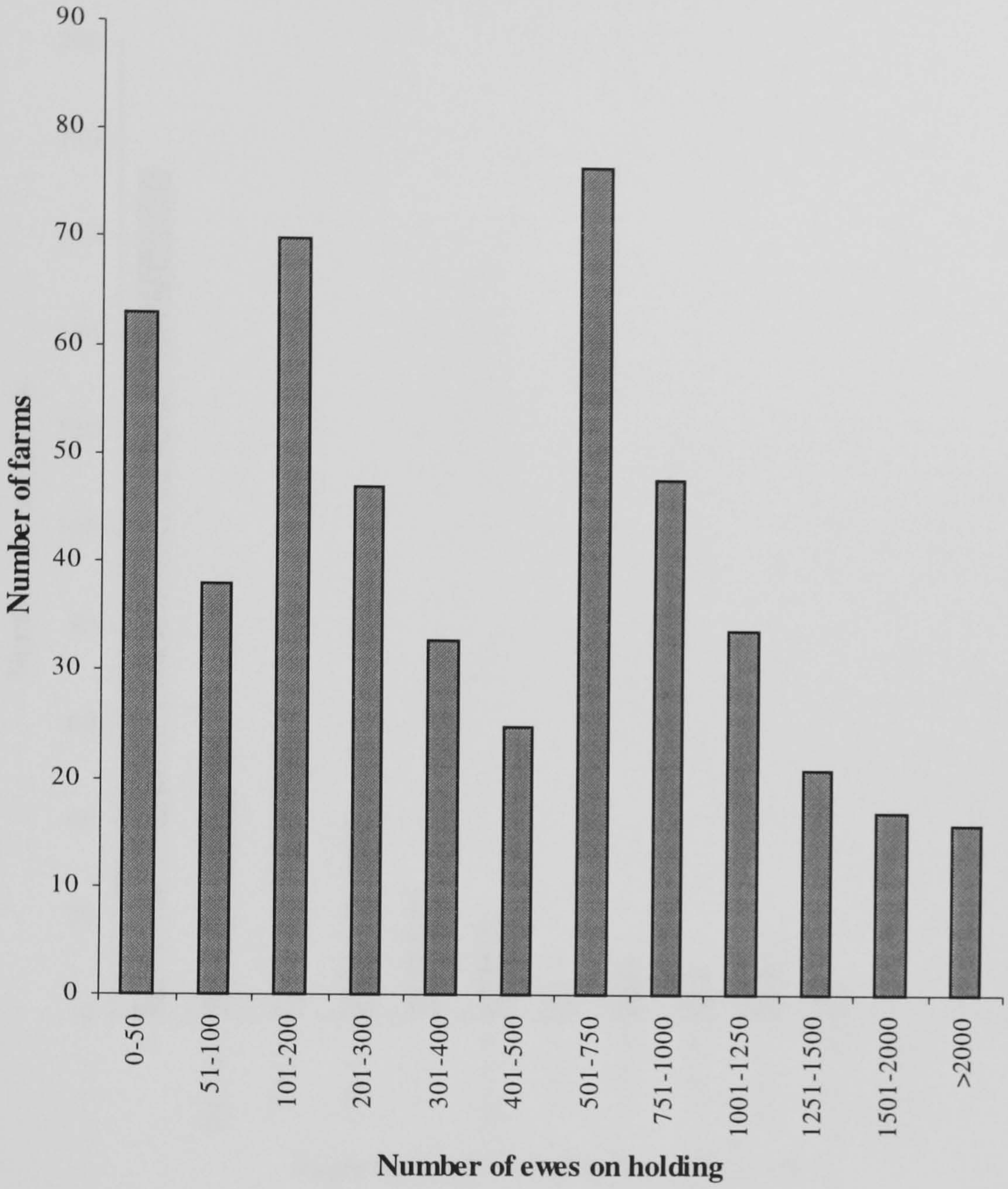


Figure 2.3: Histogram of number of ewes per holding [n = 489]

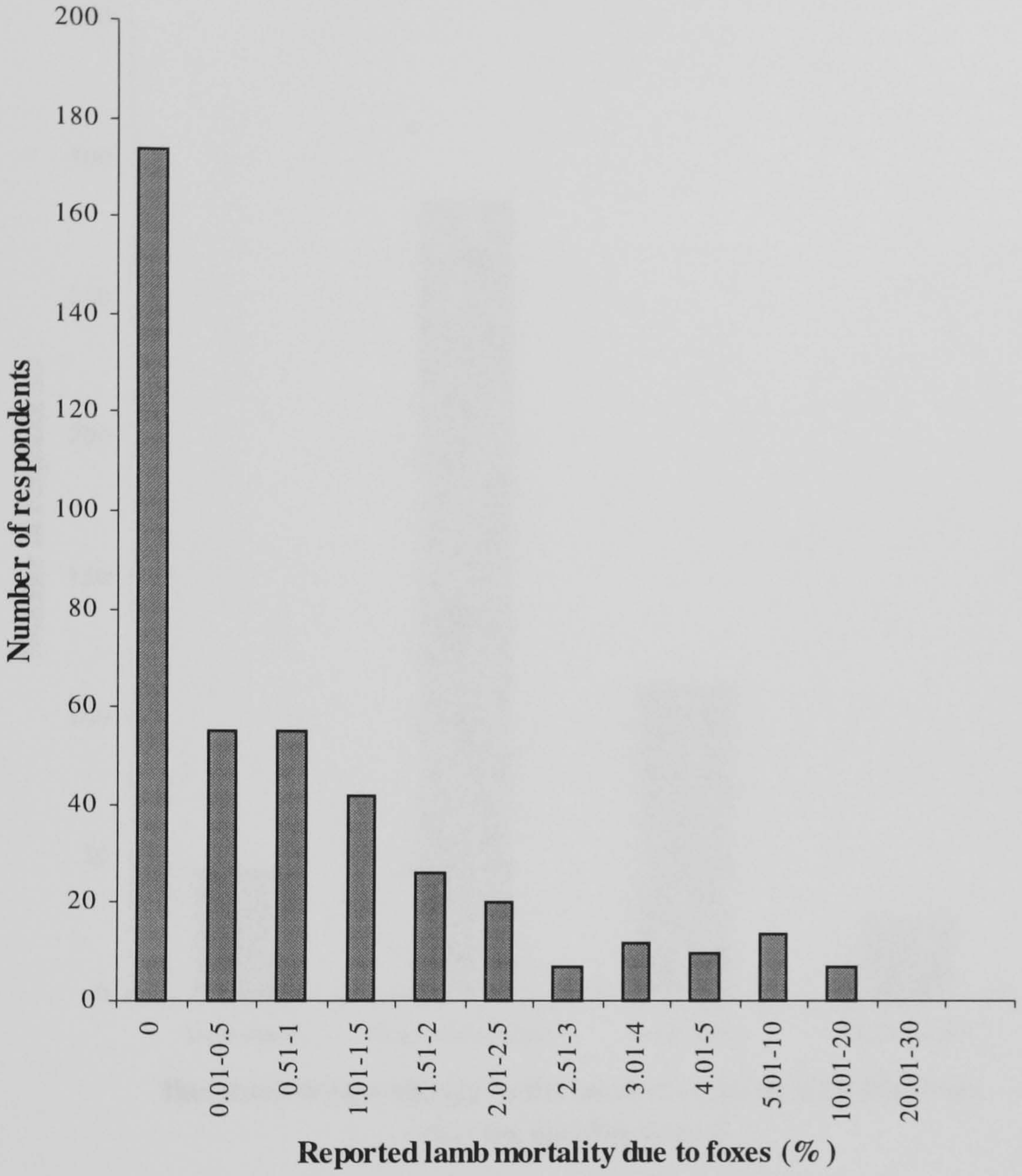


Figure 2.4: Histogram of responses for reported lamb mortality due to foxes [n = 422]

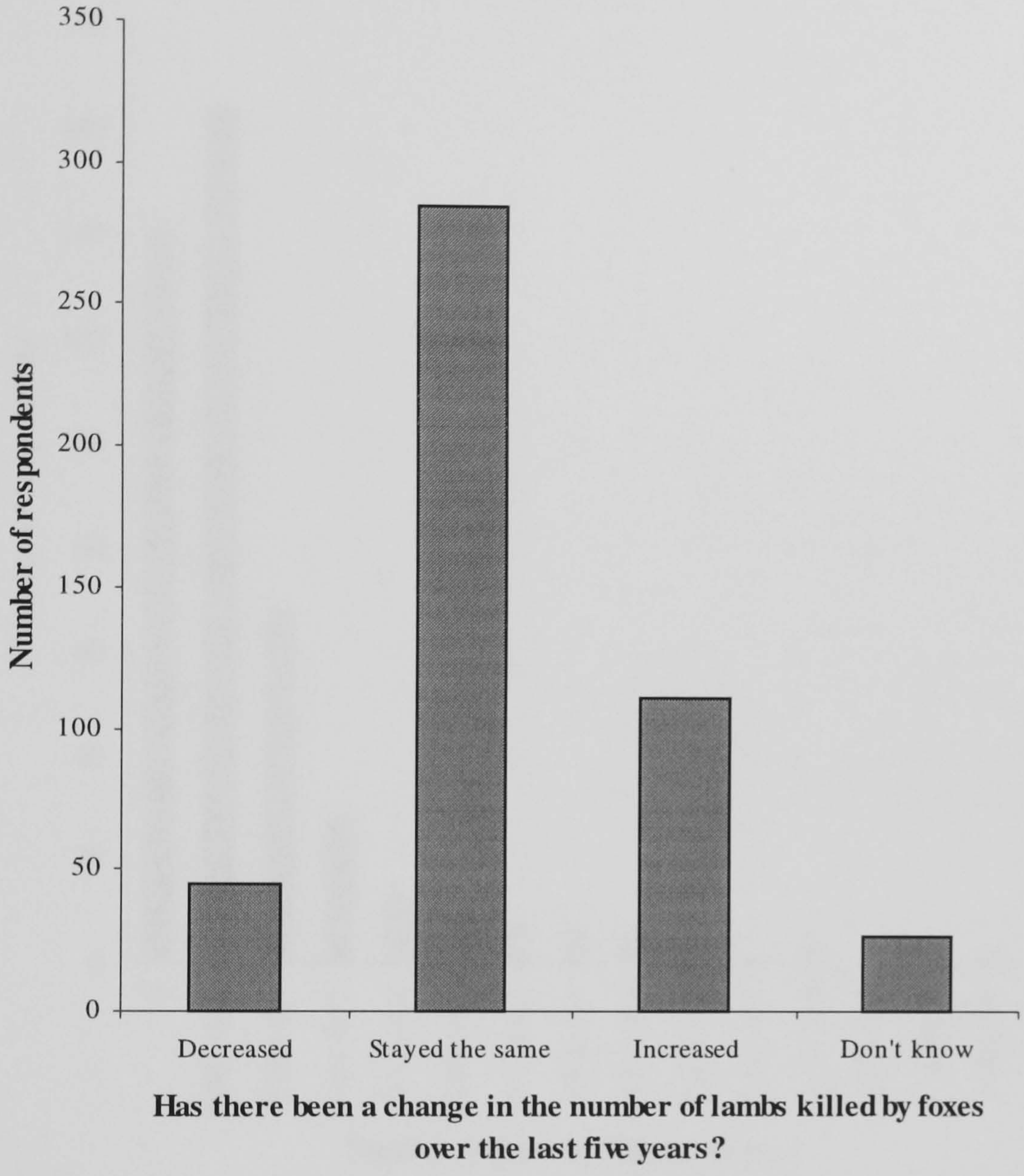


Figure 2.5: Histogram of responses to question about changes in number of lambs killed by foxes over last five years [n = 470]

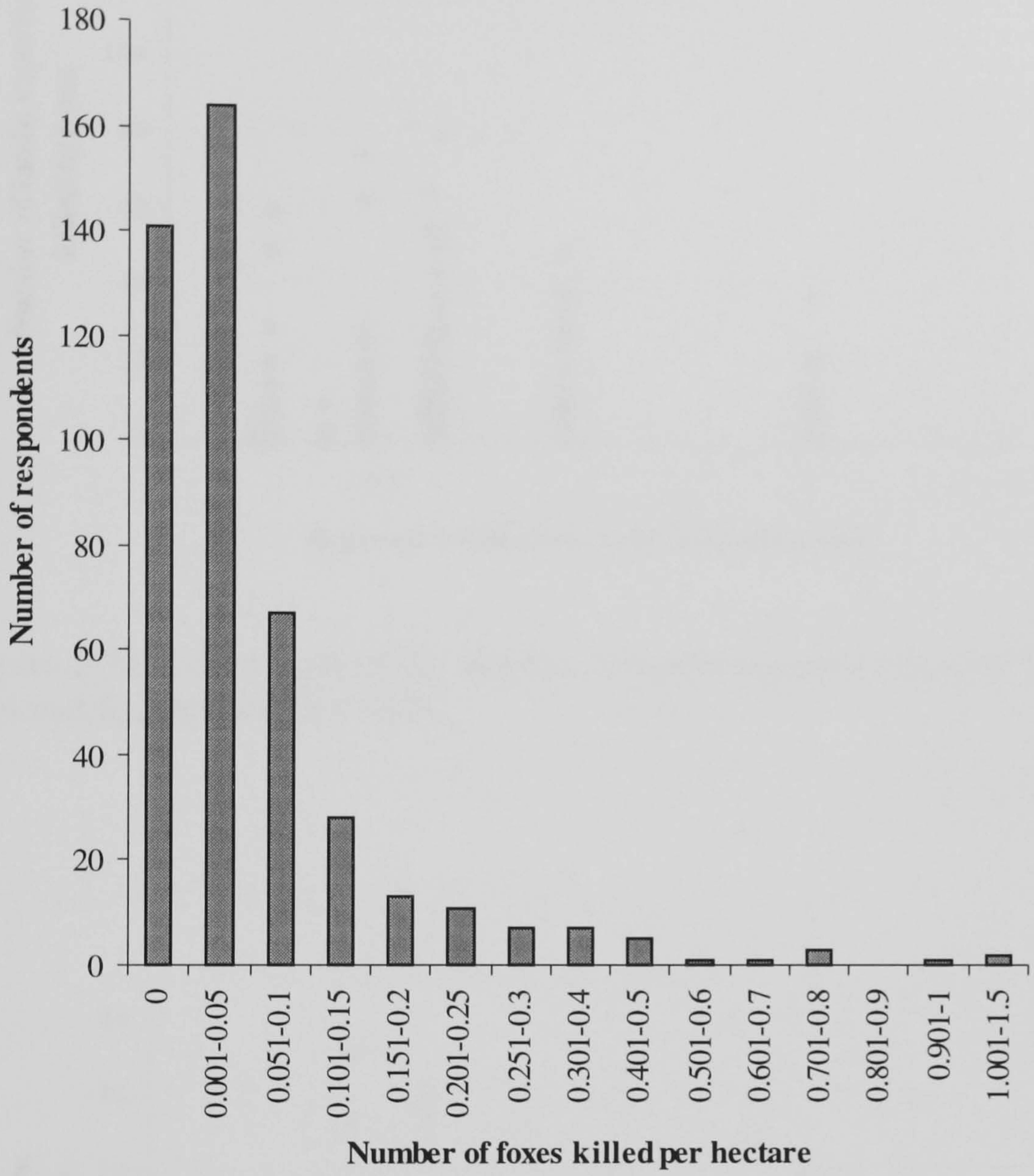


Figure 2.6: Histogram of reported number of foxes killed per hectare on sheep farms in the last year [n = 451]

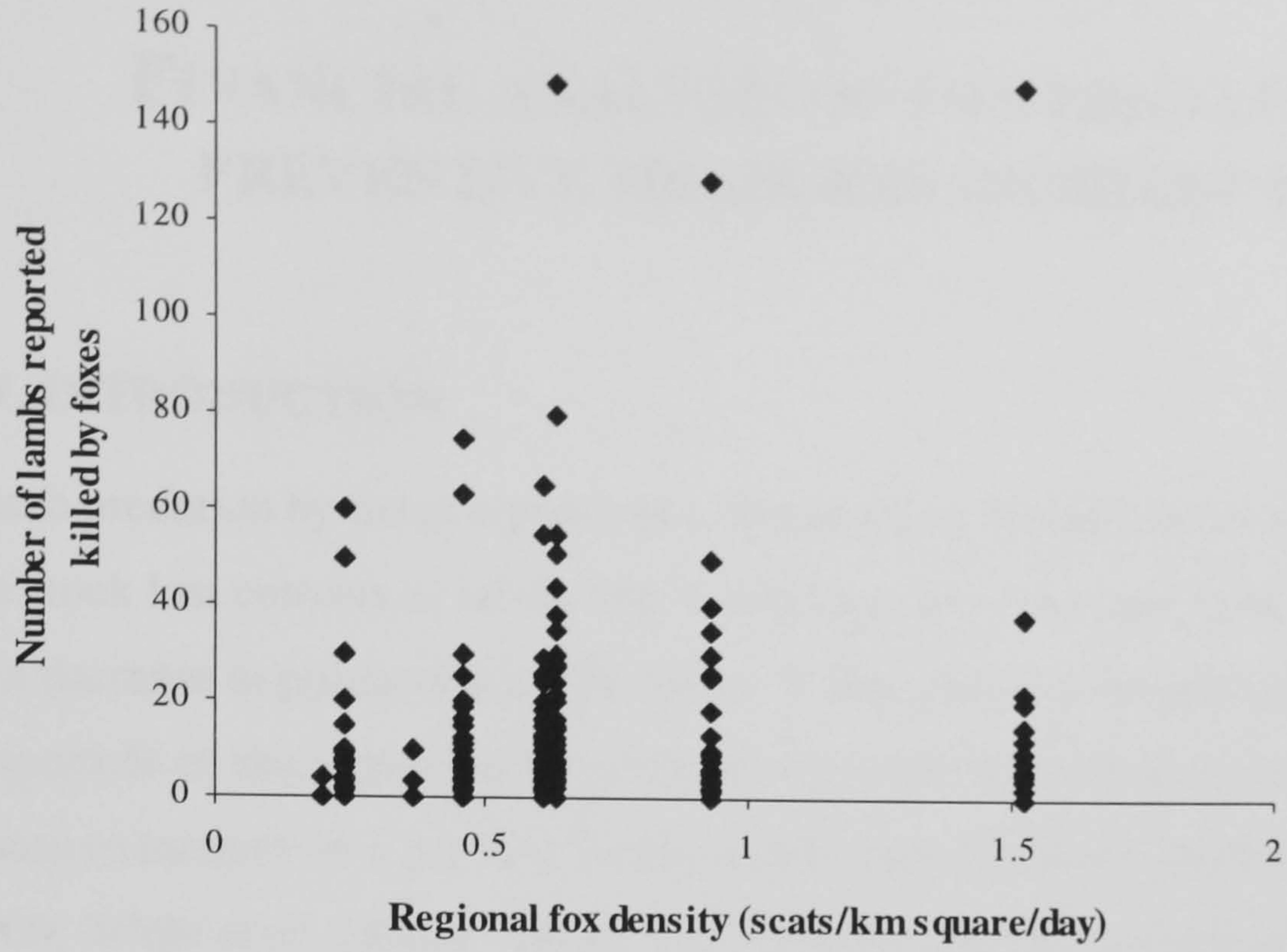


Figure 2.7a: Scatter plot of the number of lambs reported killed by foxes against regional fox density [n = 427]

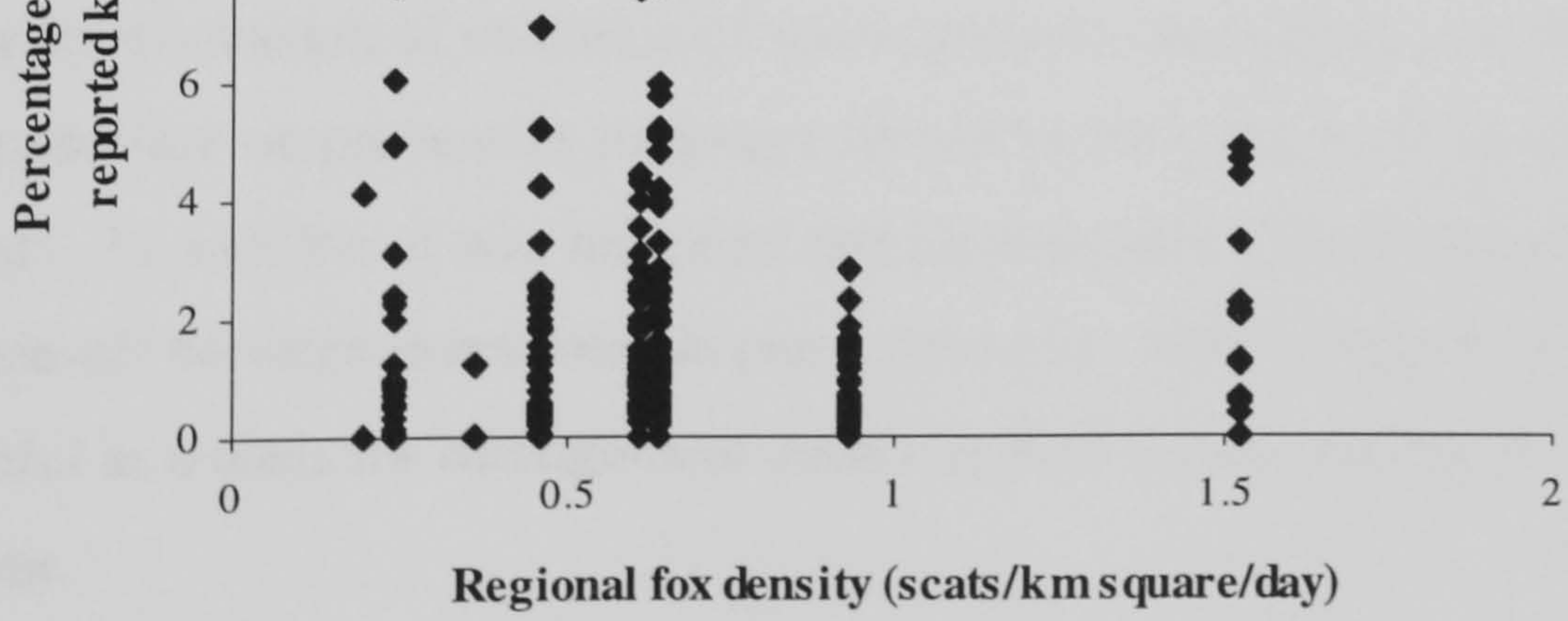


Figure 2.7b: Scatter plot of the percentage of lambs born reported killed by foxes against regional fox density [n = 422]

CHAPTER 3

FINANCIAL ANALYSIS OF FOX PREDATION AND PREVENTIVE MEASURES ON SHEEP FARMS

3.1. INTRODUCTION

Lamb predation by foxes represents a cost to sheep farmers in terms of loss of stock. If the stock lost consists of lambs that would have survived until sold, this cost translates to a decrease in production on the farm. A few studies have attempted to estimate the magnitude of the costs of lamb predation by foxes, focussing on the total costs of lamb losses to farmers on a per farm or per region basis (Produce Studies 1995; Burns *et al.* 2000; White *et al.* 2000a). White *et al.* (2000b) also estimated total losses in revenue due to fox predation, but based losses on data from post-mortem analyses of lambs on two Scottish hill farms. These studies have calculated costs by multiplying lamb losses by average market prices for lamb and average lamb liveweights. Macdonald and Johnson (1996), on the other hand, asked farmers directly about the total cost of foxes to them, including both lost stock and the cost of protecting against foxes.

Techniques for valuing the costs of stock mortality were discussed in Chapter 1, Section 1.2.2. It is difficult to value lamb losses due to fox predation because animals are not at point of sale because they are taken when young. Nevertheless, Taylor *et al.* (1979) argued that the market price for a lamb is the appropriate measure to use for predation losses because virtually all significant expenditures for lamb production are fixed. Earlier discussion of valuation of stock mortality highlighted the fact that the costs of expenditure on preventive measures should be included in an assessment of predation costs. In addition, it was indicated that an analytical framework, which considered the trade-off between investment in prevention costs and damage avoided, was far more useful as a basis for management decisions than a total cost figure for predation losses alone.

As outlined in Chapter 1 (Section 1.2.3), previous authors have suggested that measures to prevent predation could be included in a production model in order to estimate optimal management levels (Taylor *et al.* 1979). In the case of foxes and sheep farms in

Britain, Chapter 2 showed that perceived fox predation of lambs was influenced by farm location and management factors and it would therefore be inappropriate to consider the influence of population control or other preventive measures on production in isolation. In addition to these inputs, those related more directly to production, such as feed, capital and labour, should be included in such a model. The paucity of empirical studies using sheep production models in the literature (Kirby 2000) makes the estimation of such a model difficult. Whilst a production function would include preventive measures, a consideration of the cost side of the operation is more easily applicable to the problem under consideration. In addition, because fox predation impacts directly on lamb losses, information is not lost by estimating the cost function rather than the production function, except for in cases where preventive measures have additional effects to those on losses. Such additional effects are discussed later in this chapter.

This chapter aims to develop a model to be used in the identification of a financially optimal solution to the problem of preventing lamb predation by foxes at a farm level. The preventive measure under consideration is the indoor housing of ewes and lambs at and after lambing, identified as an important influence on perceived predation in Chapter 2. By combining McInerney *et al.* (1992) and McInerney's (1996) ideas with those of Fankhauser (1995) and Taylor *et al.* (1979), a theoretical model is developed. The model also includes elements of decision theory, as discussed by Norton (1976), Mumford and Norton (1984) and Hone (1994), and a logistic risk analysis, used in previous studies to predict the risk of specific pest outbreaks and aid decision-making on whether to carry out prophylactic treatment (Mutze *et al.* 1990; Wilson *et al.* 1996; Yuen *et al.* 1996; Twengström *et al.* 1998; Lindblad 2001). Data from the survey of sheep farms across Britain are used to parameterise the model. The model is used to find an optimal management solution from the farmer's point of view, by minimising the total costs associated with fox predation, in terms of lamb losses and preventive measures.

3.2. THEORETICAL MODEL

It is assumed that the farmer aims to maximise profits per ewe from lamb production on the farm. Profits will be a function of the number of lambs born and lamb losses between birth and weaning, amongst other factors (Kirby 2000). If it is assumed that all lambs surviving to weaning are sold for profit, it can be postulated that a farmer aims to maximise the number of lambs surviving to weaning per ewe subject to certain constraints.

The number of lambs surviving to weaning per ewe on the *i*th farm (W_i) is equal to the number of lambs born per ewe (B_i) minus the number dying between birth and weaning per ewe (D_i):

$$W_i = B_i - D_i. \qquad (3\text{-}1)$$

The number of lambs dying between birth and weaning per ewe is made up of lambs lost to foxes (F_i), other predators (H_i) and other causes per ewe (O_i):

$$D_i = F_i + H_i + O_i. \qquad (3\text{-}2)$$

It follows from the above that the farmer aims to minimise lamb losses to foxes per ewe in so far as is possible. However, a constraint to this is that the farmer also aims to minimise all other costs associated with lamb losses to foxes, one of these being expenditure on measures used to prevent lamb losses to foxes. If it is assumed that the only objective of these measures is the prevention of losses, then the optimal solution in financial terms for the farmer will be a trade-off between lamb losses and expenditure on measures that prevent lamb losses.

As determined in Chapter 2, lamb losses to foxes are a function of preventive measures used and other factors (such as the number of lambing ewes and the regional situation of the farm):

$$F_i = f(M_i, N_i, R_i) \qquad (3\text{-}3)$$

where:

F_i = the number of lambs lost to foxes per ewe per year on the *i*th farm

M_i = preventive measures per ewe per year on the *i*th farm

N_i = number of lambing ewes on the ith farm

R_i = regional situation of ith farm

f = function of farm characteristics determining lamb losses

The above can also be expressed in monetary terms, giving losses as a function of expenditure on preventive measures and other variables:

$$L_i = g(M_i, N_i, R_i) \tag{3-4}$$

where:

$L_i = p_{Fi} \cdot F_i$ = lamb losses to foxes per ewe per year on the ith farm (£)

p_{Fi} = value of one lamb lost to foxes on the ith farm (£)

M_i = expenditure on preventive measures per ewe per year on the ith farm (£)

g = function of farm characteristics determining monetary lamb losses

It is assumed that lamb losses decrease with increasing expenditure on preventive measures, but that there are diminishing marginal returns to the investment in preventive effort.

So, $g' = \partial g/\partial M_i < 0$, and $g'' = \partial g'/\partial M_i > 0$.

It is assumed that the optimal point for the farmer is that at which total costs ($L_i + M_i$) are minimised.

Analyses in Chapter 2 indicated that the occurrence and the scale of fox predation were determined by different combinations of variables. For example, fox population density did not influence the level of lamb predation by foxes, but appeared to have an effect on the occurrence of predation. In addition, both the percentage of ewes lambed indoors and the number of days ewes and lambs were kept in after lambing were associated with a lower likelihood of fox predation, but it was only the proportion of ewes indoors that affected the scale of predation. The percentage of ewes lambed indoors and the number of days they are kept in can be combined into one variable, the number of ewe days inside, and this can be estimated in monetary terms to give the expenditure on indoor housing at and after lambing per ewe. Therefore, there are different probabilities of lamb predation occurring at different levels of expenditure on indoor housing (Table 3.1).

Table 3.1: Predicted association between the probability of lamb predation occurring and expenditure on indoor housing

Expenditure on indoor housing per ewe (£)	Predation
Low	High probability
Medium	Medium probability
High	Low probability

Based on Table 3.1, the expected lamb predation outcomes at various levels of expenditure on indoor housing can be calculated, if we know the probability of fox predation occurring at different levels of expenditure on indoor housing and the expected monetary outcome if predation does occur. These can be derived according to various farm characteristics if expenditure on indoor housing, based on the number of days and the percentage of ewes inside, is substituted into the regression models estimated in Chapter 2 (lamb losses are expressed in monetary terms):

$$P(x = 1) = h(Y_i \cdot D_i, X_i, N_i) \tag{3-5}$$

$$L_i = j(Y_i, N_i, R_i) \tag{3-6}$$

where:

$P(x = 1)$ = probability of lamb predation by foxes having occurred on ith farm, where x is a binomial variable coded 0 when no fox predation occurred and 1 when predation occurred on the ith farm

Y_i = expenditure on indoor housing per ewe per day on the ith farm

D_i = number of days ewes and lambs are kept indoors after lambing on the ith farm

X_i = fox population density per hectare on the ith farm

L_i = lamb losses to foxes if fox predation occurs ($x = 1$) on ith farm (£)

h = function of farm characteristics determining the probability of fox predation

j = function of farm characteristics determining lamb losses to foxes if fox predation occurs

The variable Y_i accounts for the effects of the percentage of ewes that are lambed indoors and this is multiplied by the number of days inside (D_i) to account for the effect the combination of these variables has on the probability of predation occurring and to give the total expenditure on housing per ewe. Y_i is a function of the proportion of ewes lambed indoors (i.e. the number of ewes indoors per ewe) and the proportion of ewes that have multiple births:

$$Y_i = m(E_i, M_i)$$

where:

E_i = proportion of ewes lambed indoors

M_i = proportion of ewes having multiple births

m = function of ewe flock characteristics determining expenditure on housing

Therefore it is E_i and D_i that are the control variables: the management variables that the farmer changes in order to reduce lamb losses and minimise costs. The proportion of ewes having multiple births (M_i) is assumed not to be under the farmer's control.

The expected loss outcome at defined preventive expenditure levels based on these models can be calculated through looking at the pay-off matrix (Table 3.2). The expected outcome is calculated by multiplying the pay-off associated with each state of nature by the probability of occurrence of this state at a particular expenditure level and adding these figures together (Norton 1976; Mumford 1981b; Hone 1994). For example, the expected loss outcome for a farm with a low expenditure on indoor housing per ewe would be $[(P(x = 0 \mid Y_i{\cdot}D_i = \text{low}) \times 0) + (P(x = 1 \mid Y_i{\cdot}D_i = \text{low}) \times L_i(Y_i \mid Y_i{\cdot}D_i = \text{low}))]$ or simply $[P(x = 1 \mid Y_i{\cdot}D_i = \text{low}) \times L_i(Y_i \mid Y_i{\cdot}D_i = \text{low})]$, as the outcome is zero if there is no predation. This expected loss outcome is the expected gross margin at various levels of expenditure (Norton 1976).

Table 3.2: Pay-off matrix indicating lamb loss due to fox predation outcomes according to expenditure on indoor housing ($Y_i \cdot D_i$)

		States of nature	
		No predation	**Predation**
Probability of state		P(x = 0 | $Y_i \cdot D_i$ = low, medium, high)	P(x = 1 | $Y_i \cdot D_i$ = low, medium, high)
Expenditure on indoor housing per ewe (£)	Low	Zero lamb losses	Lamb losses = $L_i(Y_i \mid Y_i \cdot D_i =$ low)
	Medium	Zero lamb losses	Lamb losses = $L_i(Y_i \mid Y_i \cdot D_i =$ medium)
	High	Zero lamb losses	Lamb losses = $L_i(Y_i \mid Y_i \cdot D_i =$ high)

Because logistic regression estimates a continuous probability function and linear regression is also estimated for a continuous dependent variable, we can estimate a continuous expected lamb loss outcome, which varies according to preventive expenditure, fox population density and other farm characteristics and is analogous to equation 3-4 above:

$$Z_i = g(Y_i, D_i, X_i, N_i, R_i) = \mathrm{P}(x = 1) \times L_i \tag{3-7}$$

where:

Z_i = expected lamb loss to foxes per ewe (£)

The total costs of fox predation per ewe (TC_i) are equal to expenditure on indoor housing plus lamb losses to foxes per ewe:

$$TC_i = Y_i \cdot D_i + Z_i$$

The economic optimum is where these total costs are minimised, where the marginal costs of control equal the marginal benefits in terms of reduced lamb losses (Figure 1.1b) and, therefore, the partial derivatives of total costs with respect to the proportion of ewes lambed indoors and with respect to the number of days inside are equal to zero:

$$\frac{\partial TC_i}{\partial E_i} = \frac{\partial Y_i}{\partial E_i} \cdot D_i + \frac{\partial Z_i}{\partial E_i} = 0 \text{ and } \frac{\partial TC_i}{\partial D_i} = \frac{\partial Z_i}{\partial D_i} + Y_i = 0$$

3.3. EMPIRICAL ANALYSIS

Data for estimation of the functions were taken from the survey of sheep farmers across Britain (Chapter 2) and the fox density estimates from Webbon (2002) (both are discussed in Chapter 2, Section 2.2 Methods). Throughout, the term 'per ewe' stands for 'per lambing ewe'. Data for lamb losses to foxes were taken from the survey data as the number of lambs reported killed by foxes per lambing ewe.

3.3.1. Fox population density estimates

The data on relative fox population densities used in Chapter 2 were median scat densities based on nine regions or seven land classes. Only region-based estimates were statistically significantly related to lamb predation by foxes. It was therefore the regional fox density estimates that were used for further analyses. It was necessary to convert these relative estimates to absolute estimates, in order that fox control could be realistically linked into the models in later analysis (Chapter 4). As absolute estimates were not available from the data provided by Webbon (2002), an appropriate multiplier to convert scats found per kilometre square into absolute densities was estimated from the literature.

Data from fifteen bait marking trials (C. Webbon, pers. comm.) were used to calculate a mean number of fox scats found per day of 0.457. Free-living foxes were fed bait with markers in for 14 days and the number of marked scats found in each trial counted by volunteers (C. Webbon, pers. comm.). In each case it was known that a single fox was being fed bait (C. Webbon, pers. comm.). A few estimates for the number of scats one fox produces per day were available from the literature: a mean of 6.6 scats per day (Lockie 1959), 5 scats per day (Ryszkowski *et al.* 1971), 6 scats per day eating fruit and rabbit and 2 to 3 eating carrion (Rau 1988). Taking an average scat dry mass of 5.35g (C. Webbon, pers. comm.), a further two estimates were calculated according to figures on faeces dry weights emitted per day, of 4.08 (Artois *et al.* 1987) and 4.67 to 5.61

(Failu & Griess 1974) scats produced per day. By dividing each of these figures for scats produced per day by the number of scats found, a figure for the mean proportion of scats produced that are found was calculated. This provided a multiplier for converting the number of scats found per day (the relative density estimates) to an estimated total number of scats present per day, which was 10.8. The estimated total number of scats present per kilometre square per day was calculated for each region from the relative density estimates. Absolute fox density estimates were derived by dividing by the mean number of scats produced per day by one fox, 4.9, taken from the literature cited above (Table 3.3). Densities per kilometre square were converted to per hectare estimates by dividing by 100 to enable easy comparison with farm-based variables. The assumptions behind the conversion of relative fox densities to absolute numbers are discussed further in Chapter 4 (Section 4.5.3.2).

Table 3.3: Absolute fox density estimates based on regions

Region Code	Region	Density estimate (foxes per 1-km square)
1	N Scotland	1.02
2	S Scotland	2.05
3	N England	0.53
4	E England	0.44
5	Midlands	1.35
6	Central England	0.81
7	SW England	3.36
8	S England	1.01
9	Wales	1.41

3.3.2. Monetary valuation of lamb losses to foxes

The value of lamb losses was calculated as the market value for finished lamb per kg liveweight multiplied by the average liveweight of finished lambs sold by the farm multiplied by the number of lambs lost. This firstly assumes that all lambs sold would have been sold as finishers. There was, however, a large variation in farms, some selling store lambs, others retaining some of their stock, rather than selling them on as finishers. The finished lamb price, however, gives a convenient starting point for valuing losses as, although data on overall production on the farms were available, data were not collected on how lambs that were taken by foxes would have been sold. It is further assumed that the value of the lamb when it was lost is equal to its value at point of sale. Once again there was a lack of data on the age of lambs reported to have been taken by foxes, though, as discussed in the Introduction, Taylor *et al.* (1979) argue that the use of market price for valuing lambs is justified by the fact that virtually all significant expenditures for lamb production are fixed.

The market value of finished lamb for 1999 was taken as 92.5p per kg liveweight (Nix 1999). The average finished liveweight of lambs on the farm was taken as given by 420 farms. For the remainder of farms for which the data were not available, the liveweight was entered as the mean liveweight for that farm type from the rest of the data: 34.9kg for hill farms, 38.9kg for upland and 39.5kg for lowland farms. The average market value of finished lamb, or the average value of a lamb lost, was calculated for each farm using these data. Figures for losses per ewe in monetary terms were then obtained by multiplying the total number of lambs reported killed by foxes between birth and weaning by this average value, and dividing this by the number of ewes lambing. Table 3.4 gives summary statistics for lamb losses to foxes.

In the survey, farmers were asked for their valuation of the costs of lamb losses to foxes at their most recent lambing. It was decided, however, that this monetary value was unlikely to be as accurate as a value based on reported losses. This was partly because, in some cases, respondents were known to have included other costs in addition to those of lamb losses to foxes in these figures and it was deemed more appropriate to use a standardised method for calculating losses in monetary terms. A further reason for not using the respondents' values was that a smaller sample size of farmers gave monetary values for lamb losses to foxes than gave figures for the number or percentage of lambs they perceived they had lost to foxes. Table 3.4 gives summary statistics for reported costs of lamb losses to foxes.

Values for lamb losses calculated from the data and those given by respondents were compared in a paired t-test and the samples did not differ significantly from one another ($t = -0.929$, d.f. = 334, $p > 0.05$ [n= 335]). However, the correlation between the two sets of values was fairly low, when tested parametrically ($r = 0.422$, $p < 0.001$ [n =

335]). The non-parametric correlation coefficient showed up a much greater association between the values ($r_s = 0.947$, $p < 0.001$ [n=335]), indicating that the values were associated with one another well in relative terms, but less so in absolute terms. The calculated value gave a lower valuation of lamb losses to foxes than did the reported values. Figure 3.1 shows that this relatively low absolute association between reported and estimated costs is mainly due to a few high reported cost values.

3.3.3. Expenditure on indoor housing

The costs of indoor housing for sheep include the capital costs of the building, as well as the additional costs of extra food and bedding for the sheep and extra veterinary bills, as disease spread is more likely in an indoor environment. Capital costs were not included here because as fixed costs they should not be included in an analysis based on equi-marginality.

The figures for expenditure on indoor housing were based on the additional expenditures on feed and bedding associated with housing indoors. The amounts of feed and bedding needed per ewe per day for indoor housing were taken from Bryson (1984). In the case of straw bedding, this amount was 0.25kg per indoor ewe per day. Figures for the amounts of hay and concentrates were calculated from the amounts needed for the two weeks before lambing for a 60kg ewe. No figures were available for feed supply for lactating ewes indoors, so these were estimated by calculating the percentage difference between gestation and lactation daily nutrient requirements for both single- and twin-bearing ewes from the Committee on Animal Nutrition (1995) and then multiplying Bryson's (1984) figures up by this amount. This gave figures of 0.92kg of hay per indoor ewe per day and 0.55kg of concentrates for a single-bearing ewe and 0.96kg of concentrates for a twin-bearing ewe per day. The amounts of concentrates used per indoor ewe per day were calculated according to the percentage of ewes in each flock having multiple births, these ewes being assumed to be twin-bearing: 0.96 was multiplied by the percentage of ewes having twins and 0.55 by the percentage having only single lambs and the two figures added together.

The prices for hay and straw per kg for 1999 were taken as means from the Ministry of Agriculture, Fisheries and Food (MAFF) Hay and Straw Average Prices (Monthly) for

England and Wales for 1999. The prices used were those for big-baled wheat straw and big bale hay, at £0.022 and £0.039 per kg, respectively. The price of concentrates was calculated as the mean price given by respondents to the survey, at £0.135 per kg. This figure is in line with the figure given by Nix (1999) of £0.134 per kg and by Cottle and Cottle (1998) of approximately £0.145 per kg. Expenditure on feed and bedding for indoor housing was then calculated by multiplying the amounts of feed and bedding needed per indoor ewe for each flock by these prices. To get a 'per lambing ewe' figure, this was multiplied by the number of ewes lambed indoors and then divided by the total number of ewes lambing. Therefore, expenditure on indoor housing per ewe per day is a function of the proportion of ewes lambed indoors and the proportion of ewes having multiple births:

$$Y_i = E_i \cdot P_C(C_S(1 - M_i) + C_T \cdot M_i) + E_i \cdot P_H \cdot H + E_i \cdot P_S \cdot S$$

$$Y_i = 0.053 \cdot M_i \cdot E_i + 0.118 \cdot E_i$$

where:

E_i = proportion of ewes lambed indoors on the ith farm
M_i = proportion of ewes having multiple births on the ith farm
P_C = price of concentrates per kg (£) (£0.135)
C_S = amount of concentrates needed for a single lamb-bearing ewe per day (kg) (0.55kg)
C_T = amount of concentrates needed for a twin-bearing ewe per day (kg) (0.96kg)
P_H = price of hay per kg (£) (£0.039)
H = amount of hay needed per ewe per day (kg) (0.92kg)
P_S = price of straw per kg (£) (£0.022)
S = amount of straw needed per ewe per day (kg) (0.25kg)

Table 3.4 gives summary statistics for both expenditure on indoor housing per ewe per day and total expenditure on indoor housing per ewe for the data set. Data on the extra costs of veterinary treatment for farms that lambed indoors were not available. A survey of the costs and types of housing for a sample of the original respondents was planned, but was not possible due to the outbreak of foot and mouth disease in Britain in February 2001.

Table 3.4: Summary statistics for the cost of lamb losses to foxes per ewe and expenditure on indoor housing for the sample

Value	*n*	Mean	Median	Range
Cost of lamb losses to foxes per ewe (£) (L_i)	426	0.56	0.21	0.00-9.40
Cost of lamb losses to foxes per ewe, farms where predation occurred (£) ($L_i \mid x = 1$)	251	0.96	0.58	0.02-9.40
Reported cost of lamb losses to foxes per ewe (£)	372	0.71	0.14	0.00-38.46
Reported cost of lamb losses to foxes per ewe, farms where predation occurred (£)	195	1.13	0.48	0.00-38.46
Expenditure on indoor housing per ewe per day (£) (Y_i)	475	0.10	0.14	0.00-0.17
Expenditure on indoor housing per ewe (£) ($Y_i \cdot D_i$)	470	0.99	0.30	0.00-23.43

3.3.4. Specification of model relating expected lamb losses to expenditure on indoor housing

Models for predicting the expected lamb loss outcome due to fox predation according to expenditure on indoor housing were estimated using logistic and linear regression. As in Chapter 2, logistic regression was used to explain variation in the occurrence of fox predation, and therefore predict the probability of predation occurring, and linear regression to explain variation in the number of losses per ewe when predation occurred, i.e. only including losses of greater than zero. Expenditure on indoor housing per ewe ($Y_i \cdot D_i$) and per ewe per day (Y_i) were tested in the models both as originally calculated and ln-transformed. The original data included zero figures, which could not be logged. A positive constant that was considered to be small compared to overall figures, but not so small as to distort the distribution of the data, was therefore added on to these data (traditionally 1 is the constant added in such circumstances, but other values are acceptable and are preferable if values of the variable being transformed are small (Yamamura 1999)). The value of the constant was chosen as that for which the transformed data best fitted the assumptions of the regression model used (A. Grafen. pers. comm.). In both cases, it was 0.001. Of the un-transformed and transformed variables, that which produced a model that fitted the data best (in terms of explaining more of the variance) and met the assumptions of the model best was used in the final model.

The logistic regression model was based on that in Chapter 2, but included regional fox density and expenditure on indoor housing per ewe (ln-transformed):

$$\ln[p_i/(1-p_i)] = a_0 + a_1\ln(N_i) + a_2C_i + a_3\ln(Y_i \cdot D_i + 0.001) + a_4X_i + \varepsilon_i$$

where:

p_i = probability of lamb predation by foxes having occurred on ith farm = $P(x = 1)$

N_i = number of lambing ewes on the ith farm

C_i = dummy variable coding for whether fox control is carried out on ith farm

$Y_i \cdot D_i$ = expenditure on indoor housing per ewe on the ith farm, i.e. expenditure on indoor housing per ewe per day (Y_i) × number of days ewes and lambs kept in after lambing (D_i) on the ith farm

a_0 = constant

a_1, a_2, a_3, a_4 = coefficients of the predictor variables $\ln(N_i)$, C_i, $\ln(Y_i \cdot D_i + 0.001)$ and X_i

ε_i = error term

The dummy variable coding for whether the ith farm was in Northwest England, which was in the model in Chapter 2, was left out of this model because it was collinear with fox density. The model had an overall predictive accuracy of 78.9% (Nagelkerke R^2 = 0.484, χ^2 = 165.3, initial –2 log-likelihood = 501.3, fitted model –2 log-likelihood = 336.0, d.f. = 4, $p < 0.001$ [n = 375]). The model correctly predicted the occurrence of fox predation on 86.9% of the farms where it occurred. The coefficient estimates and significance test statistics for this model are given in Table 3.5.

Table 3.5: Coefficient estimates and significance test statistics for logistic regression model describing variation in the likelihood of fox predation of lambs ($\ln[p_i/(1-p_i)]$)

Variable	Estimate of a_n (coefficient)	Wald	p
Constant	-5.947	62.2	<0.001
$\ln(N_i)$	0.839	48.0	<0.001
C_i	1.290	19.6	<0.001
$\ln(Y_i \cdot D_i + 0.001)$	-0.211	13.9	<0.001
X_i	42.0	3.85	0.050

A dummy coding for whether fox control was carried out or not was substituted for the number of foxes killed per hectare in the Chapter 2 linear regression model estimating the number of lambs killed by foxes per ewe on farms where predation occurred. This was to allow for later consideration of lethal control to reduce fox population densities (Chapter 4). In addition, the dependent variable was changed to lamb losses valued in monetary terms and expenditure on indoor housing per ewe per day was substituted for the indoor lambing dummy variable. Expenditure on indoor housing per ewe per day un-transformed resulted in a model that better fitted the data and met the assumptions of linear regression better than the variable ln-transformed ($R^2 = 0.347$, Adjusted $R^2 = 0.326$, $F = 16.5$, d.f. = 7, 218, $p < 0.001$ [$n = 226$]) (Table 3.6):

$$\ln(L_i) = b_0 + b_1\ln(N_i) + b_2Y_i + b_3C_i + b_4A_i + b_5SW_i + b_6NE_i + b_7G_i + \varepsilon_i$$

where:

L_i = lamb losses to foxes per ewe (£) at most recent lambing on the ith farm (only farms where predation occurred)

A_i = dummy variable coding for whether ith farm has longwool sheep breeds

SW_i = dummy variable coding for whether ith farm is in Southwest England

NE_i = dummy variable coding for whether ith farm is in Northeast England

G_i = dummy variable coding for whether land used for game rearing is in surroundings of ith farm

b_0 = constant

$b_1 \ldots b_7$ = coefficients of the predictor variables $\ln(N_i)$, Y_i, C_i, A_i, SW_i, NE_i, and G_i.

Table 3.6: Coefficient estimates and significance test statistics for linear regression model describing variation in the costs of lamb losses to fox predation on farms where predation occurred (L_i)

Variable	Estimate of b_n (coefficient)	t	p
Constant	2.610	6.67	<0.001
$\ln(N_i)$	-0.562	-9.37	<0.001
Y_i	-1.918	-2.14	0.034
C_i	0.373	2.27	0.024
A_i	0.430	2.15	0.032
SW_i	0.309	1.79	0.074
NE_i	-0.475	-1.89	0.060
G_i	0.415	2.80	0.006

The logistic regression model estimates the log-odds of fox predation of lambs occurring on a farm (Sokal & Rohlf 1995). The log-odds are equal to the probability of fox predation occurring logit-transformed (Armitage & Berry 1994). Therefore the probability of predation occurring (P(x = 1)) can be calculated from the estimated coefficients for the logistic regression, given in Table 3.5:

$$P(x=1)=\frac{1}{1+\exp(5.95-0.839\cdot\ln(N_i)-1.29\cdot C_i+0.211\cdot\ln(Y_i\cdot D_i+0.001) \\ -42.0\cdot X_i)}$$

By multiplying this probability by the cost of lamb losses, expected lamb losses due to fox predation can be estimated, according to farm characteristics and expenditure on indoor housing:

$$Z_i=P(x=1)\times\exp(2.61-0.562\cdot\ln(N_i)-1.92\cdot Y_i+0.373\cdot C_i+0.430\cdot A_i+0.309\cdot SW_i \\ -0.475\cdot NE_i+0.415\cdot G_i)$$

or:

$$Z_i = \mathrm{P}(x = 1) \times L_i$$

where:

Z_i = expected lamb loss to foxes per ewe (£)

3.4. MODEL OUTPUT

Figure 3.2 shows the relationship between expected lamb loss to foxes and expenditure on indoor housing for the specified model, as outlined above. As hypothesised, lamb loss decreases with increases in expenditure on indoor housing, but at a decreasing rate. An expenditure on indoor housing per ewe per day (Y) of £0.15 is that which would be needed to house 100% of ewes on a farm where 60% of ewes have multiple births, whilst an expenditure of £0.08 would house 50% of these ewes. These curves therefore illustrate the influence that the number of days for which ewes are housed has on lamb losses and there is a steep drop-off in lamb losses with a low amount spent on indoor housing (i.e. ewes and lambs kept in for a short time only). Farm characteristics also cause upward and downward shifts in the curves. Because the number of lambing ewes on the farm affects both the probability of fox predation occurring ($\mathrm{P}(x)$) and the scale of the losses to foxes if it does occur (L), but in different directions, the number of lambing ewes (N) influences the shape of the curves. Higher numbers of ewes are associated with a shallower curve after the initial steep decrease in lamb losses with increasing expenditure, whilst lower numbers of ewes result in a steeper curve after the initial drop (Figure 3.2). In all cases, the example farms have a fox density of 0.03 per hectare.

Figure 3.3 shows the relationship between total costs and expenditure on indoor housing for the same farm types as in Figure 3.2. There is a corresponding steep drop-off in total costs at low expenditure levels and the amount that should be spend on indoor housing to minimise total costs depends on the input of farm characteristics. This amount is shown on the curves as the point at which the curve is parallel to the x-axis and corresponds to a range of expenditure levels. Higher optimal expenditure is predicted for farms in the Southwest with longwool breeds and game rearing in the surroundings than the other farm types. However, in all cases, ewes and lambs should be kept in for less than a day if 100% are housed, as all predicted optimal expenditure levels are lower than £0.15. Only for farms in the Southwest with longwool breeds and game rearing in the surroundings is there the indication that ewes and lambs should be kept in for longer than a day if only 50% are housed. The plots also indicate that the optimal expenditure on indoor housing is lower if there are more ewes lambing and higher if there are fewer.

Figure 3.4 shows the association between expenditure on indoor housing and both lamb losses and total costs for a farm in the Southwest with 200 lambing ewes and a fox density of 0.03 per hectare. It illustrates the fact that at the optimal point ($Y{\cdot}D^*$) where total costs are minimised, there are still expected to be losses of lambs to foxes and that lamb losses make up the majority of the total costs. Therefore, the farmer should accept lamb losses in order to act in a way that is financially optimal according to this model.

The expenditure on indoor housing variable combines both expenditure on indoor housing per ewe per day, which is dependent on the number of ewes that are lambed indoors out of the total flock and the percentage that have multiple births, and the number of days ewes and lambs are kept in. Because it is only expenditure on indoor housing per ewe per day that influences the scale of lamb losses to foxes, there is a difference in both lamb losses and total costs at the same levels of expenditure per ewe when the combination of the number of days and expenditure per day differ. In order to determine optimal levels of both the proportion of ewes that should be housed and the number of days ewes and lambs are housed for, it is necessary to consider Y and D separately, which can be done using three dimensional (3-D) plots (Figures 3.5 and 3.6).

Figure 3.5 shows the same steep drop-off in lamb loss as the previous figures with both increasing expenditure on indoor housing per ewe per day (Y) and increasing numbers of days inside (D) for the same example farm. Figure 3.6 shows the same variables against total cost and shows the financially optimal levels of both indoor housing per ewe per day and the number of days ewes are indoors in terms of minimising total costs. The optimal point is within the lowest contour on the figure. It can be seen that total costs decrease with increasing expenditure on housing per ewe per day, but that, after a sharp drop when ewes are housed for a short time, total costs with respect to the number of days inside rise steeply. Expenditure on housing per ewe per day is a function of both the proportion of ewes housed and the proportion having multiple births. As it is assumed that the proportion of multiple births in a flock is outside the farmer's control. this indicates that ewes and lambs should be kept in for only a very short while, but as many as possible kept in.

In this case, the optimal number of days for which ewes and lambs should be kept in after lambing is around 0.25 days or 6 hours. If 100% of ewes are housed indoors and 100% have multiple births, the cost of indoor housing per ewe per day is £0.17 (Section 3.3.3), which is the maximum possible expenditure. For an average farm, where 60% of ewes have multiple births (mean percentage of ewes having multiple births in this data set = 58.7% [n = 490]), the cost of housing all ewes indoors per day would be £0.15 per ewe. Therefore, farmers should house all their ewes indoors at lambing, but for a few hours only after lambing to minimise their costs. Variation in the other variables in the model leads to differing values of the optimal level of expenditure on indoor housing, as well as in the optimal losses to foxes per ewe in monetary terms and therefore optimal total costs. However, for all the farm types considered here, it was optimal in financial terms for the producer to house all ewes and lambs for a short time.

3.5. DISCUSSION

3.5.1. Data reliability

The fact that these data are taken from a survey means the model is based on reported lamb losses to foxes, rather than actual losses. Because, as discussed in Chapter 2, we can not be sure of the reliability of these data, we can not in turn be sure of the results of the optimisation that the model based on these data gives. Ideally, actual loss data would be used to estimate the model. However, as also discussed in Chapter 2, such data are extremely difficult to collect and given the resource constraints of this study, it was necessary to base the analysis on reported losses. The estimated losses can be seen as estimated average lamb losses to fox predation and, given that reported losses are likely to overestimate actual losses at least in some cases (Knowlton *et al.* 1999;

Macdonald *et al.* 2000; White *et al.* 2000a), there will be some positive bias in these figures.

The monetary lamb losses estimated are measured gross, rather than net, and therefore do not take the extra costs of raising surviving lambs into account (Perry & Randolph 1999). Despite the argument that the majority of expenditure on lamb production is fixed (Taylor *et al.* 1979), there will be some variable costs in lamb production that should be accounted for. For this reason, the monetary losses estimated here will be a slight overestimate of the actual cost (overestimation also being likely for additional reasons, such as predation not occurring at point-of-sale, discussed above).

3.5.2. Model criticism

The Hosmer-Lemeshow goodness-of-fit test for the logistic regression model estimated here indicated that the model fitted the data well, as the expected values did not differ significantly from the observed values (Hosmer-Lemeshow goodness-of-fit statistic (C) = 6.07, d.f. = 8, p = 0.639). The studentised residual with the largest value (with respect to predicted values) in the sample was –2.35, with ten studentised residuals having values greater than two or less than minus two. Whilst the distribution of the residuals was not normal (Kolmogorov-Smirnov Z = 2.47, $p < 0.001$), a normal distribution of residuals is not to be expected when there are continuous covariates in a logistic regression model, as there are likely to be few data points with the same covariate patterns (Hosmer & Lemeshow 1989). The use of leverage values in assessing the degree to which individual data points have influenced the model is complicated for logistic regression by the fact that interpretation of leverage values depends on the estimated probabilities (or fitted values) (Hosmer & Lemeshow 1989). The maximum analogue of Cook's distance, however, was 0.247, suggesting that no points were overly influential in estimation of the model.

The model estimating the cost of lamb losses to foxes fitted the assumption of a normal error distribution (Kolmogorov-Smirnov test on standardised residuals, Z = 0.664, p = 0.770), whilst multicollinearity appeared not to be a problem, the highest Variance Inflation Factor (VIF) being 1.14 and the lowest tolerance 0.98. The distribution of variance appeared homogeneous judging from a plot of the residuals versus fitted values (Figure 3.7). When the data were ordered according to ln(lambing ewes) (ln(N)), the

Durbin-Watson *d*-statistic was not statistically significant at 1.82, also the case when data were ordered according to ln(*Y*) ($d = 2.10$). However, when the data were ordered according to the *y*-variable (ln(*L*)) the statistic pointed to a positive association between neighbouring residuals ($d = 0.62$). This indicates that the model tends to consistently over- or underestimate the true values of the cost of lamb losses at particular y-values, but this autocorrelation did not show up when data were ordered according to the predicted values ($d = 2.04$). Other non-linear specifications of the model were estimated (by including the continuous variables untransformed in various combinations), but the presence of autocorrelation with *y* was not improved. There were no standardised residuals with values of greater than three or less than minus three, indicating that the model did not estimate values that were greatly different from those observed. No points appeared overly influential in determining the model (maximum Cook's distance = 0.08) and, whilst 27 points had leverage values of more than two times the mean (mean leverage = 0.03, maximum leverage = 0.12) [n = 226], these points did not have outstanding residuals. The RESET test indicated that the form of the model was not at fault: upon their inclusion in the model, the squared predicted values had a coefficient that was not statistically significant from zero.

The linear regression model has a relatively low adjusted R-squared value indicating that it explained 35% of the variation in lamb losses to foxes, whilst the logistic regression explained 48% of the variation in the likelihood of fox predation. Whilst there are likely to be a number of influences on lamb losses to foxes that have been left unaccounted for, some of this unexplained variation is probably a result of the nature of survey data and the amount of error they contain. Gujarati (1995) has argued, along with other authors, that the pursuit of high R-squareds in empirical analysis is undesirable, as well as unrealistic, and that researchers should be concerned rather with the dependability of the estimated regression coefficients. The coefficients for independent variables estimated here make logical and theoretical sense and are statistically significant at least at the 10% level of significance. However, there is still a noteworthy amount of unexplained variation in the data. This means that output from the model does not have the specificity to provide individual farmers with definitive management guidelines.

3.5.3. Model output

The models estimated support the theoretical prediction of a negative relationship between lamb losses to foxes and expenditure on preventive measures (in this case, indoor housing). The relationship showed that although losses declined with increasing expenditure, this was at a declining rate, due to diminishing marginal returns to preventive effort (Figures 3.2, 3.4 and 3.5), as predicted for livestock disease losses by the loss-expenditure frontier model (McInerney *et al.* 1992; McInerney 1996). A number of other variables affected this relationship significantly. Thus if one compares two farms spending the same amount on indoor housing, a farm that carries out fox control will experience higher expected lamb losses to foxes per ewe than one on which no fox control is carried out, according to this model. The same is true of a farm in the Southwest versus one elsewhere, a farm with game rearing in its surroundings and one without and a farm with longwool breeds and one without (Figure 3.2). On the other hand, a farm in the Northeast experiences lower expected losses than one elsewhere. The possible reasons behind the influences of these four variables on lamb predation by foxes are discussed in Chapter 2, but one conclusion from that discussion which should be mentioned here is that these variables may also be proxies for other farm characteristics. In any case, it is clear that, although preventive measures such as indoor housing have an influence on lamb losses to foxes, other farm characteristics, which in most cases will be beyond the farmers' control in management terms, also cause variation in these costs. The influence of the dummy coding for fox control may be due to several reasons discussed further in Chapter 2, such as an association with fox abundance or reactions to losses in previous years, but there was no evidence that a halting of fox control on a particular farm would result in reduced lamb losses to foxes. The variable is therefore assumed to be a characteristic of the farm that is outside available management options.

The number of lambing ewes on the farm had a more complicated effect on lamb losses, and therefore the minimisation of total costs, than these dummy variables. The number of ewes was positively associated with the probability of fox predation occurring, but negatively with lamb losses per ewe. Therefore, with a higher number of ewes on the farm, the probability of lamb losses was higher, but the number of lambs killed by foxes per ewe was lower than on a farm with fewer ewes. A drop in the probability of the same order of magnitude on a large and a small farm would result in a smaller difference in expected lamb losses on the large farm. This means that expenditure on indoor housing had less of an influence on expected lamb losses, once the initial drop-off in losses from zero expenditure had occurred, on larger farms. This initial rapid decrease in lamb losses is due to the fact that expenditure on indoor housing per ewe is ln-transformed in the logistic regression model, which causes a rapid drop in the probability of predation occurring when expenditure levels rise from zero.

Optimisation of the function estimated for the relationship between lamb losses to foxes and expenditure on indoor housing per ewe showed that it is worthwhile for an 'optimising' farmer, who is aiming to minimise his overall costs in terms of lamb losses to foxes and expenditure on indoor housing, to spend only a small amount on indoor housing for his ewes and lambs after lambing. Although this optimal expenditure point varies with the other independent variables in the model, it indicated that all ewes and lambs should be kept in for less than a day after lambing. As the first day after lambing is when lambs are most vulnerable to fox predation, this result makes intuitive sense. The fact that keeping ewes in for a few hours only after lambing was an optimal policy can be explained by the hypothesis that it is lambing and its associated smells which attract foxes. Therefore, simply lambing ewes indoors where they can not be reached (nor lambing sensed) by foxes may be enough of a preventive measure against fox predation, without having to keep them in for more than a few hours. The analysis indicated that, whilst the number of days for which ewes and lambs were kept indoors influenced the probability of fox predation occurring, it did not influence the number of lambs lost on farms where predation occurred. It may well be the case, however, that the length of time for which ewes and lambs are housed has an effect on the number of lambs killed by foxes, which was not detected here, in which case housing ewes for more than a few hours may be worthwhile.

As with the relationship between losses and expenditure, the other variables in the model also have a large influence over the optimal levels of total costs (Figure 3.3). On farms whose characteristics resulted in higher expected lamb losses than others (such as those in the Southwest), a higher optimal expenditure on indoor housing was predicted, whilst total costs were also higher at the point where they were minimised. The model predicted that a farm with more lambing ewes should spend less on indoor housing than one with fewer ewes. This is because the gains from housing more ewes in and/or keeping them in for longer, in terms of reduced expected lamb loss, are lower per penny spent on indoor housing for a large than a small farm.

Levels of expenditure on indoor housing would be higher in reality than those estimated from the model because the expenditure in the model does not include the fixed costs of the buildings. Addition of these fixed costs would not change the results of the model in physical terms, as marginal costs would not alter. All expenditure levels would simply be increased by a constant equivalent to this fixed cost. In practical terms, however, this additional fixed cost could mean that the optimal points estimated here may not actually be 'optimal' for the farmer concerned, as expenditure on indoor housing could reach prohibitive levels because of it, due to negative total profits.

A majority of farms (72.5% out of 480) kept their ewes and lambs indoors for longer than one day after lambing and therefore spent a considerable amount more on indoor housing than the optimal levels of spend this model suggest. Housing for over a day to protect lambs from foxes may be more beneficial (or less expensive) than this model indicates for farms where multiple births are common (White *et al.* 2000b). In addition, housing ewes and lambs indoors after lambing has advantages other than preventing fox predation, which include increased lamb production per ewe (Bryson 1984). The results of this model give the optimal levels of expenditure on indoor housing per ewe assuming that the only advantage of indoor housing is lower lamb losses to foxes, which for these farms is unlikely to be the case and provides an explanation for farmers keeping ewes inside for longer than is 'optimal'. If these further advantages of indoor housing were taken into account, the optimal amounts of expenditure on indoor lambing would be greater, which would have the knock-on effect of reducing optimal lamb losses. The framework presented here could be used to model total lamb losses, rather than just those to foxes. This would enable such additional advantages of preventive measures to be explored.

The model further assumes that lambs lost to foxes would not have died of another cause if they had not been killed by a fox, i.e. lamb losses to foxes are additive. For any data set, it is very difficult to determine whether this is the case or not, but it is likely that some degree of fox predation of lambs is compensatory, foxes tending to take weak or diseased lambs that would have died anyway (Saunders *et al.* 1997). The association between lamb losses to foxes and indoor housing may therefore be (at least partly) due to there being fewer weak or diseased lambs on farms where ewes are lambed indoors. A number of other factors are likely to determine lamb weakness and therefore how vulnerable lambs are to fox predation, some of which may be those included in this model.

3.6. CONCLUSIONS

This chapter has presented a method for analysing the costs of fox predation to sheep farmers, including both the costs of lamb losses and those of preventive measures, and using financial analysis to inform farm management decisions relating to fox predation of lambs. The model in its current form does not give output figures that are reliable enough to be used for practical farm management, due to the exclusion of variables not measured in the study, but it does provide approximate figures and indications of how fox predation could be efficiently managed. In addition, it provides a new framework for assessing the impact of and preventive measures associated with fox predation. The model suggests that the overall costs of lamb predation by foxes could be reduced on the majority of farms, but managing lamb losses to foxes efficiently does not necessarily mean that fox predation would be prevented completely. The benefits of the preventive measure considered here level off with increases in its level of use. However, it should be noted that the optimal strategies suggested by models of this kind are not necessarily available to all producers (Perry & Randolph 1999). For example, in certain lamb production systems in the UK, housing of ewes and lambs is itself impractical. Another potential preventive measure used by sheep farmers to avoid fox predation of lambs is fox population management, which is considered in Chapter 4.

3.7. SUMMARY

Lamb predation by foxes represents a cost to sheep farms in terms of loss of stock. There are a number of ways of valuing the costs of stock mortality, but an evaluation of fox predation should also include the costs of preventive measures. Economic analysis of fox predation should aid guidance of resource use or farm management decisions.

A theoretical model is presented, which assumes that lamb losses to foxes are negatively related to expenditure on a preventive measure. The model is then estimated empirically using data from the questionnaire survey of sheep farmers discussed in Chapter 2. The preventive measure considered in the models is the housing of ewes and lambs indoors after lambing.

The models estimated support the theoretical prediction of a negative relationship between expenditure on indoor housing and lamb losses to foxes, with diminishing marginal returns to expenditure. A number of other variables, which are not generally under the farmer's control in management terms, affect this relationship. Optimisation, based on cost minimisation, of the estimated function between expenditure and losses shows that it is worthwhile for a farmer to keep all ewes and lambs in for less than one day after lambing. The majority of farmers in the study are not minimising the costs of fox predation. The possible reasons for this are discussed, as are the limitations of the model.

It is concluded that the output from the model is not reliable enough to provide accurate figures for informing individual farm management decisions, but that the model is accurate in estimating the general relationships between variables and allows us to make broad recommendations. The chapter provides a new approach for assessing the costs of fox predation of lambs.

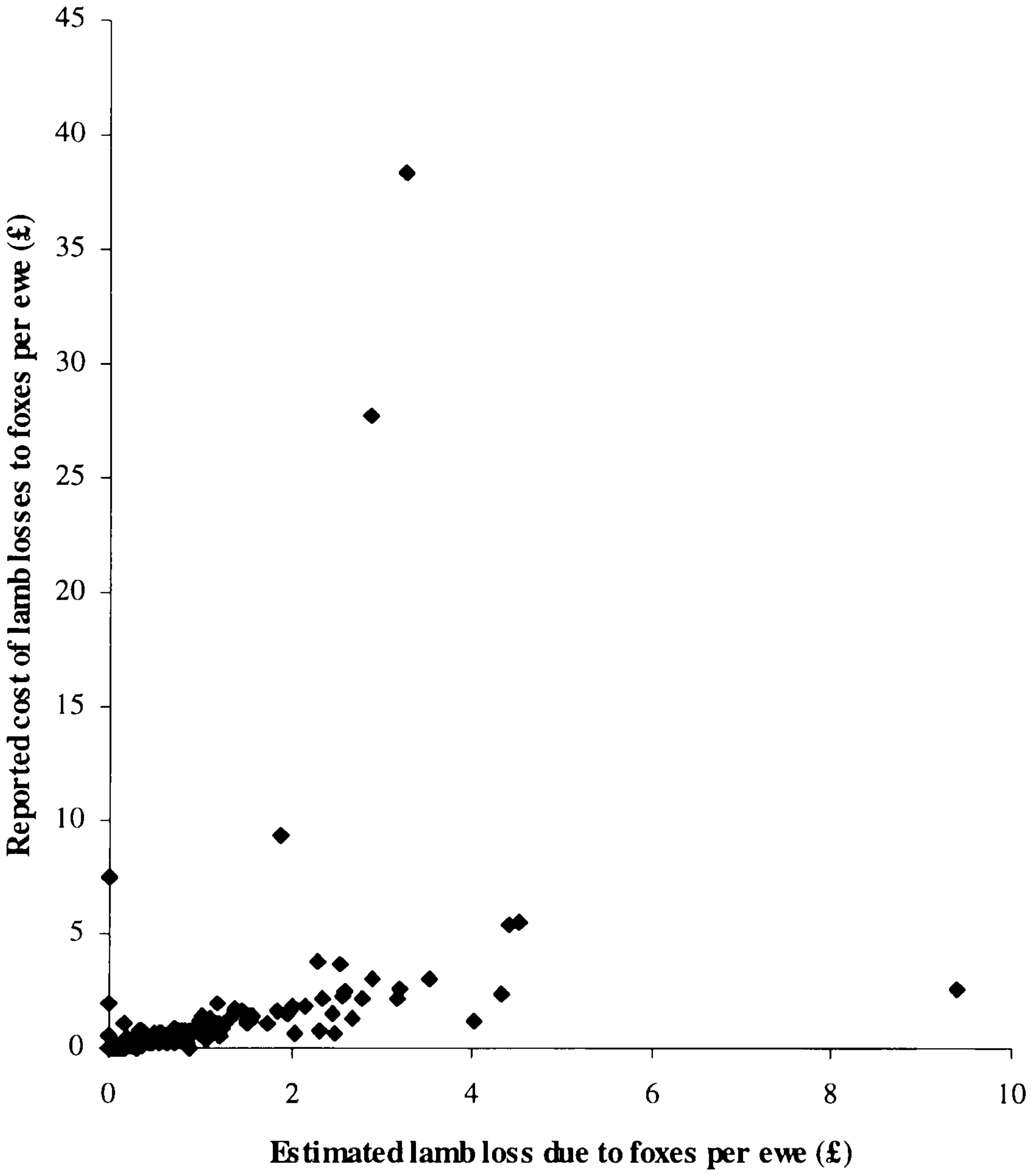


Figure 3.1: Reported costs of lamb losses to foxes per ewe compared to estimated monetary lamb loss due to fox predation per ewe [n = 335]

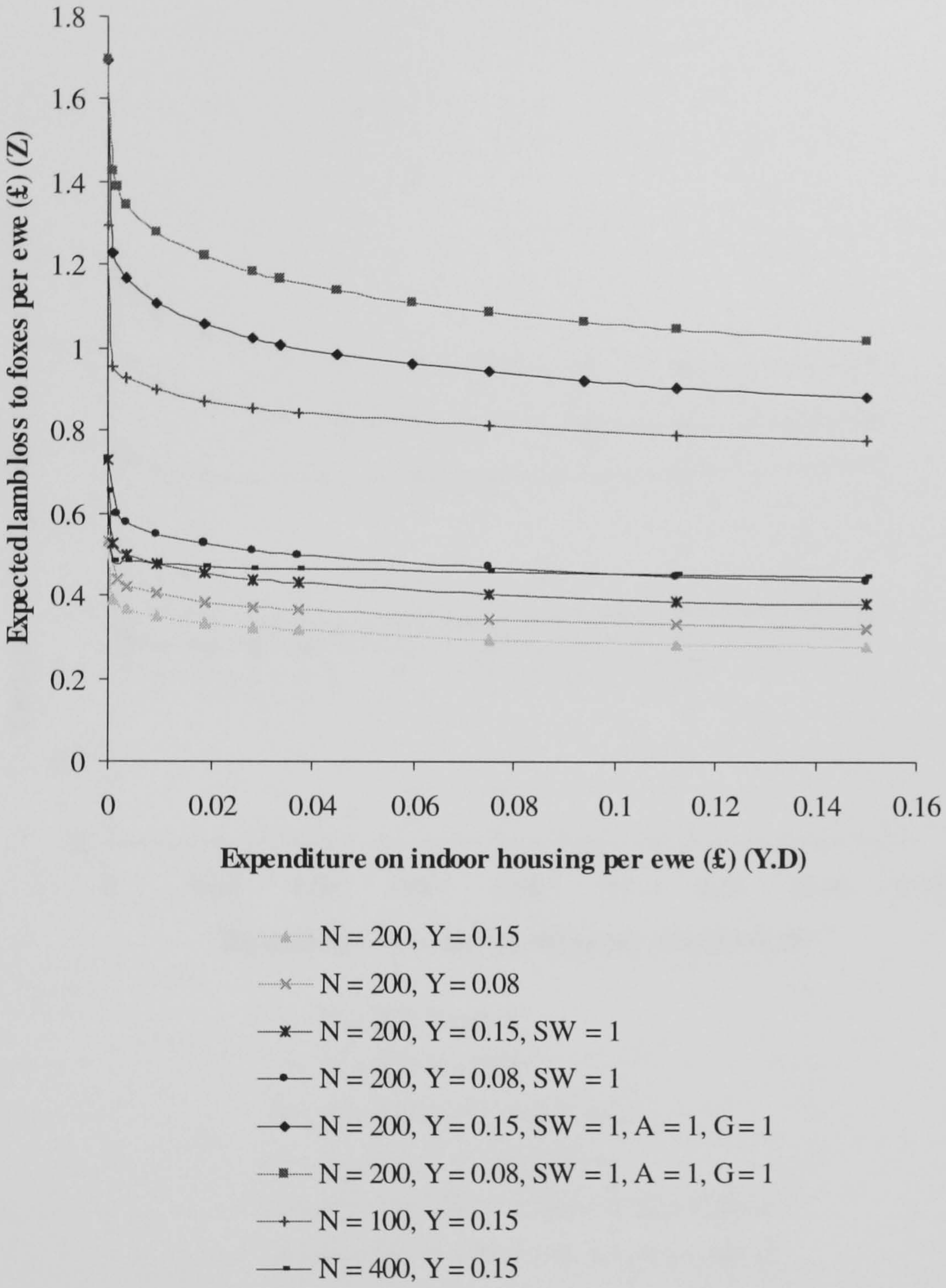


Figure 3.2: Relationship between expected lamb loss (Z) and expenditure on indoor housing per ewe ($Y{\cdot}D$) for various values of dummy variables and N (lambing ewes) and two different levels of Y ($X = 0.03$ in all cases), where Y = expenditure on indoor housing per ewe per day, X = fox population density per hectare, SW = farm in Southwest, A = farm with longwool breeds, G = farm with game-rearing in surroundings

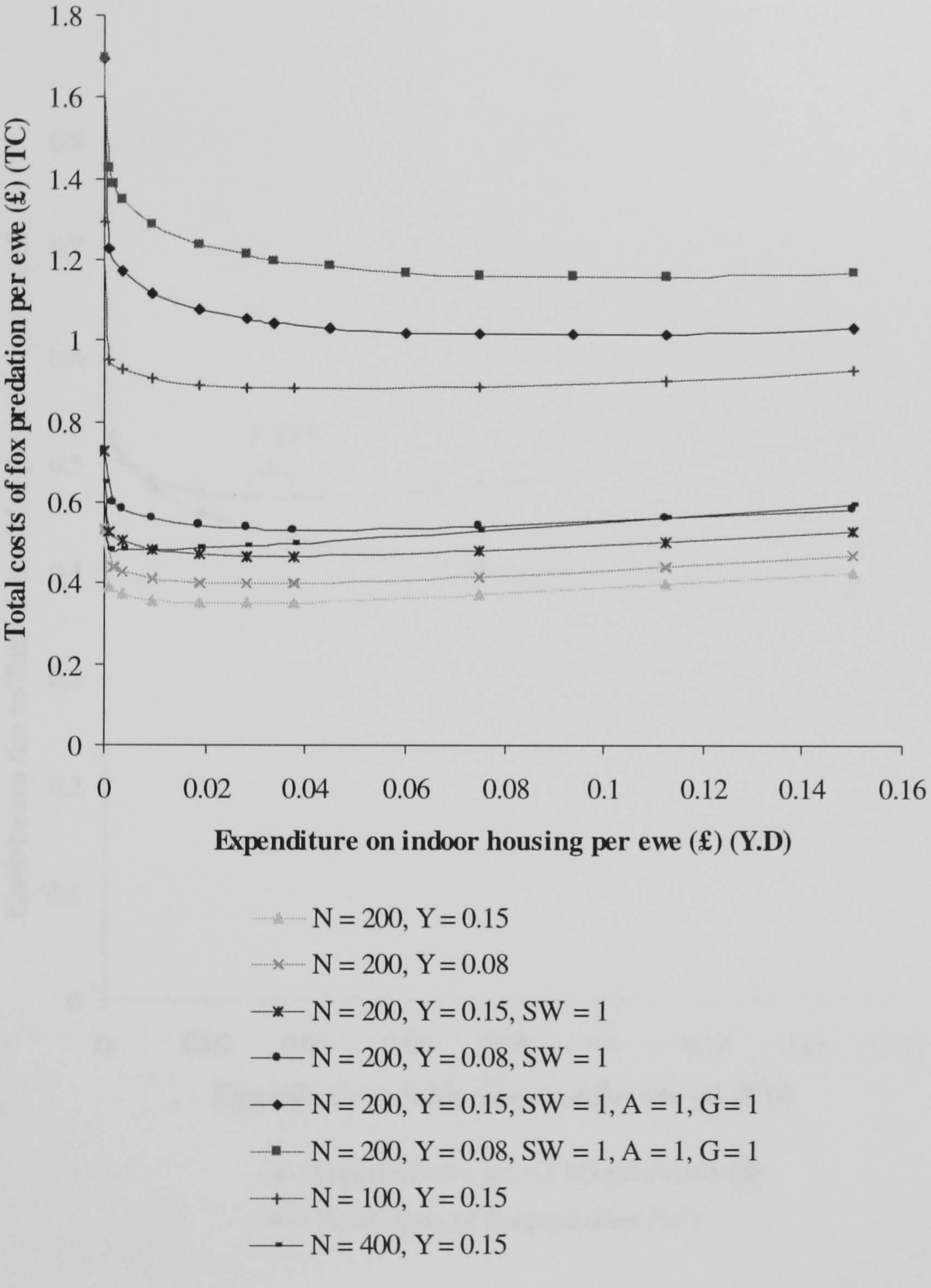


Figure 3.3: Relationship between total costs of fox predation (housing plus lamb losses) (*TC*) and expenditure on indoor housing per ewe ($Y \cdot D$) for various values of dummy variables and *N* (lambing ewes) and two different levels of *Y* ($X = 0.03$ in all cases), where Y = expenditure on indoor housing per ewe per day, X = fox population density per hectare, SW = farm in Southwest, A = farm with longwool breeds, G = farm with game-rearing in surroundings

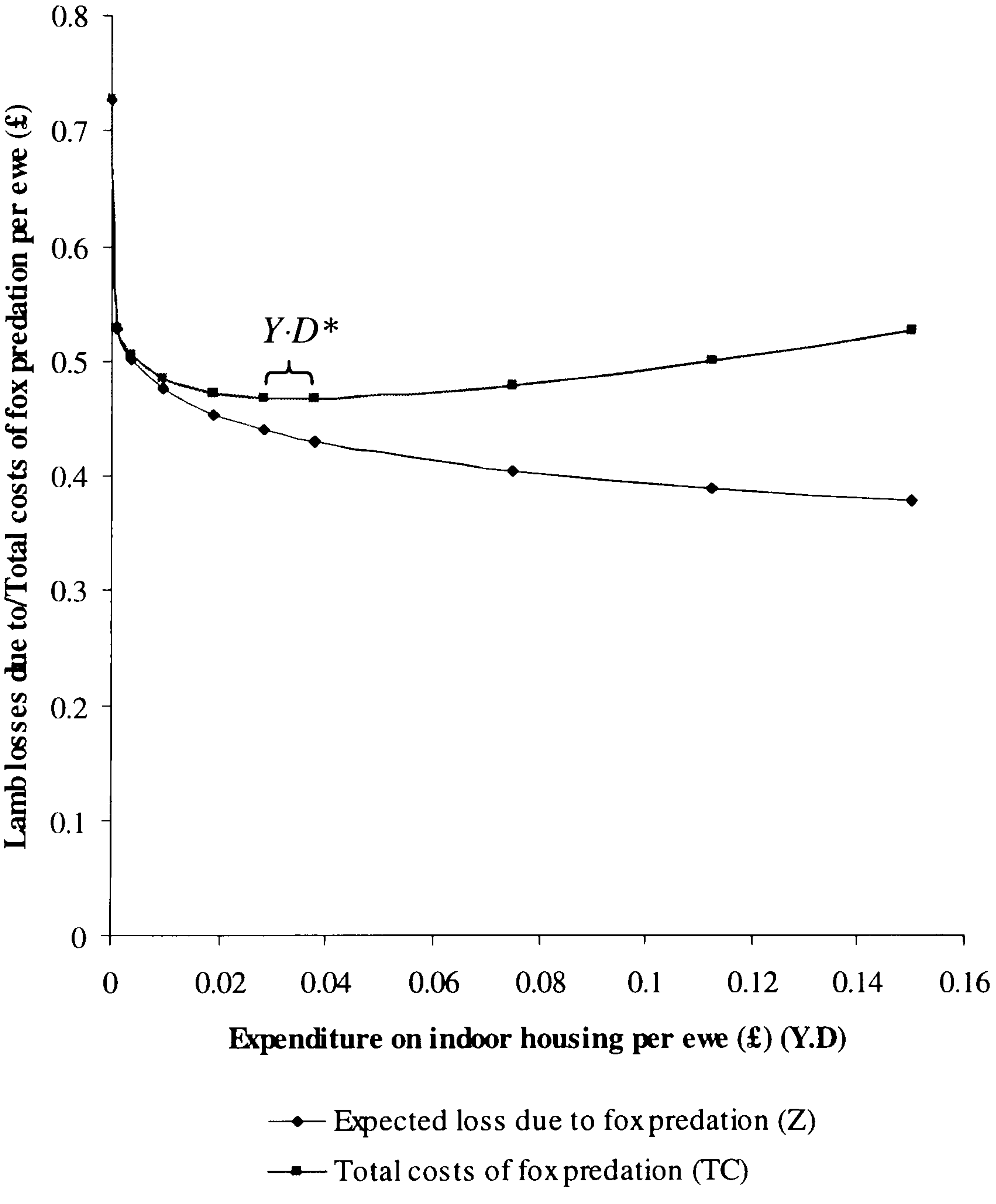


Figure 3.4: Relationships between expenditure on indoor housing (*Y·D*) and both expected lamb losses due to fox predation (*Z*) and total costs of fox predation (housing plus lamb losses) (*TC*) for a farm with 200 lambing ewes ($N = 200$), a fox density of 0.03 per hectare ($X = 0.03$) in Southwest England ($SW = 1$). Optimal point, where total costs are minimised, is marked as *Y·D**.

Original in colour

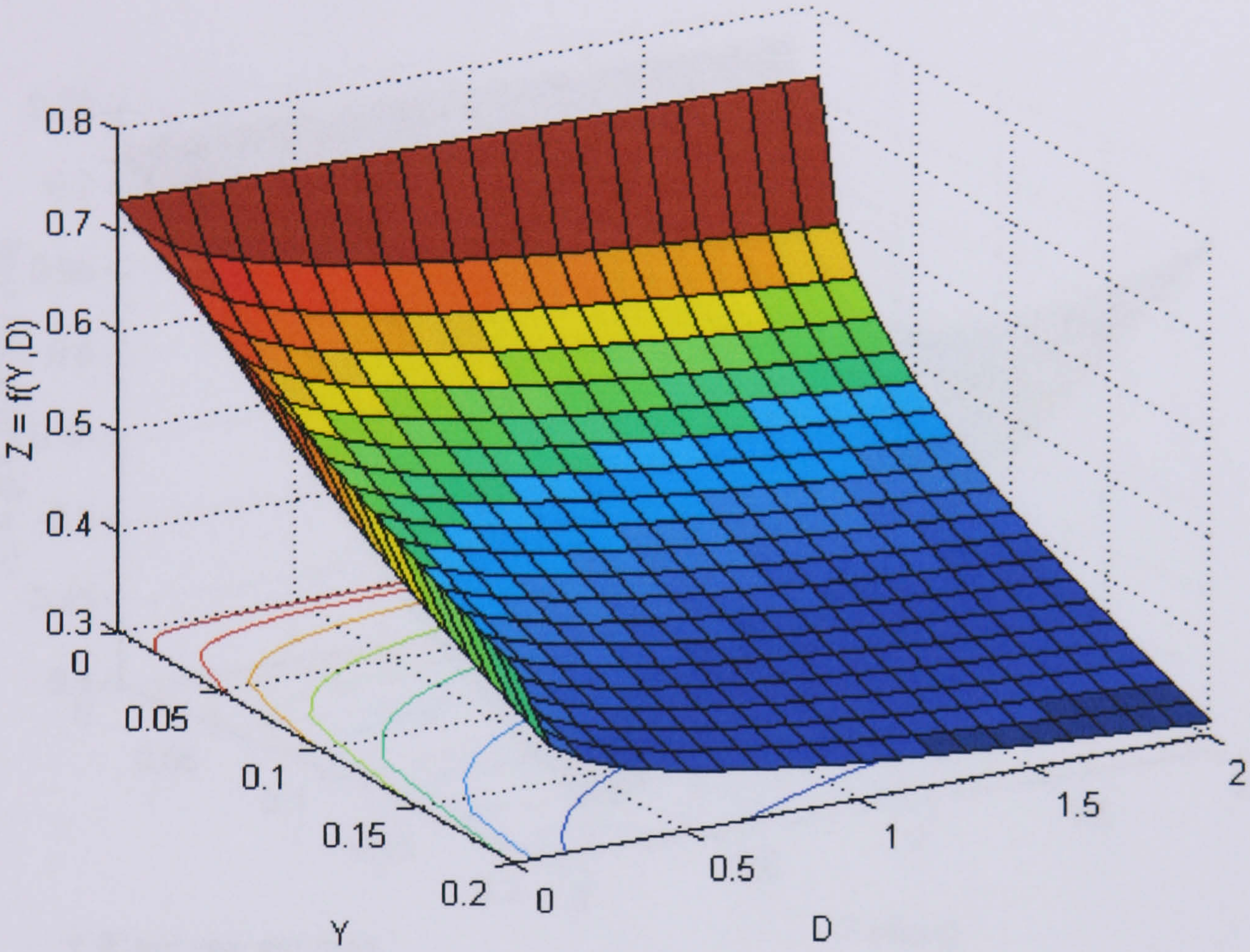


Figure 3.5: 3-D plot illustrating the relationship between expected lamb loss to foxes per ewe (*Z*) and both the number of days for which ewes and lambs are housed (*D*) and expenditure on indoor housing per ewe per day (*Y*) for the estimated model for a farm in the Southwest with 200 ewes and 0.03 foxes per hectare ($SW = 1$, $N = 200$, $X = 0.03$), where $Y = (0.053 \cdot M + 0.077)E + 0.041 \cdot E$ (M = proportion of ewes with multiple births, E = proportion of ewes housed indoors)

Original in colour

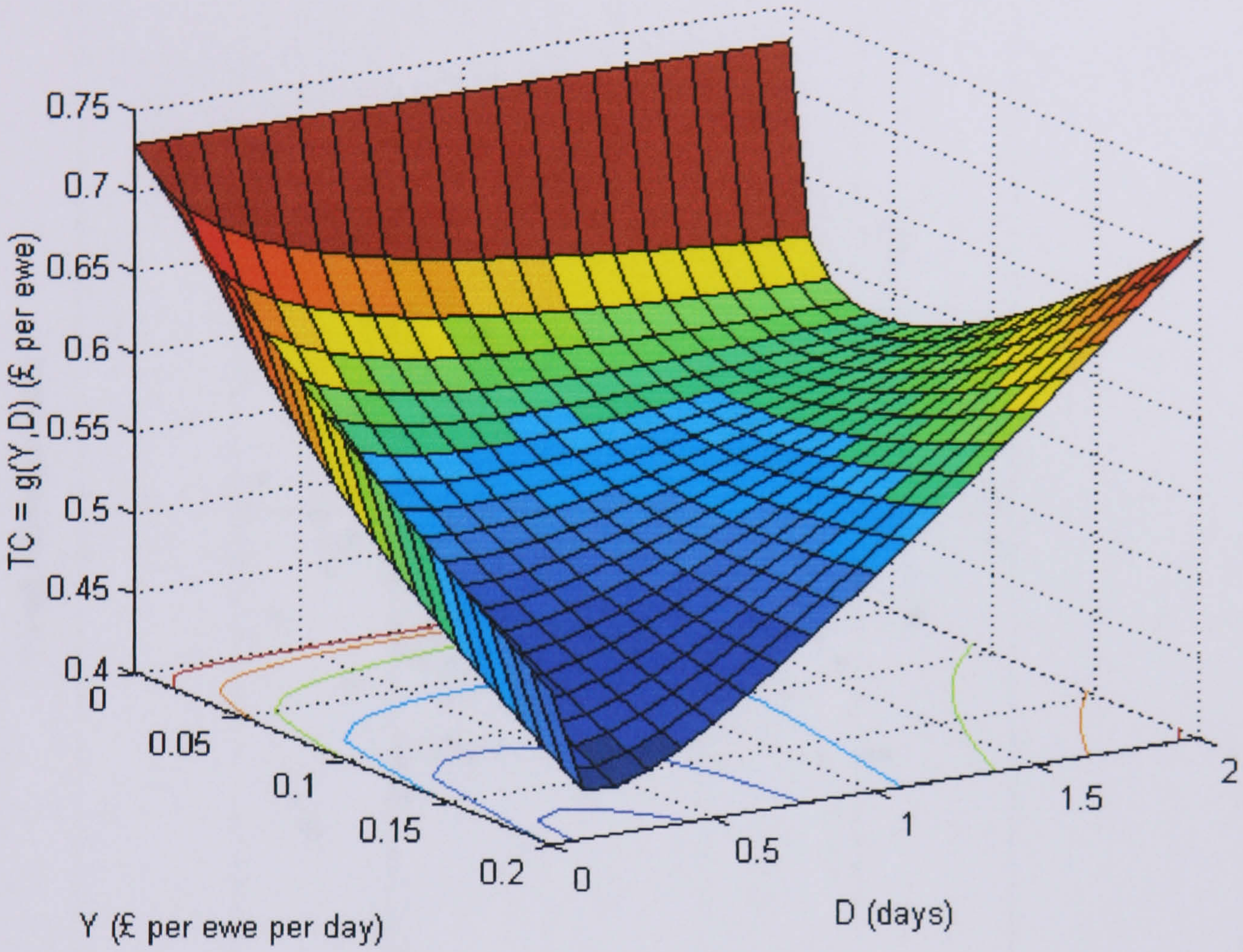


Figure 3.6: 3-D plot illustrating the relationship between total costs of fox predation (indoor housing plus lamb loss) per ewe (*TC*) and both the number of days for which ewes and lambs are housed (*D*) and expenditure on indoor housing per ewe per day (*Y*) for the estimated model for a farm in the Southwest with 200 ewes and 0.03 foxes per hectare ($SW = 1$, $N = 200$, $X = 0.03$), where $Y = (0.053 \cdot M + 0.077)E + 0.041 \cdot E$ (M = proportion of ewes with multiple births, E = proportion of ewes housed indoors)

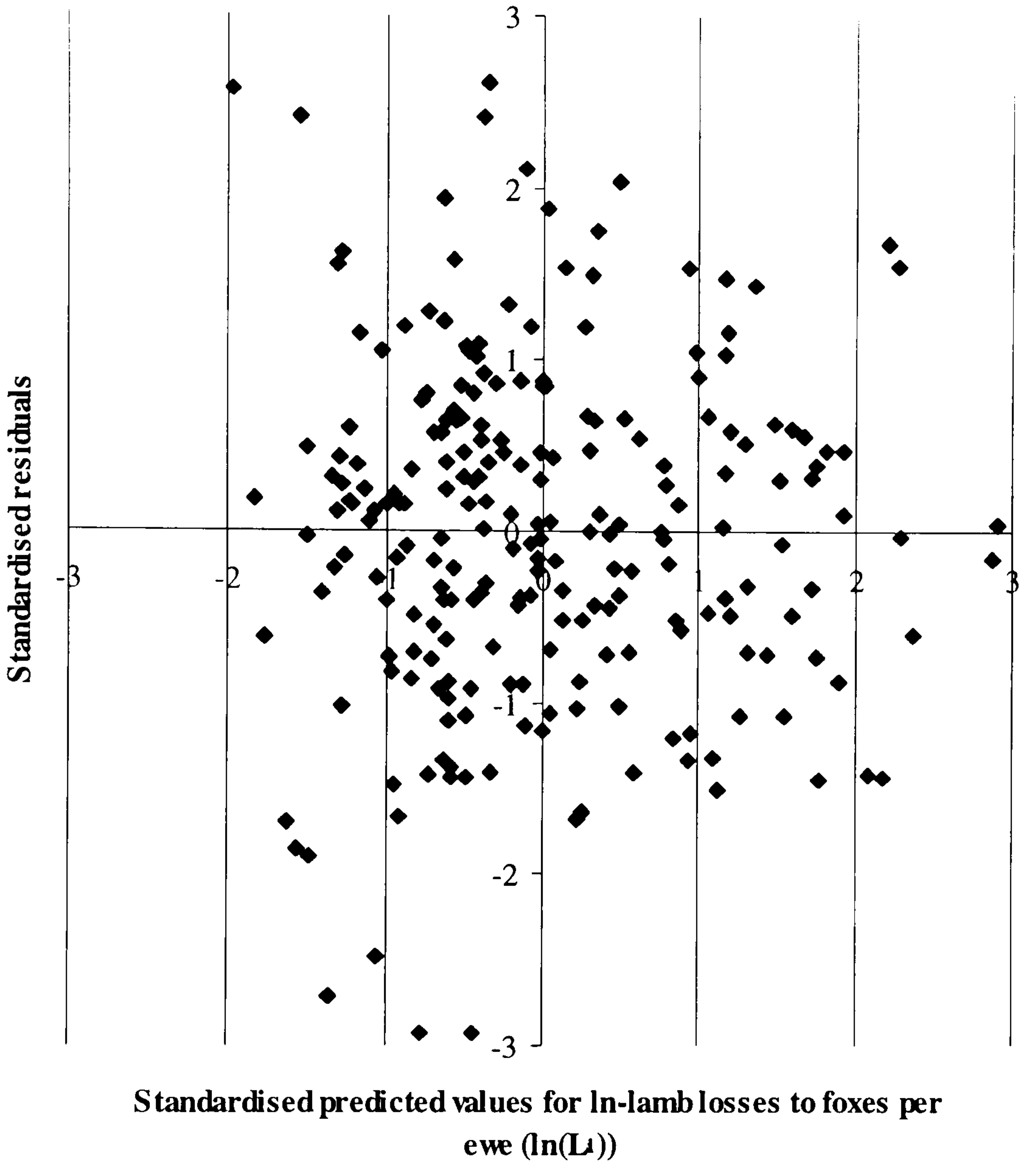


Figure 3.7: Plot of standardised residuals against standardised predicted values from regression of ln-cost of lamb losses to foxes per ewe against 7 regressors, $\ln(L_i) = 2.61 - 0.562 \cdot \ln(N_i) - 1.92 \cdot Y_i + 0.373 \cdot C_i + 0.430 \cdot A_i + 0.309 \cdot SW_i - 0.475 \cdot NE_i + 0.415 \cdot G_i$ [n = 226]

CHAPTER 4

STATIC FINANCIAL ANALYSIS OF FOX CONTROL ON SHEEP FARMS

4.1. INTRODUCTION

Prevention of predation of stock is a major reason why foxes are deliberately culled in rural areas of Britain (Macdonald 1984; Produce Studies 1995; Macdonald & Johnson 1996; Baker & Macdonald 2000; Heydon & Reynolds 2000b) and in an Australian study, fox control resulted in significant reductions in lamb predation by foxes (Greentree *et al.* 2000). Fox control can therefore be considered to be a preventive measure against predation, which, like indoor housing considered in Chapter 3, has associated costs. One would assume that a producer aims to maximise the economic benefits in terms of reduced livestock losses to foxes he or she gains from fox control. The benefits under consideration will depend on the objective of the management, for example whether this is to maximise profits, to estimate cost-effective levels of control inputs or to satisfy legislation (Birley 1979; Hone 1994).

The way that pest control is evaluated in an economic framework depends on the objectives of the evaluation exercise (Hone 1994). In general, the evaluation of pest control aims to aid producers in making decisions of whether to control the pest or not, or how much control to carry out, prior to occurrence of pest damage. Much of the research on the economics of pest management has focussed on invertebrate and fungal pests and, whilst some analogies between invertebrate and vertebrate pests can be drawn, many invertebrate pest populations are prone to large fluctuations in density over short time frames because of their high reproductive rates. These density fluctuations mean that damage by such pests tends to be temporally and spatially highly concentrated. Whilst fox populations and damage by foxes are variable over both space and time, variations in pest damage by vertebrates are generally less extreme and occur over larger scales than those by invertebrates. Control of invertebrate and fungal pests tends to be through the use of chemical pesticides. Chemical means are used for the management of vertebrates (especially rodents), but the application of such pesticides differs from that of chemicals used to control invertebrate pests.

The application of decision theory to pest management problems (discussed in Chapter 1 Section 1.2.3) has been advocated as a means to achieving optimal management solutions (Shea *et al.* 2000). Decision support systems (DSSs) with the aim of providing an integrated pest management (IPM) approach have been developed to aid decision-making for the control of crop pests (Knight 1997), examples of which include the Spruce Budworm Decision Support System (MacLean *et al.* 2001). Such systems can be used to predict the level of a pest impact, according to certain factors, and thus determine the optimal pest management strategy, given the decision-maker's objectives. In many cases, economic objectives, such as profit-maximisation, will be considered. The level of control at which the marginal cost of an extra unit of control effort equals the marginal benefit of that unit is where the maximum profit is made (Hillebrandt 1960; Mumford & Norton 1984; Hone 1994; Ramirez & Saunders 1999). The level of pest density at this optimal point is termed the Economic Injury Level (or EIL) (Stern *et al.* 1959; Headley 1972; Southwood & Norton 1973). The concepts of the EIL and economic thresholds have been applied frequently to entomological pests and marginal analysis is also fairly frequently used (Ramirez & Saunders 1999). There is, however, a shortage of applications of economic and bioeconomic analysis to vertebrate pest management (Hone 1994), despite the fact that the principles of pest management, especially integrative approaches, could be applied to vertebrates (Putman 1989).

It is assumed that by reducing fox population densities or keeping them at stable numbers, there will be a reduction in the level of fox predation from that which would occur without fox control. As discussed in Chapter 1, whilst fox control may be effective in reducing fox populations in the short-term and on a local scale (Reynolds *et al.* 1993), proof of its effectiveness on a regional scale over a longer time scale remains open to question. In addition, there has been very little research on the effects of fox control on fox predation of livestock, with no studies on this topic in Britain.

In this chapter the financial model outlined in Chapter 3 is developed further to incorporate the effects of fox control to prevent fox predation of lambs. The trade-off between the costs of fox control and lamb losses is considered alone and then the trade-offs with the costs of indoor housing are incorporated to enable a comparison of these preventive measures.

4.2. THEORETICAL BACKGROUND

In order to undertake an economic evaluation of fox management, the relationship between damage by foxes and their population density or abundance needs to be assessed. In Chapter 3, fox density was incorporated into the logistic regression model predicting the occurrence of lamb predation by foxes. As for expenditure on indoor housing, it is therefore possible to estimate the expected lamb predation outcomes at various fox population densities, by multiplying 3-5 by 3-6 to get 3-7 (the expected monetary outcome if predation occurs is not dependent on fox density):

$$\mathrm{P}(x = 1) = h(Y_i \cdot D_i, X_i, N_i) \tag{3-5}$$

$$L_i = j(Y_i, N_i, R_i) \tag{3-6}$$

$$Z_i = g(Y_i, D_i, X_i, N_i, R_i) = \mathrm{P}(x = 1) \times L_i \tag{3-7}$$

where:

$\mathrm{P}(x = 1)$ = probability of lamb predation by foxes having occurred on ith farm
Y_i = expenditure on indoor housing per ewe per day on the ith farm
D_i = number of days ewes and lambs are kept indoors after lambing on the ith farm
X_i = fox population density per hectare on the ith farm
N_i = number of lambing ewes on the ith farm
L_i = lamb losses to foxes if fox predation occurs on ith farm (£)
R_i = regional situation of ith farm
Z_i = expected lamb loss to foxes per ewe (£)
h = function of farm characteristics determining the probability of fox predation
j = function of farm characteristics determining lamb losses to foxes if fox predation occurs
g = function of farm characteristics determining expected lamb losses

The association between fox population density and lamb losses to foxes is positive, so lamb losses decrease with decreasing fox density. If lethal fox control is used to reduce fox population density, the fox control cost necessary to achieve a particular decrease in fox population density can be compared with the reduction in lamb losses associated with this density reduction to determine whether it is worthwhile for a farmer to carry out fox control. This assumes that fox control is carried out prior to the lambing event and that there is no net fox population gain due to births or immigration between the control and lambing events. A further assumption is that there is a functional relationship between the cost of fox control and the number of foxes on the farm and that the cost of fox control per ewe is negatively related to the number of ewes on the farm:

$$K_i = m(Q_i, N_i)$$

where:

K_i = cost of fox control per fox killed, or cost of killing one fox, per ewe on the ith farm (£)

Q_i = estimated number of foxes on the ith farm

N_i = number of lambing ewes on the ith farm

m = function of fox population numbers and farm characteristics determining cost of fox control per fox killed

It is assumed that control impacts directly on the number of foxes on the farm, in that one fox removed from the farm results in one fewer fox on the farm. Thus, control is the only factor affecting fox numbers on the farm.

The marginal control costs, or costs of killing one fox, depend on the number of foxes on the farm. The number of foxes on the farm is equal to the initial number of foxes on the farm minus the number of foxes killed, which is determined by the fox control action. The marginal fox control costs at any level of Q (number of foxes on the farm) is determined by the level of Q before the jth fox was killed. Therefore the marginal fox control costs can be written as:

$$K_i = m(Q_i^0 - (j-1))$$

where:

j = number of foxes killed

Q_i^0 = initial number of foxes on the *i*th farm

And the total costs of a particular fox control action are equal to the sum of the marginal costs of control at each level of fox abundance from the initial number to one more than the final number of foxes:

$$V_i = \sum_{j=1}^{j=j^T} K_i$$

where:

V_i = total costs of fox control per ewe on the *i*th farm (£)

j^T = total number of foxes killed

The fox population density on the *i*th farm can be defined as the number of foxes on the *i*th farm divided by the area of the farm:

$$X_i = Q_i/S_i$$

The total costs of fox predation, in terms of lamb losses and fox control, therefore depend on the initial number of foxes on the farm and the final number after control has been carried out:

$$TCb_i = Z_i\left(Q_i^T\right) + V_i$$

where:

TCb_i = total costs of fox predation per ewe on the *i*th farm (£)

$Z_i(Q_i^T)$ = expected lamb loss to foxes per ewe on the *i*th farm (£) at final fox population density

$Q_i^T = Q_i^0 - j^T$ = final number of foxes on the *i*th farm

The economic optimum for the farmer, where total costs are minimised, is where the marginal lamb losses divided by the marginal costs of fox control are equal to minus 1. Because the costs of fox control are estimated as costs of killing one fox (or per fox costs), it is only possible to work in 'whole fox' units rather than in marginal units. The costs of fox control are therefore already available in marginal form. Minimising total costs enables us to estimate the optimal number of foxes for the *i*th farm (Q_i*) and from this, the optimal number of foxes to be culled given a particular starting fox abundance. Total costs are minimised where marginal fox control costs equal marginal expected lamb losses (see also Figure 1.1b):

$$K_i(Q_i) = -[Z_i(Q_i - 1) - Z_i(Q_i)]$$

or

$$\frac{K_i(Q_i)}{[Z_i(Q_i - 1) - Z_i(Q_i)]} = -1$$

This is where the marginal total costs, or total costs per fox killed, are equal to zero:

$$K_i(Q_i) + [Z_i(Q_i - 1) - Z_i(Q_i)] = TCb_i(Q_i - 1) - TCb_i(Q_i) = 0$$

At fox abundance levels of greater than Q^*, it is worth killing more foxes, as there are still net benefits to be gained from fox control: the reduction in lamb losses due to fox predation is greater than the cost of fox control; but when there are fewer than Q^* foxes, fox control is no longer financially profitable for the farmer. Because the function is continuous, the value of Q^* that solves the above equality is not constrained to integer values. Total costs decrease as Q is reduced to Q^*, but at Q-values below Q^* (i.e. with further culling) total costs increase. Therefore, determining whether to stop at a number of foxes short of the optimum or whether to cull to below the optimum depends on the relative sizes of the reduction and increment in total costs on either side of Q^*. If the increase in total costs resulting from killing one fox to take Q below the optimum is small relative to the resultant reduction in costs, it is worthwhile for the farmer to cull to this level. Optimal fox population levels were determined for a number of different farm scenarios, i.e. farms with various characteristics and starting fox populations.

4.3. EMPIRICAL ANALYSIS

The model for predicting the expected loss outcome according to fox population density, expenditure on indoor housing and other farm characteristics was the same as that estimated in Chapter 3:

$$Z_i = \frac{\exp\begin{pmatrix} 2.61 - 0.562 \cdot \ln(N_i) - 1.92 \cdot Y_i + 0.373 \cdot C_i + 0.430 \cdot A_i + 0.309 \cdot SW_i \\ - 0.475 \cdot NE_i + 0.415 \cdot G_i \end{pmatrix}}{1 + \exp\left(5.95 - 0.839 \cdot \ln(N_i) - 1.29 \cdot C_i + 0.211 \cdot \ln(Y_i \cdot D_i + 0.001) - 42.0 \cdot \frac{Q_i}{S_i}\right)}$$

where:

Z_i = expected lamb loss to foxes per ewe (£)

N_i = number of lambing ewes on the *i*th farm

Y_i = expenditure on indoor housing per ewe per day on the *i*th farm

D_i = number of days ewes and lambs are kept indoors after lambing on the *i*th farm

C_i = dummy variable coding for whether fox control is carried out on *i*th farm

Q_i = number of foxes on the *i*th farm

S_i = area of the *i*th farm in hectares

$Q_i/S_i = X_i$ = fox population density per hectare on the *i*th farm

A_i = dummy variable coding for whether *i*th farm has longwool sheep breeds

SW_i = dummy variable coding for whether *i*th farm is in Southwest England

NE_i = dummy variable coding for whether *i*th farm is in Northeast England

G_i = dummy variable coding for whether land used for game rearing is in surroundings of *i*th farm

The model includes the dummy variable coding for whether fox control was carried out, as reported by questionnaire respondents. This means that the effects of extant fox control policy on the farms were taken into account. Without data from an experimental or predator exclusion study, it would not be realistic to discount these effects on the system.

4.3.1. Costs of fox control

Respondents to the national sheep producer survey (Chapter 2, Section 2.2; Appendix B) were asked for figures on the amount they had spent on predator control in the past year, either in pounds or days. They were then asked what percentage of this expenditure was spent on controlling foxes. For those respondents that gave a figure for predator control in pounds, expenditure on fox control was simply calculated as the percentage of this given. For respondents that gave a figure in days, a working day of eight hours was assumed. Expenditure on control was then taken as the opportunity cost of the time spent controlling foxes. Average earnings for a foreman were taken from Nix (1999) at £341 for a 47.4-hour week, which is a £7.19 hourly wage. The opportunity cost of fox control was calculated as the number of hours spent controlling foxes multiplied by this average wage rate. The cost of fox control per fox killed (or the cost of killing one fox) was calculated as the expenditure on fox control or opportunity cost of fox control (or whichever was the larger of these figures if both were given) divided by the number of foxes killed on the farm in the past year (also given by the respondents). This was converted to a per ewe figure by dividing by the number of ewes lambing. Of those farms that did carry out fox control, 310 out of 451 farms, a significant proportion (109) experienced no costs of fox control; foxes being killed by individuals other than those farming the sheep, at no cost to the farmer. These farms were left out of the samples used to carry out subsequent analyses. The mean cost of killing one fox per ewe was £0.117 and the median £0.034, with a range of values from £0.001 to £2.48 [n = 166].

The total number of foxes on a farm was estimated by multiplying the estimated number of foxes per hectare by the area of the farm. A mean of 3.43 foxes were estimated to be on farms and a median of 1.17, with a range from 0 to 66 [n = 485]. Models were estimated with control cost per fox killed per ewe as the dependent variable and the estimated number of foxes on the farm as the independent. The best fitting model also included farm area and the number of lambing ewes ($R^2 = 0.279$, Adjusted $R^2 = 0.265$, $F = 20.6$, d.f. = 3, 160, $p < 0.001$ [n = 164]) (Table 4.1):

$$\ln(K_i) = c_0 + c_1\ln(Q_i) + c_2S_i + c_3N_i + \varepsilon_i$$

where:

K_i = cost of killing one fox per ewe (£) on the *i*th farm

Q_i = estimated number of foxes on the *i*th farm

S_i = area of *i*th farm (hectares)

N_i = number of lambing ewes on the *i*th farm

c_0 = constant

c_1, c_2, c_3 = coefficients for $\ln(Q_i)$, S_i and N_i

Table 4.1: Coefficient estimates and significance test statistics for linear regression model describing variation in the costs of fox control (K_i)

Variable	Estimate of c_n (coefficient)	t	p
Constant	-2.80	-17.6	<0.001
$\ln(Q_i)$	-0.478	-4.12	<0.001
S_i	0.0011	3.28	0.001
N_i	-0.0008	-3.78	<0.001

4.4. MODEL OUTPUT

Figure 4.1 shows the relationship between the cost of controlling one fox per ewe and the number of foxes on a farm and farm area for the model $\ln(K_i) = -2.80 - 0.478\cdot\ln(Q_i) + 0.0011\cdot S_i - 0.0008\cdot N_i$, control costs being negatively associated with fox numbers and the number of lambing ewes and positively with farm area. Table 4.2 shows the pay-off matrix for fox control for a farm of 200 hectares with 800 ewes in the Southwest region, which has game rearing in its surroundings and 7 foxes on its land (0.035 foxes per hectare). Indoor housing for one day is assumed to cost £0.15 per ewe, equivalent to housing 100% of ewes with 60% having multiple births. Expected lamb losses per ewe decrease with the number of foxes killed, i.e. with fewer foxes on the land.

Table 4.2: Pay-off matrix illustrating the expected outcomes of fox control in terms of lamb losses for a farm of 200 hectares with 800 ewes in the Southwest, with game rearing in its surroundings and 7 foxes on its land (density of 0.035 foxes per hectare), where all ewes are lambed indoors and kept inside for one day ($S = 200, N = 800, SW = 1, G = 1, Q^0 = 7, X_0 = 0.035, Y = 0.15, D = 1$)

		States of nature		**Expected outcome (£ lamb losses per ewe)**
		Predation	**No predation**	
Outcome of state (£ lamb losses per ewe)		0.491	0	
Number of foxes killed	0	p = 0.822	p = 0.178	0.404
	1	p = 0.789	p = 0.211	0.388
	2	p = 0.752	p = 0.248	0.370
	3	p = 0.711	p = 0.289	0.349
	4	p = 0.666	p = 0.334	0.327
	5	p = 0.618	p = 0.382	0.304
	6	p = 0.567	p = 0.433	0.279
	7	p = 0.515	p = 0.485	0.253

For a farm with the same characteristics as above (200 hectares, 800 ewes, in the Southwest region, game rearing in its surroundings and 7 foxes on its land), the model predicts that the optimal point is achieved if just over 2 foxes are left on the farm ($Q^* \approx 2$), i.e. if between 4 and 5 foxes are killed (Table 4.3; Figures 4.2 and 4.3). From Table 4.3 and Figure 4.3, it can be seen that if 4 foxes are killed, the reduction in losses from killing this fox is greater than the cost of control (and the marginal lamb loss plus control cost is negative), so it is worthwhile killing it. However, if 5 foxes are killed, the benefit of killing this fox is less than the cost (and the marginal lamb loss plus cost is just positive), so killing it is not worthwhile. The optimal point, Q^*, is just below 5 foxes killed (Figure 4.3). Comparing the total lamb loss and total costs of fox control also shows that this point is optimal, as it is where the total costs are at their lowest and marginal conditions are met, illustrated in Figure 4.2. A farm with these particular characteristics was chosen for illustrative purposes because all characteristics are within a realistic range, including fox population density, whilst the number of foxes on the farm is large enough to show a range of values for the number killed.

Table 4.3: Output of model giving total and marginal benefits and costs of fox control according to number of foxes left and number of foxes killed for a 200 hectare farm with 800 ewes in the Southwest, with game rearing in its surroundings, where all ewes are lambed indoors and kept inside for one day ($S = 200, N = 800, SW = 1, G = 1, Q^0 = 7, X_0 = 0.035, Y = 0.15, D = 1$)

Number of foxes left on farm	7	6	5	4	3	2	1	0
Number of foxes killed on farm	0	1	2	3	4	5	6	7
Total cost of fox control per ewe (£)	0	0.016	0.032	0.051	0.072	0.096	0.125	0.165
Total cost of lamb losses plus fox control per ewe (£)	0.404	0.404	0.403	0.401	0.400	0.400	0.404	0.418
Marginal lamb loss per ewe if this fox is killed (£)		-0.016	-0.018	-0.020	-0.022	-0.024	-0.025	-0.026
Cost of killing this fox per ewe (£) (Marginal cost of fox control per ewe)		0.016	0.017	0.019	0.021	0.024	0.029	0.040
Marginal cost of lamb losses plus fox control per ewe if this fox is killed (£)		<0.000	-0.001	-0.002	-0.001	>0.000	0.004	0.015

Figure 4.4 shows how differences in the characteristics of farms with the same area and initial number of foxes (and therefore fox densities) influences the model output. It is only worthwhile controlling foxes at all on three of the farm types, but the number of foxes that should be killed to minimise costs decreases with increases in the number of ewes on the farm. So, for a farm with 1000 ewes, the economically optimal solution is

reached if 5 foxes are killed, whilst with 600 ewes, it is at the point where between 5 and 6 foxes are killed. (It should be noted that the marginal cost of lamb losses plus fox control for a farm with 1000 ewes is positive when one fox has been killed, meaning that control costs are greater than reductions in losses. Despite this, it is still worthwhile for a farmer to carry out further fox control because greater reductions in losses are available once 2 foxes are killed.)

Figures 4.5a and b illustrate the effect of changes in farm characteristics further, also showing the influence of differences in farm area. In all cases, these are for farms that lamb all their ewes indoors for one day ($Y = 0.15$, $D = 1$), but with all other dummy variables set to zero. Both increases in the number of lambing ewes and in the size of the farm reduce the number of foxes that should be killed to reach the economically optimal point. For these data, the mean number of lambing ewes per hectare of farm land was 4.02, so the farms with 4 ewes per hectare are closest in terms of area and lambing ewe numbers to the means for the data set. The figures also illustrate how differences in the density and number of foxes on the farms influence this optimal point. In Figure 4.5a, the number of foxes on the farms is constant at 4 and it is only worthwhile for a farmer to control foxes on a farm of 100 hectares with 400 ewes, whilst in Figure 4.5b, densities are constant at 0.04 per hectare and it is also only worthwhile for farms of 100 hectares with 400 ewes to control foxes. The differences in the density and number of foxes on the farm influence the shape of the marginal cost curves.

The number of foxes that a farmer should kill if he or she is aiming to minimise the costs of fox control with respect to lamb production varies with the initial number of foxes on the farm (or initial population density), but for a farm with a particular set of characteristics, there is an optimal number of foxes or fox population density at which the cost of killing the next fox is greater than the reduction in losses due to predation to be derived from it.

4.4.1. Modelling the total costs of lamb losses, preventive measures and fox control

This chapter has looked at the total costs of lamb losses plus fox control at fixed levels of expenditure on indoor housing, whilst the previous chapter (Chapter 3) considered the effect of expenditure on indoor housing on lamb losses at fixed levels of fox density. However, the real situation on the farm will involve a trade-off between all these costs: expenditure on housing, costs of fox control and lamb losses; and we can assume that the farmer aims to minimise the total costs of all of these. Total costs of fox predation are therefore equal to expected lamb loss plus expenditure on indoor housing plus the costs of fox control given a particular starting fox density and number of foxes killed:

$$TC_i\left(Q_i^T\right)=Z_i\left(Q_i^T\right)+Y_i\cdot D_i+V_i$$

where:

$TC_i\left(Q_i^T\right)$ = total costs of fox predation per ewe on the ith farm (£) at final fox population density $\left(Q_i^T\right)$

Figure 4.6 shows the influence of expenditure on indoor housing per ewe per day (Y), the number of days that ewes and lambs are housed indoors (D) and the number of foxes on the farm (Q) on expected lamb loss (Z) for the example farm used above: 200 hectares ($S = 200$), 800 lambing ewes ($N = 800$) in the Southwest ($SW = 1$) with game rearing in the surroundings ($G = 1$) and a starting density of 0.035 foxes per hectare ($X = 0.035$, $Q = 7$). From Chapter 3, we know that Y is a function of the proportion of ewes housed indoors and the proportion having multiple births. These plots indicate that expenditure on indoor housing per ewe (regulated by the proportion of ewes housed and the number of days they are kept inside) has a much greater effect on expected lamb loss than does a change in the number of foxes on the farm. At the point where nothing is spent on indoor housing, expected lamb loss only decreases by about £0.10 (from £0.60 to £0.50) per ewe when the number of foxes left on the farm decreases from 7 to 1.

Figure 4.7 shows Y and D plotted against the total costs of lamb losses, indoor housing and fox control per ewe (TC) for a farm with the same set of characteristics. As in Chapter 3, total costs per ewe are minimised where the proportion of ewes lambed indoors is maximised, but when they are kept inside for a very short while only. The fewer foxes that are left on the farm (i.e. the more that have been killed), the more advantage there is to housing for longer and total costs are minimised further along the *D*-axis at lower *Q*. This is also shown up by the contours under the 3-D surface. The lowest contour in every case (showing points of equal low cost) is the blue one in the right-hand corner of each plot. This contour moves away from the corner with decreasing *Q*, showing that housing ewes for longer is advantageous at low *Q*. However, costs are still minimised at *D* of less than 1 and the plots indicate ewes should be kept in for around only 5 hours after lambing. Killing foxes (i.e. causing decreases in *Q*) results in very little change in the total costs, indicating that the cost of control almost balances out the savings in lamb losses that a change in *Q* causes. However, at the point where they are minimised, total costs (*TC*) increase as *Q* decreases, i.e. when more foxes are killed on the farm, which indicates there is no financial advantage to carrying out additional fox control to that already carried out on a farm with these characteristics.

4.5. DISCUSSION

4.5.1. Model criticism

The assumptions of normality of error and a lack of multicollinearity were well met for the model estimating the cost of killing one fox per ewe (*K*) (Kolmogorov-Smirnov test on standardised residuals, Z = 0.586, p = 0.882; highest VIF = 2.61, lowest tolerance = 0.38). The maximum Cook's distance was 0.216, indicating no overly influential data points, but 17 points had leverages of more than two times the mean (mean leverage = 0.02, maximum leverage = 0.31) [n = 164]. However, these were not associated with outlying residuals, no standardised residuals having values of greater than three or less than minus three. The fit of the model was not a problem, when tested using the RESET test.

Whilst there appeared to be no heterogeneity of variance (Figure 4.8), the Durbin-Watson *d*-statistics indicated some associations between the residuals and two of the covariates and the *y*-variable. When the data were ordered according to farm area (or S_i) $d = 1.80$, which is outside the critical bounds for the statistic. However, when ordered according to ln(estimated number of foxes on the farm) or $\ln(Q_i)$, $d = 1.74$, which is just within the critical area indicating a possible positive association between neighbouring residuals at the 5% level of statistical significance (for $k = 5$ and $n = 100$). The same was true when the data were ordered according to the number of lambing ewes (N_i), $d = 1.59$. When the data were ordered according to the y-variable ($\ln(K_i)$), a statistically significant positive association between neighbouring residuals was shown up ($d = 0.49$), indicating that the model tended to consistently over- or underestimate values compared to those observed at similar y-values. When the data were ordered according to the predicted value, the d-statistic was outside the bounds for the critical values ($d = 1.81$). Other non-linear specifications of the models, combining ln-transformed and untransformed variables in a number of combinations, were tested but the autocorrelation in the residuals was not improved.

4.5.2. Model output

The model estimated for the costs of fox control supported a negative relationship between costs and the number of foxes available to be culled (Figure 4.1), as would be expected from predator-prey theory. It becomes more difficult (and costly) to catch a member of a given prey population the smaller that prey population is (Begon *et al.* 1996). This means that, according to the model, it is highly unlikely that a sheep producer will eliminate all the foxes on his or her farm.

The optimisation analysis indicates that for farms with particular characteristics and fox numbers, it would be advantageous from a financial perspective for the farmer to undertake fox control actions in addition to those currently practised. This tended to be the case for farms that were small in area and had fewer lambing ewes, which is because, for these data, although fox predation was more likely on farms with more ewes, lamb losses per ewe were lower. Thus the reductions in lamb losses due to fox control per ewe were lower on farms with more ewes and were less likely to outweigh the costs of control. As the costs of control were positively related to farm area, on larger farms the predicted lamb loss reductions were also less likely to outweigh the costs of control. The dummy variables coding for whether there was land used for game rearing in the surroundings of the farm, whether there were longwool breeds on the farm and whether the farm was in the Southwest or the Northeast region also influenced the output of the models, in terms of whether fox control was worthwhile (Figure 4.4).

For the sets of farm characteristics for which the output to the model was calculated, it appeared that fox control would only be worthwhile on a minority of farms, those of smaller area and/or flock sizes, as well as in some cases those in the Southwest or with game rearing in the surroundings. In addition, it was not worthwhile to carry out fox control at low fox densities, as the costs of control tended to outweigh the benefits (in terms of reduced lamb losses to foxes) when there were fewer than a given number of foxes on the farm. These farms already had at (or below) the optimal number of foxes (Q^*).

Analysis of the total costs of lamb losses to foxes, indoor housing and fox control per ewe indicated that variation in expenditure on indoor housing had a much greater effect on lamb losses and variation in total costs than did fox control (Figures 4.6 and 4.7). It appeared that the optimal strategy for a farmer aiming to minimise total costs was to spend money on housing as many of his ewes as possible for lambing. Keeping ewe and lambs in for longer than a few hours was not worthwhile (also shown in Chapter 3 analyses), whilst fox culling had only a small effect on reducing total costs. Incorporating the costs of indoor housing resulted in a shift in the optimal number of foxes (Q^*) upwards and therefore the optimal cull level decreased (in the case of the example farm discussed here, this shift was from 5 to no foxes culled). Therefore, it is likely that consideration of the costs of indoor housing means that additional fox control is worthwhile on a more limited set of farms than simply looking at the costs of control and lamb losses indicated. The difference between the effects of fox control and indoor housing is due to their relative effects on losses in the model. Reducing fox density has a relatively small effect on expected lamb losses and only influences the probability of predation occurring. Expenditure on indoor housing, on the other hand, influences both the probability of fox predation and the scale of lamb losses.

4.5.3. Assumptions and realism of analysis

4.5.3.1. Fox population density and lamb losses

The questionnaire data indicated a positive relationship between fox population density and the probability of fox predation of lambs. However, because fox population density estimates were only available at a regional level and because only perceived loss data were collected, the authenticity of this relationship can not be guaranteed. In any case, the coefficient estimated here indicates that fox population density has only a weak effect on the probability of fox predation: from Table 4.3, it can be seen that a reduction in the number of foxes on a farm with specified characteristics by one (equivalent to a reduction in density of 0.005 foxes per hectare) results in a reduction in lamb losses of a maximum of only £0.03 per ewe. A problem with the legitimacy of the relationship between lamb losses and fox predation estimated here is that expected lamb predation by foxes does not decrease to zero when there are no foxes on the farm. However, it could be argued that a decrease to zero would result in an unrealistically sharp fall off in the probability of fox predation with decreases in fox density, whilst, as the models do not advocate reducing fox populations to zero as a financially viable option, it is not necessary for them to be wholly reliable at fox levels of zero. Fox predation occurring when there are no foxes on a farm could be justified if predation by foxes from neighbouring farms occurred.

The likelihood of some lamb losses to foxes being compensatory is discussed in Chapter 3 (Section 3.5.3). The fox population density estimates calculated here are within the range of those in the literature for various regions of Britain (Insley 1977; Lloyd 1980; Macdonald *et al.* 1981; Hewson 1986; Harris & Lloyd 1991; Heydon *et al.* 2000), but are mostly in the upper end of this range, suggesting they may be slight overestimates. Such an overestimate will not affect the estimation of the relationship between fox density and predation damage, but the modelled impact of killing a single fox will be slightly smaller than it should be.

4.5.3.2. Ecological considerations

In using the fox population density estimates to calculate 'numbers of foxes on a farm', figures were simply multiplied up by the farm area. Foxes are territorial and live in family groups (Harris & Lloyd 1991). Therefore, the conversion of density estimates to absolute numbers in a given area will depend on a number of factors other than area, including the sizes of territories, which will vary with habitat type (Lloyd 1980; Macdonald 1980; Harris & Lloyd 1991). However, there have been few attempts to determine the relationship between comparative population indices and actual density for canid species (Harris & Saunders 1993). The analysis also makes the assumption that the fox population on the farm in question will not change between the control action and lambing. This assumption holds if lambing (and therefore fox control) occurs before foxes produce their young and if immigration of foxes from outside the farm under the control regime is negligible at this time. Lambing generally takes place between December and April, whilst the peak birth time for foxes is March (Harris & Lloyd 1991). Therefore, for many farms the assumed fox control and lambing will be over before this time period. In any case, foxes born in March will not be capable of attacking lambs even on farms that lamb later in the year.

The assumption of no immigration is less likely to hold, however, as foxes will be dispersing over these time periods. Local fox control tends to create a ‘sink’ to which foxes from outside the area under control will be drawn to replace those that have been killed (Reynolds *et al.* 1993), which explains why some farmers annually kill a greater number of foxes than realistically could be resident on their land at one period of time. The fact that this analysis fails to account for such immigration is a major shortcoming. In addition, it should be noted that because of foxes’ territoriality and dispersal habits, the effects of fox control by farms neighbouring the one under consideration will also influence its resident fox population, as may levels of fox control on a regional scale (Heydon & Reynolds 2000b). The lack of a change in fox numbers between the culling action and lambing other than due to culling further implies that lethal control is the only factor affecting fox abundance on farms. Most fox mortality is thought to be induced by man, but not all anthropogenic deaths are due to deliberate control actions, road accidents also being a mortality factor (Harris & Lloyd 1991) (Chapter 1, Section 1.5.4). In addition, natural deaths due to disease, for example, occur. Only one study, however, provides quantified data on the relative rates of mortality due to different factors and this is for a fox population in urban Bristol (Harris & Smith 1987a). In any case, the assumption that culling will be the only influence on fox numbers between the culling and lambing events is only likely to hold if there is only a short period of time between the two.

Although fox predation is only a problem for sheep producers at lambing, simply controlling foxes before lambing each year with no consideration for what effect this control has on fox population dynamics is unlikely to be very cost-effective. Making the analysis more biologically realistic would involve modelling the effects of control on the population dynamics of the fox as well as incorporating the likelihood of immigration in to the model. This would also introduce a time element in to the model, in turn making it more complex, whilst a spatial element would also be desirable. The specificity of management information provided by the model will increase with its realism. However, in order to make such models realistic a large amount of data is required, along with the estimation of a large number of parameters (Choquenot & Hone unpublished). Choquenot and Hone (unpublished) suggest that the amount of data (and therefore resource cost) required to estimate bioeconomic models grows exponentially with their degree of realism. The importance of incorporating population dynamics into pest control programs has been recognised (Stenseth & Hansson 1981) and a number of studies have assessed the effects of control on fox populations theoretically, mostly dealing with the control of rabies, e.g. Anderson *et al.* (1981), Smith and Harris (1991), Selhorst and Müller (1999) and Suppo *et al.* (2000), but there have been few empirical demonstrations of the effects of control on rural fox population numbers or dynamics (Chapter 1, Section 1.5.3), with the exceptions of Reynolds *et al.* (1993) and Heydon and Reynolds (2000a). Whilst data are available from urban fox populations, e.g. Harris & Smith 1987b, that could form the basis for a population model, the applicability of such a model to rural fox populations, and therefore its inclusion in an analysis such as this, is questionable.

4.5.3.3. Costs of fox control

Because the data on the costs of control were taken as given by respondents to the questionnaire, it is impossible to know what is included in these costs, whilst it is unlikely that all producers have calculated their costs in the same way. Some producers will not have considered the time they spent on fox control as work, so will have undervalued it, whilst others will have taken all the equipment and opportunity costs into account. In addition, producers will have used a number of different methods of control, all of which will differ in their cost-effectiveness. This explains the wide range of costs and the relatively low R-squared statistic of the estimated regression model for the costs of control. However, although these costs could be considered to be total opportunity costs as viewed by the farmer, because they are once again perceived costs, the appropriateness of aiming to minimise them can be brought in to question. Unfortunately, due to the sensitivity of the issues involved and the fact that there were constraints to the length of the questionnaire to encourage high response levels, it was not possible to ask for a break-down of the various costs of fox control, including equipment and time, nor to determine what types of control each producer used. In any case, whether producers would have accurate figures on these available is debatable.

The fact that a large number of producers paid nothing for their fox control is also a problem for this analysis. Data for farms where control was carried out at no cost to the farmer could not be included, but if 'free' control is available, there is no limit to the number of foxes that should be killed, if, as according to this analysis, the death of each fox brings financial benefit in terms of lower lamb losses. In addition, if control can be carried out at no cost, this casts doubt on the assumption of this analysis that producers will aim to minimise the costs of fox control (in terms of lamb losses and direct costs). Rather, a more realistic assumption may be that they are simply aiming to maximise the benefits of control (i.e. the reductions in lamb losses to foxes). Some types of control may even confer benefits to the producer in themselves if they are deemed to be an activity that is enjoyable to engage in. (It should be noted that 'free' fox control is likely to incur some costs elsewhere, even if not to the farmer in question.) The percentages of farms carrying out fox control at no cost tended to be higher in those regions with higher estimated fox population densities (Spearman's rank correlation of percentage of farmers reporting fox control at no cost in each region against estimated fox density per 1-km square: $r_s = 0.669$, $p = 0.049$ [$n = 9$]). This supports the negative association between fox numbers and the cost of control estimated for the data from farms that did put a cost to fox control.

4.5.3.4. Applicability of analysis

This analysis assumes the only advantage to the producers of killing foxes is a reduction in lamb losses. This may be the case for farms on which sheep production is the only activity. Other benefits to fox control for sheep farmers may include a reduction in diseases transmitted by foxes (though the risks of transmission of disease by foxes to livestock are unknown) (Macdonald *et al.* 2000; White *et al.* 2000a). There may also be disadvantages, such as reduced predation pressure on rabbit populations, which compete for grazing with the sheep (although the effect of fox predation on rabbit populations is likely to be small) (White *et al.* 2000a). In addition, the model may not accurately capture the trade-off between the use of indoor lambing and fox control as preventive measures against fox predation. Although lambing indoors for a short while was the 'optimal' strategy here, lambing indoors is not practical under some farm management systems and the benefits of fox control are likely to be greater for farmers that do not lamb indoors. (These models indicate a small drop in lamb loss with fox culling when no ewes are housed at lambing, but very little change in total costs.) In this data set, fewer than expected producers that lambed all their ewes indoors also carried out fox control (chi-square test of association: $\chi^2 = 4.50$, d.f. = 1, p = 0.034 [n = 451]). For sheep producers with other farming interests, there may be a number of additional benefits to fox control. In this data set, sheep farmers with other farming interests were more likely to undertake fox control on their land than expected (chi-square test of association: $\chi^2 = 23.3$, d.f. = 1, p < 0.001 [n = 439]), which may be due to these added advantages.

If the models can be deemed realistic enough to be applied in the management of fox predation of lambs, there remains the problem that, before knowing how many foxes he or she should kill on his or her land, the sheep producer needs to know how many foxes there are on the land. It would therefore be useful if the model allowed the producer to use some indication of fox density, rather than actual numbers, to determine how many should be controlled. One way to do this would be to convert fox density estimates back to scat densities using the multipliers calculated in Section 3.3.1 and optimal fox control levels could be calculated according to these rather than actual fox numbers. However, even the determination of scat densities through a scat survey may not be practical for many producers, whilst the time taken to carry out such a survey will have an opportunity cost for producers.

4.6. CONCLUSIONS

This analysis provides a framework for evaluations of livestock predation and management of these problems. It allows for the trade-offs between different preventive measures to be modelled and indicates the best strategies for a farmer in financial terms. The analysis performed here does not give output figures accurate enough to inform individual producers on the levels of fox control they should carry out, but the basic model could be extended (some suggestions for possible extensions are given above) to improve both its accuracy and applicability. The analysis is a step towards understanding the association between fox control, fox population density and fox predation of stock on which little information is currently available.

The analysis assumes that the objective of carrying out fox control for a sheep producer is to minimise his or her costs through reduced lamb losses. However, this may not be a realistic objective for sheep producers for various reasons, some of which are discussed above. An individual's assessment of the performance of a pest control action will depend on his or her attitude to risk, as well as their profit motive, whilst their objectives may not simply be to minimise costs but, for example, to keep in line with the pest control practices of their neighbours (Norton 1976). Because there is uncertainty in the model parameters estimated, a strategy that minimises risk or a different behavioural approach to the problem may be more appropriate to the farmer's goals (Mumford & Norton 1984). The effects of risk can be incorporated in a profit-maximising pest control decision-making framework, e.g. Pannell (1990).

4.7. SUMMARY

Prevention of predation of stock is a major reason why foxes are deliberately culled in Britain and lethal fox control can be considered as a preventive measure against predation with associated costs. This chapter evaluates fox control in an economic framework to assess optimal levels of fox control for a sheep producer in financial terms.

The relationship between expected lamb losses and fox population density was modelled according to the analysis carried out in Chapter 3. The functional relationship between the costs of fox control and fox population levels was estimated using linear regression analysis. Optimal levels of fox abundance and fox control according to the models were determined using marginal analysis. Fox control levels in these models were computed as being additional to a baseline of ‘current’ (at the time the questionnaire survey of sheep producers was carried out) levels of control.

Fox control was more costly the fewer foxes there were on a given farm, whilst the benefits of fox control increased the more foxes that were removed. Optimal levels of control and therefore whether it was worthwhile for a producer to carry out fox control were dependent on farm characteristics, with fox control being more likely to be worthwhile on farms with fewer ewes and of smaller areas, as well as on the resident number of foxes. Housing ewes and lambs at lambing had a greater effect on reducing lamb losses and the total costs of fox predation than did fox culling.

The analysis provides a framework for use in the evaluation of fox control, which can be modified to provide a more rigorous analysis, incorporating, for example, dynamic and spatial aspects to fox ecology and control, more reliable cost and loss data and the effects of risk. In addition, the analysis provides one of the first assessments of the association between fox population density and livestock predation.

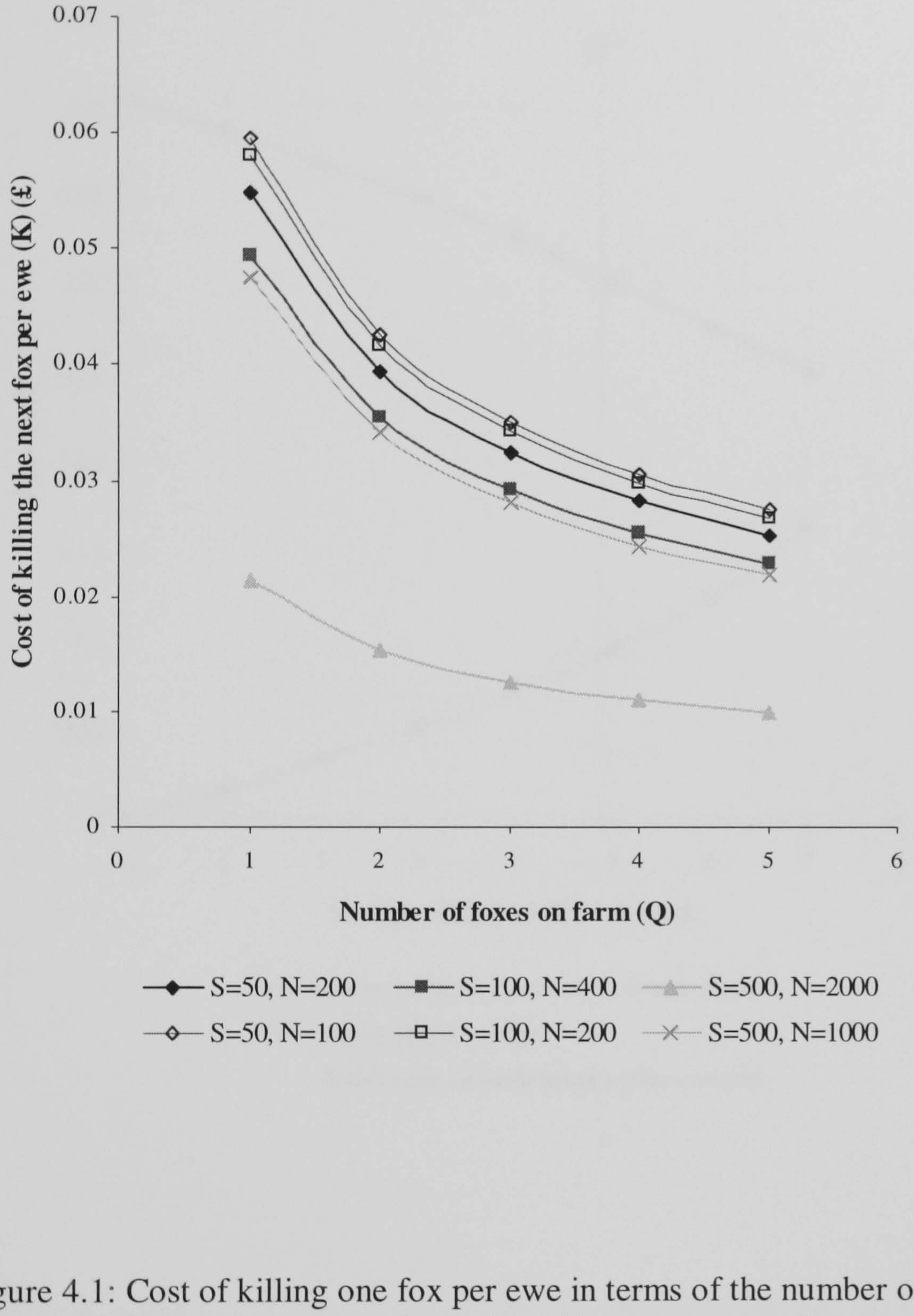


Figure 4.1: Cost of killing one fox per ewe in terms of the number of foxes on the farm for various farm areas and numbers of lambing ewes according to estimated model ($\ln(K) = -2.80 - 0.478 \cdot \ln(Q) + 0.0011 \cdot S - 0.0008 \cdot N$) ($S$ = farm area in hectares, N = number of lambing ewes)

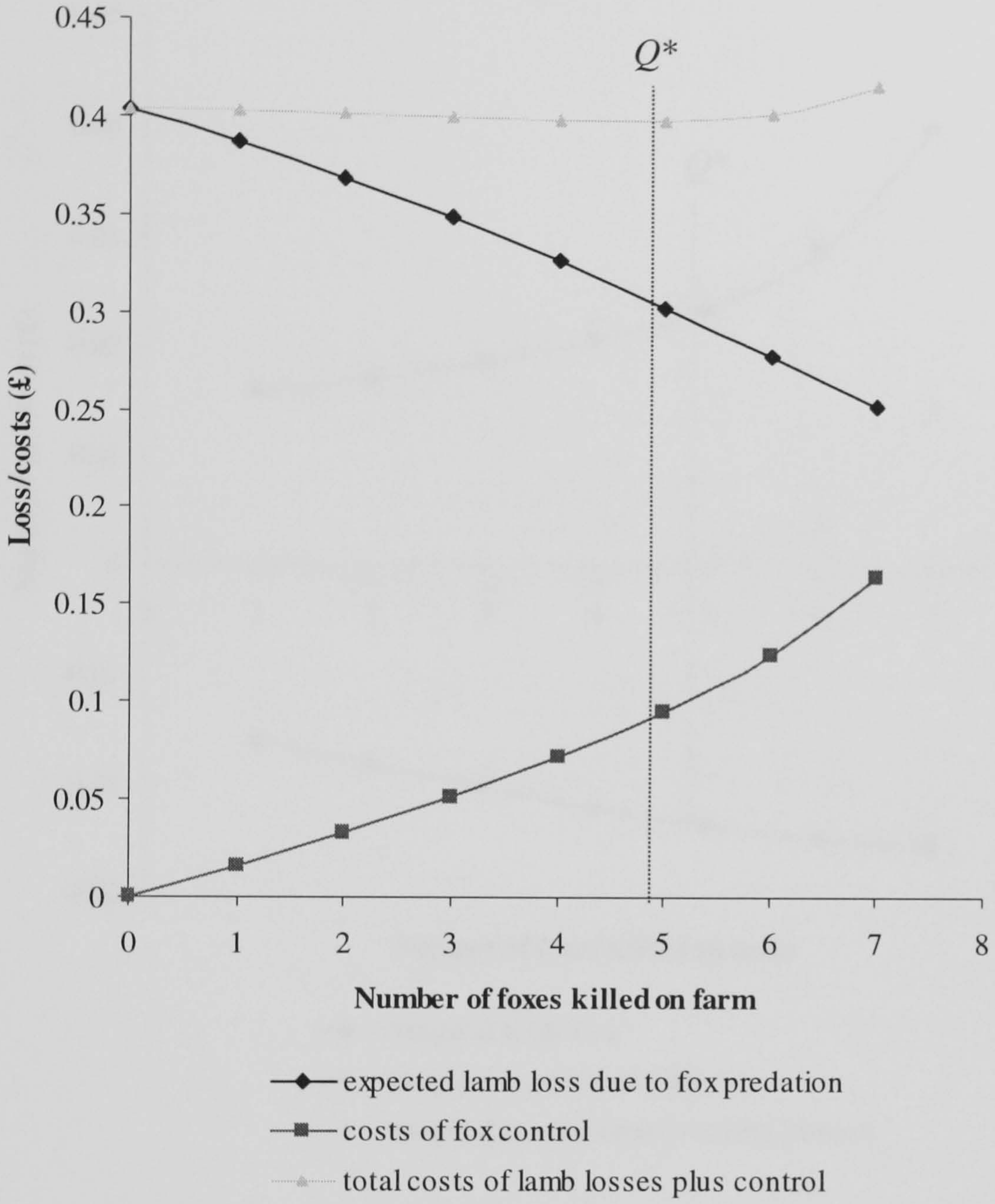


Figure 4.2: Total lamb loss due to fox predation, costs of fox control and costs of lamb losses plus control for each fox killed from a starting density of 0.035 foxes per hectare (7 foxes on the farm, $X = 0.035$, $Q = 7$) on a 200 hectare farm in the Southwest with 800 ewes, where all ewes are lambed indoors and kept inside for one day and there is game rearing in the surroundings ($S = 200$, $SW = 1$, $N = 800$, $Y = 0.15$, $D = 1$, $G = 1$). Q^* marks the optimal point where the total costs of lamb losses plus fox control are minimised.

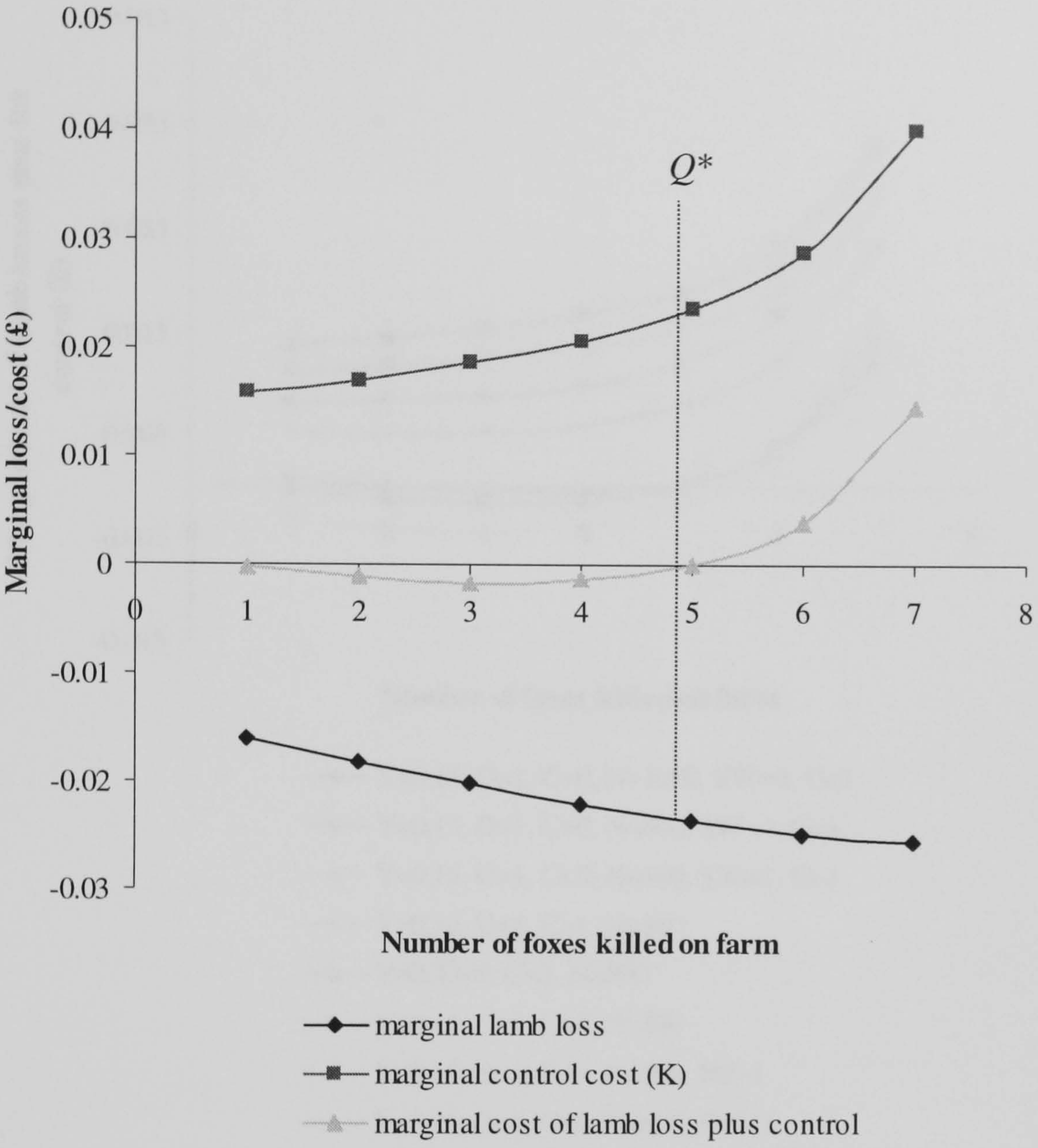


Figure 4.3: Marginal lamb loss due to fox predation, cost of fox control and cost of lamb loss plus fox control for each fox killed from a starting density of 0.035 foxes per hectare (7 foxes on the farm, $X = 0.035$, $Q = 7$) on a 200 hectare farm in the Southwest with 800 ewes, where all ewes are lambed indoors and kept inside for one day and there is game rearing in the surroundings ($S = 200$, $SW = 1$, $N = 800$, $Y = 0.15$, $D = 1$, $G = 1$). Q^* marks the optimal point where the total costs of lamb losses plus fox control are minimised.

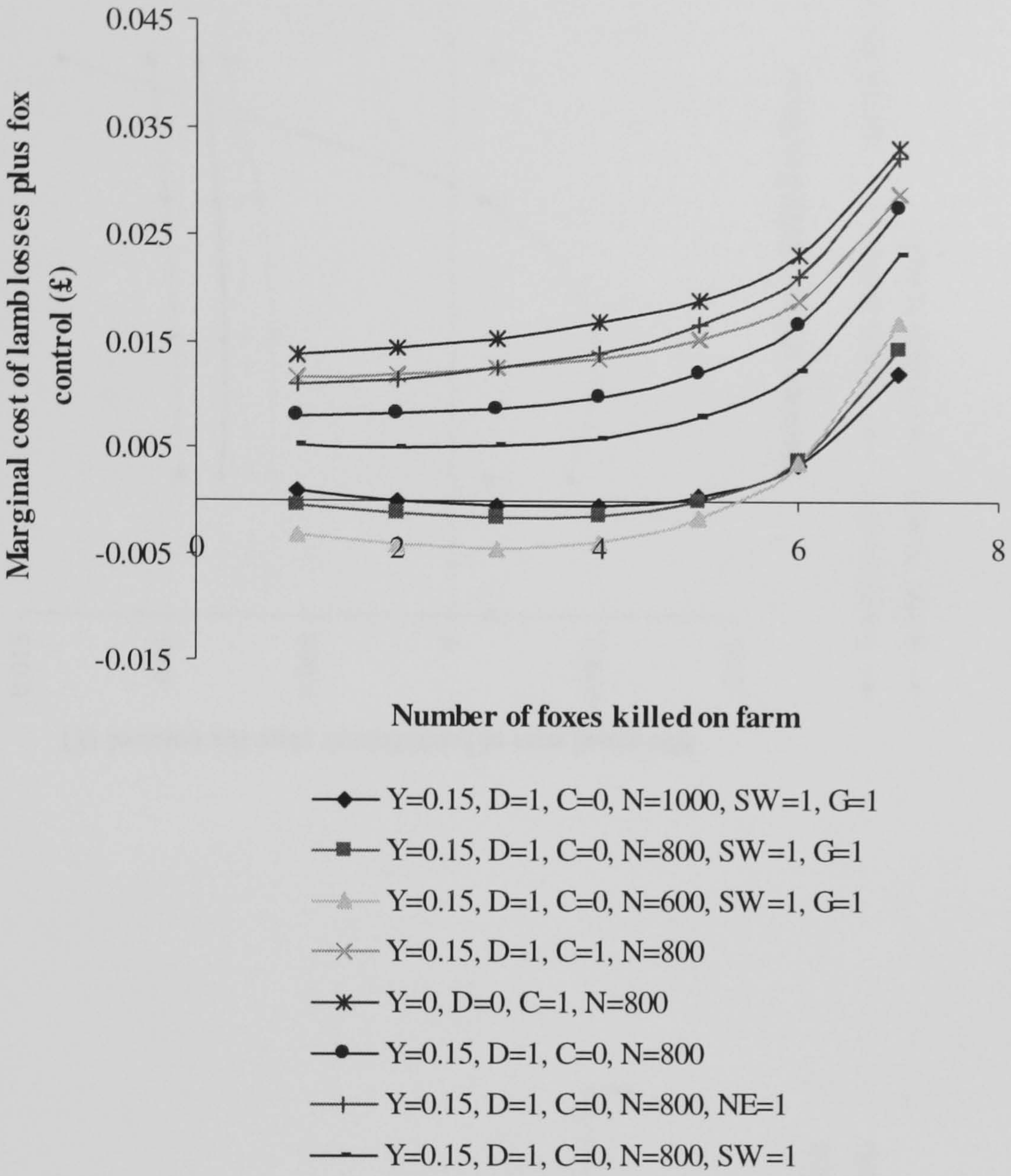


Figure 4.4: Marginal cost of lamb losses plus fox control for each fox killed on 200 hectare farms with a fox population starting density of 0.035 foxes per hectare (7 foxes on farm, $X = 0.035$, $Q = 7$) and various characteristics (Y = expenditure on indoor housing per ewe per day, D = number of days inside after lambing, C = dummy variable coding for whether fox control is carried out, N = number of lambing ewes, SW = dummy variable coding for whether farm is in Southwest England, NE = dummy variable coding for whether farm is in Northeast England, G = dummy variable coding for whether land used for game rearing is in surroundings)

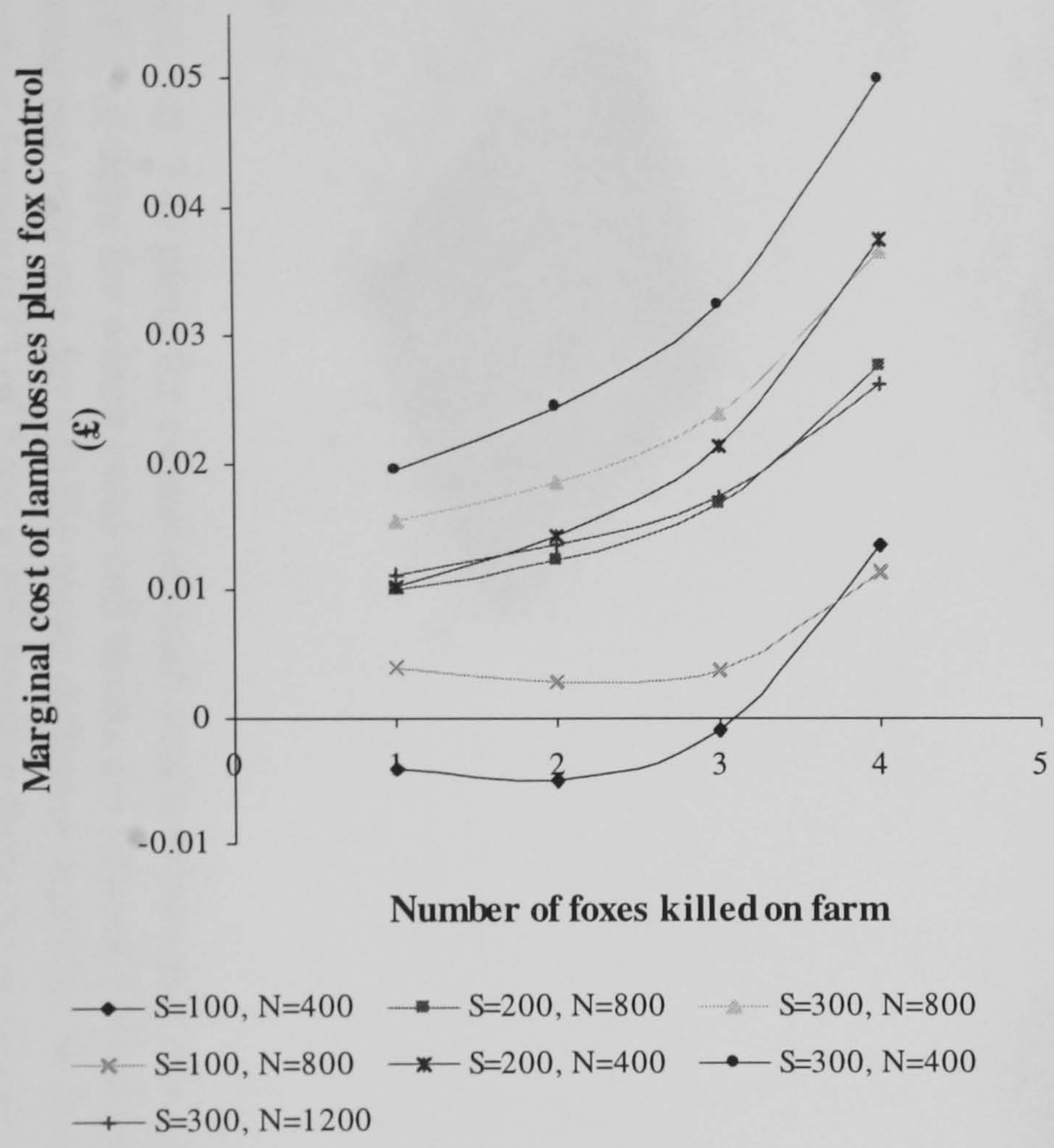


Figure 4.5a: Marginal cost of lamb loss plus fox control for each fox killed on farms with all ewes housed indoors for one day ($D = 1$) and 4 foxes in total ($Q = 4$) (densities, X, varying with area) and various size characteristics (S = farm area in hectares, N = number of lambing ewes)

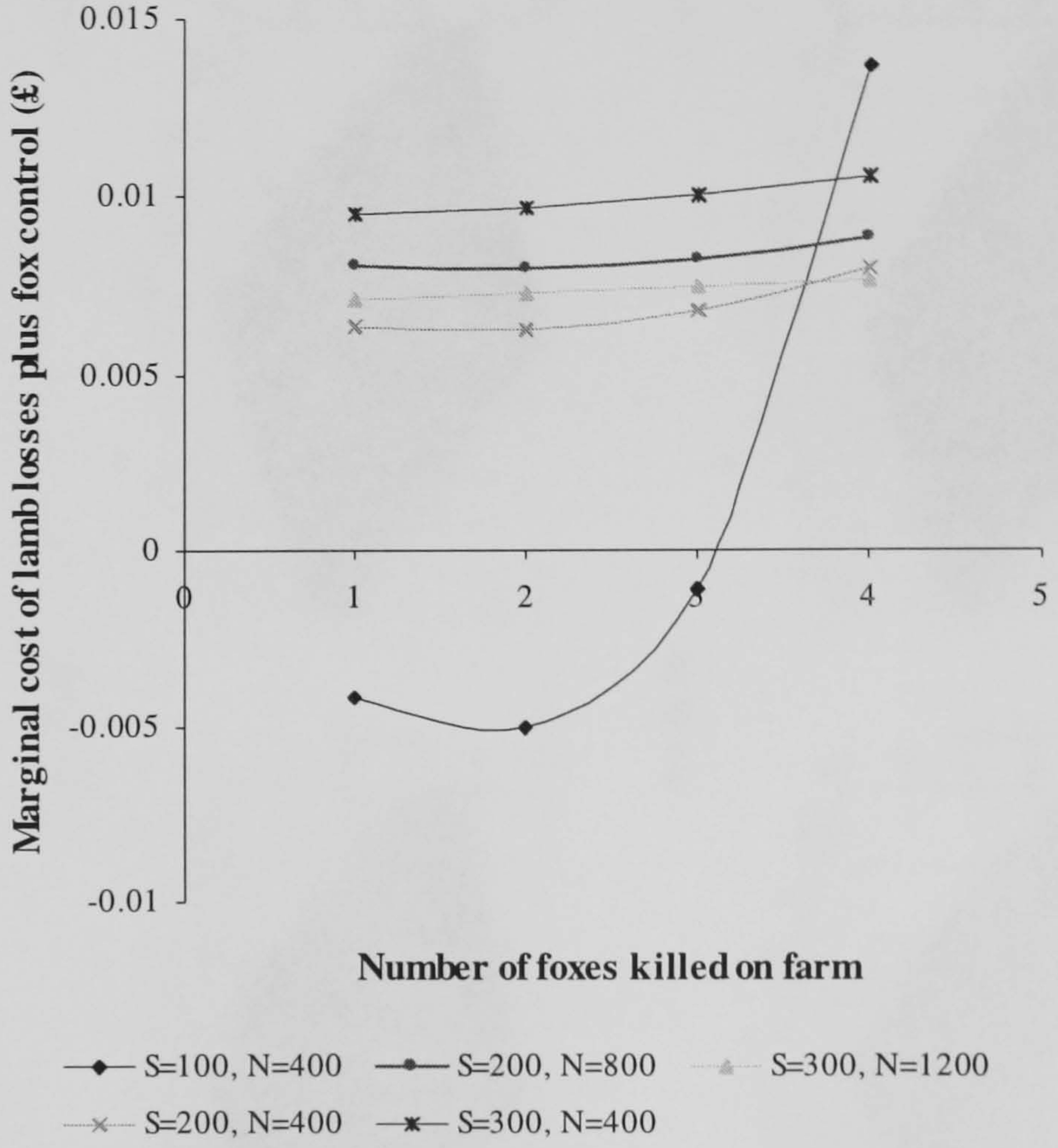
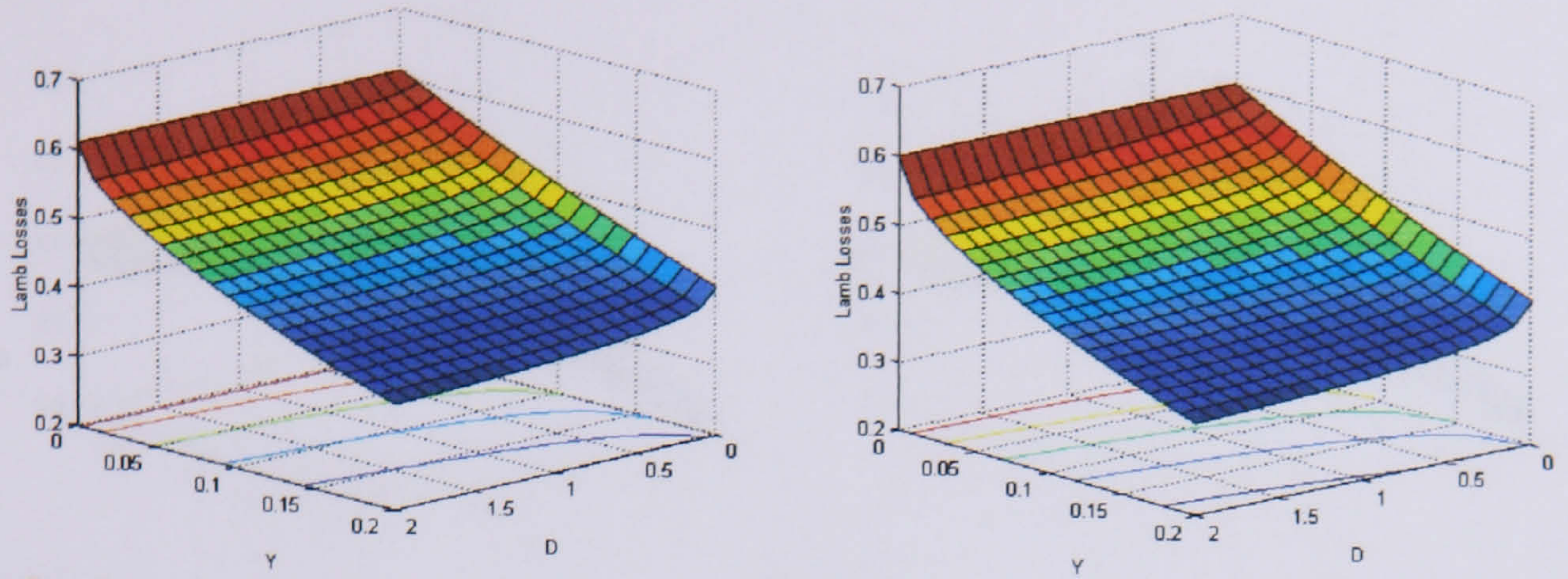
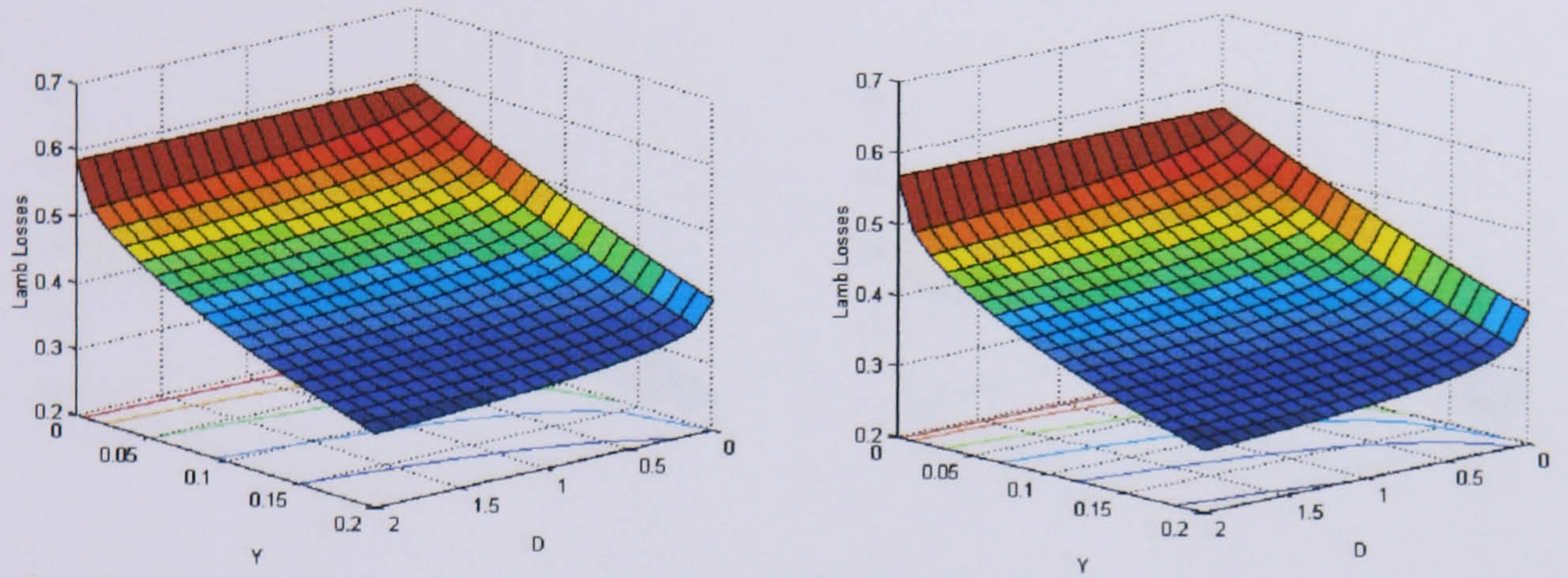


Figure 4.5b: Marginal cost of lamb loss plus fox control for each fox killed on farms with all ewes housed indoors for one day ($Y = 0.15$, $D = 1$) and a fox population density of 0.04 foxes per hectare ($X = 0.04$) (total fox numbers, Q, varying with area) and various size characteristics (S = farm area in hectares, N = number of lambing ewes)



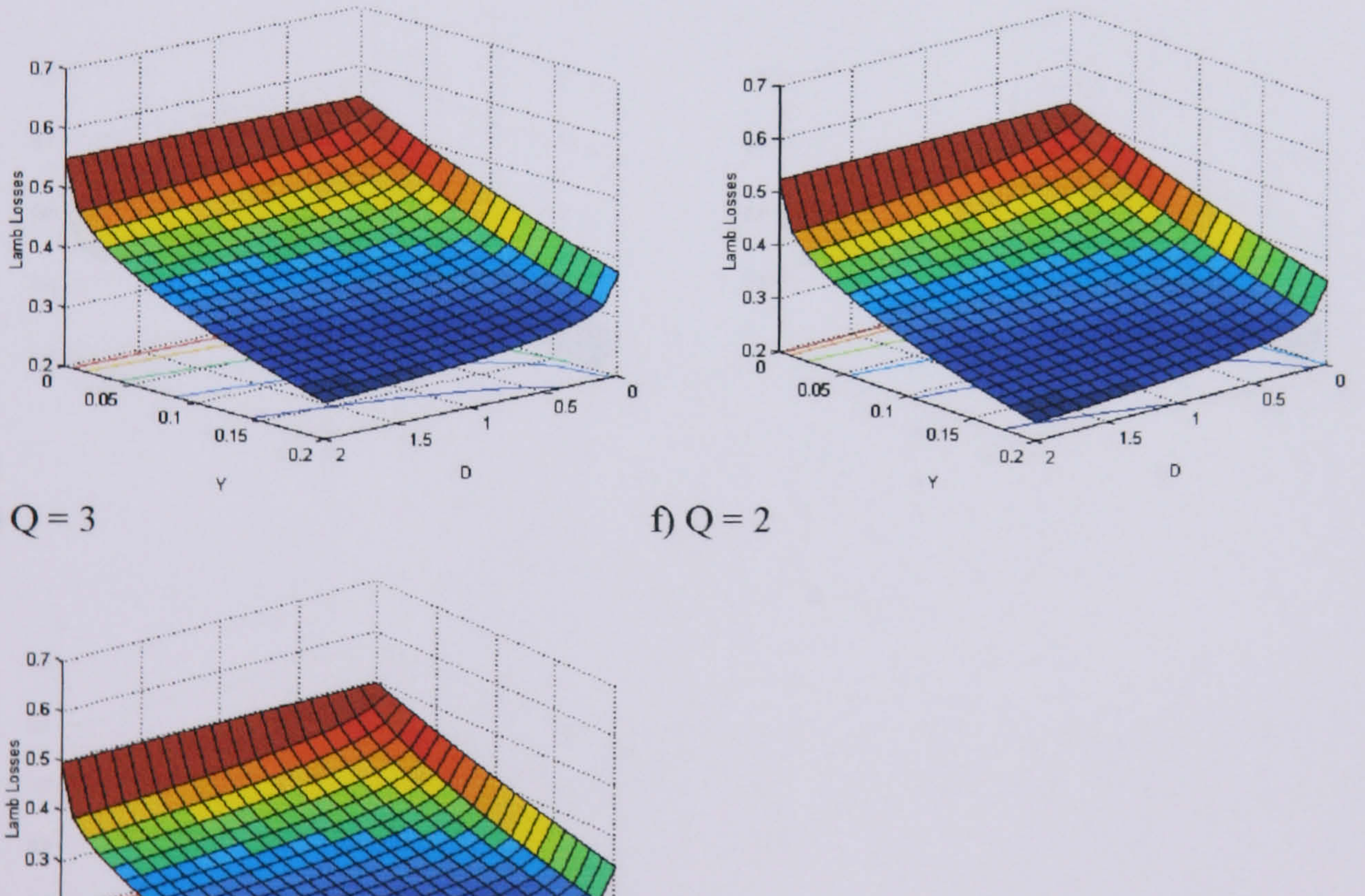
a) Q = 7

b) Q = 6



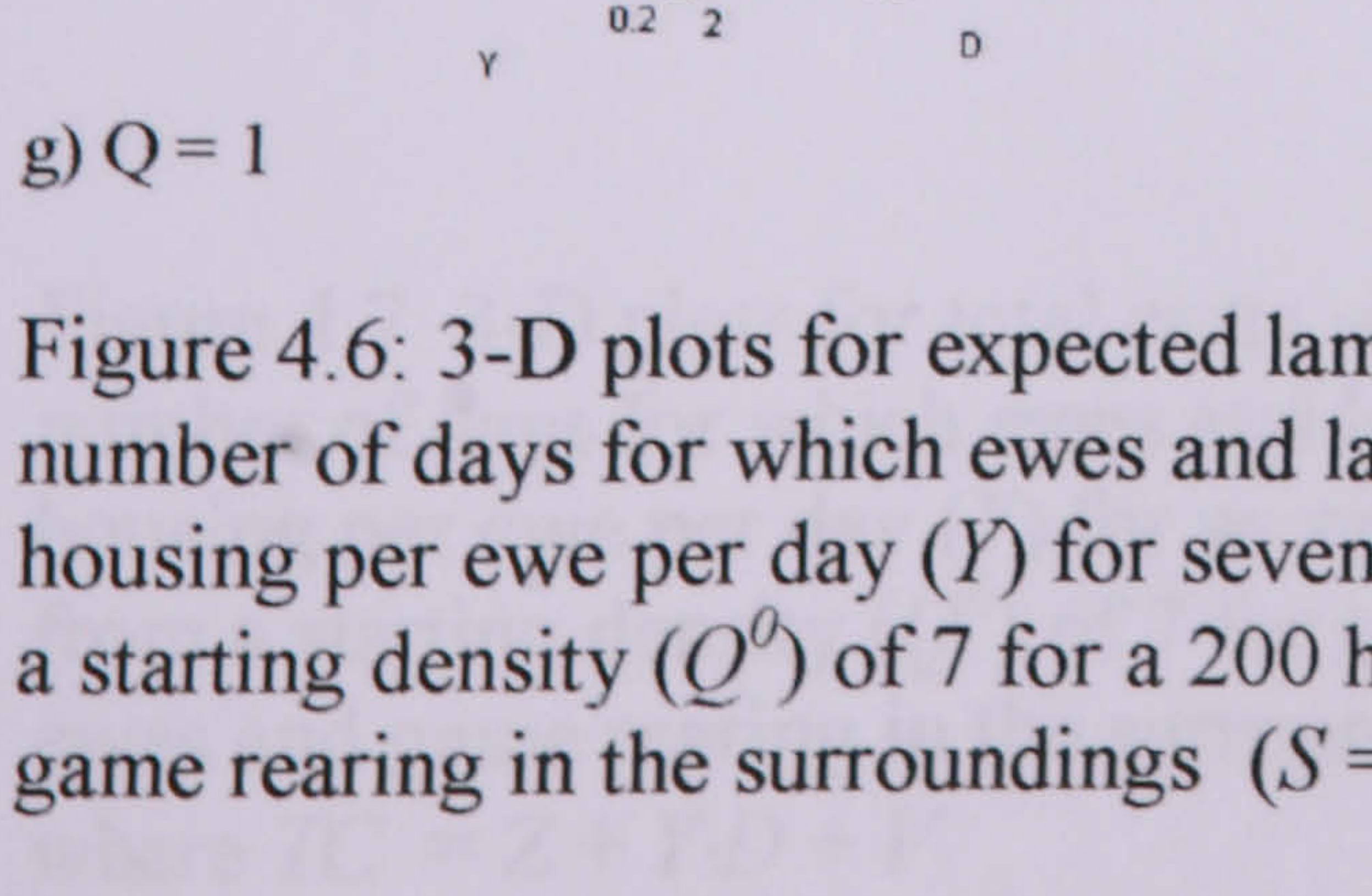
c) Q = 5

d) Q = 4



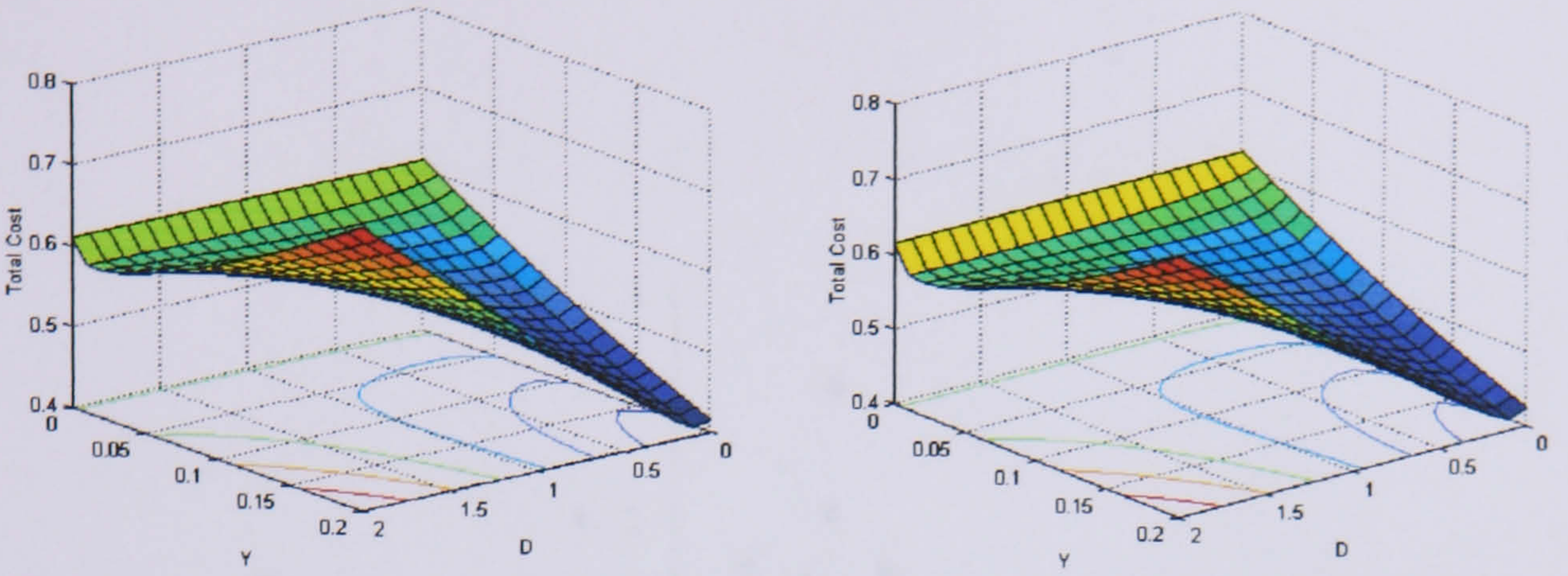
e) Q = 3

f) Q = 2

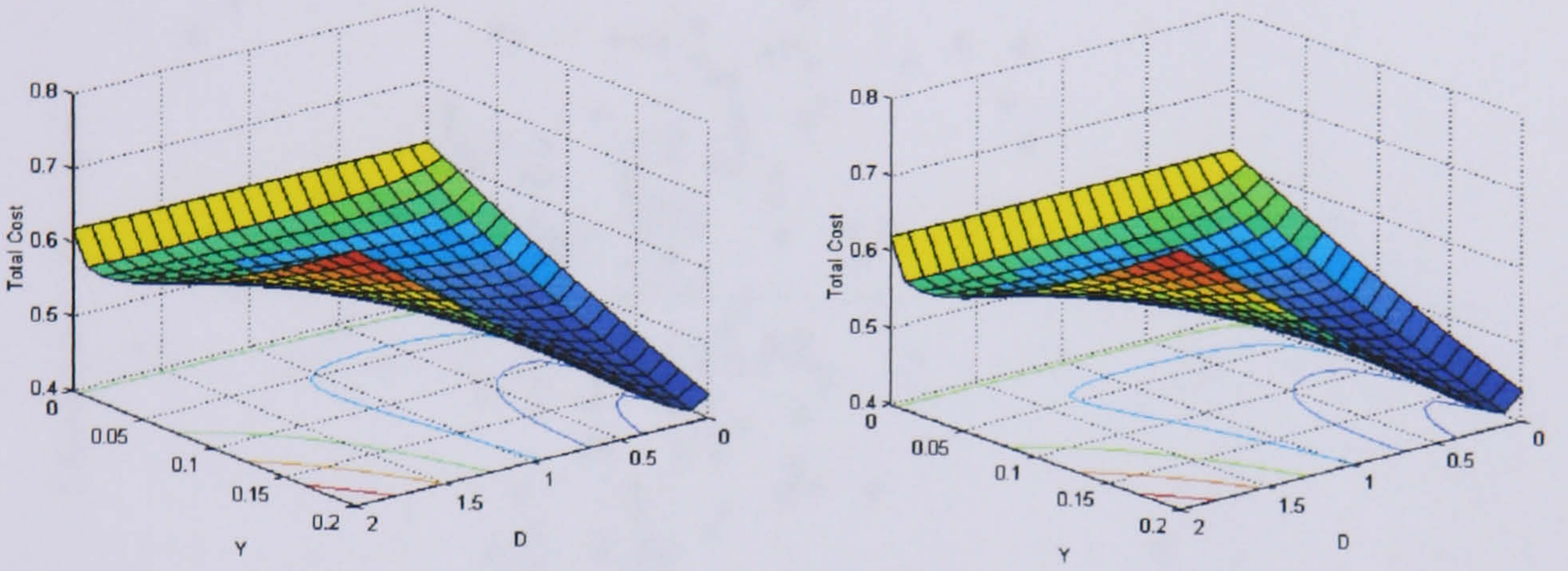


g) Q = 1

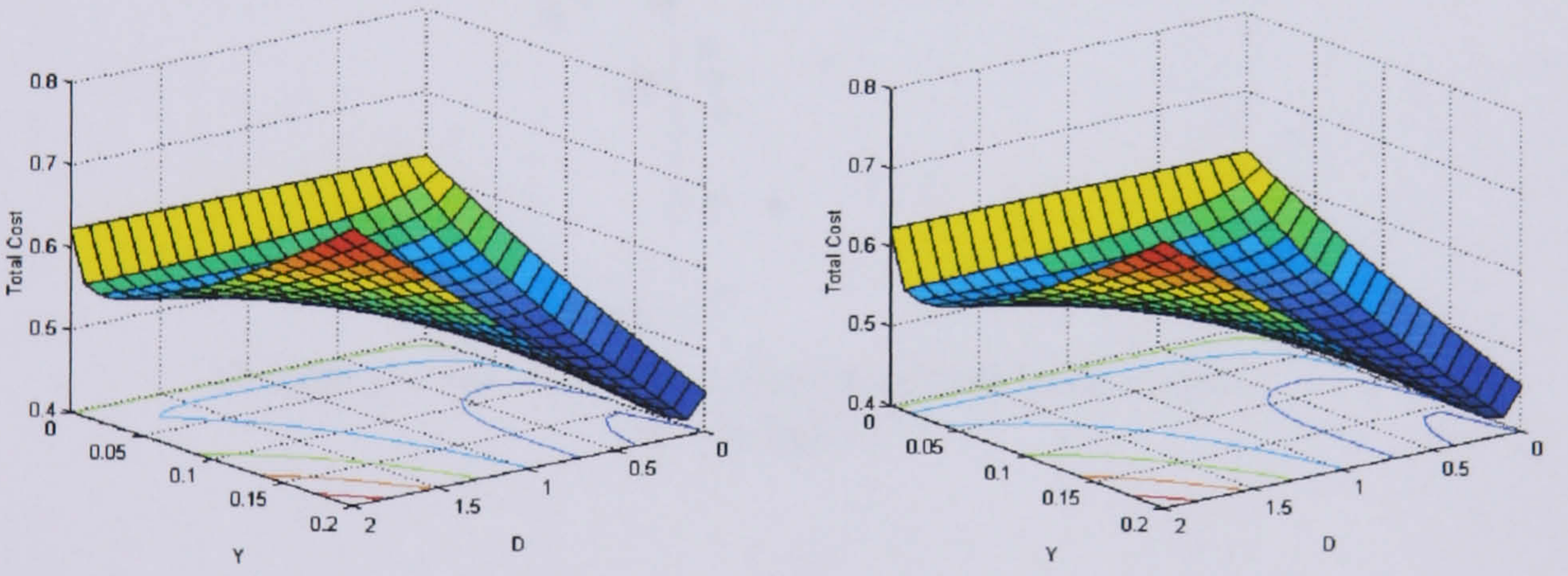
Figure 4.6: 3-D plots for expected lamb loss to foxes per ewe (Z) against both the number of days for which ewes and lambs are housed (D) and expenditure on indoor housing per ewe per day (Y) for seven different numbers of foxes on the farm (Q) from a starting density (Q^0) of 7 for a 200 hectare farm in the Southwest with 800 ewes and game rearing in the surroundings ($S = 200$, $SW = 1$, $N = 800$, $G = 1$)



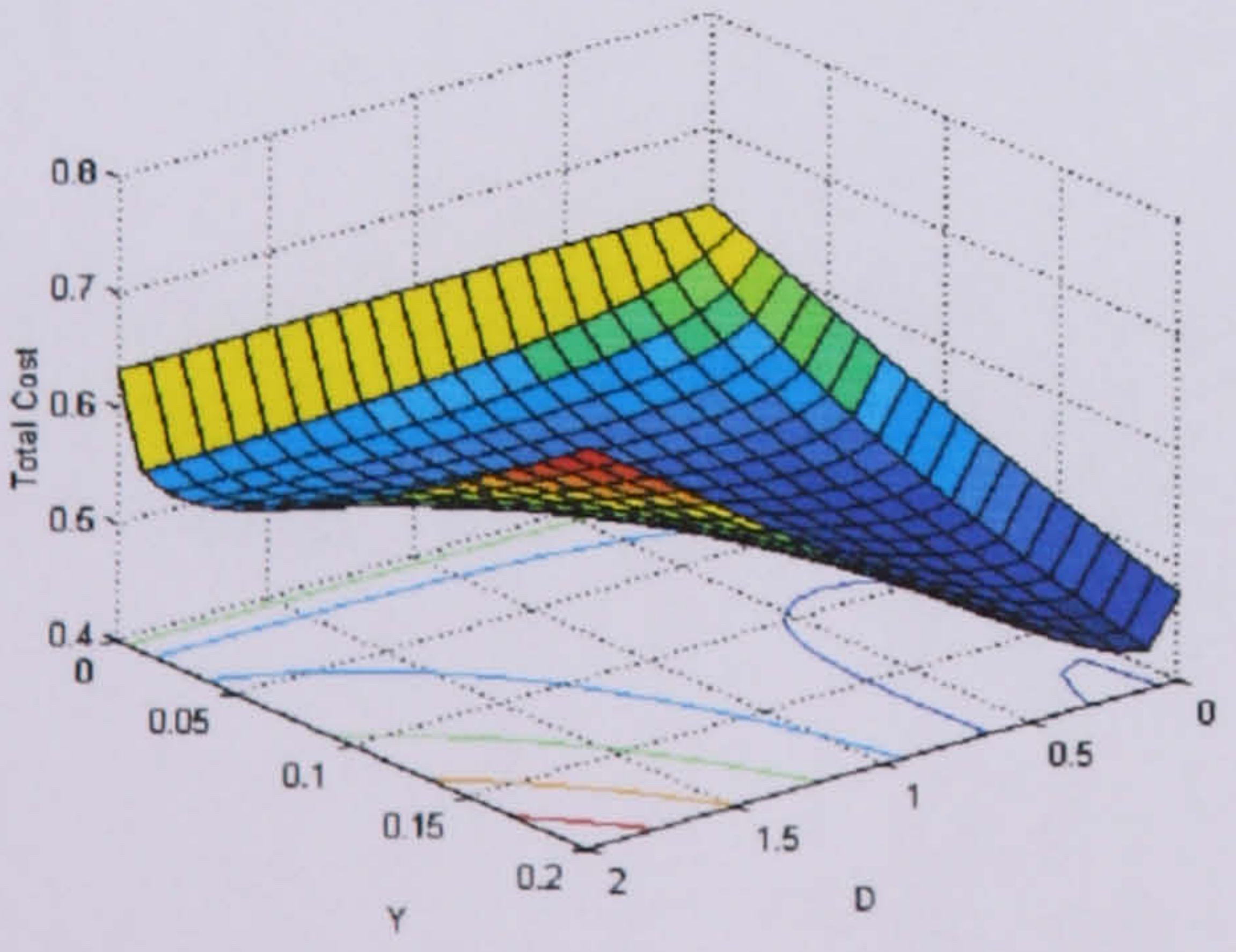
a) Q = 7 b) Q = 6



c) Q = 5 d) Q = 4



e) Q = 3 f) Q = 2



g) Q = 1

Figure 4.7: 3-D plots for total costs of fox predation per ewe (TC) against both the number of days for which ewes and lambs are housed (D) and expenditure on indoor housing per ewe per day (Y) for seven different numbers of foxes on the farm (Q) from a starting density (Q^0) of 7 for a 200 hectare farm in the Southwest with 800 ewes and game rearing in the surroundings ($S = 200$, $SW = 1$, $N = 800$, $G = 1$), where $TC = Z + Y{\cdot}D + V$

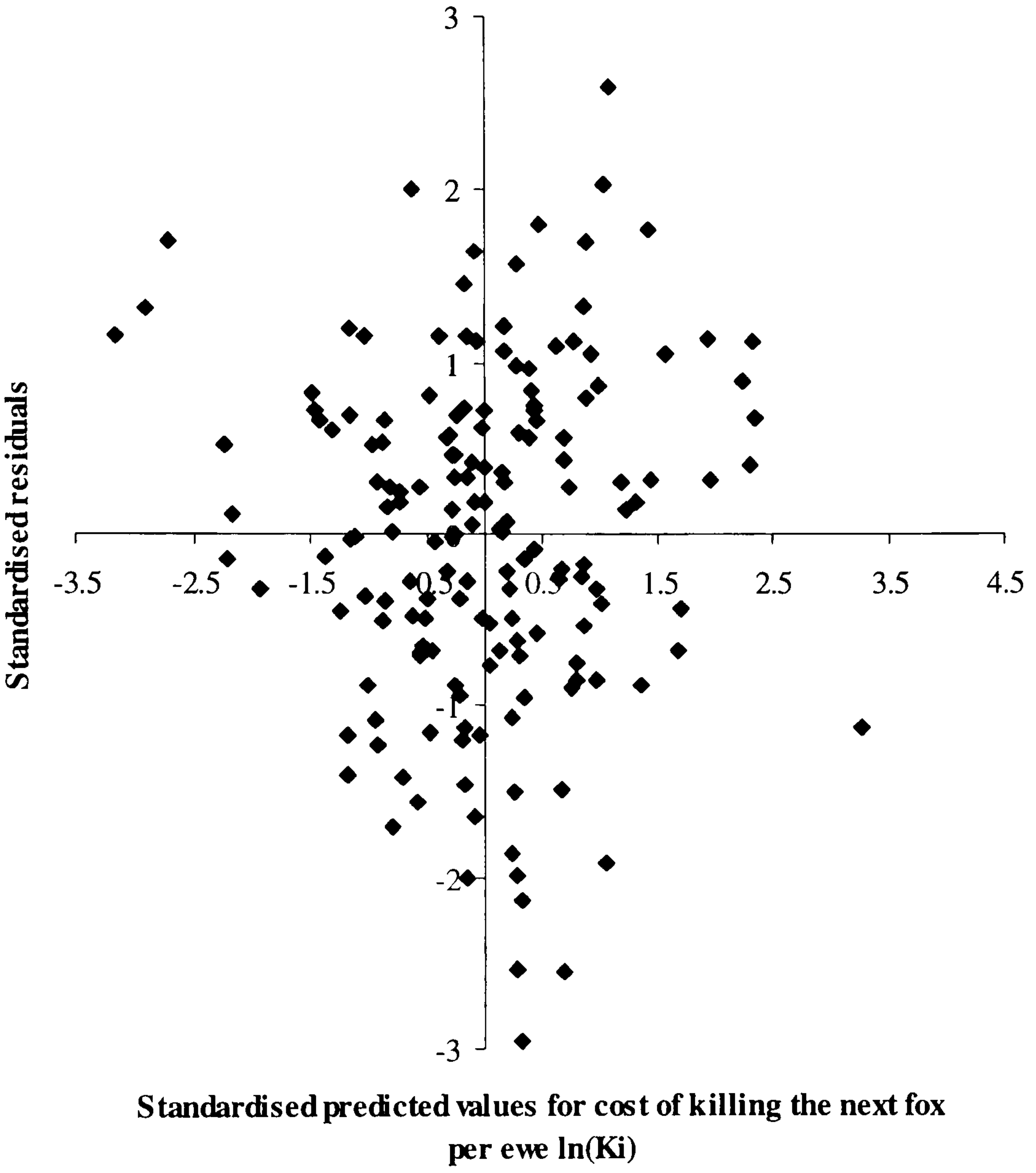


Figure 4.8: Plot of standardised residuals against standardised predicted values for ln-cost of killing the next fox per ewe (K_i) according to the model $\ln(K_i) = -2.80 + -0.478.\ln(Q_i) + 0.0011.S_i - 0.0008.N_i$ [n = 164]

CHAPTER 5

IMPACTS OF FOXES ON FREE-RANGE POULTRY PRODUCTION

5.1. INTRODUCTION

Fox predation of poultry is only possible from free-range units, as intensive, indoor units are too secure for fox predation to occur. The main types of poultry farmed in Britain are laying hens, table chickens, turkeys, geese and ducks, with the majority of these being farmed on intensive units. In a 1992 survey of egg producers in England, free-range units made up 19.9% of the sample, but they only accounted for 5.4% of the bird capacity (Roberts & Farrar 1993). More recent figures for the proportion of hens that are free-range out of the total UK flock are 11% (FAWC 1997) and 18% (NFU 2001), with 15% of eggs being produced under free-range systems (DEFRA 2000). Free-range table chickens (or broilers) make up a very small proportion of the national total (Cottle & Cottle 1998). Free-range turkeys are produced as Traditional Farm Fresh (T.F.F.) turkeys for the Christmas market. Not all Traditional Farm Fresh turkeys are produced in a free-range system and Traditional Farm Fresh turkeys make up a small proportion of the national turkey flock (1.5 million turkeys) (NFU 2001). All geese produced in Britain are kept outdoors during daylight and are therefore effectively free-range. They tend to be kept on a fairly small-scale on mixed farms. As with geese, duck production is a minor section of the British poultry industry, but the majority of ducks are farmed intensively. Free-range egg producers are therefore the largest sector of the poultry industry for which fox predation is likely to be a problem. With increased consumer concern over animal welfare issues, there has been a marked growth in the free-range egg industry in Britain over the last twenty years (Roberts & Farrar 1993). This growth is likely to continue, with growth in the free-range turkey and chicken production industries also occurring.

Predation by foxes on poultry can potentially involve high losses because of the phenomenon of surplus killing, where a large number of birds are killed by the predator but not eaten (Kruuk 1972; White *et al.* 2000a; DEFRA 2001). Such actions also provoke anger in poultry holders because the killings are seen as senseless (Kolb 1996).

In a 1995 survey of Wiltshire farmers, more farmers reported losing chickens to foxes (42.0% of the sample) than lambs, gamebirds, pigs or other livestock (Baker & Macdonald 2000). However, the median flock size in this sample was 16 birds (out of a sample of 20), indicating that poultry were not kept on a commercial scale. The proportion of farmers that reported predation of free-range chickens by foxes in Heydon and Reynolds' (2000b) regional study varied from 48.8% to 77.8% for farmers with small flocks (less than 200 birds) according to region, with median reported losses varying from 0% to 25% of birds. Losses of up to 100% of the flock were reported. The median flock size in this sample was between 17 and 30 birds. The regional incidence of losses mirrored fox abundance, being lowest in west Norfolk, highest in the east Midlands and intermediate in mid-Wales (Macdonald *et al.* 2000). Only six producers with more than 1000 birds were surveyed and they reported much lower losses to foxes, from 0.1% to 6.0% of birds (Heydon & Reynolds 2000b).

The association between flock size and poultry losses to foxes has been put down to less adequate housing and fencing on small-scale holdings (McDonald *et al.* 1997; White *et al.* 2000a). Surplus killing may also be less likely to occur in open runs, from which losses to foxes may only be of single birds (McDonald *et al.* 1997), whilst on a large-scale unit the killing of a number of birds will be equivalent to the loss of only a small percentage of the total flock. In addition to killing birds, foxes may cause birds to become stressed, even if they are unable to physically reach them. Such stress can lead to smothering and trigger outbreaks of feather pecking (DEFRA 2001) and cause deterioration of the meat on the birds or reduce their egg-laying potential.

Because of the potential threat of fox predation, commercial poultry units tend to use exclusion fencing to prevent foxes from reaching their flocks (White *et al.* 2000a), as well as housing birds indoors at night. There are generally three types of fencing used: wire and post, wire mesh (often electrified, known as 'Flexinet') and strands of electrified wire, with combinations of these fence types also used. Fences may be permanent or mobile (in that they are easily erected and taken down). DEFRA (2001) indicate that flexible electric fencing should be adequate protection against most predators and that expensive permanent fencing substantial enough to exclude foxes is usually unnecessary.

Electric fences have been used to successfully protect birds of conservation interest from foxes (Forster 1975; Patterson 1977), as well as in protecting agricultural crops and livestock from other 'problem' mammals (McKillop & Silby 1988; Hoare 1992; Poole & McKillop 1999) and are most likely to be effective for populations concentrated in a small area (Reynolds & Tapper 1996; Chadwick *et al.* 1997). However, it appears that foxes may be able to breach electric fences (B.J. Yates, Reserve Warden, in Chadwick *et al.* 1997) and Patterson (1977) suggested that killing of individual foxes that learn to cross fences may be necessary or that 'novelty' in the fence design should be regularly implemented. Fences are costly not only in terms of initial outlay, but they must also be regularly maintained and in the case of electric fences require a reliable power supply (Artois 1997; DEFRA 2001). Foxes are not the only predators of poultry in Britain; stoats, mink and, sometimes, cats, dogs, badgers and birds of prey, e.g. Sommer and Vasicek (2000), such as buzzards, also kill poultry (DEFRA 2001). Stoats are extremely difficult to fence out reliably (Reynolds & Tapper 1996), whilst the types of exclosure fencing that it is practical for poultry producers to use can not prevent predation from the air. DEFRA (2001) indicate that the siting of units is an important influence on the likelihood of predation and suggest that range areas should not be sited close to thick cover, such as conifer plantations, as this encourages foxes.

There has been only one assessment of fox predation on poultry on a national scale that considered commercial sized units. It was considered that the top 30% most profitable free-range poultry units might suffer no losses to foxes at all, whilst with poor flock protection losses of up to 2% might occur (R. Kempsey, pers. comm., cited in McDonald *et al.* 1997). The costs of hen losses to all predators nationally in 1993 were calculated by multiplying up from estimates by a few experts (McDonald *et al.* 1997). They were put at a maximum of £195,000, between a ninth and a seventh of the estimated costs of natural mortality losses (£1.3 to £1.7 million) (McDonald *et al.* 1997), with an average loss per holding per year to all predation of approximately £557.14. The surveys of producers discussed above (Baker & Macdonald 2000; Heydon & Reynolds 2000b) involved very few commercial units and only considered the problem of perceived fox predation of poultry as part of a larger study.

This chapter aims to address this lack of research on fox predation of poultry. Four types of free-range poultry producers were surveyed across Britain to assess levels of fox predation, as well as husbandry methods and fencing used to prevent losses to foxes. These producer types were egg producers, turkey producers, goose producers and chicken producers. Duck producers were not considered, the free-range sector being a very minor component of the industry. Data from the surveys were used to investigate the factors influencing variation in fox predation between farms. Such an investigation is important for determining the most appropriate husbandry and preventive strategies for the management of fox predation of poultry. The hypothesis that there are associations between fox population density, fox control and poultry predation was also tested. In addition, the effectiveness of different types of fencing was assessed. The costs of fox predation to poultry producers were evaluated and analysed in the same framework as the costs to sheep producers in Chapter 3.

5.2. METHODS

5.2.1. Questionnaire surveys

Four separate questionnaire surveys of free-range poultry and egg producers were carried out between October 1999 and March 2000. These surveys targeted free-range turkey producers, goose producers, chicken producers and egg producers. The questionnaires consisted of questions on land-uses surrounding farms, husbandry, fencing, fox control, poultry or egg production and bird losses to predation and other causes. A number of questions were specific to the type of producer the questionnaire was aimed at (Appendix C). The questionnaires were designed to fit on two sides of a single A4 sheet of paper. All forms were sent out with an explanatory letter and Freepost reply envelope.

5.2.1.1. Chicken producers

Forty questionnaires were sent out by West Country Free Range Chicken to their growers in October 1999.

5.2.1.2. Turkey producers

Forty-two questionnaires were sent out by the Traditional Farmfresh Turkey Association to their members in October 1999. A further eleven questionnaires were sent to free-range producers from 'Who's Who in the British Turkey Industry' (NFU booklet). The survey followed consultation with several producers on the suitability of the questions. Non-respondents were telephoned in November 1999 to remind them about the survey and to ascertain any response bias.

5.2.1.3. Egg producers

One hundred and eighty questionnaires were sent out by the British Free Range Egg Producers Association to their members in March 2000. This survey followed a pilot survey of Council members of the British Free Range Egg Producers Association to assess suitability of questions and likely response rate.

5.2.1.4. Goose producers

Forty-four questionnaires were sent out to members of the British Goose Producers Association in January 2000. The survey followed a pilot of several producers to test the suitability of the questions. Non-respondents to the survey were sent a reminder letter and questionnaire in February 2000 and a further reminder in April 2000. Those for which a telephone number was available were contacted by telephone so any response bias would be picked up.

5.2.2. Relative fox population density estimates

Each farm in the data-set was allocated a region-based and a land class-based relative fox density estimate (as described in Section 2.2.3) (referred to as regional fox density and land class fox density, respectively, from here on), depending on the region in which the farm was situated and the land class of the Ordnance Survey 1-kilometre grid square in which the central farm buildings were located. Grid square references were identified for each farm with an available postcode using Matchcode 5 Webnet Demo (Capscan Ltd., London).

Non-parametric correlation analyses were used to test the associations between relative density estimates and the percentages of birds reported killed by foxes, the percentage of farms within each region and land class group reporting predation, as well as the number of foxes killed on farms.

5.2.3. Analyses

5.2.3.1. Temporal distribution of predation

Turkey and goose producers were asked in which months from June (when chicks or poults are generally bought) to December (when the birds are finished) fox predation occurred. Chi-square tests were used to assess whether predation was equally likely in all months or whether it had occurred more frequently in some months than others.

5.2.3.2. Effectiveness of fencing

Respondents were asked how effective the fence surrounding the area in which their birds were kept was in terms of i) preventing foxes from getting in, ii) preventing all unwanted animals from getting in and iii) preventing birds from escaping. There were three effectiveness levels available for each: i) ineffective (coded 0), ii) somewhat effective (coded 1) and iii) very effective (coded 2). It was hypothesised that there might be trade-offs between the effectiveness levels of fences at each of these functions. This hypothesis was tested by carrying out chi-square tests of association on the frequencies of the three effectiveness levels for each prevention function against the frequencies of effectiveness levels for each of the other prevention functions.

In order to test whether different fence types were considered more or less effective, two sets of chi-square tests were performed for each preventive function. The first tested whether there was a difference between the frequencies of each effectiveness level for each fence type and the frequencies that would be expected if effectiveness levels were assigned at random (i.e. all had equal frequencies) in order to ascertain whether the fence type was generally considered effective or ineffective at the function under consideration. The second tested whether there was a difference between the frequencies of each effectiveness level for each fence type and the overall frequencies of each effectiveness level for that preventive function in the sample, i.e. expected values were calculated to be in the same proportions as the sample frequencies. This tested whether the fence type was considered to be effective or ineffective at the function under consideration more or less often than other fence types.

5.2.3.3. Factors influencing reported fox predation of chickens

Sample sizes for individual producer types were considered too small to carry out regression analyses to assess whether certain factors were related to the reported occurrence of fox predation on a farm. In addition, geese and turkeys were considered to be too different in terms of their susceptibility to fox predation for these samples to be pooled. It was decided that the table chicken and laying hen samples could be pooled, however, as the prey species in question was the same.

Chi-square tests and logistic regression analyses were used to assess the associations between the occurrence of reported fox predation on a farm and other factors. Appendix D summarises the independent variables used in these analyses. The dependent variable in all logistic regression models was a binary response variable, coded zero for no reported fox predation on the farm and one for at least one bird having been reported lost to foxes. This variable was also used in the chi-square tests. Univariate analyses were used to determine initial relationships in the data and to identify the most significant variables for inclusion in an overall multiple logistic regression model. Chi-square tests were used for all analyses involving one other categorical variable and logistic regression for analyses using a continuous variable. The overall multiple logistic regression model included those variables that retained a significant relationship with the occurrence of perceived fox predation once the effects of other variables were included. These variables were also selected for not being associated with other variables in the analysis (to avoid multicollinearity) and for causing a decrease in the –2 log likelihood of the model on their inclusion. Variables that were not significant in univariate analyses were also tested in this multivariate approach to ensure that no important variables were missed out of the model.

Because of the high degree of variation in the number of chickens reported killed by foxes and the small sample size of the data, it was considered that assessing the factors that influenced variation in the scale of chicken predation would not produce useful results, nor expand on the conclusions of the logistic regression analyses.

5.2.4. Modelling the farmers' costs of poultry predation by foxes

5.2.4.1. Theoretical model

The theoretical model of Chapter 3 (Section 3.2), which was based on the hypothesis of a negative relationship between predation losses and expenditure on preventive measures, was used as a basis for analysing the costs of poultry predation by foxes to farmers. The preventive measure considered in this case was fencing surrounding poultry pasture. The primary function of fencing is preventing birds from escaping, but it is also used to prevent predation losses. If it is assumed that there is a necessary minimum basic level of fencing (and therefore expenditure on fencing), it can be hypothesised that any additional expenditure will improve the effectiveness of the fencing at preventing fox predation. Thus, there will be trade-off between how much should be spent on fencing and how much loss due to fox predation should be tolerated. This trade-off can be assessed in an economic framework to determine how much it is worthwhile for the farmer to spend on fencing. The aim of the farmer is assumed to be the minimisation of the total costs of predation plus preventive measures. Poultry loss to foxes (in monetary terms) is therefore assumed to be a function of expenditure on the preventive measure and various other characteristics of the farm, such as regional location:

$$Lb_i = f(MF_i, R_i)$$

where:

Lb_i = poultry loss to foxes per bird per year on the ith farm (£)
MF_i = expenditure on fencing per bird per year on the ith farm (£)
R_i = regional location of the ith farm
f = function of farm characteristics determining poultry losses

The relationship between poultry losses and preventive expenditure is assumed to be negative, with diminishing returns (in terms of reduced losses) to marginal expenditure increases, reflecting the assumed trade-off between these two costs, as outlined in Chapter 1 and by McInerney (1996) for the loss-expenditure frontier (Figure 1.1). So:

$$f' = \partial f/\partial MF_i < 0, \text{ and } f'' = \partial f'/\partial MF_i > 0.$$

The optimal point, where the total costs of fox predation ($Lb_i + MF_i$) are minimised, is where marginal poultry losses equal marginal preventive expenditure.

5.2.4.2. Valuation of the costs of poultry predation by foxes

Losses due to fox predation were evaluated in terms of output loss. The proportion of birds reported killed by foxes was used in each case as this gave a figure for losses relative to flock size. The points in the growing cycle at which birds were presumed killed by foxes were not available, as it was considered unlikely that producers would be willing or able to reliably provide information on this. Data were available for turkey and goose producers on the months in which birds were reported killed, but not the numbers reported killed in each case. Therefore, turkey, geese and chickens were valued as if killed at point-of-sale. Because the financial loss increases with the age of the bird up to the point-of-sale for chickens, turkeys and geese (Williams 1999), the output loss in terms of market price will tend to overvalue losses in financial terms unless they occur at point-of-sale (McInerney 1987). However, although values for (intensively reared) broiler chickens at different ages are available, those for other poultry are more difficult to estimate (Williams 1999).

For turkey producers, output losses were estimated as the proportion of birds killed multiplied by the price fetched by the producers for each bird or, if this was not given, by the returns for a medium size turkey from Nix (1999) at £15.34. For goose producers, output losses were estimated as the proportion of birds killed multiplied by the price fetched by the producers for each bird at Christmas or, if this was not given, by the mean price of a goose from the data (a deadweight price only is available in Nix (1999)). Michelmas goose sales were negligible in this sample and, in any case, prices did not differ greatly from those for Christmas birds. Output losses to chicken producers were estimated as the proportion of birds killed by foxes multiplied by the price received per chicken. The price was calculated from West Country Free Range Chicken literature as the base payment per bird (£0.316) plus the bonus received for reaching weight and feed conversion targets (£0.253) according to the percentage of birds in the flock that reached these.

Egg-laying hens differ from the other poultry considered here, in that the value of a hen, in terms of its egg-laying potential, decreases from point-of-lay to a value of zero at end-of-lay. (End-of-lay hens were often sold at cost in 2000, so they actually had a negative net value.) Although a producer loses all the potential eggs to be laid if a bird is killed at the start of the laying cycle, there will be savings for the producer in terms of resource costs for keeping the bird and these savings should be taken into account in valuing losses. Therefore, output losses due to predation for egg producers were calculated in terms of loss of eggs laid minus resource costs. Since losses could occur at any time in the laying cycle, it was considered that an average financial loss would lie between the output loss at the start- and end-of-lay, i.e. in mid-laying cycle. Such an approach was used by Williams (1999), in that he assumed losses of table chickens (broilers) to coccidiosis occurred at a mean age of 3 weeks.

The costs of eggs lost were calculated as the proportion of hens killed by foxes multiplied by the average number of eggs per hen housed per year, if given, or by the average free-range egg yield of 288 (Nix 1999) multiplied by the price per egg (calculated from the price per dozen given or as £0.67 per dozen (Nix 1999)). Egg prices will vary according to the type of outlet to which the producers supply their eggs. In this sample, 53 producers supplied their eggs to packing stations, 26 direct to consumers, 13 to retail outlets, 7 to wholesalers and 1 to another type of outlet (such as processors) [n = 57]; the majority of producers supplied more than one type of outlet. Given prices for eggs were marginally higher for producers that supplied to retailers than for those that supplied to packing stations, but other prices given by producers did not vary with supply outlet. The cost of feed was considered to be the only significant variable cost (Roberts & Farrar 1993; Nix 1999; Williams 1999). This was taken as given by producers and divided by the flock size, if available, or calculated from the mean price of feed per ton at £137 multiplied by the quantity of feed used per bird at 0.0472 tons (Nix 1999). In order to calculate the output loss at mid-laying cycle, the figures for loss of eggs laid and feed costs were divided by two prior to subtracting one from the other.

Producers were asked to assign a cost to the losses they experienced because of fox activity. In the case of turkeys and geese this was in terms of birds killed, as well as in terms of meat deterioration caused by stress in the last year, whilst for chickens costs were split into the same two categories but the time period considered was the last growing period. Egg producers were asked how much they considered foxes had cost them in terms of financial loss of eggs laid during the last laying cycle. Estimated values for losses due to fox predation were compared to the costs due to fox predation reported by respondents in correlation and paired t-tests in order to assess whether producer valuations of predation losses were accurate assessments of output loss.

5.2.4.3. Valuation of expenditure on fencing

The costs of fencing surrounding poultry pasture when first purchased were given by producers. These costs were converted to 1999 prices using the Retail Price Index (Nix 1999). These data were only available for those producers that gave both a cost of fencing and a year in which the fence was put up. Expenditure on fencing per year was calculated by dividing the purchase cost by the estimated life span of a fence (put at 10 years). Producers were also asked how much maintenance of their fence cost them per year and this was added to expenditure on fencing to obtain a total expenditure per annum figure. This expenditure per annum was divided by the number of birds on the holding over a year to obtain expenditure per bird. The number of birds on the holding in a year were taken as given for turkey, goose and egg producers (in each case only one flock of birds for growing or laying would be present on the holding in one year). For chickens, the total number of birds on the holding in a year was calculated as the number of birds at the start of the last growing period multiplied by the number of growing periods per year. Expenditure per bird on maintaining the fence only was also calculated.

To assess whether there was an association between expenditure on fencing and the occurrence of reported fox predation, both expenditure on fencing and expenditure on fence maintenance only were included separately in the best-fit logistic regression model explaining variation in the incidence of reported fox predation estimated for the chicken and egg producer data (Section 5.2.3.3).

5.2.4.4. Empirical estimation of the model

The relationship between poultry losses to foxes and expenditure on fencing was assumed to approximate to either a negative exponential or negative power relationship, as would be expected if there are diminishing returns to preventive effort. Separate modelling of the probability and scale of predation, as carried out in Chapters 3 and 4 was considered inappropriate for these data because of the small sample size. Therefore all data were included in one model. Because of the zeroes in both the poultry loss and expenditure on fencing data, a small positive constant was added to both to enable the variables to be logged. This constant was chosen according to the principles outlined in Section 3.3.4. Four possible forms were tested for the model:

a) Linear: $Lb_{il} = \beta_0 + \beta_1 MF_{il}$

b) Exponential: $Lb_{il} = \beta_0 \times e^{\beta_1 MF_{il}}$ i.e. $\ln(Lb_{il}) = \beta_0 + \beta_1 MF_{il}$

c) Logarithmic: $Lb_{il} = \beta_0 + \beta_1 \ln(MF_{il})$

d) Log-linear (power): $Lb_{il} = \beta_0 \times MF_{il}^{\beta_1}$ i.e. $\ln(Lb_{il}) = \beta_0 + \beta_1 \ln(MF_{il})$

where:

Lb_{il} = poultry loss to foxes per bird per year on the *i*th farm plus 0.001

MF_{il} = expenditure on fencing per bird per year on the *i*th farm plus 0.0001 or expenditure on fence maintenance per bird per year on the *i*th farm plus 0.0001

β_0 = constant

β_1 = coefficient for MF_{il}

These forms were tested using linear regression analyses for both total expenditure on fencing and expenditure on fence maintenance only. Dummy variables coding for producer type were also included in the models to account for variation between producer types.

In order to test for an association between expenditure on preventive measures and the effectiveness of fencing, Kruskal-Wallis tests were used to assess whether there was a difference in expenditure between effectiveness ratings. In each case, the test variable was expenditure on fencing and the grouping variable was the effectiveness rating according to the preventive task tested.

5.3. RESULTS

The data from 136 questionnaire forms were used in this analysis, of which 27 were from turkey producers, 27 from goose producers, 24 from chicken producers and 58 from egg producers. Additional to the forms from turkey producers used in the analysis, five were returned empty because the producers did not keep free-range turkeys, whilst one was not filled in because the respondent was unwilling to participate due to confidentiality issues, making the response rate of turkey producers 62.3%. Of non-respondents that were telephoned, four were not free-range, one had stopped keeping turkeys and one was unwilling to respond because of experiencing no losses to foxes. No other non-respondents gave a reason for non-response that could have biased the sample. A further six forms were returned from goose producers, of which one was an unwilling participant, three were breeding and hatchery farms and two had given up geese. The response rate of goose producers was 75.0%. Of those non-respondents for whom telephone numbers were available, two had not responded because they no longer kept geese (one because of predation by foxes and mink), whilst the majority did not give a reason for not responding that would cause a sample bias, one being unwilling to reply as they did not have a fox problem and had an electric fence for their cattle. The response rate amongst chicken producers was 60.0%, with no returns of empty forms. A further four egg producers to the 58 used in the analysis returned forms, giving a response rate of 34.4%. These forms were not used in the analysis in one case because the respondent was unwilling to participate, two because this was their first flock and one because the operation had closed down.

Not all respondents answered all the questions on the survey form (due to lack of knowledge on the subject covered or unwillingness to supply the information asked for). Therefore the sample sizes differ between analyses. These are indicated in square brackets in the text. All figures for statistics are quoted to 3 significant figures or 2 decimal places. Estimated Beta coefficients for independent variables in regression analyses are given as 'B'. Statistical significance was taken as being at the 95% level ($\alpha = 0.05$), i.e. $p < 0.05$.

The figures for reported losses of turkeys, geese and chickens to foxes, all predators (including foxes) and other causes are summarised in Tables 5.1 to 5.4. Bird mortality is given as the percentage of birds lost to that cause out of the total number of birds on the holding. In the case of turkeys and geese, this is the total number of birds in August (just after chicks have been bought in for growing), for table chickens, it is the average number of birds over the past year and for laying hens, the number at the beginning of the last laying cycle. The end date of the chicken growing periods varied between September and November 1999 (with a median date of 21/10/1999), whilst the end date of the laying periods under consideration varied from February 1999 to April 2000 (with a median of 29/12/1999).

Table chicken losses were provided for a growing period (with a mean of 8.0 weeks length) and laying hen losses for a laying period (which ranged from 45 to 72 weeks in length, with a mean of 54.1 weeks). Figures for mortality of chickens due to fox predation were standardised to the equivalent of a laying period (54 weeks) for ease of comparison (Table 5.3). In order to do this, percentage mortality figures were assumed to approximate the probability that fox predation of a particular bird on the farm would occur. The probability that a bird would not be predated upon by a fox during the growing cycle was calculated from the data for each farm. This probability was raised to the power of the number of growing cycles in 54 weeks to determine the probability of fox predation of that bird not occurring if a growing cycle were 54 weeks long. This figure was taken away from one to determine the probability of fox predation, which was converted back into a percentage mortality figure.

Mean reported bird mortality due to fox predation was below two per cent for all producers. However, there was a marked difference between producer types in the degree to which they reported experiencing fox predation and in what proportion of farms reported fox predation (Figures 5.1 and 5.2). Egg producers reported losing many birds to foxes compared to other producer types, whilst egg producers and goose producers on average lost the highest proportions of their total flocks.

Nearly half the respondents of all producer types (47.3%) thought the numbers of birds lost to foxes had not changed over the past five years, whilst 22.5% thought these losses had increased [n = 129]. Amongst turkey producers, birds were reported to have experienced stress due to fox activity a mean of 3.8 times and a median of 2.5 times in 1998 [n = 22]. Geese were reported to have experienced stress due to foxes 5.3 times on average in 1999, with a median of 3 times [n = 19] and chickens a mean of 0.4 times in the last growing period, with a median of zero [n = 19]. Egg producers reported that their birds had experienced stress due to fox activity in the last laying cycle a mean of 5.7 times and a median of once [n = 33].

There were differences both within and between producer types in the husbandry methods and fence types used (of those that were surveyed), as well as in fox control and farm characteristics, such as location and surroundings (Tables 5.5 and 5.6).

Table 5.1: Reported losses of turkeys in 1998 to fox predation, all predation, other causes and in total

Cause of mortality		Fox predation	All predation	Other causes	All causes
Number of turkeys reported died per farm	Mean (S.E.)	21.2 (9.9)	20.8 (9.6)	208 (77.5)	233 (86.9)
	Median	3	2.5	54	73
	Range	0-233	0-233	0 – 1550	0-1783
	n	25	26	22	22
Reported turkey mortality (%)	Mean (S.E.)	0.70 (0.40)	0.69 (0.38)	3.31 (0.51)	4.14 (0.67)
	Median	0.04	0.04	3.00	3.84
	Range	0-10.0	0-10.0	0 – 10.0	0-12.5
	n	25	26	22	22
Percentage of respondents reported no turkeys lost		48.0 [n = 25]	20.8 [n = 26]	9.1 [n = 22]	9.1 [n = 22]
Percentage of respondents reported more than 10 turkeys lost		28.0 [n = 25]	26.9 [n = 26]	90.9 [n = 22]	90.9 [n = 22]

Table 5.2: Reported losses of geese in 1999 to fox predation, all predation, other causes and in total

Cause of mortality		Fox predation	All predation	Other causes	All causes
Number of geese reported died per farm	Mean (S.E.)	12.8 (4.15)	13.7 (4.65)	19.6 (4.13)	30.0 (5.56)
	Median	4	4	12	23
	Range	0-92	0-100	0 – 70	0-100
	n	25	23	21	21
Reported goose mortality (%)	Mean (S.E.)	1.43 (0.37)	1.37 (0.39)	2.52 (0.34)	4.04 (0.50)
	Median	0.54	0.48	2.40	4.27
	Range	0-6.32	0-6.32	0 – 6.0	0-7.37
	n	24	21	19	19
Percentage of respondents reported no geese lost		32.0 [n = 25]	34.8 [n = 23]	4.8 [n = 21]	4.8 [n = 21]
Percentage of respondents reported more than 10 geese lost		32.0 [n = 25]	39.1 [n = 23]	57.1 [n = 21]	71.4 [n = 21]

Table 5.3: Reported losses of table chickens during last growing cycle to fox predation, all predation, other causes and in total. (Shading indicates probability of losses standardised to a period of 54 weeks.)

Cause of mortality		Fox predation		All predation	Other causes	All causes
Number of chickens reported died	Mean (S.E.)	2.73 (1.70)		10.4 (4.22)	347 (94.4)	357 (94.5)
	Median	0		2	258	258
	Range	0-35		0-91	0-1800	3-1801
	n	22		24	18	18
Reported chicken mortality (%)	Mean (S.E.)	0.02 (0.02)	0.17 (0.10)	0.08 (0.04)	2.61 (0.37)	2.69 (0.37)
	Median	0.00	0.00	0.01	2.63	2.68
	Range	0-0.32	0-2.13	0-0.80	0 – 5.91	0.01-5.96
	n	22		24	18	18
Percentage of respondents reported no chickens lost		77.3 [n = 22]		45.8 [n = 24]	5.6 [n = 18]	5.6 [n = 18]
Percentage of respondents reported more than 10 chickens lost		9.1 [n = 22]		25.0 [n = 24]	88.9 [n = 18]	94.4 [n = 18]

Table 5.4: Reported losses of laying hens during last laying cycle to fox predation, all predation, other causes and in total

Cause of mortality		Fox predation	All predation	Other causes	All causes
Number of hens reported died	Mean (S.E.)	169 (33.7)	170 (32.3)	772 (111)	955 (127)
	Median	75	80	500	650
	Range	0-1000	0-1000	0-2780	0-3247
	n	49	52	50	49
Reported hen mortality (%)	Mean (S.E.)	1.99 (0.41)	1.97 (0.40)	6.04 (0.67)	8.08 (0.90)
	Median	0.50	0.50	5.00	6.84
	Range	0-11.3	0-11.6	0 – 20.0	0-26.8
	n	50	53	51	50
Percentage of respondents reported no hens lost		22.4 [n = 49]	19.2 [n = 52]	2.0 [n = 50]	2.0 [n = 49]
Percentage of respondents reported more than 10 hens lost		73.5 [n = 49]	73.1 [n = 52]	94.0 [n = 50]	95.9 [n = 49]

Table 5.5: Percentage of poultry producer respondents with various factor levels for husbandry, fencing, farm surroundings, farm location, fox control and fox predation factors by producer type. Fox control and fox predation figures are for 1998 for turkey producers, 1999 for goose producers, 1998 and during the last growing period, respectively, for chicken producers and the last year and during the last laying cycle, respectively, for egg producers.

Factor	Factor levels	Producer type							
		Turkey		Goose		Chicken		Egg	
		Percentage of respondents (%)	N	Percentage of respondents (%)	N	Percentage of respondents (%)	N	Percentage of respondents (%)	N
Housing type	Fixed only	88.9	27	96.3	27	95.8	24	94.8	58
	Mobile only	0.0		3.7		4.2		1.7	
	Both	11.1		0.0		0.0		3.4	
Availability of housing	All times	88.9	27	40.7	27	100	24	98.3	58
	Night only	11.1		59.3		0.0		1.7	
Proportion of 24 hour day birds are outside	0-25%	14.8	27	0.0	26	13.6	22	0.0	58
	26-50%	51.9		30.8		77.3		44.8	
	51-75%	25.9		53.8		9.1		44.8	
	76-100%	7.4		15.4		0.0		10.3	
Fox control	Fox control carried out in last year	72.0	25	80.8	26	58.3	24	76.4	55
Fox predation	Fox predation reported to have occurred in last year	48.1	25	68	25	22.7	22	78.0	50

Table 5.5

		Turkey		Goose		Chicken		Egg	
Fence type	Permanent perimeter	77.8	27	92.6	27	79.2	24	96.6	58
	Mobile	22.2		0.0		20.8		8.6	
	Electric	33.3		37.0		70.8		72.4	
	Wire and post	44.4		59.3		41.7		37.9	
	Flexinet	48.1		7.4		41.7		32.8	
Effectiveness of fence at preventing foxes from getting into range area	Ineffective	22.2	27	28.0	25	8.3	24	22.4	58
	Somewhat effective	48.1		36.0		54.2		41.4	
	Very effective	29.6		36.0		37.5		36.2	
Effectiveness of fence at preventing all unwanted animals from getting into range area	Ineffective	7.7	26	33.3	24	8.3	24	13.8	58
	Somewhat effective	53.8		45.8		41.7		43.1	
	Very effective	38.5		20.8		50.0		43.1	
Effectiveness of fence at preventing birds from escaping	Ineffective	7.4	27	0	25	20.8	24	8.8	58
	Somewhat effective	59.3		4.0		50.0		42.1	
	Very effective	33.3		96.0		29.2		49.1	
Land class group (as Table 2.4)	1	3.7	27	18.5	27	4.5	22	20.4	49
	2	63.0		44.4		0		34.7	
	4	25.9		22.2		95.5		28.6	
	5	7.4		14.8		0		14.3	
	6	0		0		0		2.0	

Table 5.5

		Turkey		Goose		Chicken		Egg	
Region in which farm is situated (as Table 2.1)	Southwest	7.4	27	14.8	27	100	24	28.6	56
	Southeast	22.2		7.4		0		14.3	
	South	18.5		11.1		0		17.9	
	Anglia	33.3		25.9		0		10.7	
	Midlands	11.1		18.5		0		10.7	
	Northeast	3.7		3.7		0		8.9	
	Northwest	3.7		7.4		0		3.6	
	Wales	0		11.1		0		5.4	
Land uses surrounding farm	Arable	100	26	75.0	24	79.2	24	68.4	57
	Livestock	50.0		87.5		95.8		66.7	
	Game rearing	12.0		8.3		12.5		17.5	
	Forestry	31.0		29.2		41.7		42.1	
	Village	42.3		41.7		16.7		22.8	
	Urban	11.1		4.2		4.2		3.5	

Table 5.6: Summary statistics on flock size and foxes killed for poultry producers by producer type. Flock size is that in August 1998 for turkey producers, August 1999 for goose producers, on average in 1998 for chicken producers and at the start of the last laying cycle for egg producers. The 'last year' is 1998 for turkey producers and 1999 for goose producers.

Variable		**Producer type**			
		Turkey	**Goose**	**Chicken**	**Egg**
Flock size	Mean (S.E.)	4380 (880)	887 (139)	16508 (3021)	16780 (2750)
	Median	3000	700	11200	11000
	Range	300-16000	30-2500	5500-61000	35-130000
	n	27	24	24	55
Number of foxes killed on farm in last year	Mean (S.E.)	4.88 (1.29)	7.42 (1.81)	3.63 (0.95)	12.1 (4.04)
	Median	4	4	2.5	3
	Range	0-30	0-30	0-18	0-208
	n	27	26	24	24

5.3.1. Relative fox population density estimates

Land class fox density was negatively correlated with both the percentage ($r_s = -0.247$, $p = 0.009$ [$n = 111$]) and number ($r_s = -0.198$, $p = 0.037$ [$n = 111$]) of birds out of the total flock reported killed by foxes. There were no statistically significant associations between regional fox density and either the number ($r_s = -0.097$, $p = 0.295$ [$n = 119$]) or percentage ($r_s = -0.109$, $p = 0.239$ [$n = 119$]) of birds reported killed by foxes. The percentage of respondents reporting fox predation of birds in each land class group was not associated with land class fox density ($r_s = -0.100$, $p = 0.873$ [$n = 5$]), nor was the percentage of respondents reporting predation in each region associated with regional fox density ($r_s = 0.000$, $p = 1.000$ [$n = 7$]). The number of foxes killed on farms was not associated with either land class ($r_s = -0.054$, $p = 0.561$ [$n = 119$]) or regional fox density ($r_s = -0.069$, $p = 0.436$ [$n = 128$]).

Because of the differences in reported fox predation between producer types, these associations were also tested separately for each producer type, with the exception of chicken producers, as they were only from one region and two land class groups. Neither land class nor regional fox density were associated with the number or percentage of birds killed by foxes or with the number of foxes killed for any producer type (Table 5.7). Land class fox density was not associated with the percentage of turkey producers ($r_s = -0.800$, $p = 0.200$ [$n = 4$]), goose producers ($r_s = 0.800$, $p = 0.200$ [$n = 4$]) or egg producers ($r_s = 0.051$, $p = 0.935$ [$n = 5$]) reporting fox predation in each land class group, nor was regional fox density associated with the percentage of turkey producers ($r_s = 0.698$, $p = 0.123$ [$n = 6$]), goose producers ($r_s = 0.385$, $p = 0.393$ [$n = 7$]) or egg producers ($r_s = -0.091$, $p = 0.846$ [$n = 7$]) reporting fox predation in each region.

Table 5.7: Spearman's rank correlation associations between land class and regional fox density and the percentage and number of birds reported killed by foxes and the number of foxes killed on farms in the last year by poultry producer type

Relative fox density	**Variable association tested with**	**Producer type**								
		Turkey			**Goose**			**Egg**		
		r_s	p	n	r_s	p	n	r_s	p	n
Land class	Number of birds reported killed by foxes	-0.015	0.944	25	-0.096	0.646	25	-0.085	0.601	40
	Percentage of birds reported killed by foxes	-0.043	0.838	25	-0.184	0.390	24	-0.104	0.518	41
	Number of foxes killed on farm in last year	0.277	0.181	25	-0.300	0.136	26	-0.021	0.891	46
Regional	Number of birds reported killed by foxes	0.123	0.559	25	0.269	0.194	25	0.020	0.891	47
	Percentage of birds reported killed by foxes	0.085	0.686	25	0.249	0.240	24	0.026	0.861	48
	Number of foxes killed on farm in last year	0.000	0.998	25	0.098	0.633	26	-0.036	0.798	53

5.3.2. Temporal distribution of predation

Turkey and goose predation incidences were reported by at least one of the surveyed producers in every month between June and December (Figure 5.3). Chi-square tests revealed no significant differences between the frequencies of occurrence of reported predation between months for either turkeys ($\chi^2 = 8.29$, d.f. = 6, $p > 0.10$ [n = 25]) or geese ($\chi^2 = 6.5$, d.f. = 6, $p > 0.10$ [n = 25]). However, it should be noted that the chi-square test is not wholly appropriate for these data, as more than 20% of the expected values in each case were less than 5. Amalgamating cells by combining months together was considered inappropriate. The results would be highly dependent on which months were put together and it appeared from visual examination of contingency tables that there were no large differences between months in the frequency of reported predation. Losses of turkeys were slightly more likely to have been reported as occurring in October and November.

5.3.3. Effectiveness of fencing

Respondents classified the fences surrounding the areas on which their birds were kept as electric, Flexinet and/or wire and post and a large proportion of producers (44.9%) used combinations of these fence types [n = 136]. For analysis, three dummy variables were used, which were coded one for respondents with each type of fencing (electric, Flexinet and wire and post fencing). Thus producers might be coded one for more than one variable, if they used more than one fence type. A further three dummies were used to distinguish those producers that used one type of fencing only. These were coded one for producers with electric fencing only, Flexinet fencing only or wire and post fencing only. 57.4% of producers had electric fencing, 32.4% Flexinet, 44.1% wire and post, 23.5% electric only, 13.2% Flexinet only and 18.4% wire and post only [n = 136].

Chi-square tests of association for the effectiveness levels of fences at different functions revealed that there was a significant association between effectiveness levels for preventing entry of foxes and for preventing entry of unwanted animals ($\chi^2 = 79.2$, d.f. = 4, $p < 0.001$ [n = 132]). There was also an indication of an association between effectiveness levels for preventing entry of unwanted animals and preventing escapees ($\chi^2 = 9.25$, d.f. = 4, $p = 0.055$ [n = 131]), but not between those for preventing entry of foxes and escapees ($\chi^2 = 4.95$, d.f. = 4, $p > 0.10$ [n = 133]). However, it should be noted that 22.2% of cells had an expected value of less than 5 for the test of association between effectiveness at preventing entry of unwanted animals and escapees. In any case, it appeared that rather than there being a trade-off between the effectiveness of fences at different functions, effectiveness levels tended to be associated with one another for different functions, i.e. a fence that was considered effective at one function tended to be considered effective at others too, the opposite also being the case.

5.3.3.1. Effectiveness at preventing entry of foxes

Out of all poultry producer respondents to the relevant question, 20.9% reported their fence to be ineffective at preventing foxes from entering the area in which birds were kept, 44.0% reported their fence to be somewhat effective at this job and 35.1% reported it to be very effective at achieving this [n = 134]. Respondents with electric and with Flexinet fencing were more likely to have reported their fences to be effective at preventing entry of foxes than would be expected by chance (Table 5.8). Those with wire and post fences only reported their fences as being ineffective significantly more often than those with other fence types (Table 5.9). If the level of statistical significance was relaxed from 5% to 10% further trends in the data were revealed, with more respondents with wire and post fences only reporting their fences to be ineffective at preventing fox entry than would be expected by chance (Table 5.8) and more respondents with electric and Flexinet fencing than those with other fence types reporting their fences to be being effective at preventing the entry of foxes (Table 5.9).

5.3.3.2. Effectiveness at preventing entry of unwanted animals

Out of all the respondents to the relevant question, 15.2% reported that their fence was ineffective at preventing all unwanted animals from entering the area in which birds were kept, 45.5% reported that their fence was somewhat effective at this job and 39.4% that it was very effective at achieving this [n = 132]. As was the case for preventing the entry of foxes, both respondents with electric and Flexinet fences were significantly more likely to report their fences as being effective than would be expected by chance (Table 5.10). However the frequencies of the three fence effectiveness levels reported by respondents with these fence types did not differ from those of the overall sample (Table 5.11). A higher proportion of respondents with wire and post fences reported their fences as being ineffective at preventing the entry of all unwanted animals than did those in the sample overall (Table 5.11).

5.3.3.3. Effectiveness at preventing escapees

Of respondents to the relevant question, 9.0% reported that their fence was ineffective at preventing birds from escaping, 39.8% reported that their fence was somewhat effective at doing this and 51.1% that it was very effective at this [n = 133]. With the exception of respondents with Flexinet fencing only, a significantly higher proportion of respondents reported their fences as being somewhat or very effective at preventing birds from escaping than would be expected by chance (Table 5.12). The frequencies of fence effectiveness levels reported by respondents did not differ from those of the rest of the sample for any of the tested fence types (Table 5.13).

Table 5.8: Observed and expected frequencies of fence effectiveness ratings for preventing foxes from entering areas where birds were kept for tested fence types and chi-square test statistics for associations between frequencies, with equal expected frequencies for each rating

Fence type	**N**	**Observed or Expected Frequencies**	**Fence effectiveness rating**			χ^2	**d.f.**	**p**
			0	**1**	**2**			
Electric	78	Observed	8	37	33	19.0	2	<0.001
		Expected	26	26	26			
Flexinet	44	Observed	3	24	17	15.6	2	<0.001
		Expected	14.7	14.7	14.7			
Wire and post	60	Observed	18	23	19	0.70	2	>0.10
		Expected	20	20	20			
Electric only	32	Observed	3	16	13	8.69	2	0.013
		Expected	10.7	10.7	10.7			
Flexinet only	18	Observed	2	9	7	4.33	2	>0.10
		Expected	6	6	6			
Wire and post only	25	Observed	13	8	4	4.88	2	0.087
		Expected	8.3	8.3	8.3			

Table 5.9: Observed and expected frequencies of fence effectiveness ratings for preventing foxes from entering areas where birds were kept for tested fence types and chi-square test statistics for associations between frequencies, with expected frequencies for each rating proportionate to those of the total sample

Fence type	N	Observed or Expected Frequencies	Fence effectiveness rating			χ^2	d.f.	p
			0	1	2			
Electric	78	Observed	8	37	33	5.59	2	0.061
		Expected	16.3	34.3	27.4			
Flexinet	44	Observed	3	24	17	5.44	2	0.066
		Expected	9.2	19.4	15.4			
Wire and post	60	Observed	18	23	19	3.02	2	>0.10
		Expected	12.5	26.4	21.0			
Electric only	32	Observed	3	16	13	2.57	2	>0.10
		Expected	6.7	14.1	11.2			
Flexinet only	18	Observed	2	9	7	1.05	2	>0.10
		Expected	3.8	7.9	6.3			
Wire and post only	25	Observed	13	8	4	15.0	2	<0.001
		Expected	5.2	11.0	8.8			

Table 5.10: Observed and expected frequencies of fence effectiveness ratings for preventing all unwanted animals from entering areas where birds were kept for tested fence types and chi-square test statistics for associations between frequencies, with equal expected frequencies for each rating

Fence type	N	Observed or Expected Frequencies	Fence effectiveness rating			χ^2	d.f.	p
			0	1	2			
Electric	77	Observed	9	34	34	16.2	2	<0.001
		Expected	25.7	25.7	25.7			
Flexinet	44	Observed	3	25	16	16.7	2	<0.001
		Expected	14.7	14.7	14.7			
Wire and post	59	Observed	12	24	23	4.51	2	0.105
		Expected	19.7	19.7	19.7			
Electric only	31	Observed	5	11	15	4.90	2	0.086
		Expected	10.3	10.3	10.3			
Flexinet only	18	Observed	1	9	8	6.33	2	0.042
		Expected	6	6	6			
Wire and post only	24	Observed	10	9	5	1.75	2	0.417
		Expected	8	8	8			

Table 5.11: Observed and expected frequencies of fence effectiveness ratings for preventing all unwanted animals from entering areas where birds were kept for tested fence types and chi-square test statistics for associations between frequencies, with expected frequencies for each rating proportionate to those of the total sample

Fence type	**N**	**Observed or Expected Frequencies**	**Fence effectiveness rating**			χ^2	**d.f.**	**p**
			0	**1**	**2**			
Electric	77	Observed	9	34	34	1.8	2	>0.10
		Expected	11.7	35	30.3			
Flexinet	44	Observed	3	25	16	1.35	2	>0.10
		Expected	6.7	20	17.3			
Wire and post	59	Observed	12	24	23	3.37	2	>0.10
		Expected	9	26.8	23.2			
Electric only	31	Observed	5	11	15	1.33	2	>0.10
		Expected	4.7	14.1	12.2			
Flexinet only	18	Observed	1	9	8	1.29	2	>0.10
		Expected	2.7	8.2	7.1			
Wire and post only	24	Observed	10	9	5	13.6	2	<0.001
		Expected	3.6	10.9	9.5			

Table 5.12: Observed and expected frequencies of fence effectiveness ratings for preventing birds from escaping for tested fence types and chi-square test statistics for associations between frequencies, with equal expected frequencies for each rating

Fence type	N	**Observed or Expected Frequencies**	**Fence effectiveness rating**			χ^2	**d.f.**	**p**
			0	**1**	**2**			
Electric	77	Observed	8	33	36	18.4	2	<0.001
		Expected	25.7	25.7	25.7			
Flexinet	44	Observed	4	23	17	12.9	2	0.002
		Expected	14.7	14.7	14.7			
Wire and post	60	Observed	4	24	32	20.8	2	<0.001
		Expected	20	20	20			
Electric only	31	Observed	4	10	17	8.19	2	0.017
		Expected	10.3	10.3	10.3			
Flexinet only	18	Observed	2	8	8	4.00	2	>0.10
		Expected	6	6	6			
Wire and post only	25	Observed	1	10	14	10.6	2	0.005
		Expected	8.3	8.3	8.3			

Table 5.13: Observed and expected frequencies of fence effectiveness ratings for preventing birds from escaping for tested fence types and chi-square test statistics for associations between frequencies, with expected frequencies for each rating proportionate to those of the total sample

Fence type	N	Observed or Expected Frequencies	Fence effectiveness rating			χ^2	d.f.	p
			0	1	2			
Electric	77	Observed	8	33	36	0.62	2	>0.10
		Expected	6.9	30.6	39.3			
Flexinet	44	Observed	4	23	17	3.05	2	>0.10
		Expected	4	17.5	22.5			
Wire and post	60	Observed	4	24	32	0.43	2	>0.10
		Expected	5.4	23.9	30.7			
Electric only	31	Observed	4	10	17	1.05	2	>0.10
		Expected	2.8	12.3	15.8			
Flexinet only	18	Observed	2	8	8	0.34	2	>0.10
		Expected	1.6	7.2	9.2			
Wire and post only	25	Observed	1	10	14	0.82	2	>0.10
		Expected	2.3	10	12.7			

5.3.4. Factors influencing reported fox predation of chickens

5.3.4.1. Univariate analyses

Few of the factors considered were statistically significantly related to the occurrence of reported fox predation. The coefficient estimates and significance test results of continuous variables that were significant are given in Table 5.14. Only two categorical variables were significantly associated with the likelihood of fox predation, tested with chi-square tests of association. Egg producers reported experiencing predation more often than expected (and chicken producers significantly less often) ($\chi^2 = 19.6$, d.f. = 1, $p < 0.001$ [n = 72]). A higher than expected number of producers that reported experiencing fox predation also carried out fox control, whilst a higher than expected number that reported experiencing no predation did not carry out fox control ($\chi^2 = 12.4$, d.f. = 1, $p < 0.001$ [n = 69]).

Table 5.14: Coefficient estimates and significance test statistics for variables that were significantly related to the occurrence of reported fox predation of chickens in univariate logistic regression analyses

Variable	B	Wald	p	n
Range area	0.130	10.4	0.001	71
Stocking density	-0.0003	12.1	0.001	69
Number of chickens reported lost to causes other than predation (square-root transformed)	0.050	4.68	0.030	61
Number of foxes killed on farm in last year	0.094	4.184	0.041	69
Regional fox density	-1.93	13.6	<0.001	70
Land class fox density	-3.83	6.37	0.012	62

5.3.4.2. Overall logistic regression model

The associations between the dependent variable and range area, stocking density, number of foxes killed, regional and land class fox density were no longer significant when the dummy variable coding for egg producers was included in a logistic regression model with them. These associations were a result of the differences between the chicken producers and egg producers surveyed. Egg producers tended to have larger range areas than chicken producers: the mean range area for egg producers was 18.9 hectares (S.E. = 2.95) [n = 58] and the mean for chicken producers 2.33

hectares (S.E. = 0.74) [n = 23]. However, egg producers tended to have lower stocking densities of birds than chicken producers: the mean number of chickens per hectare amongst egg producers was 945 (S.E. = 52.1) [n = 55], whilst the mean for chicken producers was 9281 (S.E. = 52.1) [n = 24]. Egg producers tended to have killed more foxes on their farm than chicken producers (Table 5.6). All chicken producers were in the Southwest region of England and therefore had the same relative fox density estimate of 1.52 scats per kilometre square, the highest of the estimates, whilst 95.5% of chicken producers were in Ordnance Survey grid squares of land class group 4 (Table 5.5) with a land class-based relative density estimate of 0.833, the second highest of the estimates. Because of the strong association between occurrence of predation and being an egg producer, all other independent variables were re-tested in a logistic regression model with 'egg' also included as a dummy to ensure that any relationships had not been missed. No further associations with the dependent variable were found.

The overall model estimated for the occurrence of fox predation of chickens included the dummy variable for egg producers, the dummy for fox control being carried out and the number of chickens reported lost to causes other than predation (square root-transformed) and had a predictive accuracy of 79.3% (-2 log likelihood of fitted model = 47.4, $\chi^2 = 28.5$, d.f. = 3, $p < 0.001$ [n = 58]) (Table 5.15). The model correctly predicted predation on 83.8% of the farms where fox predation had occurred. Farms that reported losing more chickens to causes other than predation were more likely to have reported fox predation, as were farms that carried out fox control and those that were egg producers.

Table 5.15: Coefficient estimates and significance test statistics for overall logistic regression model describing variation in the occurrence of reported fox predation of chickens between farms

Variable	**B**	**Wald**	**p**
Constant	-3.05	10.6	0.001
Producer is egg producer	2.26	8.62	0.003
Fox control carried out	1.92	5.29	0.021
Number of chickens reported lost to causes other than predation (square root-transformed)	0.063	3.84	0.050

5.3.5. Modelling the farmers' costs of poultry predation by foxes

The reported costs of fox predation were highest per bird for geese, mainly because each bird was valued higher than any of the other poultry types (Table 5.16). There appeared to be no association between the reported value of one bird killed by foxes and the month in which the bird was killed for turkey and goose producers. Both turkey and goose producers reported additional costs in terms of meat deterioration caused by stressing of birds by foxes but none of the chicken producers assigned any cost to stress caused by foxes. Table 5.16 gives summary statistics for both reported and estimated costs of fox predation. Whilst reported costs for turkey and goose producers were similar to output loss estimates at low cost levels (i.e. when few birds had been taken), they tended to be lower than output losses at high cost levels (Figures 5.4 and 5.5). Costs reported by turkey producers were highly correlated with estimated output loss ($r = 0.879$, $p < 0.001$ [$n = 24$]) and paired sample t-tests indicated that both costs were similar ($t = 1.53$, $p = 0.139$). Costs reported by goose producers were also highly correlated with estimated output loss ($r = 0.906$, $p < 0.001$ [$n = 21$]) and similar to output loss ($t = 1.88$, $p = 0.074$), although the lack of a difference between reported costs and output loss was less convincing than for turkey producers ($p < 0.10$).

Reported costs of losses due to fox predation from egg producers tended to be somewhere between losses estimated at point-of-lay and those estimated for mid-laying cycle, with valuations at mid-cycle being greater than reported losses at high cost levels (Figure 5.6). Whilst reported costs were correlated with both point-of-lay and mid-laying cycle output losses ($r = 0.613$, $p < 0.001$ [$n = 36$] for both), paired t-tests indicated that it was the mid-laying cycle estimates that these reported costs were similar to ($t = 0.126$, $p = 0.901$) and that they were significantly lower than point-of-lay output loss ($t = 2.64$, $p = 0.012$). The estimated output losses for mid-laying cycle were exactly half those at point-of-lay. A figure for estimated versus reported costs is not shown for chicken producers because only six producers considered their losses to foxes cost anything [$n = 19$]. Chicken producers tended to report costs to fox predation that were similar to estimated output losses ($r = 0.996$, $p < 0.001$, $t = -0.010$, $p = 0.992$ [$n = 18$]; those producers that reported costs only: $r = 0.995$, $p < 0.001$, $t = -0.009$, $p = 0.993$ [$n = 5$]).

Although the reported costs of predation were generally similar to estimated costs, estimated costs were used in the subsequent model estimation because it was not known what had been included in the producers' own assessments and because their value appeared to decrease with increases in losses. A standard method of valuing costs was therefore considered more appropriate than using reported figures.

Goose producers tended to spend more on their fencing per bird than other producer types, whilst expenditure on fence maintenance per year was on average also greater for these producers (Table 5.17). Chicken producers spent the least on their fencing per bird (Table 5.17). Figures 5.7 and 5.8 show expenditure on fencing compared to loss due to foxes. Output losses due to foxes are given at mid-laying cycle for egg-laying hens. There were two outliers in the data with expenditure on fencing per bird of greater than £1.00, so only expenditure figures of less than £1.00 are plotted. No obvious relationship is apparent between losses and expenditure for either reported or estimated losses, nor if the maintenance expenditure on the fence per year is considered only. However, there does appear to be some reduction in the variability of losses with increasing expenditure on fence maintenance.

Neither expenditure on fencing per bird per annum nor expenditure on fence maintenance only per bird per annum (untransformed or logged) were significantly associated with the occurrence of predation for chicken and egg producers only when included in the logistic regression model estimated in Section 5.3.4.2. The same was true when each was included in a logistic regression model with the dummy variable coding for whether producers were egg producers and the same dependent variable. There were indications of a positive association between expenditure on fence maintenance (log-transformed) and the occurrence of reported fox predation ($B = 0.330$, Wald $= 3.63$, $p = 0.057$ [$n = 50$]).

Table 5.16: Summary statistics for the reported costs of fox kills, stress and the reported value of one bird killed by a fox and for estimated output losses due to fox predation for each poultry producer type

Producer type	Variable	N	Mean	Median	Range
Turkey	Reported cost of fox kills per bird (£)	26	0.052	0.003	0-0.333
	Reported cost of fox kills and stress per bird (£)	23	0.122	0.090	0-0.533
	Reported value of one bird killed by foxes (£)	12	16.75	19.62	1-31.25
	Estimated output loss due to fox predation per bird (£)	25	0.147	0.009	0-2.00
Goose	Reported cost of fox kills per bird (£)	23	0.326	0.073	0-0.950
	Reported cost of fox kills and stress per bird (£)	13	0.557	0.438	0-1.80
	Reported value of one bird killed by foxes (£)	16	28.75	23.11	5.71-75.00
	Estimated output loss due to fox predation per bird (£)	23	0.440	0.165	0-1.84
Chicken	Reported cost of fox kills per bird (£)	19	0.000	0.000	0-0.020
	Reported cost of fox kills and stress per bird (£)	17	0.000	0.000	0-0.002
	Reported value of one bird killed by foxes (£)	5	0.614	0.500	0.50-1.00
	Estimated output loss due to fox predation per bird (£)	22	0.000	0.000	0-0.002
Egg	Reported cost of losses per bird (£)	42	0.117	0.025	0-0.690
	Reported value of one bird killed by foxes (£)	31	6.86	6.00	0-20.00
	Estimated output loss due to fox predation per bird at start-of-lay (£)	44	0.241	0.050	0-1.50
	Estimated output loss due to fox predation per bird mid-laying cycle (£)	44	0.121	0.025	0-0.75

Table 5.17: Summary statistics for expenditure on fencing per bird per year and for expenditure on fence maintenance per bird per year for each poultry producer type

Producer type	Variable	N	Mean	Median	Range
Turkey	Expenditure on fencing per bird (£)	15	0.076	0.026	0-0.48
	Expenditure on fence maintenance per bird (£)	23	0.055	0.020	0-0.33
Goose	Expenditure on fencing per bird (£)	10	0.323	0.208	0.07-1.13
	Expenditure on fence maintenance per bird (£)	12	0.124	0.087	0.03-0.37
Chicken	Expenditure on fencing per bird (£)	14	0.024	0.011	0-0.149
	Expenditure on fence maintenance per bird (£)	15	0.001	0.000	0-0.003
Egg	Expenditure on fencing per bird (£)	39	0.189	0.053	0.003-5.04
	Expenditure on fence maintenance per bird (£)	43	0.026	0.01	0-0.222

5.3.5.1. Empirical estimation of model

Table 5.18 gives a summary of the results of regression analyses testing the form of the relationship between poultry losses and expenditure on fencing. The poultry output loss is taken as the mid-laying cycle figure for laying hens (assumed to provide the most accurate estimate of losses). Expenditure on fencing did not have a coefficient that differed significantly from zero ($p < 0.05$) in any of the models estimated. The lowest p-value for expenditure on fencing was $p = 0.080$ for expenditure on fence maintenance (MFx_{i1}) in the model estimating a power function (log-linear) ($\ln(Lb_{i1}) = B_0 + B_1\ln(MFx_{i1}) + B_2Egg_i + B_3Gs_i + B_4Tk_i$), where the coefficient was a positive figure. There were no obvious outliers that could have affected the estimation of a negative relationship between poultry losses and fencing expenditure.

There was no difference in expenditure on fencing or fence maintenance between effectiveness ratings for preventing entry of foxes, tested using Kruskal-Wallis analysis of variance ($\chi^2 = 2.15$, d.f. = 2 $p > 0.10$ [n = 78] and $\chi^2 = 0.97$, d.f. = 2 $p > 0.10$ [n = 93], respectively) or between the ratings for preventing escapees ($\chi^2 = 0.31$, d.f. = 2 p >

0.10 [n = 78] and $\chi^2 = 0.12$, d.f. = 2 $p > 0.10$ [n = 93], respectively). However, there was a difference in expenditure on fencing between effectiveness levels at preventing entry of unwanted animals that was close to statistical significance ($\chi^2 = 5.61$, d.f. = 2 p = 0.061 [n = 77]). This suggested that higher expenditure on fencing was associated with lower levels of effectiveness (mean rank for rating of 0 = 56.4, mean rank for rating of 1 = 35.8, mean rank for rating of 2 = 38.3). This was not the case for expenditure on fence maintenance ($\chi^2 = 2.20$, d.f. = 2 $p > 0.10$ [n = 92]).

Table 5.18: Coefficient estimates and adjusted R^2 values for regression models estimated for relationship between poultry losses to foxes and expenditure on fencing, where Lb_{il} = poultry output losses to foxes per bird per year on the ith farm plus 0.001, MF_{il} = expenditure on fencing per bird per year on the ith farm plus 0.0001, MFx_{il} = expenditure on fence maintenance per bird per year on the ith farm plus 0.0001, Egg_i = dummy variable coding for egg producers, Gs_i = dummy variable coding for goose producers, Tk_i = dummy variable coding for turkey producers and * indicates $p < 0.05$ and ** indicates $p < 0.01$

Model form	**B_0**	**B_1**	**B_2**	**B_3**	**B_4**	**n**	**Adj. R^2**
$Lb_{il} = B_0 + B_1 MF_{il} + B_2 Egg_i + B_3 Gs_i$	0.044	-0.031	0.102	0.496**		68	0.22
$Lb_{il} = B_0 + B_1 MFx_{il} + B_2 Egg_i + B_3 Gs_i$	0.060	-0.331	0.080	0.478**		80	0.21
$\ln(Lb_{il}) = B_0 + B_1 MF_{il} + B_2 Egg_i + B_3 Gs_i + B_4 Tk_i$	-6.77**	-0.599	3.52**	5.29**	2.53**	68	0.36
$\ln(Lb_{il}) = B_0 + B_1 MFx_{il} + B_2 Egg_i + B_3 Gs_i + B_4 Tk_i$	-6.80**	0.028	3.39**	5.09**	2.25**	80	0.33
$Lb_{il} = B_0 + B_1 \ln(MF_{il}) + B_2 Egg_i + B_3 Gs_i$	0.081	0.010	0.088	0.464**		68	0.22
$Lb_{il} = B_0 + B_1 \ln(MFx_{il}) + B_2 Egg_i + B_3 Gs_i$	0.064	0.003	0.080	0.436**		80	0.21
$\ln(Lb_{il}) = B_0 + B_1 \ln(MF_{il}) + B_2 Egg_i + B_3 Gs_i + B_4 Tk_i$	-6.14**	0.145	3.19**	4.69**	2.35**	68	0.34
$\ln(Lb_{il}) = B_0 + B_1 \ln(MFx_{il}) + B_2 Egg_i + B_3 Gs_i + B_4 Tk_i$	-5.33**	0.188	2.86**	4.06**	1.68*	80	0.36

5.4. DISCUSSION

5.4.1. Data reliability

As was the case for the accuracy of data from the survey of sheep farmers discussed in Chapter 2 (Section 2.4.1.1), there is likely to have been some over-estimation of poultry losses by respondents to these surveys. One reason for this is that it is difficult to establish what has killed birds, especially as a number of predator species could be implicated.

Perhaps a more important issue relating to the reliability of these data is that of self-selection and non-response error in survey samples (Oppenheim 1992). The follow-ups of goose and turkey producer non-respondents did not reveal an evident response bias in these samples. However, such follow-ups were not possible for the chicken and egg producers due to data confidentiality issues. The response rate was fairly high for chicken producers at 60%, which reduces the level of likely response bias. However, that for egg producers was lower at 34% (such a percentage response is to be expected for a mail survey with no follow-up (Barnett 1991)) and the existence of response bias in this sample can not be ruled out. The existence of such a bias may be a reason why egg producers reported experiencing fox predation more than other producer types. Although it was pointed out in the covering letter sent with the questionnaires that producers without a 'fox problem' should also fill in the form, such producers would have been less likely to consider the study relevant or of use to them and therefore would be less likely to respond. However, Packer and Birks (1999) state that surveys conducted by ADAS indicate that the presumption that self-selection of respondents, who only reply because of a positive interest in the subject, occurs is unfounded and there is no reason to suspect that views of non-respondents differ from those that do reply. In any case, for this study, although it is still valid to compare differences between farms in whether reported fox predation occurred, differences may occur simply because of the lack of respondents with particular characteristics in one group, whilst this may not be the case in the overall population. This is especially likely when the sample is small.

Because this is the first large-scale investigation of fox predation on free-range poultry, there is a lack of figures on predation in the literature with which the ones from this survey can be compared. However, a few figures for overall mortality are available. Overall losses of turkeys (all predation plus other causes) were generally lower than the average 8% quoted in the British Poultry Meat Federation's T.F.F. Turkey Costings for July 1999 (Table 5.1). Those for free-range egg producers were similar to those from Roberts and Farrar (1993) of between 8.3% and 11.6%, depending on the profitability of the unit (Table 5.4). The mean mortality rate in a study of 50 free-range poultry flocks in Germany was 7.2% (Sommer & Vasicek 2000). Heydon and Reynolds (2000b) surveyed only six farmers with more than 1000 free-range chickens (assumed to be laying hens), for which mortality losses to foxes were between 0.1% and 6.0%, also similar to those found here.

5.4.2. Reported fox predation of poultry

The high levels of fox predation reported by some respondents in Heydon and Reynolds' (2000b) study were not reported here, the highest percentage of birds reported lost to foxes out of the flock being 11.3% (of egg-laying hens). However, there were only three farms in the sample with flocks of less than 200 birds, two of which were turkey producers that did not report any fox predation. (It was the respondents with less than 200 birds that reported high levels of predation in Heydon and Reynolds' study.) It was not known how many fox predation events occurred to produce the loss levels seen here and therefore not possible to determine whether surplus killing of birds occurred. However, from the median numbers of birds reported killed by foxes (Tables 5.1 to 5.4), it seems unlikely that most predation events involved surplus kills, except perhaps in the case of laying hens. Whilst predation by animals other than foxes was not significant for turkey, goose and egg producers (levels of all predation do not differ greatly from levels of fox predation in Tables 5.1, 5.2 and 5.4), predation by other predators accounted for a fair proportion of overall predation losses to chicken producers (Table 5.3). There is therefore a possibility that foxes were blamed for deaths caused by other animals by the non-chicken producers.

The differences between producer types in reported losses due to fox predation are partly a function of the size of the flocks they keep. Although losses of turkeys to foxes were generally higher than those of geese in terms of numbers, percentage mortality of geese due to foxes was higher because their flocks were on average around a fifth of the size of turkey flocks. Flock size does not account for the fact that a higher percentage of goose producers reported experiencing fox predation than did turkey producers, however. Differences in predation levels may be explained by differences in the ease with which birds could be caught, reflected both in the differences between the species themselves and between producer types in husbandry methods used. Turkey producers were more likely than goose producers to have housing available for their birds at all times, rather than at night only, and geese tended to be outside for more of the time than turkeys (Table 5.5). In addition, only two goose producers used Flexinet fencing, compared to nearly 50% of turkey producers.

The large differences between reported fox predation for chicken and egg producers can not be explained by flock size, as both mortality rates and overall numbers of birds reported killed are low for chicken producers. There are no obvious differences in the husbandry factors assessed, although egg-laying hens tended to be outside for a greater proportion of the day than table chickens (Table 5.5). The most obvious difference between chicken and egg producers is in the length of time for which birds are kept on farms and therefore the length of time during which predation may have taken place. If fox predation can be considered to be a random event in time, there will be more chances for it to occur in the 54-week long laying cycle of egg producers than the eight week growing cycles of chicken producers. However, estimated figures for the percentage of chickens that would be lost in a theoretical 54-week growing cycle were still lower than losses experienced by egg producers (Tables 5.3 and 5.4).

The logistic regression analyses carried out indicated that factors related to range area and the density of flocks on the ranges were important in explaining differences in the occurrence of predation between egg producers and chicken producers. The larger the range area the more difficult it is likely to be to maintain the fence enclosing it, which may explain why levels of reported predation for egg producers were higher than for chicken producers. Egg producers were more likely to have reported their fences as being ineffective at preventing foxes and unwanted animals from entering range areas than chicken producers (Table 5.5). However, a larger proportion of chicken producers reported their fences to be ineffective at preventing escapees than reported their fences to be ineffective at preventing foxes or unwanted animals. Therefore, differences in fencing and the functions that fencing consequently best fulfils, which it was not possible to detect in the data from this survey, may well explain the difference in predation levels between these producer types. Another potential reason for the difference is the possible sample bias amongst the egg producers discussed earlier.

In addition to the differences between the producer types, variation between farms in the occurrence of reported chicken predation by foxes was associated with differences in whether fox control was carried out and how many birds died of causes other than predation on the farm. Fox control was important in explaining variation in the scale of perceived predation of lambs on sheep farms (Chapter 2). As discussed there (Section 2.4.2.2), the positive association between these variables is likely to be a result of reactive control to perceived losses, but may also point to a link between fox population density and predation or the perception of the fox as a problem (for which no association was found in these data). The only apparent association between fox density and fox predation was a negative one, but this appeared to be a function of differences between producer types, most probably because of the concentration of chicken producers in land class group 4. This land class group had the highest fox density estimate of those in the poultry sample. No associations were found when producer types were considered alone.

The positive association between the number of chickens lost to causes other than predation and reported fox predation suggests that factors relating to the overall care of birds may be connected to the likelihood of fox predation occurring. However, this association may also reflect a link between flock size and the likelihood of fox predation. Farm husbandry characteristics related to housing and the type of fences producers used were not significantly associated with the likelihood of reported fox predation. However, there was a lack of variation in the sample with respect to housing variables, the majority of producers using fixed housing that was available to birds at all times of day.

5.4.3. Effectiveness of fencing

Electric and Flexinet fences were generally perceived as being effective both at preventing foxes and at preventing unwanted animals from entering the areas in which birds were kept, whilst wire and post fences tended to be more often perceived as ineffective at these functions (although this was not the case where wire and post fences used in conjunction with another fence type were also considered). All three fence types were thought to be generally effective at preventing birds from escaping. The distinction between a 'Flexinet' and an 'electric' fence is ambiguous for these data. Flexinet fences are often electrified meaning that a fence classed as Flexinet in these data, but not as 'electric', could still have been an electric fence. It is therefore assumed that fences classed only as electric were those with electrified wire strands. In any case, it is clear that electric fencing is generally perceived as being effective at preventing foxes (and other animals) from reaching birds. It should be noted that the exclusion of foxes from a given area does not necessarily remove the likelihood of fox activity stressing birds.

5.4.4. Costs of poultry predation by foxes

Overall, out of all the producer types, goose producers reported the highest costs of fox predation per bird (and had the highest estimated costs of fox predation). This was partly due to higher valuations of one goose compared to other birds (reflecting the relative values and prices of the birds considered) and also due to the high reported mortality levels due to fox predation of geese with respect to flock size. Chicken producers, on the other hand, reported low mortality levels, their birds had low values and therefore the costs of fox predation were lowest out of the four producer types.

The fact that, in general, reported losses were similar to those estimated for output losses indicates that producers tended to value losses as if they had lost a point-of-sale bird. As discussed in Chapter 1 (Section 1.2.2), the actual output loss is extremely difficult to estimate if an animal is not lost at point-of-sale (McInerney 1987). However, a number of producers (especially amongst chicken producers) valued their losses as lower than these estimated costs, suggesting they might be taking into account the time at which the bird was presumed killed. For goose and turkey producers, the scale of losses appeared to influence how these estimated and reported costs compared, suggesting that at high loss levels, perceived costs may be based less on market valuations of birds.

In the case of laying hens, two output loss values were calculated for each producer in an attempt to take into account some of the variation in time with respect to when losses occurred. Loss valuations included the savings in resource expenditure due to the bird's death. In the survey, egg producers were asked to value their losses to foxes in terms of financial loss of eggs laid. Because they were not asked to take savings in resource expenditure into account, one might expect their valuations of costs to be higher than those estimated. This was generally not the case, however, with losses being valued as low as zero in some cases. These low valuations may be due to losses being nearer to the end-of-lay, or simply because these producers did not consider predation losses important, perhaps including them in overall expected mortality, so they therefore cost very little in terms of financial loss of eggs laid. Whilst a more rigorous investigation of the costs of losses to foxes would take into account the points in the laying (or growing) cycle at which birds were lost, different valuation methods would be necessary to account for the effects of meat deterioration or reduction in egg production caused by the stressing of birds by foxes. However, reliable figures for the number of birds affected by and the effects on meat or egg production of stressing by foxes would be extremely difficult to collect. The fact that the estimated and reported costs of predation tended to match fairly well indicates that assessments of the costs of predator impacts based on producers' valuations can be reliable.

The apparent decrease in the variability of losses due to fox predation with increasing expenditure on fence maintenance gives some support to a negative relationship between these, which would be expected if fencing is a preventive measure against predation. The lack of clear negative relationship is probably due to a number of factors, one being that fencing is not solely an anti-fox device (as seen by the effectiveness ratings for the three functions of fences considered here). With the exception of chicken producers, smaller proportions of respondents in each producer group considered their fences to be ineffective at preventing birds from escaping than considered their fences to be ineffective at preventing entry of foxes or unwanted animals. As one might assume, it appears that preventing escapees is considered to be a more important function of fencing than is preventing predation. Therefore additional expenditure on fencing might be directed towards this function rather than towards preventing predation in a number of cases. In addition, being based on the survey data, the costs are not wholly accurate, whilst, for total fencing expenditure, inaccuracies will have been caused by the use of a uniform fence lifespan figure.

Amongst producer groups there appeared to be an association between high costs of fox predation and higher expenditure on fencing (goose and egg producers) and vice versa (turkey and chicken producers), if one considers the average figures (Tables 5.16 and 5.17). The higher expenditure levels associated with the lower fence effectiveness rating for preventing entry of unwanted animals also seem to point to a relationship opposite to the one that would be expected, but this may simply be because a higher proportion of goose producers than producers in the other groups reported their fence to be ineffective at preventing entry of unwanted animals. In addition, it should be noted that the mean reported cost of fencing for producers with wire and post fencing (standardised to per metre costs) was higher, at £3.24 [n = 37], than that for those with Flexinet (£1.85 [n = 27]) or electric fencing (£2.45 [n = 49]). Wire and post fencing was considered ineffective at preventing entry of foxes more often than were other fence types. Therefore, the hypothesised negative association between expenditure on preventive measures and predation losses may be unrealistic for poultry production.

5.5. CONCLUSIONS

This study was the first to assess fox predation of free-range poultry on commercial units on a nation-wide scale (including more than a few farms) and to attempt to identify the factors associated with variation in poultry predation between units. The analyses identified the use of Flexinet and electric fences as being perceived to be a good strategy for preventing losses of birds to foxes.

The lack of a negative relationship between expenditure on fencing to prevent fox predation and the cost of reported losses to foxes meant that a financial analysis of the trade-offs between these two costs for poultry producers (similar to that in Chapter 3 for sheep farmers) was not possible. It was possible to look at the costs of losses due to fox predation in this case and assess their magnitude, but these underestimate the ‘true’ costs of fox predation to producers in that they do not include the costs of preventive measures. The costs of poultry losses to foxes were generally fairly low in this study. However, some producers surveyed experienced high losses with respect to their flock size, reported costs of fox kills being up to £0.95 per bird and estimated output losses up to £1.82 per bird. It appears, from a comparison of the results of the two previous studies on poultry predation by foxes (Baker & Macdonald 2000; Heydon & Reynolds 2000b) with those from this investigation, that non-commercial producers tend to experience higher losses of birds and are more likely to experience fox predation than commercial producers.

5.6. SUMMARY

Predation by foxes on free-range poultry can involve potentially high losses of birds. Losses are thought to be a function of the husbandry methods used on holdings, with exclusion fencing being the main way commercial poultry producers prevent fox predation.

This chapter assessed losses to fox predation via a questionnaire survey of the four main free-range poultry producer groups in Britain: egg, chicken, turkey and goose producers. The association between losses and husbandry methods was investigated, as were the effectiveness of fencing and the costs of fox predation to farmers in terms of losses and expenditure on fencing.

Reported losses of birds to foxes varied between the four producer groups, the most obvious distinction being between egg and chicken producers. Egg producers reported higher likelihoods and levels of fox predation than chicken producers. These may have been due to differences in the effectiveness of fences at preventing fox predation, as well as sampling error. Differences in the likelihood of reported fox predation between farms with chickens were not associated with any of the considered husbandry factors. However, electric and Flexinet fences were considered effective at preventing foxes from entering the areas in which birds were kept.

Financial losses due to foxes varied similarly between producer types, with the costs of losses as reported by respondents being generally similar to those estimated. The values of predation losses are difficult to estimate accurately unless birds are at point-of-sale or point-of-lay. A clear association between expenditure on fencing and losses to foxes was not apparent, which suggested that the theoretical model of a trade-off between losses and preventive expenditure might not be realistic for poultry production.

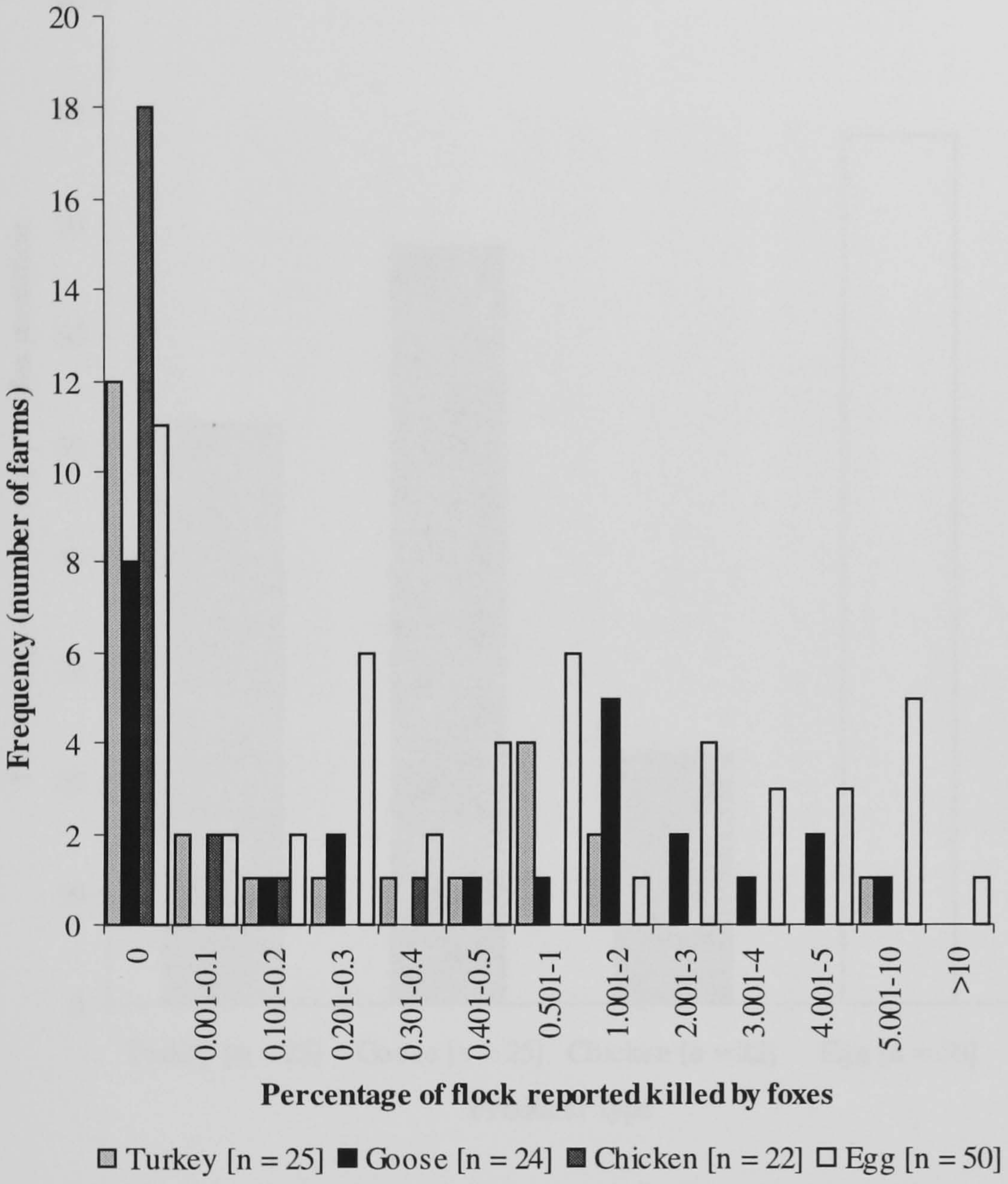


Figure 5.1: Histogram of percentage of flock reported killed by foxes by poultry producer type

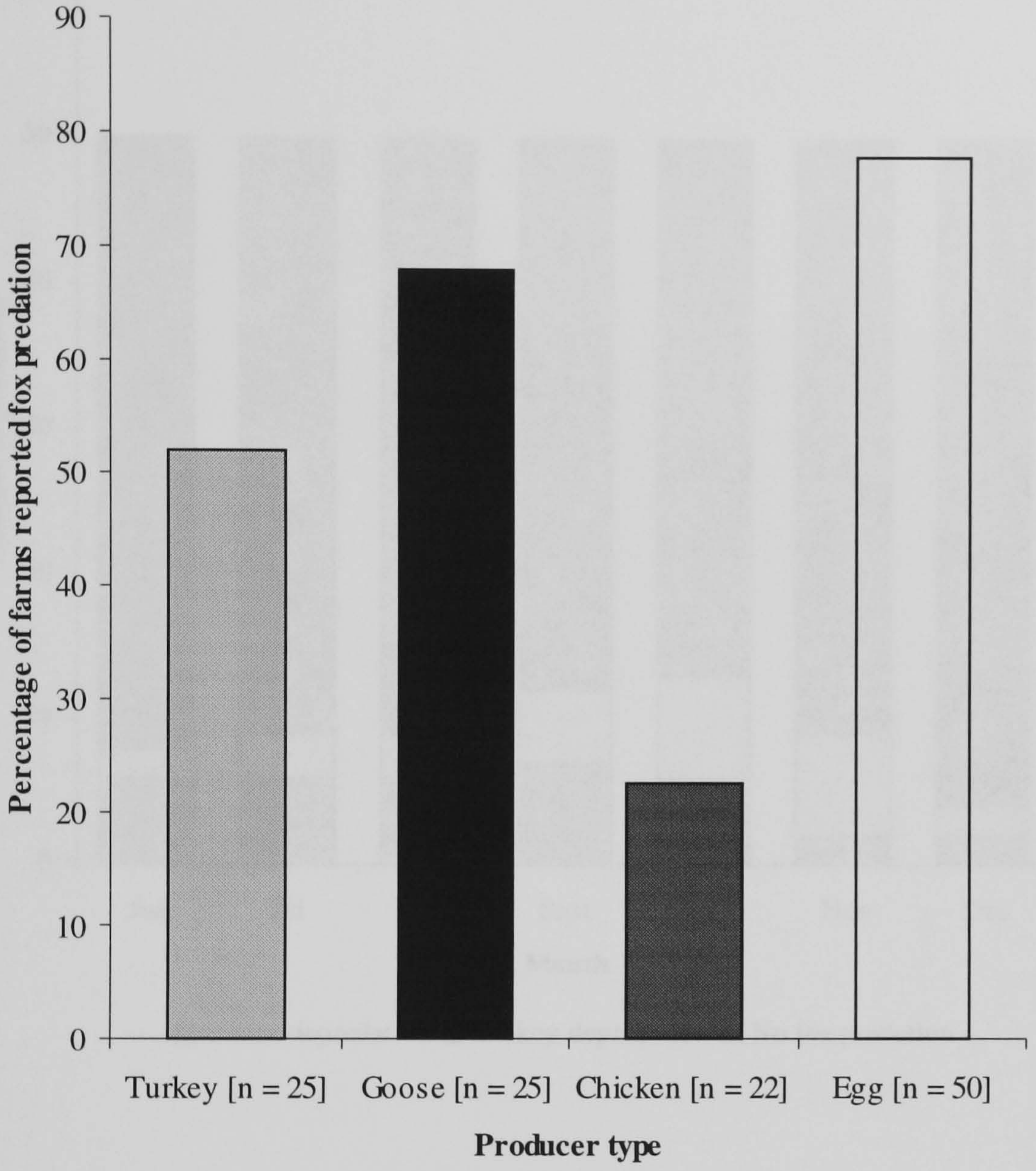


Figure 5.2: Histogram of percentage of farms that reported fox predation according to poultry producer type

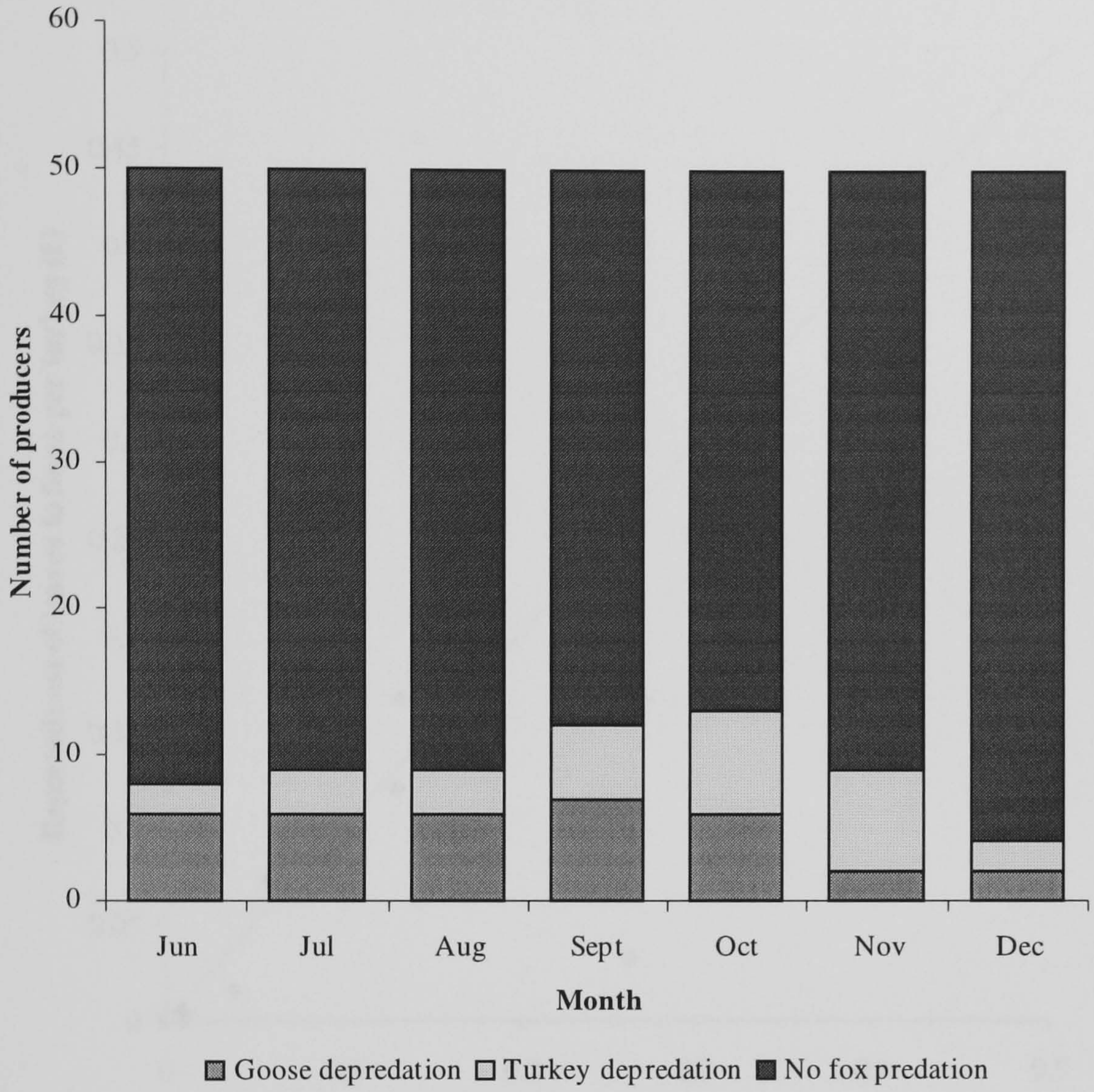


Figure 5.3: Histogram of producers reporting goose and turkey depredation by foxes per month [n = 50]

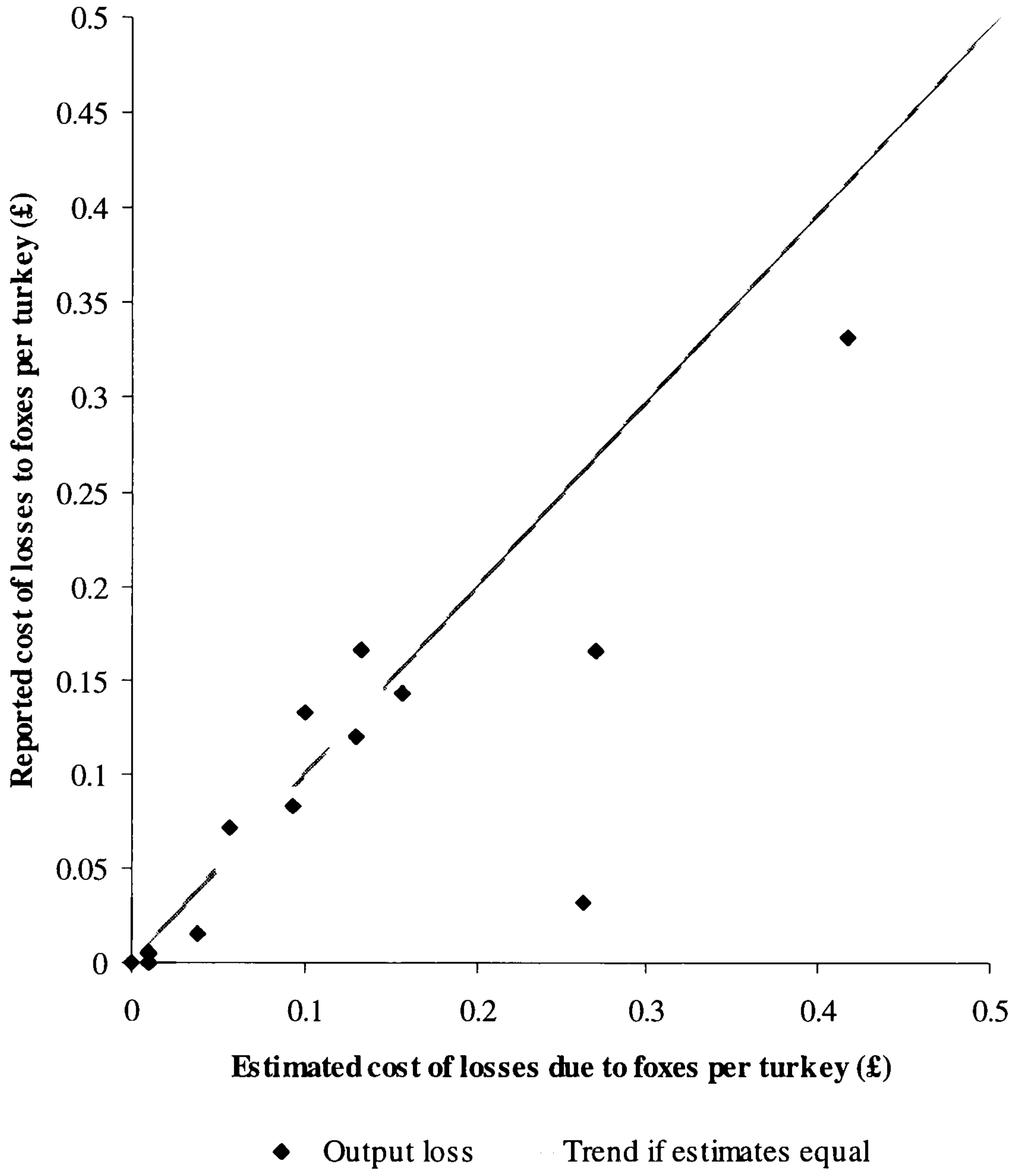


Figure 5.4: Reported costs of losses of turkeys to foxes per turkey compared to estimated output losses due to fox predation per turkey [n = 25]

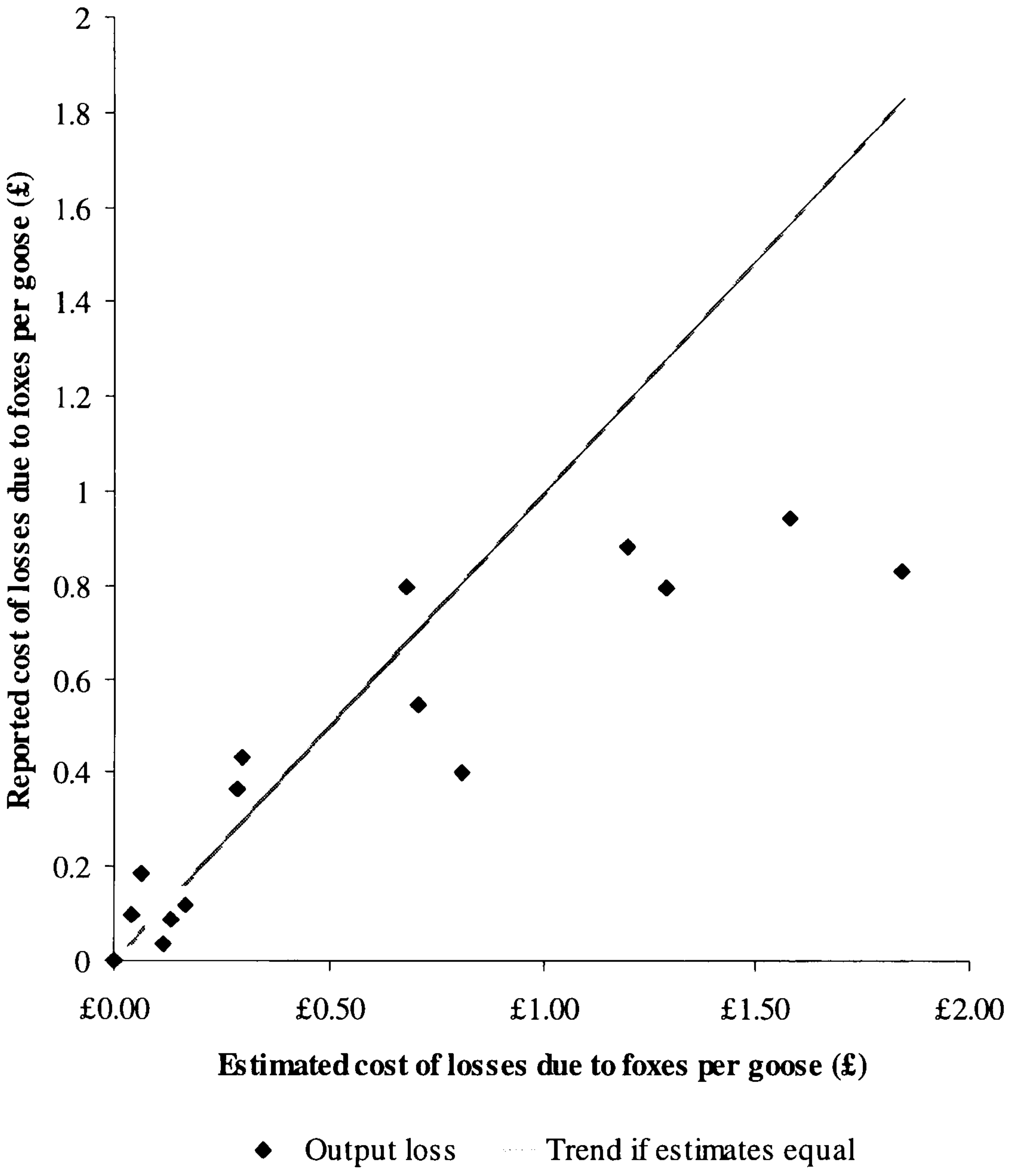


Figure 5.5: Reported costs of losses of geese to foxes per goose compared to estimated output losses due to fox predation per goose [n = 23]

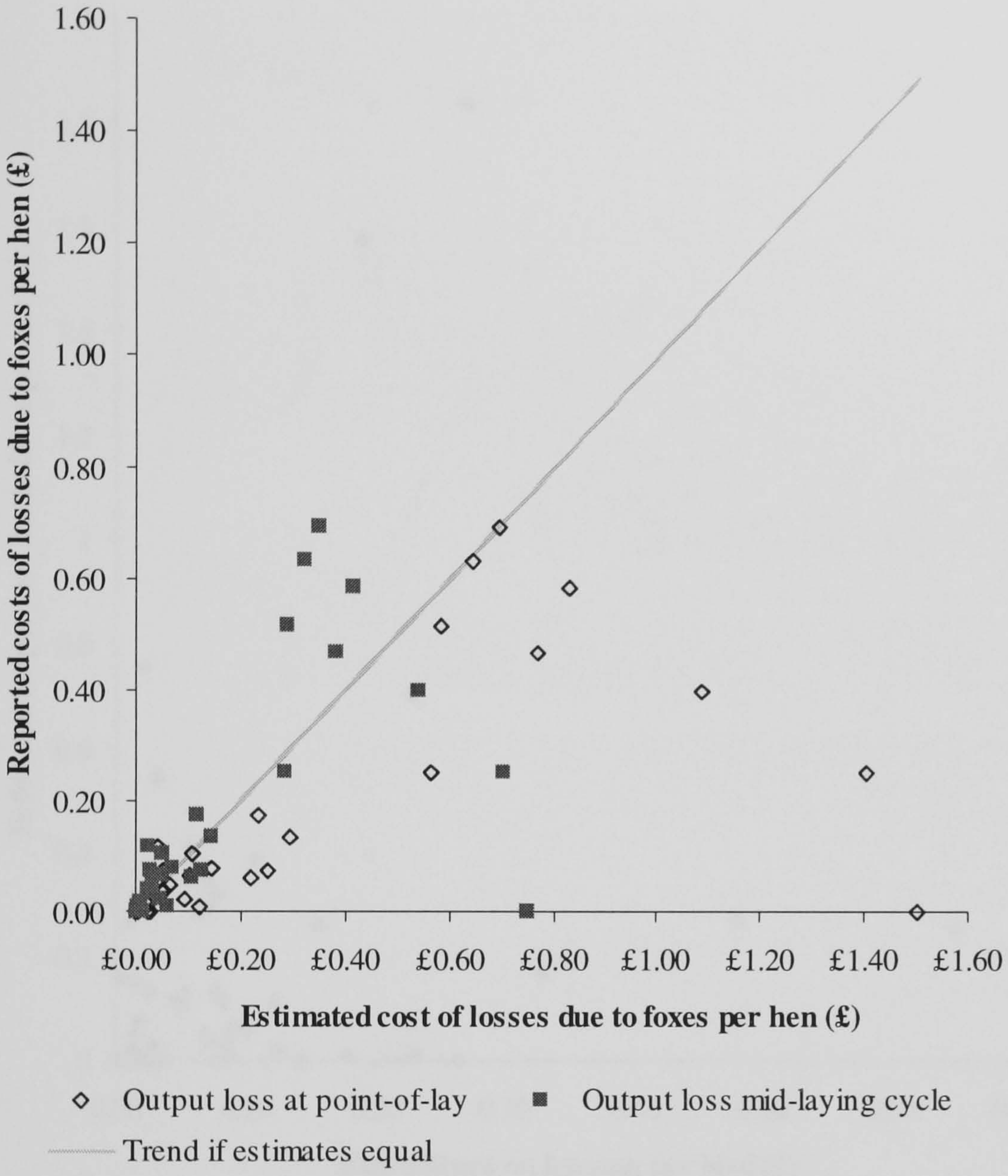


Figure 5.6: Reported costs of losses of laying hens to foxes per hen compared to estimated output losses at point-of-lay and mid-laying cycle due to fox predation per hen [n = 45]

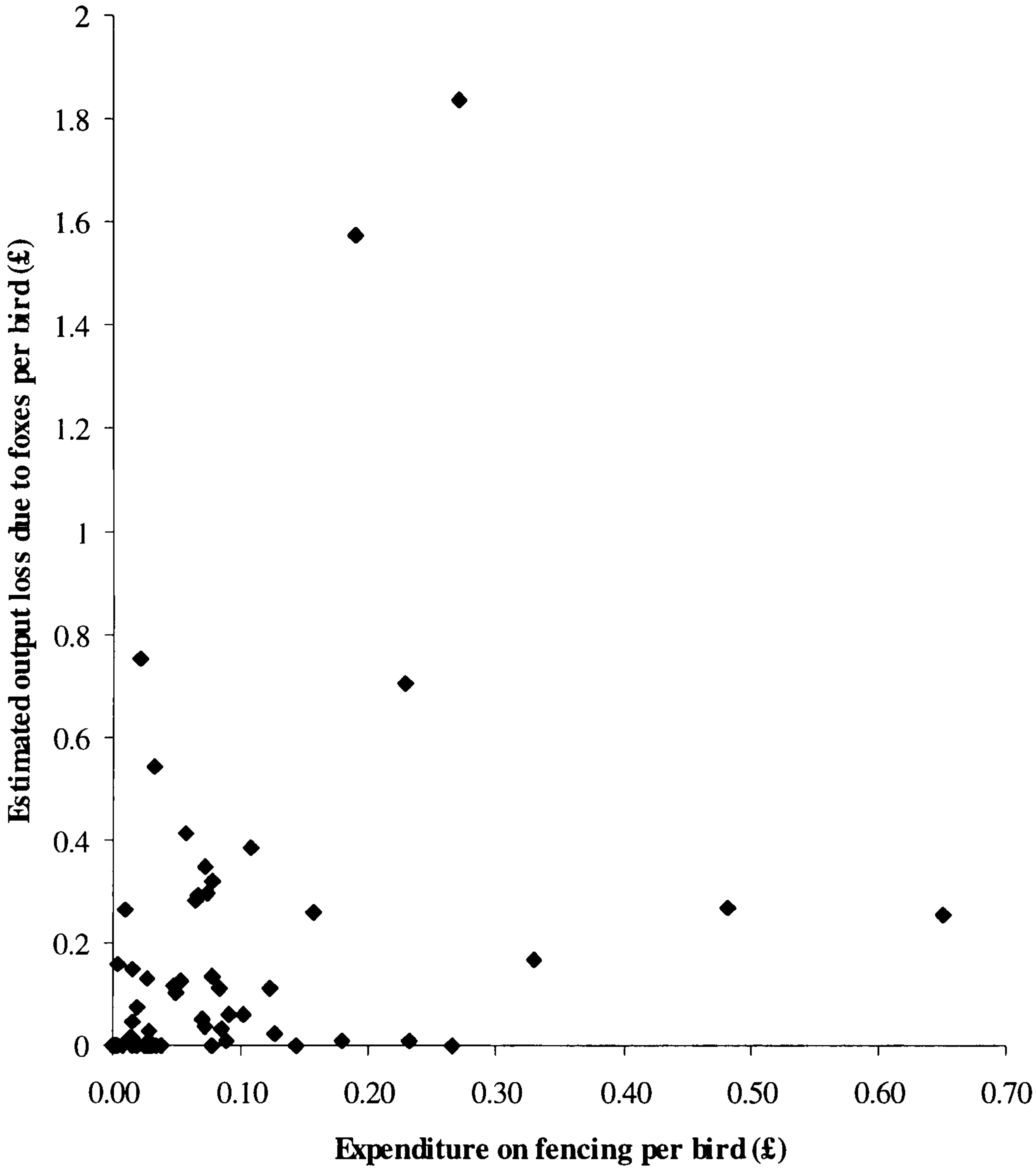


Figure 5.7: Estimated output loss due to foxes per bird compared to expenditure on fencing per bird [n = 67]

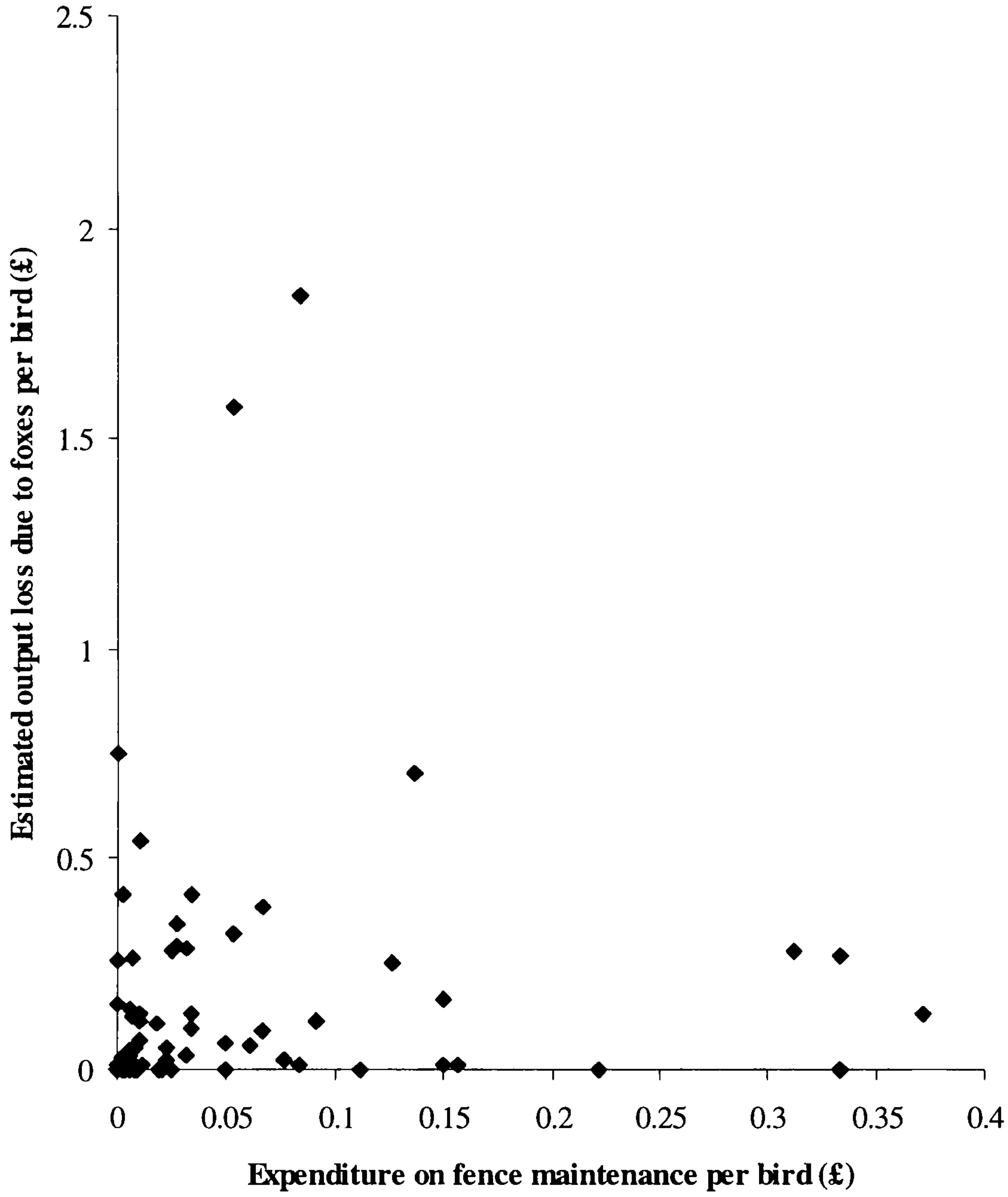


Figure 5.8: Estimated output loss due to foxes per bird compared to expenditure on fence maintenance per bird [n = 82]

CHAPTER 6

IMPACT OF FOXES ON OUTDOOR PIG PRODUCTION

6.1. INTRODUCTION

Large-scale outdoor pig production in Britain was first developed in the 1950s by Richard Roadnight (Thornton 1988). Commercial pressures and increasing concerns about the welfare of animals in intensive systems have led to a rapid rise in the production of pigs outdoors in the last fifteen years (Edwards *et al.* 1994; Potter 1998). Around 20-30% of the UK sow population is now kept outdoors (Abbott *et al.* 1996; FAWC 1996; Potter 1998; Sheppard 1998b) and around 18% farrows (or gives birth to piglets) outdoors (Sheppard 1998b). Only herds that farrow outdoors experience predation of piglets, with some herds said to experience serious losses due to predation, principally by foxes (FAWC 1996; Potter 1998).

There is a wide range in the housing systems and paddock layouts used by outdoor pig producers across Britain (Thornton 1988; Cottle & Cottle 1998). Generally herds are divided into paddocks according to their age and breeding status. They are provided with huts (or arks) for shelter. Sows due to give birth are kept in farrowing paddocks and give birth to their piglets in farrowing huts. Farrowing huts usually have fenders to keep the litter confined and prevent cross-suckling, whilst some may have rails to prevent crushing injuries (Thornton 1988; Cottle & Cottle 1998). Crushing or over-laying by the sow is the most common cause of piglet death (Edwards *et al.* 1994; Abbott *et al.* 1996; Potter 1998; Marchant *et al.* 2001) and disturbance of sows by foxes is said to lead to an increased likelihood of crushing (FAWC 1996; Potter 1998). However, whether a crushing incident was caused by fox disturbance will be very difficult to assess and evidence for this phenomenon is likely to be anecdotal in nature.

There have been a number of studies assessing the causes of piglet mortality in outdoor herds, e.g. Edwards *et al.* (1994), although none have addressed the problem of fox predation, so information on piglet predation by foxes is largely anecdotal (McDonald *et al.* 1997; Macdonald *et al.* 2000). A survey of outdoor units in southern England indicated that losses of piglets to foxes were generally low, but that some producers might have experienced fairly high levels of piglet mortality, with 31% of producers reporting some predation of piglets by foxes (R. McDonald and S. Harris, unpublished data, in White *et al.*, 2000a). In another survey of outdoor units, carried out by Cambac JMC Research in 1993/4, 20% of units reported a fox problem (H.J. Guise, pers. comm. in Macdonald *et al.*, 2000). Predation by corvids, such as hooded crows, can also be a major problem for some herds (Edwards *et al.* 1994; FAWC 1996).

The use of plastic flaps over hut entrances has been suggested as a preventive measure against predation (FAWC 1996), along with electric fencing to prevent foxes from entering the farrowing site and a pest control programme (FAWC 1996; Potter 1998; Macdonald *et al.* 2000). However, predator fencing can be a substantial financial investment and Macdonald *et al.* (2000) indicate that occasional fox culling is necessary in addition to fencing to prevent fox predation. No scientific studies to date have assessed what husbandry factors are associated with fox predation of piglets and there has been no quantitative assessment of piglet depredation by foxes in Britain.

This chapter aims to assess the extent of piglet predation by foxes across Britain and identify husbandry, management or other factors influencing variation between farms, as for sheep in Chapter 2 and poultry in Chapter 5. The associations between fox population density, control and predation are tested. In addition, the costs of fox predation to producers in terms of piglet losses and expenditure on fencing are evaluated. The hypothesis of a negative relationship between losses and expenditure with decreasing marginal returns to expenditure is tested with the aim of finding an optimal predation management solution from the farmer's point of view.

6.2. METHODS

6.2.1. Questionnaire survey of outdoor pig producers

A sample of outdoor pig producers was obtained by telephoning pig farmers from a list of Soil Association members with pigs and from the Yellow Pages (using *www.yell.co.uk* and searching for 'pig farmers' and 'pig breeders'). Producers were asked whether they farrowed their sows outdoors and, if so, whether they were willing to take part in the survey. Further addresses were obtained from Western Quality Pigs and Cotswold Pig Development, as well as from a number of individuals upon contacting them. Questionnaires on two sides of an A4 sheet of paper with a explanatory letter and Freepost reply envelope were sent to 94 producers in several batches between 8th November and 1st December 2000. (Producers in regions for which the swine fever outbreak of August-November 2000 would have posed problems were contacted later than those in other regions.) The questionnaire consisted of questions on land uses surrounding pig paddocks, farrowing, husbandry methods and measures associated with arks with possible anti-predator attributes, fencing surrounding paddocks, losses of piglets to predation and other causes that year, fox control and production of pigs for market on the farm (Appendix E). It was designed with the help of a pilot survey of a small number of outdoor producers and Signet pig management consultants. A further questionnaire form and reminder letter were sent to non-respondents to the survey on the 8th January 2001.

6.2.2. Relative fox population density estimates

Each holding in the data set was allocated both a region-based and a land class-based relative fox density estimate (termed ‘regional fox density’ and ‘land class fox density’), as described in Sections 2.2.3 and 5.2.2. Non-parametric correlation analyses were used to test the associations between relative density estimates and the numbers and percentages of piglets reported killed by foxes, the percentage of farms within each region and land class group reporting predation, as well as the number of foxes killed on farms.

6.2.3. Factors influencing reported fox predation of piglets

Chi-square and logistic regression analyses were used to assess the factors associated with the occurrence of reported fox predation of piglets. The variables used in these analyses are summarised in Appendix F. These were transformed where necessary to meet the assumptions of normality of error and homogeneity of variance for regression analysis. The dependent variable in all logistic regression models was a binary response variable, coded zero for no reported fox predation on the farm and one for at least one piglet having been reported lost to foxes. This variable was also used in the chi-square tests. Uni- and multivariate analyses were used to assess relationships between the dependent variable and the various factors considered. All variables were tested against the dependent variable on their own at first. Chi-square tests were used for all analyses involving one other categorical variable and logistic regression for analyses with a continuous independent variable. Subsequently all variables were tested once again in a model including those variables that were statistically significant at the 5% level ($p < 0.05$) in the first round of tests in order to identify an overall multiple logistic regression model accounting for variation in the likelihood of reported fox predation.

6.2.4. Costs of piglet predation by foxes

6.2.4.1. Theoretical model

The theoretical model of Chapters 3 (Section 3.2) and 5 (Section 5.2.4) was used as a basis for the analysis of the costs of piglet predation to farmers. In the case of pig production, the preventive measure considered was fencing surrounding pig paddocks. As for poultry, it is assumed that the primary function of fencing is preventing escapees and that there is a necessary minimum basic level of fencing (and therefore expenditure on fencing), with additional expenditure above this level resulting in improvements in the effectiveness of the fencing at preventing fox predation. Piglet losses to foxes in monetary terms are assumed to be a function of expenditure on fencing surrounding pig paddocks and other farm characteristics (such as location):

$$La_i = f(MF_i, R_i) \qquad (6\text{-}1)$$

where

La_i = piglet losses to foxes per sow per year on the ith farm (£)
MF_i = expenditure on fencing per sow per year on the ith farm (£)
R_i = regional location of the ith farm
f = function of farm characteristics determining piglet losses to foxes

The existence of a negative relationship between losses and expenditure, reflecting the trade-off between these two costs of fox predation, is tested, with diminishing returns to marginal effort as outlined in Chapter 3 and by McInerney *et al.* (1992) and McInerney (1996) for the loss-expenditure frontier (see Figure 1.1). The total costs of fox predation are piglet losses due to fox predation plus expenditure on fencing:

$$TC_i = La_i + MF_i \qquad (6\text{-}2)$$

where:

TC_i = total costs of fox predation on the ith farm

Total costs are minimised where the first derivative of total costs with respect to expenditure equals zero. This optimal point is where the first derivative of losses of piglets to foxes with respect to expenditure on fencing per sow is equal to minus one; where the marginal piglet loss equals the marginal expenditure on preventing piglet losses.

6.2.4.2. Valuation of piglet losses due to fox predation and expenditure on boundary fencing

The value of piglet losses to foxes was estimated as the output loss value of the piglet according to the marketed products of the farm. Only losses due to reported predation were included, as it was considered that losses due to fox disturbance of a sow were unlikely to be reliable. Generally, piglets may be sold at three ages: as weaners at weaning (at around 6kg weight), as grown-on weaners (at 25-30kg in weight) and as finished pigs (usually sold by deadweight at 50-80kg) (Cottle & Cottle 1998; Sheppard 1998a; Nix 1999), with outdoor units tending to sell pigs as weaners more often than as finishers (Cottle & Cottle 1998; Sheppard 1998b). The price of a weaner at 30kg was taken from Nix (1999), as £32.00, but the price of younger weaners was not available. The deadweight price of 1kg finished pig was taken as the mean price for 2000 from DEFRA UK Weekly Commodity Prices, at £0.95. The deadweight was calculated as 0.7 times the liveweight, if this was given (Nix 1999) and the market value of a finisher calculated as the average deadweight as given by producers multiplied by the price.

Because piglets are killed by foxes at a young age, the farmer gains the extra expenditure on resources that would have been necessary to produce a weaner or finisher. Therefore, resource costs were subtracted from the market price of the product. It was assumed that the only resources necessary to produce a piglet prior to it being predated are those spent on the sow, as the piglets will be suckling, and that these resources are negligible per piglet. Therefore the full resource cost needed to produce a weaner or finisher was used here. The only resource considered was feed, other variable costs being insignificant in comparison (Sheppard 1998a; Nix 1999) and data on these not being available from the survey. The amount of feed used by producers per sow or per piglet was extremely variable between holdings and it was considered that using these data would introduce unreliability into the estimates of resource costs. Therefore, the amount of feed needed to produce a 30kg weaner was taken from Nix (1999) as 0.85 ton (this does not include feed for sows or boars). The amount of feed needed to produce a finisher depends on the finishing weight of the animal, whether it is a porker, cutter or baconer. Figures for the amount of feed needed for each were taken from Nix (1999). The products were classified as porkers if the average finisher deadweight given by producers was less than 59kg, as cutters if the deadweight was between 60kg and 69kg and as baconers if the average finisher deadweight was greater than 69kg. The prices for feed per ton were taken as given by producers and multiplied by the amounts of feed needed for each product to calculate the resource cost of producing each.

The output loss for the loss of a weaner and for the loss of a finisher were calculated for each farm by subtracting the resource cost from the market value in each case. The relative numbers of weaners and finished pigs sold by each holding were calculated from the data collected in the survey. The mean value of one piglet for each holding was calculated as the proportion of pigs sold as weaners multiplied by the output loss value of a weaner plus the proportion of pigs sold as finishers multiplied by the output loss value of a finisher. This value was multiplied by the number of piglets reported killed by foxes per sow in the last year to give the output loss due to fox predation of piglets.

Expenditure on fencing per year includes the costs of first erecting the fence as spread over its life-time and the costs of maintaining the fence per year. The costs of both erecting and maintaining fences were reported by 15 respondents. Erection costs were converted to 2000 prices using the Retail Price Index (Nix 1999). Costs of erecting fences were estimated for a further 15 respondents, who had stated both the type of fence they had and its length (or in the case of specialist fox fences both length and number of strands). Four respondents did not have fences, only having a hedge or bank surrounding their paddocks, for which initial costs were taken as zero. The cost of specialist fox fences were calculated by multiplying the mean cost of a specialist fox fence per strand per metre in 2000 from those reported by eight respondents (£0.158) by the length and number of strands of the fences for which a cost was unavailable. A mean cost of permanent wire and post fences per metre in 2000 was also calculated, at

£1.69 [n = 6], and used to estimate fence costs for those with wire and post fences that had provided no cost figures. Data were not collected on the number of strands general (i.e. not specialist anti-fox) electric fences had. Therefore the price for electric fencing was taken as £0.435 per metre, the average price from a number of electric fence suppliers, and multiplied by the length of fence for those with electric fences. Fences were assumed to last for ten years, so the costs of erecting the fence were divided by ten to give a per year figure. The costs of fence maintenance per year were taken as reported [n = 25]. For expenditure on fencing per year, the costs of erecting and maintaining the fence were added together, whilst the costs of fence maintenance per year were also considered alone.

To assess whether there was an association between expenditure on fencing and the occurrence of reported fox predation, both expenditure on fencing and expenditure on fence maintenance only were included separately in the best-fit logistic regression model explaining variation in the incidence of reported fox predation (Section 6.2.3). Fence expenditure variables were also included alone in logistic regression models with the occurrence of reported fox predation as the dependent variable.

6.2.4.3. Empirical estimation of the model

Regression analyses were used to estimate the form of the relationship between losses of piglets to fox predation and expenditure on fencing. The relationship was expected to approximate either a negative exponential or negative power relationship. Therefore three functional forms were tested (linear, exponential and power or log-linear):

a) Linear: $La_{i1} = \beta_0 + \beta_1 MF_{i1}$

b) Exponential: $La_{i1} = \beta_0 \times e^{\beta_1 MF_{i1}}$ i.e. $\ln(Lb_{i1}) = \beta_0 + \beta_1 MF_{i1}$

c) Log-linear (power): $La_{i1} = \beta_0 \times MF_{i1}^{\beta_1}$ i.e. $\ln(Lb_{i1}) = \beta_0 + \beta_1 \ln(MF_{i1})$

where:

La_{i1} = piglet losses to foxes per sow per year on the ith farm +0.1 (£)

MF_{i1} = expenditure on fencing per sow per year on the ith farm +0.01 (£)

Because of the necessity for logging the variables and the fact that they both included zero values, a positive constant that was considered small in comparison to overall figures was added to the data. In the case of loss of piglets, this was 0.1 and in the case of expenditure on fencing 0.01.

The functional form that best fitted the data was used as a basis for a multiple linear regression model in which the variables in Appendix F that were significantly related to losses to foxes per sow were included. The first derivative of the function estimated from the regression model was taken with respect to expenditure on fencing and used to find the optimal point in terms of the expenditure on fencing that minimised total costs. Optimal total costs (fencing plus piglet losses due to fox predation) were estimated and compared with actual total costs of fox predation to estimate the avoidable costs of fox predation to each holding.

6.3. RESULTS

Of the 315 pig producers contacted by telephone, the majority (61.8%) farrowed their herds indoors, whilst 12.7% no longer kept pigs. Only one outdoor producer contacted was unwilling to participate in the survey. There were 55 questionnaire forms returned through the survey (a response rate of 58.5%), of which 48 were used in analyses and seven were returned uncompleted, five because the questionnaire was not relevant to the producers concerned. A summary of some of the characteristics of the sample is given in Table 6.1. Whilst there were respondents from all regions considered, apart from South Scotland, the majority came from East England and the Midlands, with a fair proportion from South and Southwest England. These regional biases in outdoor pig production mirror those of the National Survey of Pig Production Systems in 1998 (Sheppard 1998b).

Not all respondents answered all the questions on the survey form, so the sample sizes differ between analyses. These are indicated in square brackets in the text. All figures for statistics are quoted to 3 significant figures or 2 decimal places. Estimated Beta coefficients for independent variables in regression analyses are given as 'B'. Statistical significance was taken as being at the 95% level ($\alpha = 0.05$), i.e. $p < 0.05$.

Table 6.2 provides summary statistics on reported losses of piglets between birth and weaning to foxes and other causes and Figure 6.1 illustrates the range in reported piglet mortality due to fox predation. Of those that reported losses of piglets to foxes, 38.1% reported losses of less than 1% of piglets born in the last year, the median reported mortality loss due to fox predation amongst these producers being 1.5% (range: 0.12-5.00) [n = 21]. Median reported losses to foxes per sow amongst producers reporting fox predation were 0.263 piglets per sow (range: 0.030-1.11) [n = 20]. More than a third of producers (37.2%) considered that the number of piglets killed by foxes over the past five years had increased, whilst 34.9% thought it had stayed the same and 14.0% that there had been a decrease [n = 43]. Table 6.3 gives summary statistics for sow numbers, piglets born and fox control.

6.3.1. Relative fox population density estimates

Land class fox density was not significantly correlated with either the number of piglets reported killed by foxes in the past year ($r_s = -0.164$, $p = 0.355$ [n = 34]), the percentage of piglets reported killed by foxes out of the total number born ($r_s = -0.161$, $p = 0.355$ [n = 35]) or the number of piglets reported killed by foxes per sow ($r_s = -0.146$, $p = 0.409$ [n = 34]). There were also no statistically significant associations between regional fox density and either the number ($r_s = 0.138$, $p = 0.417$ [n = 37]), percentage ($r_s = 0.202$, $p = 0.225$ [n = 38]) or number per sow ($r_s = 0.201$, $p = 0.233$ [n = 37]) of piglets reported killed by foxes. The percentage of respondents reporting fox predation of piglets in each land class group was not associated with land class fox density ($r_s = 0.232$, $p = 0.658$ [n = 6]), nor was the percentage of respondents reporting predation in each region associated with regional fox density ($r_s = 0.096$, $p = 0.820$ [n = 8]). The number of foxes killed on farms was not associated with regional fox density ($r_s = -0.056$, $p = 0.718$ [n = 44]), but was negatively correlated with land class fox density ($r_s = -0.374$, $p = 0.015$ [n = 42]).

Table 6.1: Characteristics of pig producer sample in terms of use of possible anti-predation measures, fencing, fox predation, farm surroundings and location and reported fox predation

Characteristic	N	**Factor levels**	**Percentage of respondents (%)**
Possible anti-predation measures	48	Sows and piglets shut in arks overnight for first 48 hours after farrowing	8.3
		Piglets retained by fenders in front of arks prior to weaning	72.9
		Plastic flaps on ark entrances	35.4
Type of fence surrounding paddocks	48	Specialist fox fence	20.8
		Permanent	37.5
		Mobile	12.5
		Wire and post	37.5
		Flexinet	2.1
		Electric	56.3
		Alternative (hedge, bank or wall)	25.0
Score for effectiveness of fence at preventing foxes from getting into paddocks	48	Ineffective	56.3
		Somewhat effective	31.3
		Very effective	12.5
Score for effectiveness of fence at preventing all unwanted animals from getting into paddocks	48	Ineffective	29.2
		Somewhat effective	58.3
		Very effective	12.5
Score for effectiveness of fence at preventing pigs from escaping	48	Ineffective	10.4
		Somewhat effective	18.8
		Very effective	70.8
Incidence of fox predation of piglets between farrowing and weaning	38	Fox predation reported to have occurred in the last year	55.3
Incidence of fox disturbance of sows	27	Piglets reported to have died due to fox disturbance of sow(s)	51.9
Fox control	44	Fox control carried out in last year	77.3

Table 6.1

Month of year in which losses to foxes reported to have occurred	21	January	22.9
		February	20.8
		March	22.9
		April	25.0
		May	27.1
		June	20.8
		July	20.8
		August	25.0
		September	18.8
		October	18.8
		November	12.5
		December	14.6
Land uses surrounding paddocks	48	Arable	91.7
		Livestock	45.8
		Game rearing	31.3
		Forestry	54.2
		Village	33.3
		Urban	4.2
		Other (e.g. road)	12.5
Region in which farm is situated (as Table 2.3)	48	North Scotland	4.2
		North England	10.4
		East England	29.2
		Midlands	22.9
		Central England	4.2
		Southwest England	10.4
		South England	12.5
		Wales	6.3
Land class group of farm land (as Table 2.4)	45	1	13.3
		2	35.6
		3	4.4
		4	17.8
		5	24.4
		6	4.4

Table 6.2: Summary statistics on reported losses of piglets to fox predation, all predation and all causes between birth and weaning. Mortality was calculated as the percentage of piglets reported lost to that cause out of the total number of piglets born alive on each farm.

Cause of piglet mortality		Fox predation	Fox disturbance of sow	All predation	All causes
Number of piglets reported died per farm	Mean (S.E.)	117 (32.5)	152 (45.6)	109 (38.6)	1562 (277)
	Median	1	1.5	5.5	1107
	Range	0-855	0-855	0-1140	0-8159
	n	37	26	34	42
Number of piglets reported died per sow	Mean (S.E.)	0.220 (0.054)	0.207 (0.048)	0.224 (0.059)	2.41 (1.70)
	Median	0.033	0.056	0.033	2.46
	Range	0-1.11	0-0.709	0-1.11	0-4.33
	n	37	26	34	44
Reported piglet mortality (%)	Mean (S.E.)	1.04 (0.24)	1.13 (0.27)	1.03 (0.26)	10.9 (0.70)
	Median	0.30	0.27	0.19	11.0
	Range	0-5.0	0-5.0	0-5.0	0-20.0
	n	38	26	35	43
Percentage of respondents reported no piglets lost		45.9 [n = 37]	50.0 [n = 26]	44.1 [n = 34]	4.8 [n = 42]
Percentage of respondents reported more than 10 piglets lost		45.9 [n = 37]	46.2 [n = 26]	47.1 [n = 34]	88.1 [n = 42]

Table 6.3: Summary statistics for numbers of sows, piglets born and fox control.

Variable	N	Mean	Median	Minimum	Maximum
Number of sows on holding, on average	46	570	440	2	2800
Number of piglets born in last year	43	12973	10000	21	60000
Number of piglets born per sow over year, on average	43	20.4	21.7	3.8	27.0
Number of piglets born per sow at one farrowing, on average	48	10.7	10.8	8.9	12.0
Number of foxes killed on farm in last year	44	19.5	12.5	0	96

6.3.2. Factors influencing reported fox predation of piglets

Few factors were associated with the likelihood of reported fox predation of piglets in univariate analyses. The stocking density of sows was positively associated with the occurrence of reported fox predation (B = 0.087, Wald = 3.83, $p = 0.050$ [n = 36]). Farms where fox control was carried out were more likely than expected to have reported fox predation ($\chi^2 = 8.89$, Fisher's exact $p = 0.005$ [n = 36]). There were indications of other relationships in the data when the level of statistical significance was relaxed to 10%. The total number of sows (ln-transformed) was positively associated with the occurrence of reported fox predation at this level of significance (B = 0.336, Wald = 3.64, $p = 0.056$ [n = 38]). This was also the case for the number of foxes killed on the farm (B = 0.051, Wald = 3.50, $p = 0.061$ [n = 36]). Farms in the East England region were less likely than expected to have reported fox predation ($\chi^2 = 3.41$, $p = 0.065$ [n = 38]).

Whether farms carried out fox control was the only variable to remain statistically significant ($p < 0.05$) on the inclusion of other variables in the model. However the ability of the model to predict no fox predation on farms where no fox predation was reported increased (from 46.7% to 73.3%) on inclusion of the dummy variable coding for a farm being in East England. The overall predictive accuracy of the model did not change, however, remaining at 75.0%, and the estimated coefficient for East England was only significantly different from zero at the 10% level (-2 log likelihood of Model 1 = 36.7, $\chi^2 = 12.2$, d.f. = 2, $p = 0.02$ [n = 36]) (Table 6.4).

Table 6.4: Coefficient estimates and significance test results for multivariate logistic regression model 1 explaining variation in the occurrence of reported fox predation of piglets

Variable	**B**	**Wald**	**p**
Constant	-1.71	1.08	0.115
East England	-1.45	2.73	0.098
Fox control carried out	3.12	6.81	0.009

There was a slight positive association between whether farms carried out fox control and whether they had a village in their surroundings ($\chi^2 = 3.34$, Fisher's exact p (one-sided) = 0.069 [n = 44]), as well as between carrying out fox control and the number of sows on the holding (Mann-Whitney U = 58.5, Z = -3.12, p = 0.002 [n = 44]). A second best-fit model (Model 2) was estimated without the dummy coding for whether fox control was carried out to avoid any multicollinearity between variables. Model 2 did not have as high a predictive accuracy as Model 1, at 73.7%, but had a higher chi-square value and included more of the observations (-2 log likelihood of Model 2 = 36.9, χ^2 = 15.4, d.f. = 3, p = 0.002 [n = 38]) (Table 6.5). The model correctly predicted no fox predation on 64.7% of farms where no predation occurred. It included the total number of sows on the holding, whether the farm was in East England and whether the farm had a village in its surroundings. Farms with villages in their surroundings were more likely to have experienced fox predation of piglets.

Table 6.5: Coefficient estimates and significance test results for multivariate logistic regression model 2 explaining variation in the occurrence of reported fox predation of piglets

Variable	B	Wald	p
Constant	-1.76	2.46	0.117
East England	-3.14	6.09	0.014
Total number of sows (ln-transformed)	0.462	4.16	0.041
Village b	2.32	3.20	0.074

6.3.3. Costs of piglet predation by foxes

Over half of the respondents (27) produced at least some finished pigs and 19 produced finished pigs exclusively (n = 42). Summary statistics for the estimated and reported costs of losses due to fox predation are given in Table 6.6. Generally reported costs were similar to output losses (Figure 6.2). However, losses tended to be valued as lower by respondents when they had lost large numbers of piglets. Reported costs of piglet losses and estimated values were compared in paired t-tests and correlation tests. Estimated output loss was correlated with reported costs (r = 0.511, p = 0.003 [n = 32]) and the two samples did not differ significantly (t = -1.30, p = 0.205 [n = 32]). These results indicate that the estimated costs are close to producers' assessments of losses and therefore are likely to reflect their behavioural actions with respect to losses and expenditure. Estimated rather than reported losses were used in subsequent analyses because there was a higher sample size for estimated losses and because of the fact that a standard technique was used to estimate costs, which was not the case for producer reported costs.

Table 6.6: Summary statistics of estimated and reported costs of piglet losses to foxes per sow per year

Value	n	Mean	Median	Range
Estimated output loss (£)	36	9.51	0.96	0 – 73.06
Reported costs (£)	33	4.31	0.00	0 – 33.33

Table 6.7: Summary statistics of expenditure on fence maintenance and total expenditure on fencing per sow per year

Value	n	Mean	Median	Range
Expenditure on fence maintenance (£)	25	2.64	0.36	0 – 40.00
Total expenditure on fencing (£)	24	5.25	0.88	0 – 46.51

As was the case for losses to foxes, expenditure on fencing per sow was highly variable between producers (Table 6.7). Scatter plots gave the indication that a loss-expenditure type relationship could be expected for these data, as predicted (Figures 6.3 and 6.4). However, there was a noticeable outlier within the data for both total fence costs and fence maintenance costs, data point 14 (marked on Figures 6.3 and 6.4), whilst a further data point (12) had a very high expenditure on fencing per sow (also marked on Figures 6.3 and 6.4).

Neither the cost of fencing per sow per annum nor the cost of fence maintenance only per sow per annum (untransformed or logged) were significantly associated with the occurrence of predation when included in the logistic regression model estimated in Section 6.3.2. The same was true when each was included alone in a logistic regression model with the same dependent variable.

6.3.3.1. Empirical estimation of the model

All functional forms fitted indicated negative relationships between piglet loss and expenditure on fencing, but none were statistically significant (Table 6.8). Removal of data points 12 and 14 allowed an exponential model ($La_{i1} = b_0 \times e^{b_1 MF_i}$) for which the significance level was below 5% to be fitted, with the costs of fence maintenance as the dependent variable (Table 6.8). The removal of these data points was justified by the fact that they were outliers to the remainder of the data and overly influential in the fit of models estimated (Cook's distance of data point 12 for model fitted with data point 14 removed from data set = 80.9, Leverage = 0.93, mean leverage = 0.05; Cook's distance of data point 14 for model fitted with data point 12 removed from data set = 6.57, Leverage = 0.69, mean leverage = 0.05). Expenditure on both fencing and fence maintenance was double that of the next highest spender for data point 12, the same being true for fence maintenance for data point 14.

Table 6.8: Model output for regression models with piglet losses to foxes per sow as the dependent variable, $La_{i1} = f(MF_{i1})$. Results for model used in later analyses are in bold type.

Independent variable (MF_i)	Outliers removed	Model form	R^2	n	F	p	β_0	β_1
Total expenditure on fencing	none	Linear	0.02	21	0.41	0.531	13.4	-0.236
		Exponential	0.04	21	0.88	0.361	2.34	-0.047
		Power	0.02	21	0.41	0.529	1.84	-0.186
Expenditure on fence maintenance	none	Linear	0.02	21	0.33	0.570	12.8	-0.275
		Exponential	0.07	21	1.34	0.262	2.23	-0.075
		Power	0.08	21	1.69	0.209	1.20	-0.293
Total expenditure on fencing	612, 614	Linear	0.04	19	0.70	0.416	13.7	-0.681
		Exponential	0.03	19	0.47	0.504	2.23	-0.075
		Power	0.02	19	0.39	0.539	1.73	-0.213
Expenditure on fence maintenance	612, 614	Linear	0.07	19	1.34	0.264	14.7	-3.86
		Exponential	**0.21**	**19**	**4.53**	**0.048**	**3.56**	**-0.874**
		Power	0.11	19	2.12	0.164	0.883	-0.395

Piglet loss was logged, after the addition of 0.1, in order to estimate an exponential functional form in linear regression. The best-fit model included the dummy variables coding for whether a farm had a village in its surroundings, whether the farm was in the East England region, whether it was in the Midlands region and whether an electric paddock boundary fence was used, in addition to expenditure on fence maintenance ($R^2 = 0.730$, Adjusted $R^2 = 0.626$, $F = 7.03$, d.f. = 5, 13, $p = 0.002$ [$n = 19$]) (Table 6.9):

$$\ln(La_{il}) = b_0 + b_1 MF_i + b_2 V_i + b_3 Eas_i + b_4 Mid_i + b_5 EL_i + \varepsilon_i$$

where

La_{il} = piglet loss to foxes per sow per year on the *i*th farm +0.1 (£)

MF_i = expenditure on fence maintenance per sow per year on the *i*th farm (£)

V_i = dummy variable coding for whether *i*th farm has a village in its surroundings

Eas_i = dummy variable coding for whether *i*th farm is in East England region

Mid_i = dummy variable coding for whether *i*th farm is in Midlands region

EL_i = dummy variable coding for whether electric boundary fencing is used on *i*th farm

b_0 = constant

$b_1 \ldots b_5$ = coefficients for MF_i, V_i, Eas_i, Mid_i and EL_i

ε_i = error term

Table 6.9: Coefficient estimates and significance test statistics for multiple linear regression model, with piglet loss to foxes per sow as the dependent variable, $\ln(La_{il}) = b_0 + b_1 MF_i + b_2 V_i + b_3 Eas_i + b_4 Mid_i + b_5 EL_i$ without data points 12 and 14

Coefficient	**Estimate of coefficient**	**S.E. of estimate**	**t**	**p**
b_0	2.33	0.718	3.24	0.006
b_1	-1.26	0.310	-4.07	0.001
b_2	2.30	0.746	3.08	0.009
b_3	-2.63	0.901	-2.92	0.012
b_4	-2.58	1.03	-2.50	0.027
b_5	-1.72	0.786	-2.18	0.048

Figure 6.5 shows the relationship between piglet losses and expenditure on fencing according to this model and how variation in the dummy variables (farm location and use of electric fencing) influences this relationship. The relationship between loss and expenditure for farms with a village in their surroundings but none of the other dummy variable characteristics is not shown because losses in this case were much greater than in the others. Therefore including it would make distinction between other curves difficult. The dummy variables influence the magnitude of the effect expenditure on fencing has on piglet losses. For example, on farm with a village in its surroundings ($V = 1$) and electric fencing surrounding its pig paddocks ($EL = 1$), each penny spent on fencing has a substantial effect on losses, whereas on a farm in the Midlands ($Mid = 1$) with electric fencing ($EL = 1$), increases in preventive expenditure have very little effect on losses.

The aim of this analysis is to determine the optimal level of expenditure on fence maintenance per sow per year (MF^*) that minimises total costs. The first derivative of the function obtained from the regression with respect to MF_i is:

$$\frac{\partial La_i}{\partial MF_i} = -1.26e^{2.33-1.26\cdot MF_i+2.30\cdot V_i-2.63\cdot Eas_i-2.58\cdot Mid_i-1.72\cdot EL_i}$$

The optimal point in terms of minimising the total costs of fox predation is where this first derivative is equal to –1, which is where:

$$MF_i = 2.03 + 0.794(2.30V_i - 2.63Eas_i - 2.58Mid_i - 1.72EL_i)$$

From the optimal expenditure on fence maintenance (MF_i^*), it is possible to calculate the optimal loss of piglets the producer should accept (La_i^*), by substituting MF_i^* into the loss-expenditure function determined above. MF_i^* depends on the values of the dummy variables (V_i, Eas_i, Mid_i and EL_i), but La_i^* remains constant at all values of V_i, Eas_i, Mid_i and EL_i (Table 6.10). (The La^* values in Table 6.10 differ slightly due to the fact that figures of four significant figures were used in the calculations and subsequent rounding-up results in slightly different values.) Because La is an exponential function of MF, $\partial La/\partial MF$ is dependent on the value of La and constant at constant values of La. Therefore, at $\partial La/\partial MF = -1$, La is constant. Figure 6.6 shows the relationship between total costs and expenditure on fencing, illustrating the optimal point where total costs are minimised, for three different sets of farm characteristics (MF^*). It shows that, whilst expenditure up to the optimal point does not make much difference to total costs on a farm with an electric fence, total costs increase steeply above this point. For farms with the other two sets of characteristics illustrated (one with no dummy characteristics and the other in East England ($Eas = 1$) with a village in its surroundings ($V = 1$)), spending on fence maintenance results in steep reductions in total costs up to close to the point where they are minimised.

According to this model, in some cases it is not worthwhile for the producer to spend anything on fence maintenance, indicated by the negative values of MF_i^* for variations in farm location (Table 6.10). As would be expected from this result, the large majority of producers in the sample have higher total costs of fox predation (piglet losses plus fence maintenance) than the estimated optimal total cost (Figure 6.7). (Avoidable costs were calculated by taking negative expenditure figures as zeros, as it is not possible to spend negative amounts of money.)

Table 6.10: Variation in optimal expenditure on fence maintenance per sow per year (MF_i^*) and optimal losses of piglets the farmer should accept per sow per year (La_i^*) with the values of V_i, Eas_i, Mid_i and EL_i according to the model $\ln(La_{il}) = 2.33 - 1.26 \cdot MF_i + 2.30 \cdot V_i - 2.63 \cdot Eas_i - 2.58 \cdot Midi - 1.72 \cdot EL_i$

Value of V_i	Value of Eas_i	Value of Mid_i	Value of EL_i	MF_i^* (£)	La_i^* (£)
0	0	0	0	2.031	0.694
0	1	0	0	-0.060	0.695
1	0	0	0	3.856	0.693
1	1	0	0	1.765	0.694
0	0	1	0	-0.002	0.695
1	0	1	0	1.809	0.694
0	0	0	1	0.668	0.694
0	1	0	1	-1.423	0.695
1	0	0	1	2.494	0.693
1	1	0	1	0.403	0.694
0	0	1	1	-1.378	0.695
1	0	1	1	0.447	0.694

6.4. DISCUSSION

6.4.1. Data reliability

A couple of studies have addressed the accuracy of producer-recorded causes of pre-weaning mortality in piglets (Vaillancourt *et al.* 1990; Christensen & Svensmark 1997). These have indicated that there tends to be variation between producers in their ability to assess mortality causes, as well as variation amongst mortality causes in how well they can be identified or are likely to be mis-classified. Mortality due to predation was not a cause that was specifically assessed, but these studies indicate that producer diagnoses of causes of death can be unreliable (Vaillancourt *et al.* 1990). Rare mortality causes with primarily internal signs tended to be most mis-classified in one study (Christensen & Svensmark 1997). As fox predation is likely to leave external signs on piglets, it would not fall into this category. However, for the reasons outlined elsewhere in this thesis, predation losses will often be overestimated. Foxes sometimes carry piglets away from farms (Lloyd 1980), but, as is the case with lambs, foxes may be blamed for taking missing animals when they have been taken by another animal or go missing for some other reason. Edwards *et al.* (1994) point out that it is difficult to attribute piglet deaths to one sole cause and the ultimate cause of death may not be the most important mortality factor. Therefore piglets of low viability or that become hypothermic are more liable to be crushed (Edwards *et al.* 1994) and, one would assume, be predated upon. Bird predation of piglets was a problem on Edwards *et al.*'s (1994) study unit and they indicate that, whilst fox predation is a recognised problem, losses due to predation by birds may have been underestimated, which is potentially the case for these data.

Various studies from the literature provide figures on overall pre-weaning piglet mortality in outdoor systems to which those from this survey can be compared in order to assess their representativeness. Mean piglet mortality was slightly lower at 10.9% than that determined in two other studies based on survey data, for which the figures were 12.1% (Abbott *et al.* 1996) and 12.9% (Sheppard 1998a). It was considerably lower than on Edwards *et al.* (1994)'s study farm, where mean mortality was 20%, but this figure includes piglets born dead. Mortality in a Iowan study comparing different farrowing hut types ranged from 3.7% to 21.6% with a mean of 10.5% (Honeyman *et* *al.* 1999), whilst that of outdoor piglets in Britain is put at 10.6%, on average (MLC 1997). Figures from this study are therefore at the bottom end of the range of piglet mortality losses, but are comparable with those available from other studies indicating that the sample is representative in terms of loss figures.

Despite the fact that it was made clear both during telephone conversations with producers and on the covering letters accompanying survey forms that both producers with and without a 'fox problem' should reply, there is likely to have been a bias in the survey sample towards producers that considered this issue important. The herd size distribution of holdings was compared to that from the National Survey of Pig Production Systems using a chi-square test and found to differ significantly to that which would be expected if they were the same ($\chi^2 = 20.8$, d.f. = 6, p = 0.002 [n = 7]). There were more small holdings and more large holdings than expected. This may in part reflect a change in the structure of outdoor production since 1998, but also indicates that the herds surveyed here may not be fully representative of those in England and Wales.

6.4.2. Reported piglet predation by foxes

As was found for other producer types (Chapters 2 and 5), fox predation generally resulted in low reported losses on the majority of farms, but some farms reported experiencing high losses, of more than one piglet per sow per year in two cases. Despite the potential problems with birds predating upon piglets, reported predation by animals other than foxes was generally insignificant, mean and median losses due to all predation being very similar to those for fox predation only.

Relative fox density was not an influence on reported fox predation, but whether fox control was carried out was. This appeared not to be a reflection of positive associations between fox control and fox density, the only association found between these being a negative one. Other reasons for this could be that fox control is reactive or that it is ineffective in achieving the aim of reducing piglet losses. Some of the reasons for associations between fox control and losses have been discussed earlier (Chapter 2) and these associations will be discussed further in Chapter 8, as they were a feature of all the data sets.

None of the assessed husbandry factors were associated with the likelihood of reported fox predation having occurred. Rather, the occurrence of reported fox predation was associated with non-management factors, such as farm location and herd size. It may be that any associations between predation and the husbandry methods considered here are obscured by regional and other variation between holdings. Farms in East England were less likely to have reported experiencing fox predation of piglets, East England also being the region with the lowest of the relative fox density estimates. Whilst this may be a coincidence, it may reflect an association between fox density and fox predation or between the abundance of foxes and the perception of the fox as a problem. An explanation for reported predation being more likely to have occurred where villages were in the proximity of the farms is not immediately apparent. However, it may be that foxes are blamed for predation by dogs (kills by medium-sized dogs and foxes are indistinguishable from teeth marks (Swire 1978; Harris & Lloyd 1991)), given that dogs are more likely to be present near villages, or possibly that fox numbers are higher in and around villages. Farms with more sows were more likely to have experienced fox predation of piglets. With a larger herd size, the likelihood of at least one piglet having been predated by a fox (or believed to have been predated by a fox) will be higher than on farms with few piglets. In addition, smaller herds may be more protected from fox predation because a higher degree of surveillance by producers and farm workers per piglet is possible.

6.4.3. Costs of piglet predation by foxes

Although husbandry factors were not associated with the occurrence of reported fox predation of piglets, expenditure on fence maintenance was negatively related to piglet losses. The lack of a relationship between total expenditure on fencing and piglet losses is probably due to inaccuracies in the estimation of this expenditure. A number of producers had not given the cost of their fence when first erected and the data that were collected about the fences were not specific enough to accurately estimate these costs on an individual basis. It could also be the case that expenditure on fence maintenance more accurately captures the extra expenditure needed to fence out foxes than total expenditure on fencing does.

As predicted, losses were reduced with increasing expenditure, but at a declining rate. The analysis indicated that, in some cases, it was not worth spending on fence maintenance to prevent fox predation and that the majority of producers were experiencing avoidable costs to fox predation. The major reason for this is that fencing has a number of functions other than preventing fox predation, the most obvious being to keep pigs in. Therefore, although it may not be worthwhile financially to spend money on fence maintenance to keep foxes out, this does not mean it is not worth fencing at all. Rather, it indicates that it is not worth spending more on fencing than would be spent if losses to fox predation were not taken into account. In addition, because it is expenditure on fence maintenance that is considered here rather than expenditure on fencing overall, it can not be assumed that nothing should be spent on fencing at all to prevent fox predation in these cases. The use of electric fencing also resulted in lower piglet losses to foxes indicating that the expenditure variable did not account for all the effects of fencing in terms of reducing fox predation. This will at least be in part because electric fencing is not necessarily more expensive to maintain than other fencing types. This association reveals electric fencing to be an effective preventive measure against fox predation of piglets.

Both piglet losses and expenditure on fencing were based on figures reported by respondents. As discussed previously (Chapter 3 Section 3.5.1), there are a number of problems with using reported data in an economic model such as this. These figures will not be wholly accurate, whilst the criteria that individual producers have taken into account when reporting the amount they spent on fence maintenance in the previous year are unknown. A further problem with the model is that fox predation may be a compensatory rather than an additive mortality factor for piglets. This is supported by the fact that piglets are unlikely to die from one sole cause, as discussed earlier, and complicates the assessment of the loss of piglets due to fox predation. If piglet losses due to fox predation were not wholly compensatory, the minimisation of predation losses would seem an advantageous strategy for producers to adopt, as the direct loss of suckling pigs results in a loss of profit (Thornton 1988). Nevertheless, McOrist *et al.* (1997) suggest that the impact of serious mortality may be less important to advanced sectors of the pig industry than production diseases.

A problem that foxes may pose to outdoor pig producers, which was not considered here, is their involvement in disease spread. Pigs are probably susceptible to more diseases than any other livestock species (Cottle & Cottle 1998) and foxes may be carriers of some of these. For example, Enemark *et al.* (2000) suggest that *Trichinella* infection in Danish foxes might constitute a serious risk for the expanding outdoor pig sector. The risk of disease spread to livestock by foxes in Britain is unknown, but is generally considered to be relatively low (Macdonald *et al.* 2000; White *et al.* 2000a).

6.4.4. Model criticism

A number of tests were performed to assess whether the regression model of piglet losses due to fox predation against expenditure on fence maintenance and the various dummy variables ($\ln(La_{i1}) = 2.04 - 1.17 \cdot MF_i + 2.18 \cdot V_i - 2.58 \cdot Eas_i - 2.18 \cdot Mid_i - 1.60 \cdot EL_i + \varepsilon_i$) fitted the assumptions of regression and therefore whether the model was appropriate. The hypothesis that the error was normally distributed could not be rejected, tested using a Kolmogorov-Smirnov test of the goodness-of-fit of the standardised residuals from the regression to a normal distribution (Z = 0.506, p = 0.960 [n = 19]). A plot of standardised residuals against predicted values revealed no obvious heterogeneity of variance. However, this was difficult to ascertain with such a small sample. A Levene's test of equality of error variances was performed and the null hypothesis that the variance was homogeneous was not rejected at the 5% level of significance (F = 2.77, d.f. 8, 10, p = 0.067 [n = 19]). There was no cause to suspect multicollinearity between variables, the highest Variance Inflation Factor (VIF) being 1.29 and the lowest Tolerance 0.776. No points appeared overly influential in determination of the model (maximum Cook's distance = 0.325, maximum centred Leverage = 0.496, mean Leverage = 0.263) with no standardised residuals having values of greater than two or less than minus two.

The Durbin-Watson *d*-statistic for the model, when data were sorted according to expenditure on fence maintenance, suggested there may be a problem with the form of the model fitted in that there was potentially a negative autocorrelation between residuals ($d = 2.81$, $4 - d_{\text{Ucrit}} = 2.23$, $4 - d_{\text{Lcrit}} = 3.44$ at $\alpha = 0.01$ (n = 19, k = 5), i.e. d is within the critical region). The *d*-statistic calculated for the model when data were ordered according to the y-variable indicated that the model consistently over- or underestimated the true values of piglet losses at particular y-values ($d = 1.39$, $d_{\text{Ucrit}} = 1.77$, $d_{\text{Lcrit}} = 0.56$ at $\alpha = 0.01$ (n = 19, k = 5), d is within the critical region), but this was not the case when data were ordered according to predicted value ($d = 1.83$). This may be a symptom of the small number of data points in the sample for the regression meaning that heterogeneity of variance is more likely across the fitted values and that there will be very few data points with the same covariate patterns. The model explained over 70% of the variance in piglet losses ($R^2 = 0.730$) and all the estimated coefficients were significant at least at the 5% level (Table 6.9).

The small size of the sample of pig producers for which this model was estimated is also a problem for using the results of the model in generalising to outdoor pig producers in Britain. In the overall sample for which data were available, 40713 sows were surveyed, which is approximately 30% of the herd of outdoor sows in England and Wales, based on figures from the National Survey of Pig Production Systems in 1998 (Sheppard 1998b). This sample therefore should be fairly representative of outdoor producers across the country, given that producers from all regions, except South Scotland, were represented, if the presence of a sample bias can be disregarded. However, as discussed earlier, the size distribution of holdings appeared not to be representative. Herd size was a significant factor affecting reported fox predation, but not piglet losses. Therefore the fact that small and large farms may have been over-represented in the sample compared to farms nationally may not be important for determining the applicability and generality of results.

6.5. CONCLUSIONS

It was possible to apply the loss-expenditure approach to the data collected on losses of piglets to foxes on outdoor units. This enabled electric fencing to be identified as a preventive measure against fox predation, as well as suggesting that fox predation was not significant enough a problem to warrant expenditure to prevent it on a number of farms. There were limitations with the data, in that the sample size was small and that they contained potential inaccuracies, meaning that specific output figures from the model should be interpreted with caution. Although logistic regression analyses did not identify any management or husbandry factors linked to fox predation, they identified those farm characteristics that were associated with reported predation. These enable the identification of farms where foxes are (or are perceived to be) a problem, at which measures to reduce these problems could be targeted.

SUMMARY

Some outdoor pig producers are said to experience serious losses of piglets to foxes. However, whilst studies have assessed pre-weaning mortality in outdoor herds, none have addressed the problem of fox predation. This chapter aimed to investigate levels of fox predation, assess what husbandry and management factors are associated with fox predation of piglets in Britain and evaluate the costs of fox predation to pig producers.

A questionnaire survey of outdoor pig producers was carried out and these data used to investigate the association between fox population density and piglet predation, as well as the factors affecting the occurrence of reported fox predation on farms via correlation, chi-square and logistic regression analyses. The theoretical model of Chapter 3 was used as a basis for analysing the costs of piglet predation by foxes, in terms of piglet losses and fencing costs.

Reported fox predation of piglets was generally low for most producers, but over half the producers surveyed (54%) reported at least one piglet killed by a fox. Fox control was associated with a higher likelihood of fox predation and farm location factors were also important. In addition, farms with larger herds were more likely to have experienced predation.

Although none of the assessed husbandry factors were associated with the occurrence of reported fox predation, there was a negative relationship between expenditure on boundary fence maintenance and piglet losses. Assessment of the trade-off between expenditure and losses in an economic framework enabled electric fencing to be identified as an effective measure against fox predation, as well as indicating that some producers should not spend anything on fence maintenance specifically to prevent fox predation.

As with all survey data, the reliability of the loss and expenditure data collected here is unlikely to be completely accurate. However, the analyses enabled the economic efficiency of fencing to prevent fox predation to be assessed. In addition, the characteristics of farms where fox predation is more likely to be (or be perceived to be) a problem were identified, which can be used to target measures to reduce these problems on individual holdings.

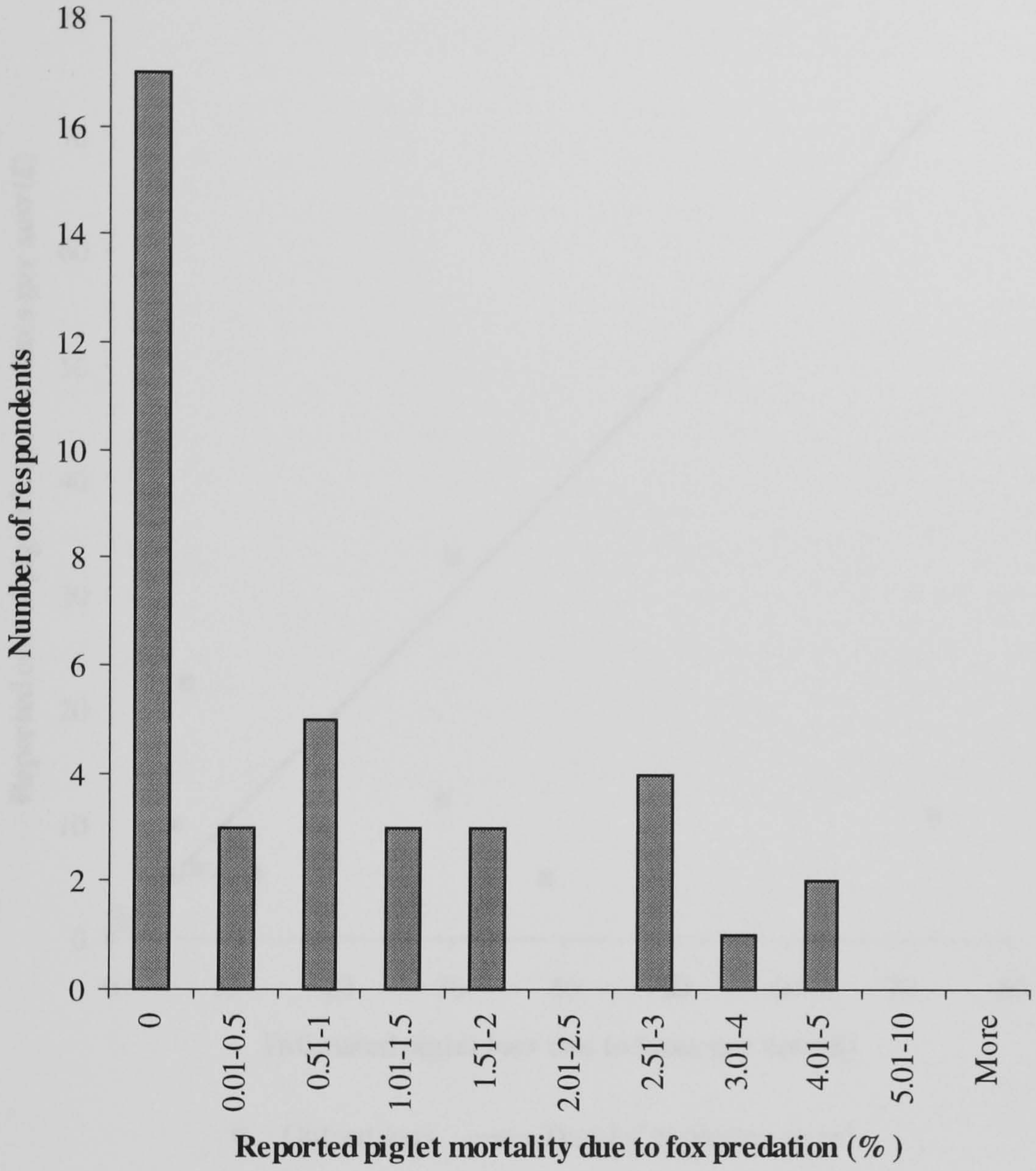


Figure 6.1: Histogram of responses for reported piglet mortality due to fox predation [n = 38]

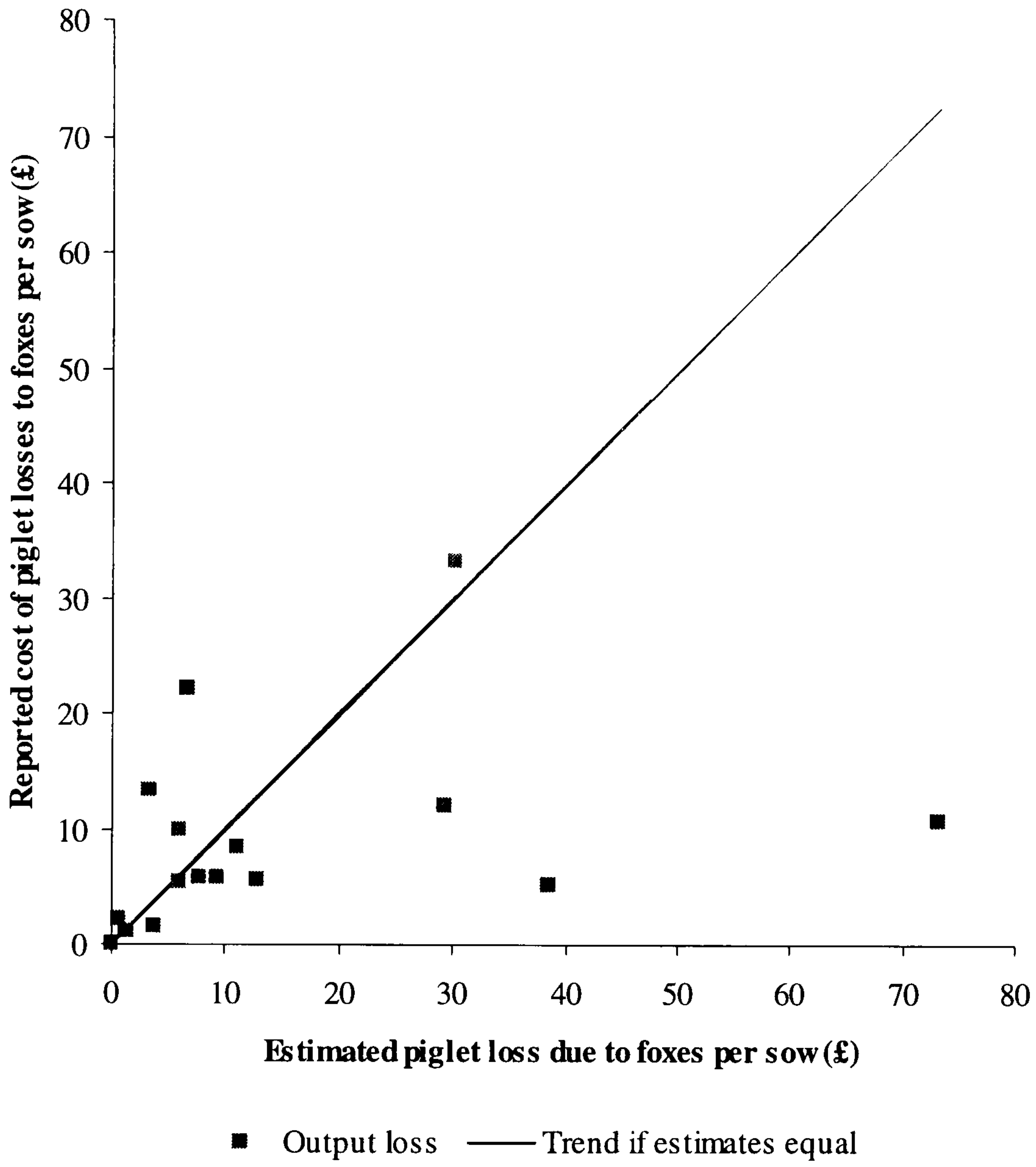


Figure 6.2: Reported costs of piglet losses to foxes per sow compared to estimated output loss due to fox predation per sow [n = 32]

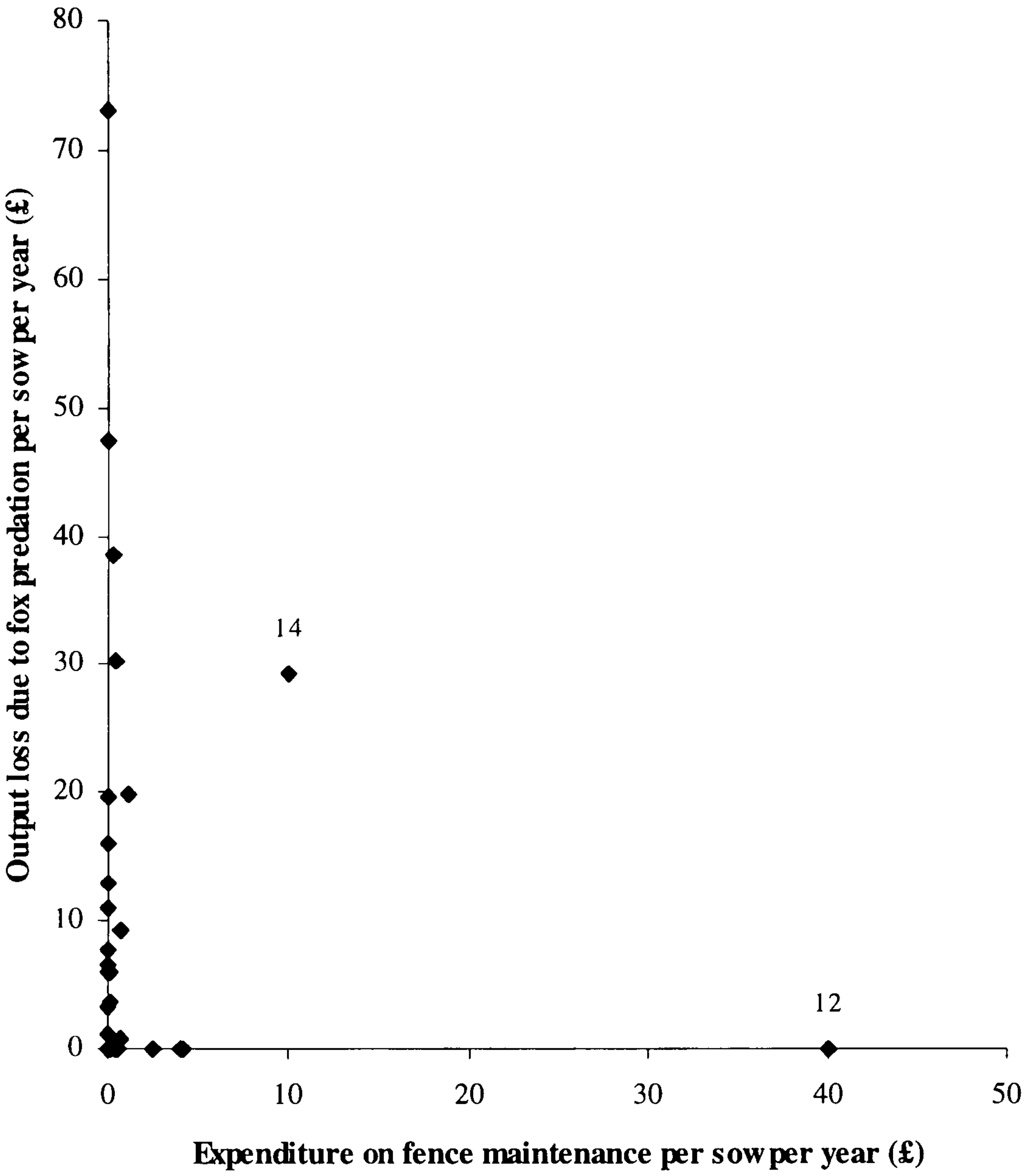


Figure 6.3: Total costs of fencing per sow per year compared with output loss due to fox predation [n = 21], data points 12 and 14 are marked

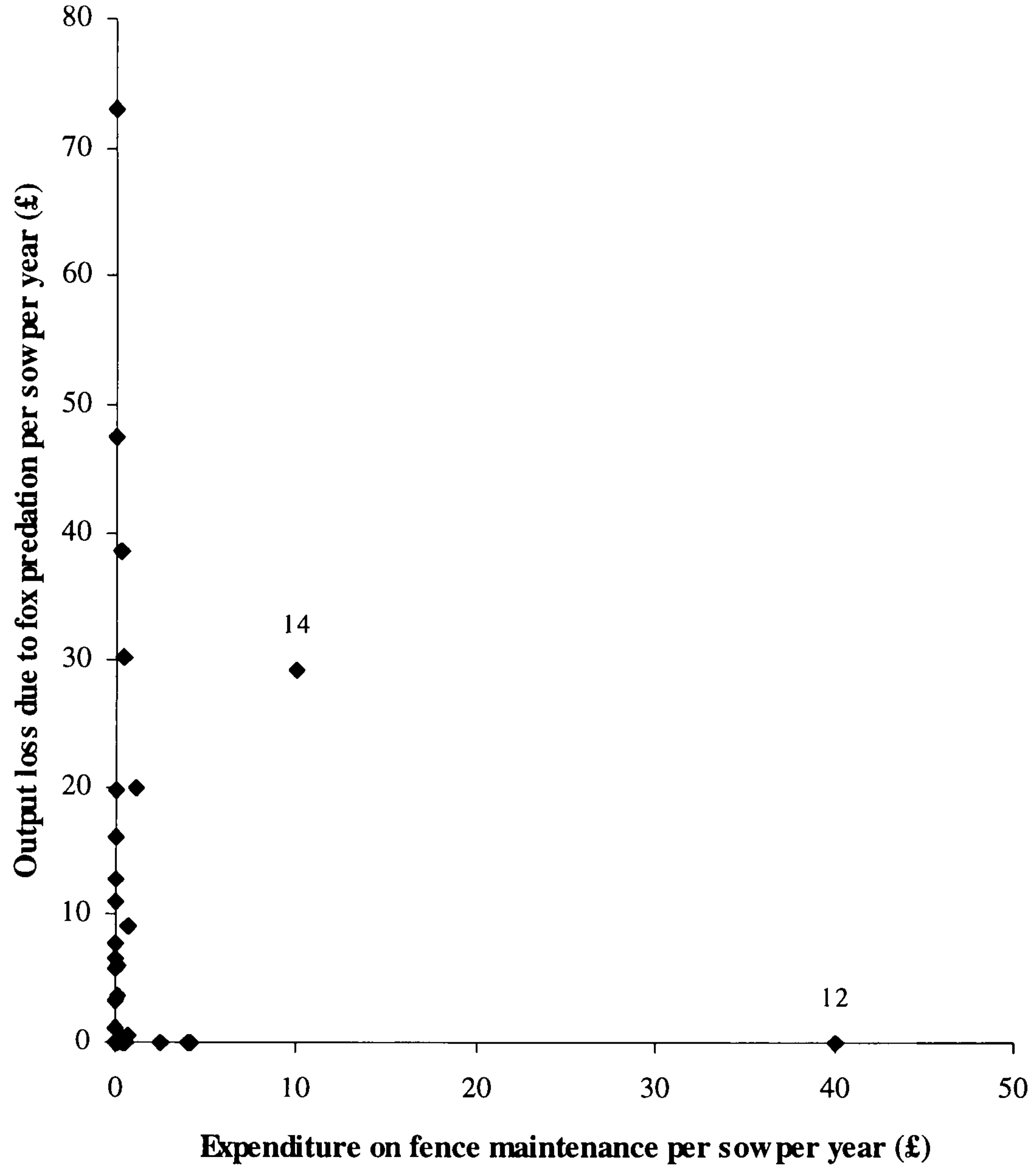


Figure 6.4: Costs of fence maintenance per sow per year compared with output loss due to fox predation [n = 21], data points 12 and 14 are marked

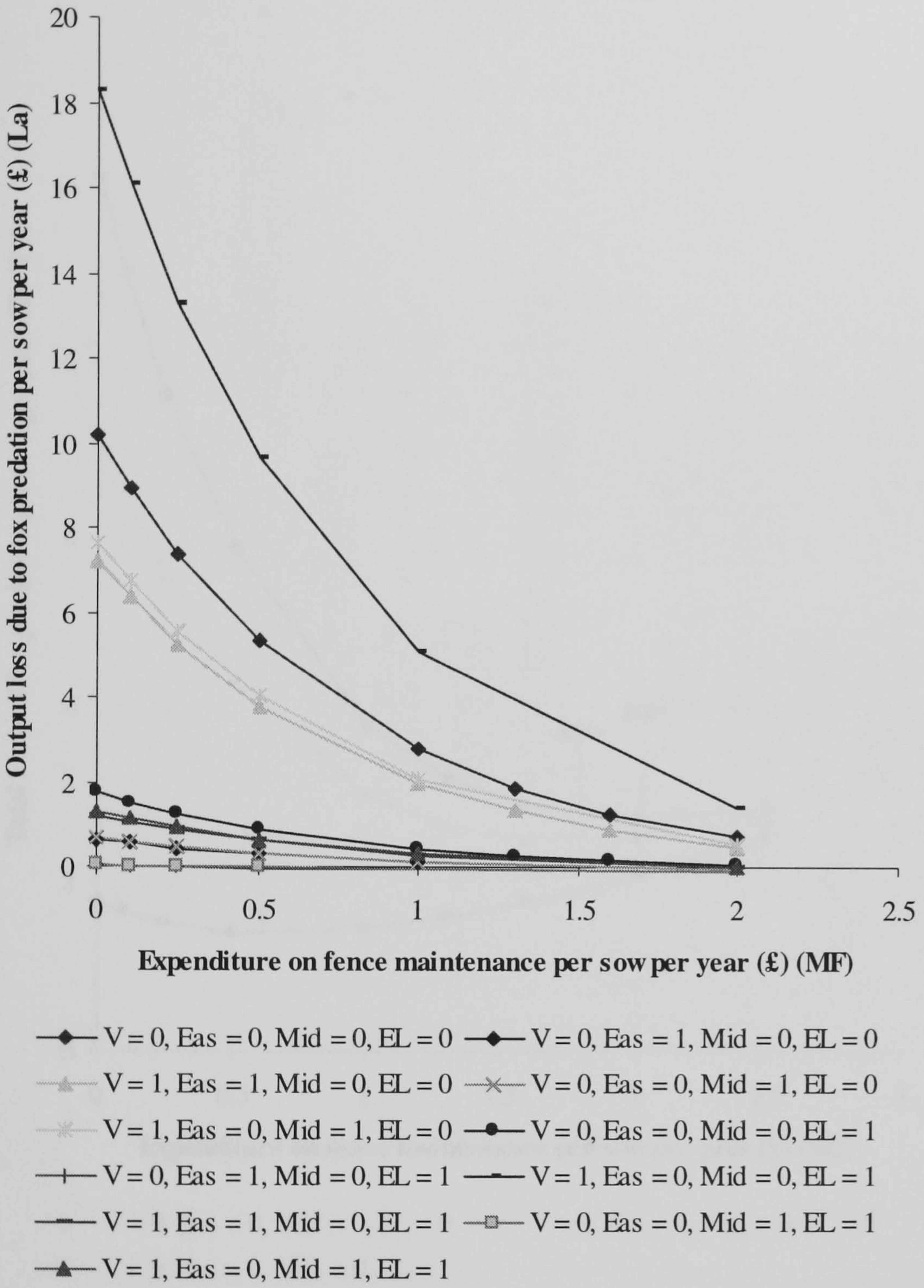


Figure 6.5: Relationship between piglet losses to foxes and expenditure on fence maintenance with variation in farm characteristics, according to the model, $\ln(La_{i1}) = 2.04 - 1.17 \cdot MF_i + 2.18 \cdot V_i - 2.58 \cdot Eas_i - 2.18 \cdot Mid_i - 1.60 \cdot EL_i$ (V = farm has village in surroundings, Eas = farm in East England, Mid = farm in Midlands, EL = electric fencing used)

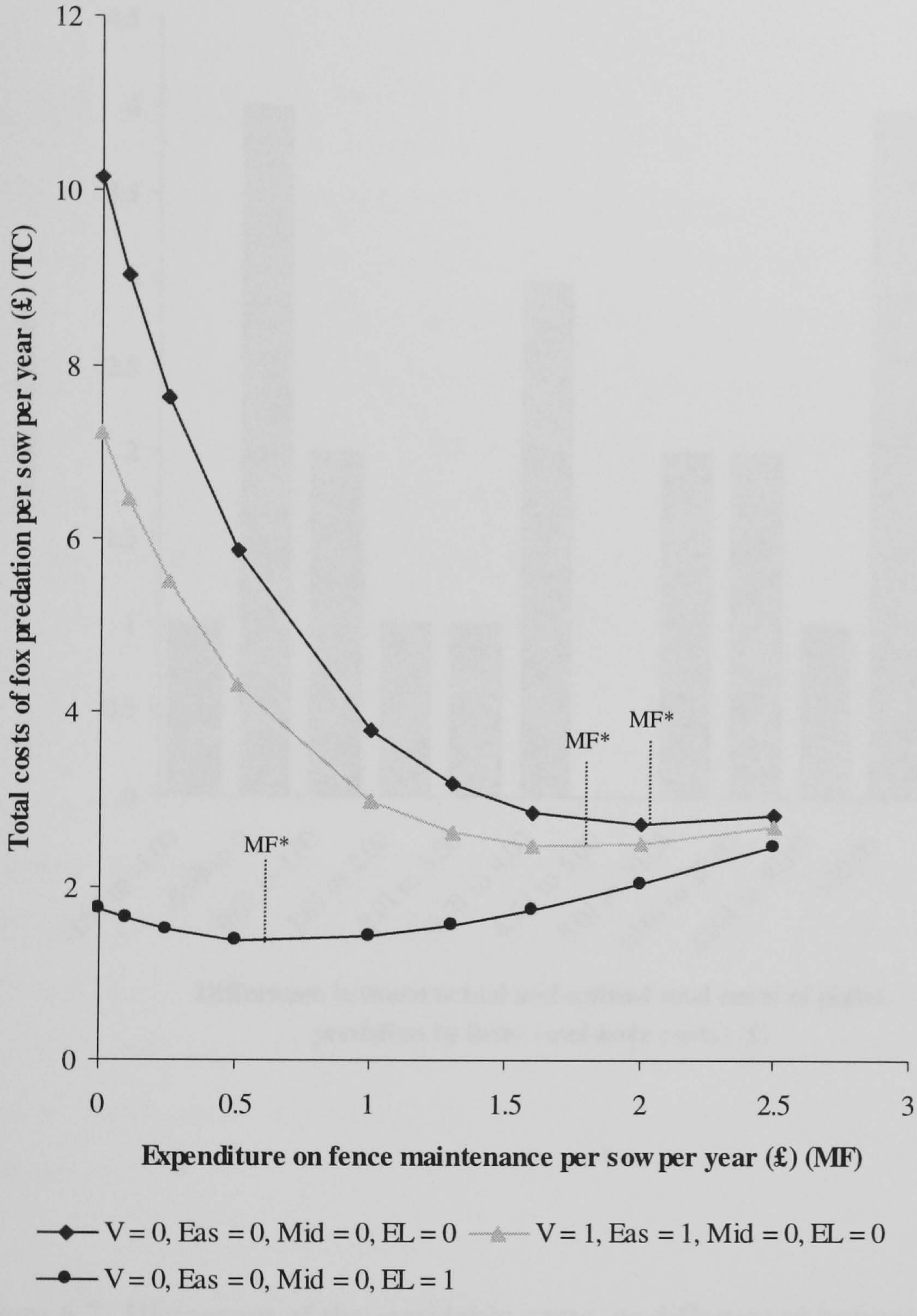


Figure 6.6: Relationship between total costs of fox predation and expenditure on fence maintenance with variation in farm characteristics, showing the point where total costs are minimised in each case, marked *MF** (*V* = farm has village in surroundings, *Eas* = farm in East England, *Mid* = farm in Midlands, *EL* = electric fencing used)

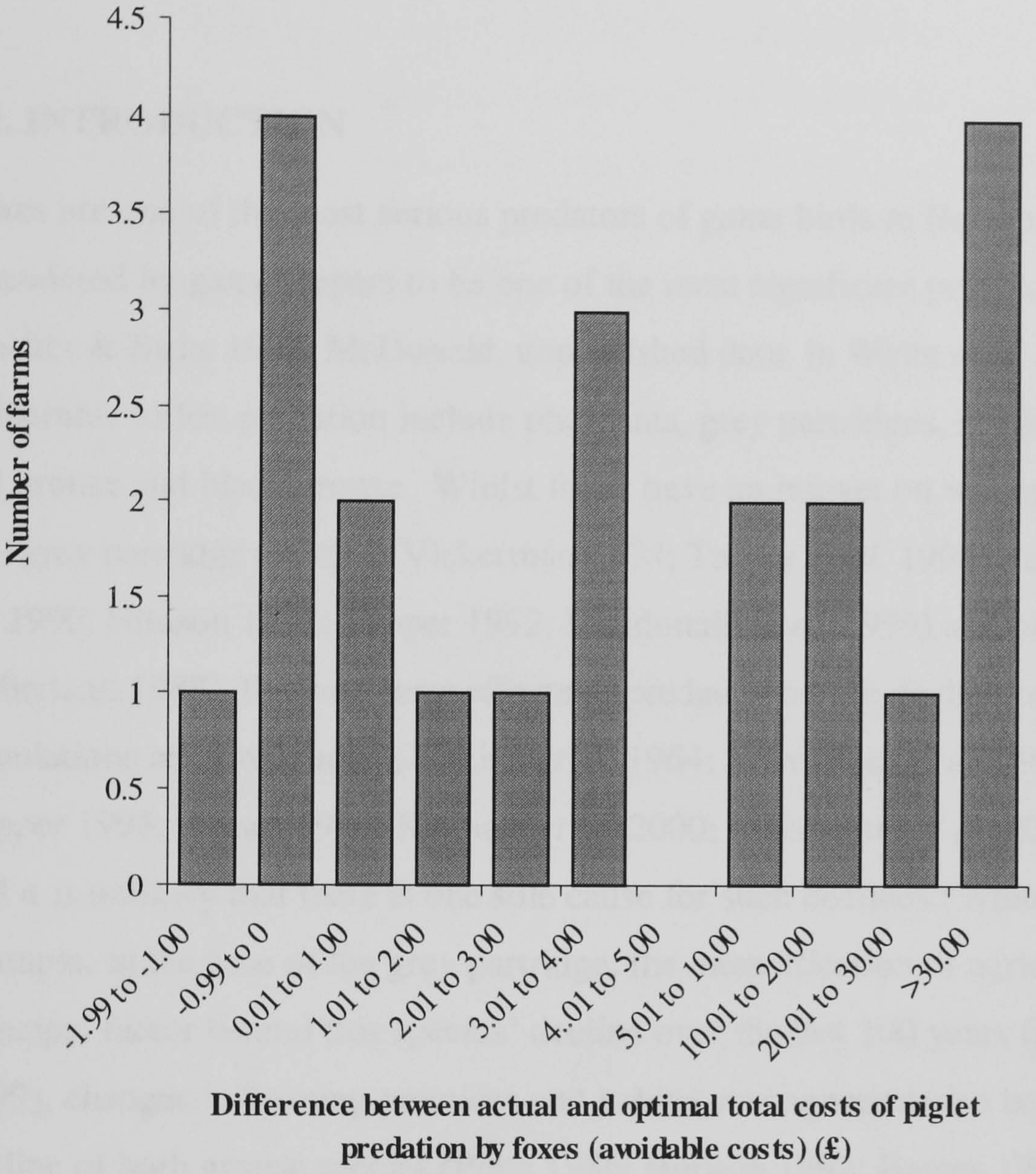


Figure 6.7: Histogram of the avoidable costs, or differences between actual and estimated optimal total costs, of fox predation to pig producers (including the costs of piglet losses and the costs of boundary fence maintenance) [n = 21]

CHAPTER 7

IMPACTS OF FOXES ON GAME INTERESTS: PREDATION ON RELEASED PHEASANTS

7.1. INTRODUCTION

Foxes are one of the most serious predators of game birds in Britain and they are considered by gamekeepers to be one of the most significant pests to their interests (Packer & Birks 1999; McDonald, unpublished data, in White *et al.*, 2000a). Species vulnerable to fox predation include pheasants, grey partridges, red-legged partridges, red grouse and black grouse. Whilst foxes have an impact on wild game populations, e.g. grey partridge (Potts & Vickerman 1974; Tapper *et al.* 1996), red grouse (Moss *et al.* 1990; Hudson 1992; Tapper 1992; Macdonald *et al.* 1999) and pheasants (Hill & Robertson 1988), the long-term effects of predators on the decline of wild game populations are ambiguous (Jenkins *et al.* 1964; Märcstrom *et al.* 1988; Reynolds & Tapper 1995; Baines 1996; Kauhala *et al.* 2000; Macdonald *et al.* 2000; Kauhala 2001) and it is unlikely that there is one sole cause for such declines (White *et al.* 2000a). For example, in the case of the grey partridge, the intensification of agriculture has been the principal factor behind this species' decline over the last 100 years (Potts 1986; Smith 1999), changes in farming practices and habitat management also being important in the decline of both grouse species (Potts 1986; Hudson 1992; Baines 1996). Disease is another important determinant of grouse density and productivity (Duncan *et al.* 1979; Hudson 1992).

One of the problems with studies on the effects of fox predation on wild game populations is that they have tended to investigate the impacts of a number of predators rather than focus on foxes, e.g. Jenkins *et al.* (1964), Märcstrom *et al.* (1988), Hudson *et al.* (1992) and Tapper *et al.* (1996). It appears that whilst fox predation can account for the deaths of a substantial proportion of resident wild game bird populations, game birds are generally a small component of fox diets (Hill & Robertson 1988; Lovari & Parigi 1995; Reynolds, unpublished data, in Macdonald *et al.*, 2000), but are more important to foxes in years when rodent numbers are low (Leckie *et al.* 1998). The significance of the impact of foxes on wild game shoots will depend on the objectives of the manager with respect to game bird populations, for example, whether population sizes are to be maximised in the short-term or long-term or whether bag quality rather than quantity is preferred.

The most serious predation impact of foxes for game shooting in terms of numbers of birds killed, and therefore in economic terms, is on reared game (Smith 1999) (although the potential long-term effects on wild game populations are highly significant in conservation terms). Pheasants make up the majority of the national annual shooting bag of those ground-nesting game birds that are vulnerable to fox predation (Cobham Resource Consultants 1983), the importance of pheasants as a game bird having increased dramatically during the 20th century from making up around 15% of all game birds shot at the turn of the century to more than 55% in the 1980s (Tapper 1992). This increase was primarily due to an increase in the number of birds reared and released for driven shoots, as the wild pheasant population is unlikely to have increased over this period (Tapper 1999). It appears that the numbers of pheasants shot have not increased in proportion with increases in the numbers released, however (Hill & Robertson 1988). Although the management of wild pheasants is fairly common in Norfolk, where they may contribute up to 50% of the bag, game-shooting relies heavily on reared birds (Bingham 1993). In a survey of British gamekeepers in 1998, the majority of which were located in England, 80% of respondents worked on shoots classified as relying primarily on released pheasants (McDonald & Harris 1999).

The majority of pheasants are released into release pens as poults, at an age of six to seven weeks, in July or August prior to the start of the pheasant shooting season in November (Game Conservancy 1983; Hill & Robertson 1988). It has been estimated that 20 million pheasants are released each year and 12 million are shot, implying there is an annual mortality of 40% of released birds (Anon 1997), although a number of birds that are not shot will join the wild population (White *et al.* 2000a). Whilst bad weather, road kills, disease and pen deaths account for some of this mortality, the major cause of pheasant death is predation, with foxes being their main predator (Hill & Robertson 1988; Robertson 1997). Hand-reared birds generally experience their greatest mortality between release and the start of the shooting season (Hill & Robertson 1988). In a study of pheasants released on an estate in Co. Kildare, Ireland, foxes accounted for 93% of the losses due to predation (Robertson 1988) and 64% of total losses (Hill & Robertson 1988), whilst, in Hampshire, losses to foxes comprised 80% of birds killed by predators (M. Gill, unpublished data, in Hill and Robertson 1988). Foxes were responsible for the majority of mammalian kills of pheasants in a study of poult mortality from 32 release pens in southern England (Kenward *et al.* 2001). Although foxes tended to cache or remove kills, they left feathers that had been bitten through the shaft (Kenward *et al.* 2001), an indication of fox predation (Harris & Lloyd 1991).

Most pheasants are released into permanent, large, open-topped pens sited in woodland habitats (Game Conservancy Trust 1996). They remain in the pens until able to fly out, which may be up to a few weeks after release, but still return to the pens after this time through one-way entrances in the netting, especially at night to roost (Hill & Robertson 1988; Game Conservancy Trust 1996). Because of the vulnerability of poults to predation in the release pens, gamekeepers use various anti-predator measures at their pens (Game Conservancy Trust 1996; Packer & Birks 1999). These include fox grids over entrances to prevent foxes from entering (though cubs and small adults may still be able to pass these), extra wire netting at the top of the pen to act as an anti-fox or anti-predator fringe, extra wire netting at the bottom to prevent digging under (this may be dug-in or penned down), electric fencing, a 'wall' of fox snares around the pen and scarers, such as flashing lights (Hill & Robertson 1988; Game Conservancy Trust 1996; Packer & Birks 1999; Kenward *et al.* 2001).

Losses from release pens are likely to be affected by factors including how well pens are constructed, the habitat within the pen and predator control in the vicinity (Hill & Robertson 1988). Pheasants are particularly vulnerable to birds of prey in the release pens (Hill & Robertson 1988; Game Conservancy Trust 1996), though these losses may be of little significance in comparison to overall losses to foxes (Hill & Robertson 1988). Losses to birds of prey are affected by the amount of cover inside pens (Lloyd 1975; Kenward *et al.* 2001), whilst predation by buzzards is more likely to occur where more birds are released (Kenward *et al.* 2001). Released bird losses tend to be highest during the period when they first emerge from the pens and before they are able to roost in trees properly, fox predation being especially high at this time (Hill & Robertson 1988). However, if they are able to breach pen defences, mammalian predators may carry out mass kills of birds within pens (Game Conservancy Trust 1996), for which the financial costs can equate to more than just the birds killed, as pheasants may flee and not return to the pen area (Balharry & Macdonald 1999).

Whilst some shoots rear their own pheasants for release, a large number are reared intensively on commercial game farms. As with poultry, game birds are also subject to fox predation during this rearing stage and game farms or individual rearers must invest in measures to prevent predation from having an impact (Game Conservancy 1983; McGill 1999). However, the majority of losses of breeding adults are due to disease (Pennycott 2000).

Pheasants are primarily released for driven shoots, which rely on high densities of birds to produce large bags for sportsmen paying fees. Driven shoots involve a line of beaters driving the quarry to the sportsmen or guns. The main income of such shoots comes from shooting fees, carcass sales being insignificant (SAC 2001), a slump in pheasant prices in 2000 making income from sales even lower (NFU 2000). Rough shoots generally involve wild birds, as densities of birds do not have to be as high as for driven shoots. They are less commercially valuable than driven shoots, but often provide indirect revenue to rural communities. The fees paid for a day's shooting are dependent on the number of birds shot or the bag size, this being agreed beforehand with the guns. Thus the shoot owner or manager will maximise profits through maximising the number of birds shot.

A number of studies have assessed predation of released pheasants by both mammalian and avian predators, including foxes, e.g. Lloyd (1975), Kenward (1977), Robertson (1988), Hill and Robertson (1988), Sodeikat *et al.* (1995), Packer and Birks (1999) and Kenward *et al.* (2001). Research by Baker and Macdonald (2000) involved asking farmers if they had experienced losses of gamebirds to foxes and assessing how this was associated with fox control and perceptions of the fox as a pest. However, no studies to date have addressed what factors affect fox predation of released pheasants or the effectiveness of preventive measures and fox population control. In addition, studies have not considered variation in predation of pheasants on a regional scale.

This chapter assesses the problem of fox predation of released pheasants for driven shoots. Only losses of birds from release pens were considered. Although fox predation is likely to be the cause of some losses of birds once they have left the pens completely, a field study would be the best way of assessing this problem. This is also true of predation of wild birds. Data for this chapter were collected via a survey of gamekeepers, in order that variation in pheasant predation by foxes across Britain could be considered. Analyses were carried out to assess the factors associated with reported fox predation of pheasants from release pens, including fox population density. The costs of pheasant predation, as well as preventive measures and fox control, to shoots were considered in the economic framework developed in Chapter 3 and the hypothesis of a negative relationship between losses and preventive expenditure tested. In addition, associations between fox control and fox density on shoots were considered.

7.2. METHODS

7.2.1. Questionnaire survey of gamekeepers and estates

On the 13th October 2000, 202 questionnaires with an explanatory letter and Freepost envelope were sent directly to contacts from the Yellow Pages, The Field, Shooting Times and Hotbarrels (*www.hotbarrels.com*). Searches were performed on the Yellow Pages web-site (*www.yell.co.uk*) for 'Gamekeepers', 'Estate Managers' and 'Stately Homes' to obtain addresses, whilst in the case of The Field, Shooting Times and Hotbarrels, addresses of shoots or estates were taken directly from advertisements. In a few cases, where only telephone numbers were available, calls were made beforehand to obtain addresses and permission to send questionnaires. The questionnaire consisted of questions on the types of shoots run and area of shoot, land-uses surrounding shoots, fox control, pheasant release pens and losses to predation and other causes from release pens that year (Appendix G). The questionnaires were designed to fit on two sides of a single A4 sheet of paper. Reminder questionnaires and letters were sent to non-respondents on the 21st November 2000.

7.2.2. Relative fox population density estimates

Each holding in the data-set was allocated a region-based and a land class-based relative fox density estimate, termed 'regional fox density' and 'land class fox density' (as described in Sections 2.2.3 and 5.2.2). Non-parametric correlation analyses were used to test the associations between relative density estimates and the numbers and percentages of pheasants (out of the total released) reported killed by foxes and the percentage of shoots within each region and land class group reporting predation.

7.2.3. Factors influencing reported fox predation of pheasants from release pens

Statistical analyses were used to assess whether factors on which information was collected were associated with the occurrence of reported fox predation of pheasants from release pens and the scale of reported fox predation. The variables used in these analyses are summarised in Appendix H. Data were transformed where necessary to meet the assumptions of normality of error and homogeneity of variance for linear regression. Chi-square tests and logistic regression analyses were used to assess the associations between the occurrence of reported fox predation on a holding and other factors. The dependent variable in all logistic regression models was a binary response variable, coded zero for no reported fox predation of pheasants from pens and one for at least one bird having been reported killed by foxes. This variable was also used in the chi-square tests. Uni- and multivariate analyses were used to assess relationships between the dependent variable and the various factors considered. All variables were tested against the dependent variable on their own at first. Chi-square tests were used for all analyses involving one other categorical variable and logistic regression for analyses using a continuous variable. Subsequently all variables were tested once again in a model including those variables that were statistically significant in the first round of tests in order to identify an overall multiple logistic regression model accounting for variation in the likelihood of reported fox predation.

Where predation occurred, linear regression models were applied to examine relationships between the variables under consideration (Appendix H) and the proportion of pheasants killed out of those released on shoots where fox predation occurred. Data for holdings where no losses to foxes occurred were removed. This dependent variable was natural log-transformed to reduce the right skew of the data distribution. Initially all variables were tested against the dependent variable in univariate regression analyses. They were then included in a model with those variables that were statistically significantly associated with the dependent variable on their own, enabling an overall linear regression model to be identified.

7.2.4. Costs of pheasant predation by foxes from release pens

7.2.4.1. Theoretical model

The theoretical model of Chapters 3 (Section 3.2) and 5 (Section 5.2.4) was used as a basis for analysing the costs of pheasant predation by foxes from release pens to shoots. Two preventive measures were considered: fox control by gamekeepers on the shoot (assumed to be a measure preventing foxes from being in the vicinity of the pens) and release pen design characteristics used to prevent fox predation. Losses of pheasants to foxes (in monetary terms) were assumed to be a function of expenditure on the preventive measure(s) and various other characteristics of the shoot, such as regional location:

$$Lc_i = f(MF_i, R_i)$$

where:

Lc_i = pheasant loss to foxes from release pens per bird released per year on the ith shoot (£)

MF_i = expenditure on preventive measures per bird released per year on the ith shoot (£)

R_i = regional location of the ith shoot

f = function of shoot characteristics determining pheasant losses to foxes from release pens

The hypothesis is that the relationship between pheasant losses and preventive expenditure is negative, with diminishing returns (in terms of losses) to marginal expenditure increases, reflecting the assumed trade-off between these two costs, as outlined in Chapter 3 and by McInerney (1996) for the loss-expenditure frontier (Figure 1.1). It is assumed that the shoot manager or owner aims to minimise the total costs of fox predation of pheasants, which are equal to pheasant losses to foxes plus expenditure on the preventive measure(s). The optimal point where this is achieved is where marginal pheasant losses equal marginal preventive expenditure.

7.2.4.2. Valuation of pheasant losses due to fox predation from release pens

It was assumed that pheasants killed by foxes in release pens would have survived to be shot, if they had not been killed. This assumption is not wholly realistic because, as discussed in the Introduction, mortality of released pheasants is high and birds that were reported killed by foxes may have died later from another cause other than shooting. Therefore estimates of a pheasant's value, as calculated here, will be positively biased. The value of a pheasant when it is shot was estimated from data on the prices of driven shoots with respect to daily pheasant bags. The prices per gun for a day's shooting, the number of guns and the pheasant bag of 33 pheasant shoots across Britain were taken from Hotbarrels.com. The total income from a day's shoot was calculated by multiplying the price per gun by the number of guns. This total income per shoot day was regressed against the pheasant bag to estimate the value of a shot pheasant. The region in which the shoot was in was also included as a dependent variable, as was the number of guns. (The market price of a pheasant carcass was considered an unrealistic measure of its value. Market prices for pheasants are low and their main value lies in the shooting fees, as discussed earlier.) The value of a shot pheasant will overestimate the value of a pheasant taken from a release pen. An alternative to using this value is to use the price of a poult when they are bought in. The price of a seven week old pheasant poult is around £2.50. This value, however, will underestimate the true value of the pheasant partly because it does not include the extra resource cost up to the point that the pheasant was killed. Both the value at shooting and the value of a poult were multiplied by the proportion of pheasants reported killed by foxes out of the total released to obtain two estimates of the losses of predation by foxes per pheasant released in monetary terms.

7.2.4.3. Expenditure on fox control by gamekeepers

Expenditure on fox control was estimated as a proportion of the cost of employing gamekeepers on the shoot. Respondents were asked how many full-time, part-time and casual gamekeepers were employed on their shoot. One data point was removed from the sample, for a shoot where no gamekeepers were employed and only one fox was killed. Expenditure on employing gamekeepers was calculated as £17,725 per annum for a full-time keeper (equivalent to a foreman's wage in Nix, 1999). Employer's National Insurance contributions were added to this by taking off the earnings threshold of £4385 and taking 12.2% of this remainder (£1627), giving a total expenditure of

£19,352. Hourly wages for part-time and casual workers were taken from Nix (1999) as £4.36 and £3.69 respectively. Part-time workers were assumed to work a 16-hour week for 52 weeks of the year and casual workers a 39-hour week for 12 weeks of the year. These calculations meant the expenditure on employing a part-time keeper was £3628 per annum and that of employing a casual keeper £1727 per annum. The total expenditure on employing gamekeepers on the shoot was estimated by adding up the expenditures on employing full-time, part-time and casual keepers according to the numbers of each employed. This total expenditure was converted to the expenditure on fox control by taking the percentage of their time that keepers spent on fox control (as given by respondents). This was divided by the number of pheasants released to give the expenditure on keeper fox control per pheasant released.

7.2.4.4. Expenditure on release pens and associated preventive measures

A height of release pen netting of 1.8m was assumed (as per Game Conservancy recommended minimum netting height (Game Conservancy Trust 1996)), with an extra 30cm at the top for an anti-fox fringe and another extra 30cm for dug-in or penned-down netting (Game Conservancy Trust 1996). Mean prices for netting per metre were calculated from a number of suppliers, according to the height of netting required: £1.04 per metre for a height of 1.8m; £1.22 per metre for a height of 2.1m (i.e. either an anti-fox fringe or dug-in or penned-down netting); and £1.39 per metre for a height of 2.4m (i.e. an anti-fox fringe and dug-in or penned-down netting). Information on whether pens had an anti-fox fringe and dug-in or penned-down netting were taken as given in the survey. The total length of netting used was multiplied up from the length of netting allowed per bird as given, or as 1m per poult if less than 500 poults were released in each pen and 0.6m per poult if 500 or more birds were in each pen (Game Conservancy 1983), by multiplying by the number of pheasants released. (The number of birds released per pen was calculated by dividing the number of pheasants released by the number of pens.) Expenditure on netting for pens was calculated by multiplying this total length of netting by the price per metre, according to the estimated amount used, and this was divided by the number of years for which pens were expected to last (as given) to give a per year figure.

Expenditure on electric fencing (for those shoots that used this on their pheasant release pens, as stated by respondents) was taken as the mean for polywire from a number of electric fence suppliers at £0.10 per metre for a three strand fence multiplied by the number of metres of netting as calculated above. To this was added the price of an energiser, at £55 per pen for pens with less than 260m of fencing and £85 per pen for pens with 260m or more. (The amount of fencing per pen was calculated as the total netting length divided by the number of pens.) This figure was also divided by the number of years pens were expected to last to give a per year expenditure figure.

For respondents using fox grids over the pen entrances, it was assumed that there would be one entry point per 50m of netting or, if pens used less than 200m of netting, four entrances per pen (as is advised by the Game Conservancy (Game Conservancy Trust 1996)). The mean price for a fox grid, from two suppliers, was £8.00 and this was multiplied by the assumed number of fox grids and then divided by the expected lifespan of the pens. It was assumed that 20 snares would be used per pen for snare walls (for those respondents stating they used snare walls) and that snares were bought new each year. The price of one snare was taken as £2.30 (£1.30 for the snare and £1.00 for the tealer), the mean price from two suppliers.

Flashing lights, used as scarers, and radios (also scarers as stated by some respondents under 'other' measures used to prevent foxes from entering pens) were assumed to last three years. Two flashing lamps were assumed to be used per pen at a mean price of £9.50 per lamp (taken from two suppliers) and one radio was assumed to be used per pen at a price of £10. These were multiplied up by the number of pens for those respondents using these measures and divided by the number of years they were assumed to last. Those respondents that used Renardine to deter foxes were assumed to buy one 5L bottle per year, at a mean price of £25.

Total expenditure on pens and preventive measures was calculated by adding up expenditure on netting, electric fencing, fox grids, snares, scarers and deterrents and this was divided by the number of pheasants released to give a figure per pheasant released. Expenditure on pen preventive measures only was also calculated by only including the extra costs of release pen netting for dug-in or penned down netting and anti-fox fringes, i.e. not the cost of the standard 1.8m of netting, in the calculation.

Expenditure on keeper control, expenditure on release pens and preventive measures and the two of these added together (both untransformed and log-transformed) were included separately in the estimated best-fit logistic regression and linear regression models explaining variation in the likelihood and scale of fox predation of pheasants, respectively, to assess whether expenditure on preventive measures was directly related to fox predation.

7.2.4.5. Empirical estimation of the model

The relationship between pheasant losses to foxes and expenditure on preventive measures was assumed to approximate either a negative exponential or negative power relationship. Four possible forms were tested for the model: linear, exponential, logarithmic and log-linear or power:

a) Linear: $Lc_{i1} = \beta_0 + \beta_1 MF_i$

b) Exponential: $Lc_{i1} = \beta_0 \times e^{\beta_1 MF_i}$ i.e. $\ln(Lc_{i1}) = \beta_0 + \beta_1 MF_i$

c) Logarithmic: $Lc_{i1} = \beta_0 + \beta_1 \ln(MF_i)$

d) Log-linear (power): $Lc_{i1} = \beta_0 \times MF_i^{\beta_1}$ i.e. $\ln(Lc_{i1}) = \beta_0 + \beta_1 \ln(MF_i)$

where:

Lc_{i1} = pheasant loss to foxes from release pens per bird released per year on the *i*th shoot (£) plus 0.01
β_0 = constant
β_1 = coefficient for MF_i

Models were estimated for pheasant losses and expenditure on keeper fox control, expenditure on release pens and preventive measures, expenditure on pen preventive measures only and expenditure on keeper fox control plus release pens. A small positive constant (0.01) was added to pheasant loss values to allow for logging. The pheasant loss values for shot birds rather than poults were used, the difference between these two values being only in scaling, both having been estimated for the same loss data.

Given the assumption that both fox control and pheasants pens and associated preventive measures were used to prevent fox predation of pheasants from pens, a trade-off between expenditure on these two would be expected. The association between expenditure on the two preventive measures was tested using correlation analyses.

7.2.5. Fox control and estimated relative fox density

The associations between the number of foxes killed on the shoot and the number of foxes killed per hectare and relative fox density estimates were tested via parametric and non-parametric (Spearman's rank) correlation tests. The associations between total expenditure on keeper fox control and expenditure on keeper fox control per fox killed and relative fox densities and the number of foxes killed were tested in a similar manner. The number of foxes killed per hectare was calculated by dividing the number of foxes killed on the shoot by the area of the shoot (as given), whilst expenditure on keeper fox control per fox killed was calculated by dividing the figure estimated earlier for expenditure on keeper fox control by the number of foxes killed on the shoot (as given).

7.3. RESULTS

The data from 62 questionnaires were used in this analysis. An additional 29 forms were returned uncompleted. Of these, 18 were sent back by estates for whom the form was not relevant because they did not run commercial shoots, two because the information needed to fill in the form was unavailable, one because the respondent was unwilling to take part in the survey for political reasons and one due to time constraints, whilst for seven forms, the reasons are unknown. The response rate to the questionnaire was therefore 45.0%. Because of the sensitive nature of this study topic, especially to gamekeepers, the returns were not expected to be high. A number of telephone calls were received from recipients of questionnaires concerned with data confidentiality and other issues with respect to the study.

Of these 62 respondents, not all answered all the questions on the survey form, meaning that sample sizes differ between analyses. Sample sizes are given in square brackets in the text. Estimated Beta coefficients for independent variables in regression analyses are given as 'B'. All figures for statistics are quoted to 3 significant figures or 2 decimal places. Statistical significance was taken as being at or above the 95% level ($\alpha = 0.05$), i.e. $p < 0.05$.

Most respondents (55) ran driven shoots, 22 ran walked up shoots, 7 dogging and 27 duck-flighting [n = 60]. Various characteristics of the sample, including preventive measures used on pens, location and experience of fox predation, are summarised in Table 7.1 according to the percentage of respondents with those characteristics. Statistics summarising reported deaths of pheasants in pens to all causes, all predation and fox predation only are given in Table 7.2. Mortality of pheasants is given as the number of pheasants that were reported to have died due to that cause out of the total released. Summary statistics for data on pheasants released, shoot areas, the numbers of foxes killed on shoots and fox kills in comparison to losses due to other causes are in Table 7.3. Figure 7.1 illustrates the range in pheasant mortality due to fox predation. The majority of respondents (45.8%) thought that the number of pheasants killed by foxes in release pens over the past five years had not changed, while equal proportions (22.0% in each case) thought that there had been an increase or a decrease in these numbers [n = 59].

Table 7.1: Characteristics of game interest sample in terms of use of various release pen preventive measures, land uses surrounding shoots, location and reported fox predation of pheasants in release pens

Characteristic	N	Factor levels	Percentage of respondents (%)
Preventive measures used on release pens	59	Overhanging anti-fox fringe	37.3
		Electric fencing	61.0
		Fox grids over entrances	72.9
		Dug-in or penned down netting	83.1
		Snare walls	30.5
		Flashing lights (scarers)	22.0
		Other (chemical repellent, scarers (incl. radios), etc.)	22.0
		Radio as scarer (as stated under 'other')	13.6
Score for effectiveness of release pens at preventing foxes from getting in	58	Ineffective	3.4
		Somewhat effective	31.0
		Very effective	65.5
Score for effectiveness of release pens at preventing all unwanted animals from getting in	57	Ineffective	12.3
		Somewhat effective	40.4
		Very effective	47.4
Land uses surrounding shoot	62	Arable	83.9
		Livestock	82.3
		Game rearing	43.5
		Forestry	82.3
		Village	46.8
		Urban	12.9
		Other	16.1
Region in which shoot is situated (as Table 2.3)	62	North Scotland	25.8
		South Scotland	9.7
		North England	16.1
		East England	14.5
		Midlands	14.5
		Southwest England	8.1
		South England	6.5
		Wales	4.8

Table 7.1

Land class group of shoot (as Table 2.4)	62	1	8.1
		2	22.6
		3	17.7
		4	12.9
		5	25.8
		6	8.1
		7	4.8
Fox predation of pheasants from release pens	44	Fox predation reported to have occurred in last year	63.6

Table 7.2: Summary statistics on reported losses of pheasants from release pens due to fox predation, all predation and other causes. Figures in parentheses are standard errors of the means.

Cause of mortality		**Fox predation**	**All predation**	**All causes**
Number of pheasants reported died	Mean (S.E.)	105 (30.8)	203 (37.1)	249 (46.4)
	Median	18.5	113	168
	Range	0-879	0-1000	0-1500
	n	44	46	45
Reported pheasant mortality (%)	Mean (S.E.)	1.39 (0.39)	6.17 (1.48)	6.67 (1.43)
	Median	0.50	2.81	4.04
	Range	0-13.3	0-50	0-62.5
	n	42	46	47
Percentage of respondents reported no pheasants lost		36.4 [n = 44]	6.5 [n = 46]	2.2 [n = 45]
Percentage of respondents reported more than 10 pheasants lost		56.8 [n = 44]	84.8 [n = 46]	91.1 [n = 45]

Table 7.3: Summary statistics for pheasants released, shoot area, foxes killed on shoot and losses to foxes as percentages out of totals

Variable	**N**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Number of pheasants released	51	5375	5470	40	28000
Age of pheasants at release (weeks)	59	7.09	1.16	5	12
Area of shoot (hectares)	61	2217	3297	30	22680
Number of foxes killed on shoot in last year	59	57.4	45.7	1	200
Number of foxes killed per hectare in last year	58	0.059	0.089	0	0.635
Fox kills as percentage of total reported pheasant losses	38	19.9	24.0	0	80
Fox kills as percentage of reported pheasant losses to predators	40	35.3	35.6	0	100

7.3.1. Relative fox population density estimates

Land class fox density was not significantly correlated with either the number of pheasants in release pens reported killed by foxes in that year ($r_s = -0.256$, $p = 0.093$ [$n = 44$]) or the percentage of pheasants reported killed by foxes out of the total released ($r_s = -0.252$, $p = 0.107$ [$n = 42$]). There were also no statistically significant associations between regional fox density and either the number ($r_s = -0.093$, $p = 0.549$ [$n = 44$]) or percentage of pheasants reported killed by foxes ($r_s = 0.036$, $p = 0.822$ [$n = 42$]). The percentage of respondents reporting fox predation of birds in each land class group was not associated with land class fox density ($r_s = -0.691$, $p = 0.086$ [$n = 7$]), though there were indications of a negative relationship between these two. The percentage of respondents reporting predation in each region was not associated with regional fox density ($r_s = -0.240$, $p = 0.568$ [$n = 8$]).

7.3.2. Factors influencing fox predation of pheasants from release pens

Of the 62 respondents for which data were available, 59 gave figures for released pheasants on their shoot, whilst 44 reported the amount of fox predation they considered had occurred from their pens that year.

Only three of the variables tested were significantly associated with the occurrence of reported fox predation of pheasants. The number of birds released (square-root-transformed) was included in a univariate logistic regression model and allowed the likelihood of reported fox predation to be predicted with an accuracy of 72.5% ($\chi^2 = 11.9$, -2 log likelihood of model = 39.9, $p = 0.001$ [$n = 40$]). Reported fox predation of pheasants tended to have occurred at a higher frequency where an above average numbers of birds were released ($B = 0.047$, Wald = 7.91, $p = 0.005$; B (constant) = -2.10, Wald = 4.66, $p = 0.031$). Predation was more likely to have occurred than expected where snare walls were used ($\chi^2 = 9.43$, d.f. = 1, $p = 0.002$ (Fisher's exact test) [$n = 44$]) and where radios were used as a preventive measure at pens ($\chi^2 = 4.76$, d.f. = 1, $p = 0.037$ (Fisher's exact test) [$n = 44$]).

Predation was less likely than expected to have been reported on holdings in the Midlands region ($\chi^2 = 4.64$, d.f. = 1, $p = 0.051$ (Fisher's exact test) [$n = 44$]), though this was just statistically insignificant at the 5% level.

Inclusion of Midlands in the model with the number of birds released (square-root-transformed) increased its predictive accuracy to 77.5% ($\chi^2 = 15.9$, -2 log likelihood of model = 35.9, $p < 0.001$ [n = 40]) (Table 7.4). Neither of the dummies for preventive measures used on pens were statistically significant when included in a model with the number of birds released. The model correctly predicted fox predation on 84.6% of holdings on which predation occurred.

Table 7.4: Coefficient estimates and significance test statistics for logistic regression model with best accuracy for predicting the likelihood of reported fox predation of pheasants

Variable	B	Wald	p
Constant	-1.93	3.38	0.066
Number of pheasants released (square-root-transformed)	0.05	7.14	0.008
Midlands	-2.47	3.30	0.069

With respect to the scale of reported fox predation, few variables were significantly associated with the dependent variable. The number of pheasants reported to have died of causes other than predation (square-root-transformed) was positively associated with the dependent variable ($B = 0.057$, $t = 2.45$, $p = 0.024$ [n = 21]), as was the percentage of pheasants reported died of other causes (arcsine-transformed) ($B = 4.69$, $t = 2.55$, $p = 0.020$ [n = 21]).

The model that best explained variation in the scale of reported predation, judged on the adjusted R^2, included the percentage of pheasants reported died of other causes (arcsine-transformed), the number of foxes killed per hectare on the shoot in the last year, whether the shoot was in the Southwest of England, whether it was in Wales and whether it was in Eastern England ($R^2 = 0.83$, Adjusted $R^2 = 0.77$, $F = 13.0$, $p < 0.001$ [n = 19]) (Table 7.5). The two continuous variables were not correlated ($r = -0.04$, $p > 0.10$) and the hypothesis that the error was normally distributed could not be rejected (Kolmogorov-Smirnov test of distribution of residuals: $z = 0.657$, $p > 0.10$). There was also no pattern apparent in the residuals when plotted against fitted values, so the model fitted the assumptions of regression. Losses of pheasants tended to be higher on farms where more foxes had been killed per hectare, in the Southwest and in Wales, whilst they tended to be lower in East England.

Table 7.5: Coefficient estimates and t-test statistics for best-fit linear regression model explaining variation in the scale of reported fox predation of pheasants

Variable	**B**	**t**	**p**
Constant	-5.78	-26.3	<0.001
Percentage of pheasants reported died from causes other than predation (arcsine-transformed)	4.40	3.16	0.007
Foxes killed per hectare in last year	7.34	2.29	0.039
Southwest England	0.930	2.88	0.013
East England	-1.21	-2.48	0.028
Wales	1.83	3.53	0.004

7.3.3. Costs of pheasant predation by foxes from release pens

Pheasant bag was positively associated with income per shoot day, with an estimated coefficient of 21.40 ($R^2 = 0.910$, Adjusted $R^2 = 0.908$, $F = 335.1$, $p < 0.001$ [$n = 35$]) (Table 7.6). Neither region (dummies coding for England and Scotland) nor the number of guns on the shoot were statistically significant when also included in the model. Therefore pheasants shot on all the estates in the sample were taken as having the same value, of £21.40, since the constant in the regression analysis also did not statistically significantly differ from zero. Summary statistics for estimated pheasant losses due to predation by foxes from release pens based on values of shot birds and poults, expenditure on keeper fox control per pheasant released and expenditure on release pens and preventive measures per pheasant released are given in Table 7.7.

Table 7.6: Coefficient estimates and t-test statistics for linear regression model of pheasant bag against total income per shoot day

Variable	**B**	**t**	**p**
Constant	-135.9	-0.456	0.651
Pheasant bag	21.40	18.30	<0.001

Table 7.7: Summary statistics of values of pheasant losses and expenditure on keeper fox control and release pens and preventive measures

Value	**n**	**Mean**	**Median**	**Range**
Pheasant losses (shot bird value) due to fox predation from release pens per pheasant released (£)	37	0.334	0.107	0.00-2.853
Pheasant losses (poult value) due to fox predation from release pens per pheasant released (£)	37	0.039	0.013	0.00-0.333
Expenditure on keeper fox control per pheasant released per year (£)	45	2.201	0.923	0.065-15.482
Expenditure on release pens and preventive measures per pheasant released per year (£)	50	0.381	0.186	0.046-5.441
Expenditure on pen preventive measures only per pheasant released per year (£)	50	0.142	0.073	0.00-1.634
Expenditure on keeper fox control plus release pens and preventive measures per pheasant released per year (£)	45	2.603	1.367	0.127-15.59

Whilst there appeared to be a decrease in the variance of costs of pheasant predation with increasing expenditure on keeper fox control per pheasant released and release pens and preventive measures, there was no obvious relationship between losses and expenditure, there being a number of shoots on which both losses and expenditure on control or preventive measures were low (Figures 7.2, 7.3, 7.4 and 7.5). Neither expenditure on keeper fox control per pheasant released, expenditure on release pens and preventive measures per pheasant released nor the two of these added together (when untransformed or logged) were statistically significant in either the logistic or linear regression models estimated in Section 7.3.2, either when included alone or in multivariate models.

7.3.3.1. Empirical estimation of the model

The relationship between pheasant losses and preventive expenditure was not significant for any of the model forms estimated (Table 7.8). The estimated β-coefficient for expenditure on keeper fox control was negative in all cases, as for the hypothesised model, but not statistically significant. There were no overly influential outliers in the data (Cook's distance > 1), except in the case of data points 12 and 51 in the models for losses against expenditure on pens and preventive measures and against expenditure on pen preventive measures only (marked on Figures 7.3 and 7.4). However, the relationship between pheasant losses and preventive expenditure remained statistically insignificant with a low R^2 when these data points were removed from the data set.

There was no significant association between expenditure on fox control and expenditure on release pens and associated preventive measures ($r = -0.054$, $p = 0.723$; $r_s = 0.221$, $p = 0.144$ [$n = 45$]) (Figure 7.6).

Table 7.8: Model output for regression models with pheasant losses to foxes (plus 0.01) as the dependent variable, $Lc_{il} = f(MF_i)$

Independent variable	**Model form**	R^2	n	F	p	β_0	β_1
Expenditure on keeper fox control	Linear	0.00	33	0.00	0.988	0.380	-0.001
	Exponential	0.00	33	0.12	0.733	0.128	-0.049
	Log	0.00	33	0.03	0.860	0.376	-0.014
	Power	0.01	33	0.43	0.515	0.114	-0.154
Expenditure on release pens and preventive measures	Linear	0.01	36	0.25	0.618	0.314	0.055
	Exponential	0.02	36	0.73	0.398	0.083	0.291
	Log	0.03	36	0.86	0.361	0.484	0.093
	Power	0.03	36	0.86	0.361	0.148	0.291
Expenditure on pen preventive measures	Linear	0.00	35	0.01	0.933	0.351	-0.031
	Exponential	0.01	35	0.44	0.510	0.088	0.739
	Log	0.01	35	0.19	0.670	0.442	0.039
	Power	0.02	35	0.67	0.418	0.174	0.225
Expenditure on keeper fox control plus pens and preventive measures	Linear	0.00	30	0.03	0.856	0.351	0.008
	Exponential	0.00	30	0.00	0.954	0.109	0.008
	Log	0.00	30	0.01	0.933	0.373	-0.080
	Power	0.04	30	0.14	0.715	0.114	-0.102

7.3.4. Fox control and estimated relative fox density

In most cases the majority of foxes killed on the shoot were killed by lamping (use of a lamp and rifle at night) (mean percentage of foxes killed by this method out of total killed on shoot = 58.3%), with snaring and shooting by day being the next two most common methods (mean percentage of foxes killed by these methods out of total = 17.9% and 14.2%, respectively). Table 7.3 includes summary statistics on the numbers of foxes culled.

There were no significant ($p < 0.05$) associations between the number of foxes killed in total or per hectare on the shoot and either regional or land class fox densities according to the correlation tests performed. Expenditure on fox control per fox killed was negatively associated with regional fox density ($r = -0.298$, $p = 0.028$; $r_s = -0.403$, $p = 0.003$ [$n = 54$]) and with the number of foxes killed per hectare ($r = -0.231$, $p = 0.099$; $r_s = -0.402$, $p = 0.003$ [$n = 52$]), but not with land class fox density ($r = -0.137$, $p = 0.324$; $r_s = -0.129$, $p = 0.354$ [$n = 54$]) nor the total number of foxes killed on the shoot ($r = -0.242$, $p = 0.081$; $r_s = -0.188$, $p = 0.178$ [$n = 53$]). Total expenditure on keeper fox control was negatively associated with regional fox density ($r = -0.317$, $p = 0.019$; $r_s = -0.405$, $p = 0.002$ [$n = 55$]) and to a lesser extent with land class fox density ($r = -0.230$, $p = 0.091$; $r_s = -0.271$, $p = 0.045$ [$n = 55$]). Total expenditure on fox control was positively associated with the number of foxes killed on the shoot ($r = 0.426$, $p = 0.002$; $r_s = 0.432$, $p = 0.001$ [$n = 52$]), but not with the number of foxes killed per hectare ($r = -0.095$, $p = 0.509$; $r_s = -0.190$, $p = 0.182$ [$n = 51$]).

The negative relationship between expenditure on keeper fox control per fox killed and regional fox density would be expected if it becomes more difficult to kill foxes with decreasing fox densities. Estimated absolute fox density estimates were calculated as in Chapter 3 (Section 3.3.1). The functional form of the relationship between expenditure on keeper fox control per fox killed and regional fox density was estimated using regression analysis and found to approximate a power relationship, as was also the case for sheep farms in Chapter 4 ($R^2 = 0.15$, Adjusted $R^2 = 0.13$, $F = 9.04$, $p = 0.004$ [$n = 53$]) (Table 7.9). However, in Chapter 4, the dependent variable accounted for the number of ewes on the farm, whilst the total number of foxes on the farm was estimated rather than the density. Figure 7.7 shows the relationship between these variables both for the actual and fitted data. It should be noted that a number of variables other than fox density will influence expenditure on keeper control per fox killed, many of which will be specific to individual shoots.

Table 7.9: Estimated coefficients and t-test statistics for relationship between regional fox density (log-transformed) and expenditure on keeper fox control per fox killed (log-transformed)

Variable	Estimated coefficient	S.E.	t	p
Constant	4.34	0.147	29.5	<0.001
Regional fox density per km^2 (log-transformed)	-0.758	0.252	-3.01	0.004

7.4. DISCUSSION

7.4.1. Data reliability

As with all animal kills, it is often difficult to judge whether a fox or other predator has killed a pheasant or whether the bird was scavenged. Jenkins *et al.* (1964) found that differentiation between fox and wild cat kills of red grouse in Scotland was difficult and Kenward *et al.* (2001) indicated that pheasant kills by birds of prey, such as buzzards, may be mistakenly attributed to foxes because foxes scavenge some of these kills (Kenward 1977). For these data, average reported pheasant predation was lower than in other studies. Only one study provides figures for losses from release pens, where 9.5% of poults were killed by all predators and 3.2% by foxes (Kenward *et al.* 2001), higher than the averages for these data, but at the low end of the data ranges. Kenward *et al.*'s (2001) study was carried out in Dorset and losses in this study were higher in the Southwest, which may explain this difference. In addition, it is not clear from the data collected here how much predation occurred outside release pens. This is a fault of the survey design. For Kenward *et al.*'s (2001) study, gamekeepers searched both the pens and their vicinity for dead pheasants. In a study of pheasants released in Germany, 30% of the birds died in the first 32 days after release and of these, 44% of deaths were attributed to foxes, equivalent to a mortality of 14% due to fox predation (Sodeikat *et al.* 1995). Other studies are not comparable with the results of this one because pheasant predation was considered over a longer time frame.

7.4.2. Reported fox predation of pheasants from release pens

Reported losses of pheasants to foxes in this study were generally low in percentage terms and a significant proportion of respondents (36%) did not report any fox predation of poults from pens. However some high losses were reported, whilst predation overall was a significant mortality factor for pheasants. In addition, although average percentage losses of birds to foxes were low, the average numbers of birds lost were fairly high considering that losses would only have accrued over a short time period of a few weeks. Other studies, such as Robertson (1988) and M. Gill (unpublished data, in Hill and Robertson, 1988), observed much higher losses to foxes than those reported here and foxes are probably the most significant predator of pheasants outside the pens (Hill & Robertson 1988; White *et al.* 2000a). Therefore this study does not take into account the full impact of fox predation on released pheasants. Unlike the other producer types surveyed in this thesis, gamekeepers expect predation of pheasants released into the wild to occur. Minimisation of losses will be attempted, but it should not be expected that losses could be as low as those experienced by these other producers.

There was some evidence for a negative association between relative fox density and fox predation of pheasants, which is the opposite direction to that which would be expected. A number of reasons could be put forward to explain this. The most likely of these is that the relative density estimates were not an accurate measure of fox densities on the ground. The high degree of fox control generally carried out on these holdings is likely to have affected the fox population density they support. Therefore, relative fox density estimates based on medians for land class groups are unlikely to accurately reflect actual fox densities in these cases. The association may reflect a link between land class type and the likelihood and/or scale of fox predation or perceptions of the fox as a pest. However, it was not significant at the 5% level of significance (only at 10%), whilst neither relative density nor land class groups were included in the overall models explaining variation in the scale and likelihood of reported fox predation. It is therefore more likely that the univariate correlation reflects an underlying association with another variable or that there was a Type 1 error. In addition, it should be noted that the land class group for the shoot as a whole was taken as that of the estate offices or central buildings (for which the postcode was available). As shoots were on average over 10 square kilometres in area (median shoot area = 1215 hectares), they may well have comprised more than one land class type.

In a study assessing the factors affecting buzzard predation on released pheasants, predation by buzzards was more likely to have been recorded at release pens with a large number of pheasants (Kenward *et al.* 2001). The number of birds released was also an important factor determining the likelihood of fox predation here. However, in this case, it was the total number of birds released, rather than the number per pen that was important. This association may simply reflect the fact that the more pheasants there are available to be predated upon, the more likely one is to be taken by a fox, especially because the number of pheasants released was not an important factor in determining the amount of fox predation reported. The number of pheasants released was positively associated with the number per pen (the number released divided by the number of release pens used) ($r = 0.769$, $p < 0.001$ [$n = 51$]) and foxes may also be more attracted to pens with larger numbers of pheasants. Kenward *et al.* (2001) distinguish between site attraction and prey vulnerability in explaining the difference between factors determining whether predation takes place and the proportion of pheasants killed.

Rather than the number released, the percentage of birds that died of causes other than predation was important in explaining variation in the proportion of pheasants killed by foxes. Losses to foxes were higher where overall losses were higher. This implies that there is a link between overall mortality and fox predation, perhaps reflecting an association between predation and the health status of birds or their general ability to survive. Alternatively, respondents may have been considering losses over different time frames and the association reflects the fact that more birds were lost overall and also more lost to foxes over time. All the loss figures are subject to the perceptions of the respondents. Therefore, it can be hypothesised that a gamekeeper who reports high losses overall might also report relatively high losses to foxes.

Regional factors affected both the likelihood that fox predation had occurred and the levels of predation. The lower likelihood of predation in the Midlands and lower levels of predation in East England may reflect higher regional fox control effort in these areas (Heydon & Reynolds 2000b). Higher reported loss levels in the Southwest may relate to the high relative fox abundance in this region. However, this regional variation may instead reflect other regional differences, which result in differences in losses of pheasants to foxes and/or differences in the perceptions of the fox as a pheasant predator. It is likely that differences in the habitats within pens will also have affected both the likelihood of fox predation and the numbers of losses, as is the case for predation by birds of prey (Lloyd 1975; Hill & Robertson 1988; Game Conservancy Trust 1996; Kenward *et al.* 2001), although this will probably be a more significant factor for aerial than ground predators. Data were not available on the habitat within pens, this being a difficult variable to assess through a questionnaire survey.

As was observed in the data sets for other producer types, fox control (in this case, the number of foxes killed per hectare) was positively associated with reported losses to foxes. Whether such an association is likely to reflect the influence of fox population density on losses, if fox cull density is a reliable population index, or reflect the use of reactive control is discussed in Chapter 2, Section 2.4.2.2. Previous studies have discussed reactive fox control by farmers (Baker & Macdonald 2000; Heydon & Reynolds 2000b), but reactive control by gamekeepers has not been considered. It seems less likely that control by gamekeepers would be reactive to pheasant losses than control by livestock and poultry farmers is to their losses. One reason for this is that fox control is part of a gamekeepers' job. Another is that figures for fox culling supplied here were for the last year, that for which the data on released pheasant losses were also provided, so the total annual cull is unlikely to capture reaction to these losses.

7.4.3. Costs of fox predation of pheasants from release pens

Use of the value of a shot bird resulted in a much higher valuation of pheasant losses to foxes than that for the poult price (nearly ten times the value). The true value lies somewhere between these two, but the costs of losses to foxes may be higher than those based on pheasant kills if birds have been unavailable for shooting because they fled after the predation event (Balharry & Macdonald 1999). Losses of pheasants to foxes after they have left the pens will also increase costs. However, neither of these additional losses could be estimated for these data. The difference in the valuation of pheasant losses only leads to a difference in total cost estimates and did not influence subsequent analyses because it only affected the scaling of values. The wide range in pheasant losses per bird released reflected the range of reported percentage loss figures.

There was also a large degree of variation in expenditure on keeper fox control and expenditure on release pens and preventive measures per pheasant released.

The lack of an association between expenditure on fox control and losses to foxes indicates that fox control was not a measure to prevent losses of pheasants to foxes from release pens. There could be a number of reasons for this. One is that fox control is carried out primarily to keep fox numbers down in the vicinity of release pens and the rest of the shoot in order to prevent foxes from predating upon pheasants once they have left the pens. Fox control is also carried out to prevent predation of wild birds. Therefore it could be argued that a significant relationship between pheasant losses from release pens and expenditure on control would not be expected. It may also be that the calculation of expenditure was not accurate enough to enable identification of any such relationships. However, across the data set, there was no negative association between foxes killed on shoots and losses, nor was there a link between fox densities and losses that could support an association between expenditure on fox control and losses. The effect that control has will be dependent on the starting density of foxes on the shoot, so without these associations or an accurate measure of fox densities on the ground it is difficult to accurately model the link between fox control and losses in any case.

The fact that there was no trade-off between expenditure on release pen preventive measures and pheasant losses is less easy to explain. Whilst it may be that the costings for these variables were not very accurate, the only associations between dummy variables coding for the use of these preventive measures and variation in either the occurrence or scale of reported fox predation were positive (for snare walls and radios). It may be that variation in other factors between shoots, such as pen habitat, was too great for such a trade-off between expenditure and losses to show up. In addition, these loss figures probably include pheasants killed outside pens, which would not be expected to be affected by the pen construction. Despite this lack of an apparent trade-off between preventive measures and losses, 65% of respondents considered their pens to be very effective at preventing foxes from entering them (and only 3.4% believed they were ineffective). Most of these measures associated with pens, such as electric fencing, anti-predator fringes and scarers, are used to prevent predation by a range of predators including foxes (Game Conservancy Trust 1996; Packer & Birks 1999), so are likely to have additional financial benefits that may explain their use. If expenditure on fox control and on pens were both considered to be measures to prevent fox predation at pens, a trade-off between the two would be expected, but there appeared to be no such financial trade-off for these data.

One problem with analysing these data in a financial framework is that shoots are less likely to be run with the aim of maximising profit and minimising costs than the other producer types considered in this thesis. In some cases, their objectives may not involve economic considerations at all. A further issue with the costs considered here is whether the fees paid by sportsmen, which reflect the general shooting experience rather than the values of shot birds alone, are a valid assessment of the losses to the shoot in terms of predated birds.

7.4.4. Fox control and fox density

Despite the lack of relationships in the expected directions between fox density or fox control and pheasant losses, the associations between expenditure on fox control and both fox density and the number of foxes killed fitted those expected from theory. Fox control was less costly per fox killed in regions with higher fox densities and on shoots where more foxes were killed per hectare, whilst the more foxes that were killed, the more it cost in total. The fitted relationship between control expenditure and fox density was non-linear (Figure 7.7), indicating diminishing decreases in expenditure per fox killed with increasing fox density, it becoming progressively more difficult (and therefore more costly) to kill foxes the fewer of them there are. Although these relative fox density estimates may not reflect actual densities on shoots well, as discussed earlier, the regional estimates do reflect relative differences between regions in fox density. Therefore, whilst there is considerable variation in the expenditure on fox control per fox killed in each region, the over-riding link between the costs of control and fox density is still apparent. Holding-specific density estimates would enable this relationship to be more accurately assessed. The relationship at least supports the accuracy of the valuation of fox control expenditure.

7.5. CONCLUSIONS

The factors that influence variation in fox predation of pheasants from release pens did not appear to be those that were under potential management by gamekeepers or shoot owners. Reducing the number of birds in each pen may decrease the likelihood of fox predation, whilst having healthier birds is also likely to be an important factor determining losses. However, these recommendations are only indistinctly indicated by the analyses, it being unclear what determines the influences of the number of birds released and the percentage dying of causes other than predation. The fact that the effect of fox control appeared to act in a direction counter to that which would be expected and that expenditure on fox control was not related to losses suggests that fox control is not hugely important in preventing losses of pheasants from pens. The same was true of preventive measures used on pens. An experimental set-up might be more conducive to assessing the effects of these measures in reducing fox predation and it would also enable the effects of habitat within pens to be investigated. The analyses carried out enabled regional factors to be identified as important influences on fox predation of pheasants. The data indicated that kills by foxes are less important that those by other predators when pheasants are in or in close proximity to their pens, but that foxes can cause significant losses on individual holdings.

7.6. SUMMARY

Foxes are one of the most serious predators of game birds in Britain and their most significant impact in terms of the numbers of birds killed is on released pheasants. This chapter considered fox predation of pheasants from release pens, attempting to identify the causes of variation in predation between shoots and to carry out a financial analysis to assess the costs of fox predation of pheasants.

A survey of gamekeepers across Britain was carried out to provide data for the analyses and these were combined with relative fox density data.

Predation by animals other than foxes was an important mortality factor for these birds. Although 36% of respondents reported losing no birds to foxes, some holdings experienced significant losses with up to 13% of birds reported killed by foxes. Losses to foxes are also likely to be significant once birds have left the pens.

Regional factors and fox control were associated with differences in losses due to fox predation, as were the number of birds released and pheasant mortality due to other causes.

Shoots that spent more on their release pens and associated preventive measures did not experience losses any lower than those spending less. The same was true for expenditure on fox control. Whilst fox control may be carried out for reasons other than preventing predation from release pens, the reason for a lack of a link between preventive measures and pheasant predation from pens is less clear. An experimental study would probably be able to address these issues more effectively.

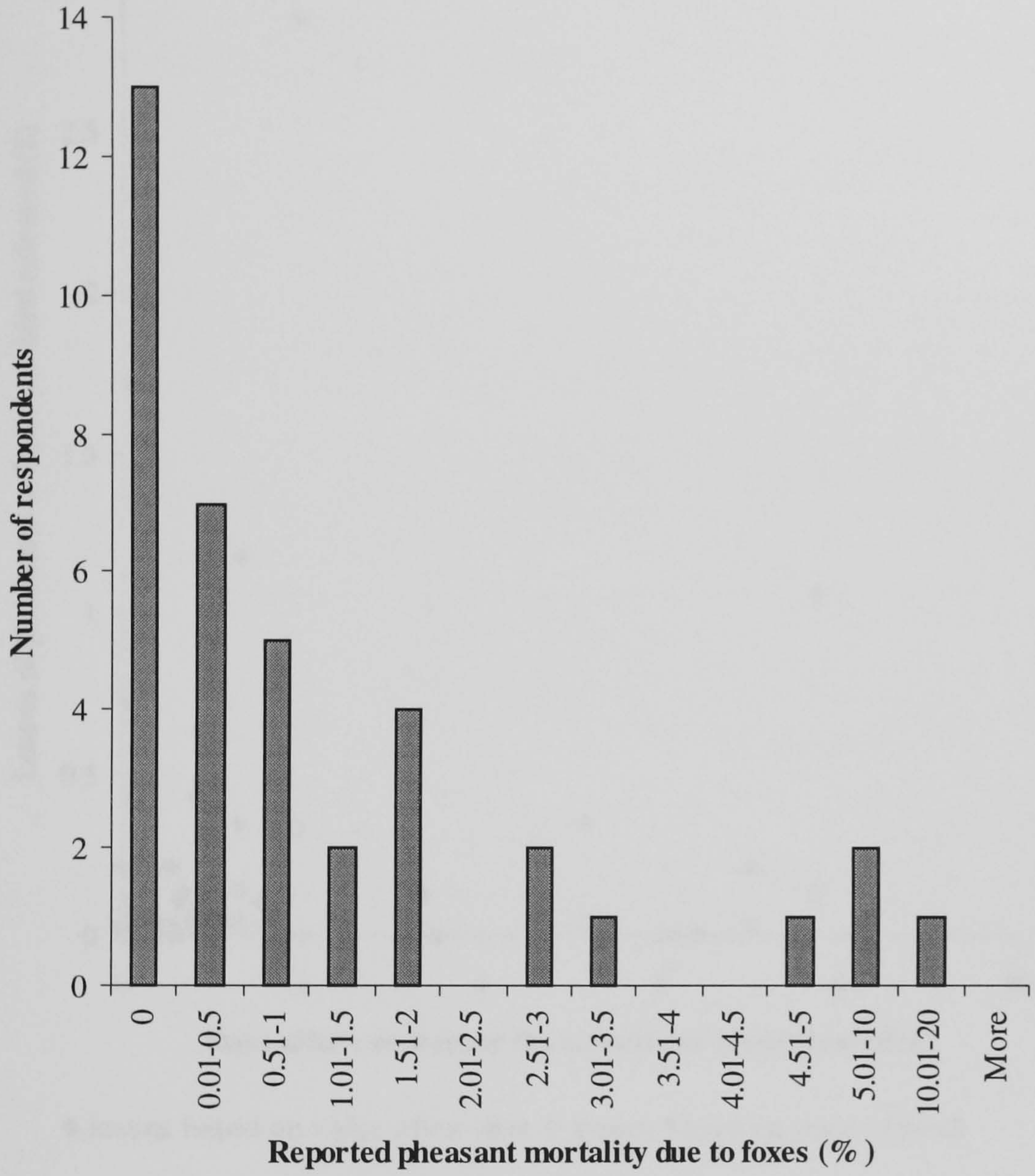


Figure 7.1: Histogram of responses for reported pheasant mortality due to fox predation [n = 42]

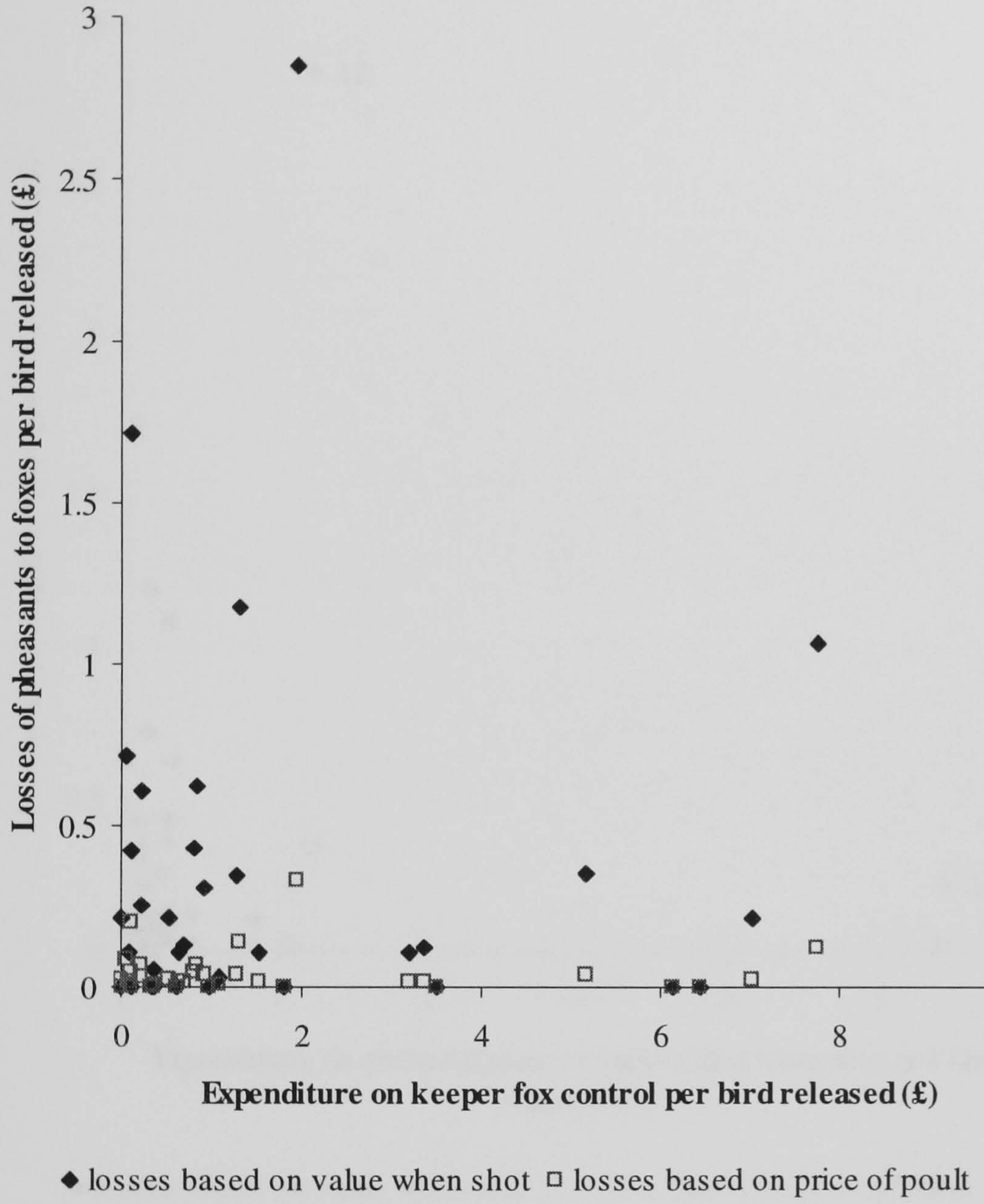


Figure 7.2: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on keeper fox control per bird released [n = 33]

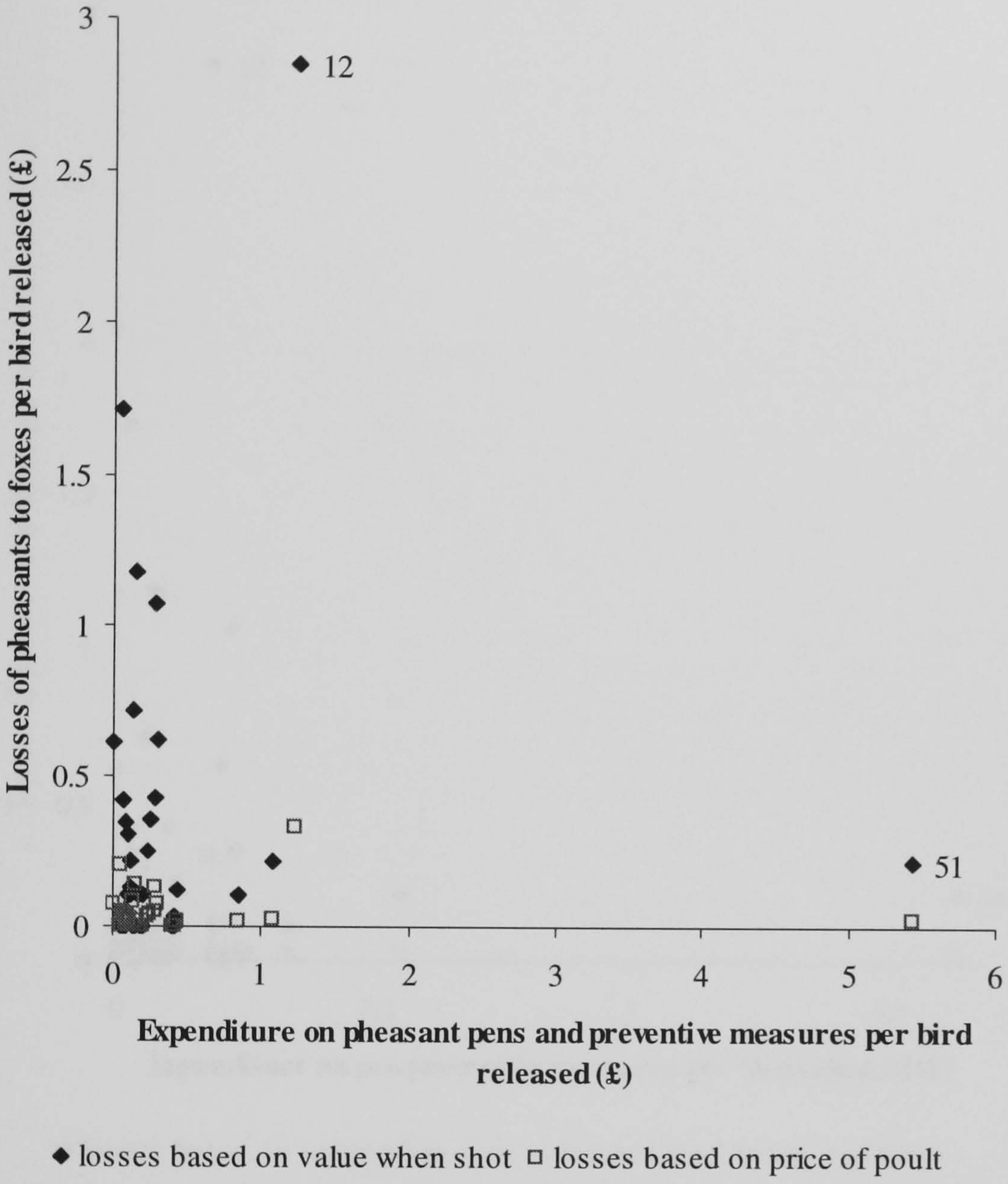


Figure 7.3: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on release pens and preventive measures per bird released [n = 36]

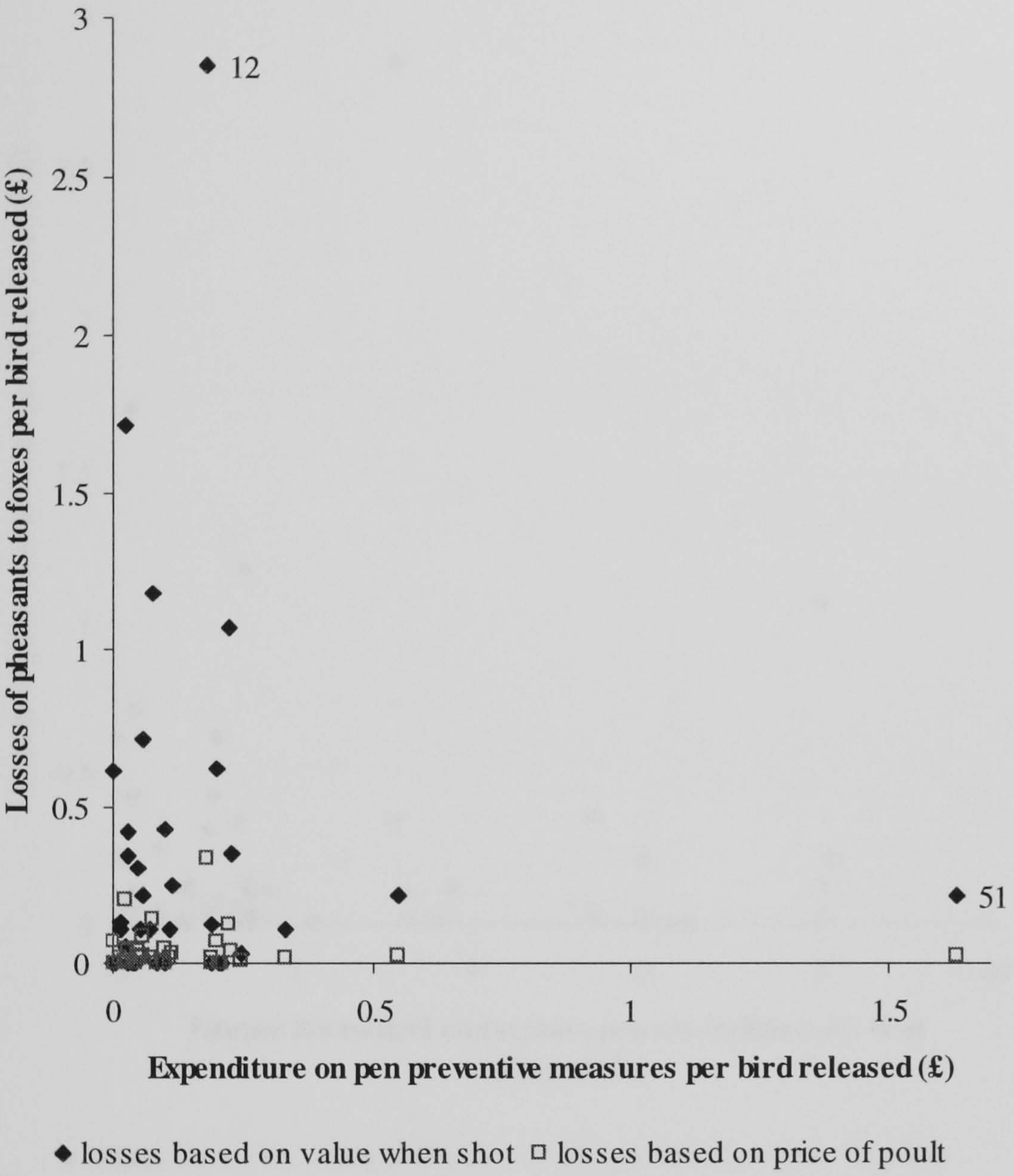


Figure 7.4: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on pen preventive measures per bird released [n = 36]

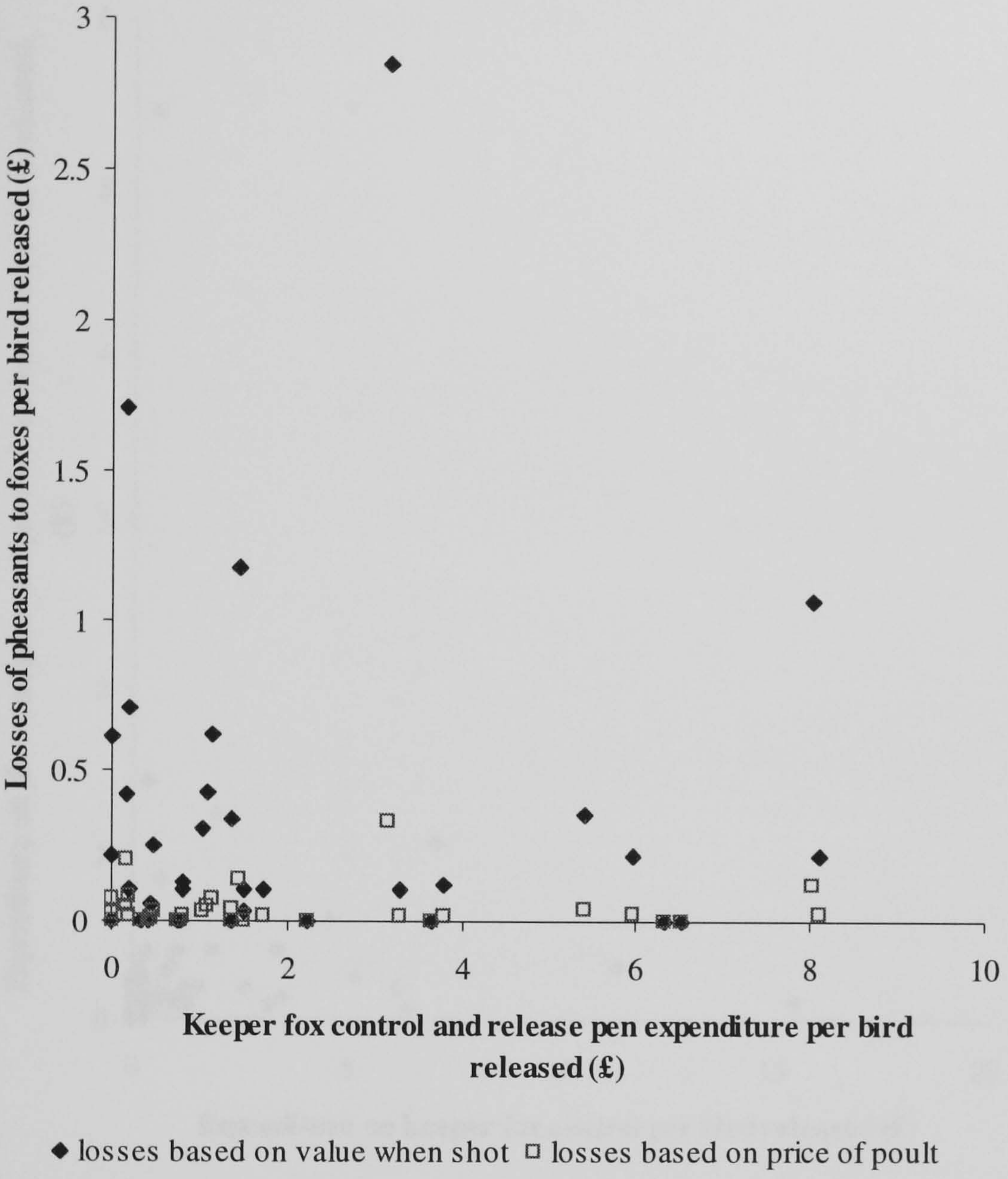


Figure 7.5: Losses of pheasants to foxes from release pens per pheasant released compared with expenditure on keeper fox control plus release pens and preventive measures per bird released [n = 33]

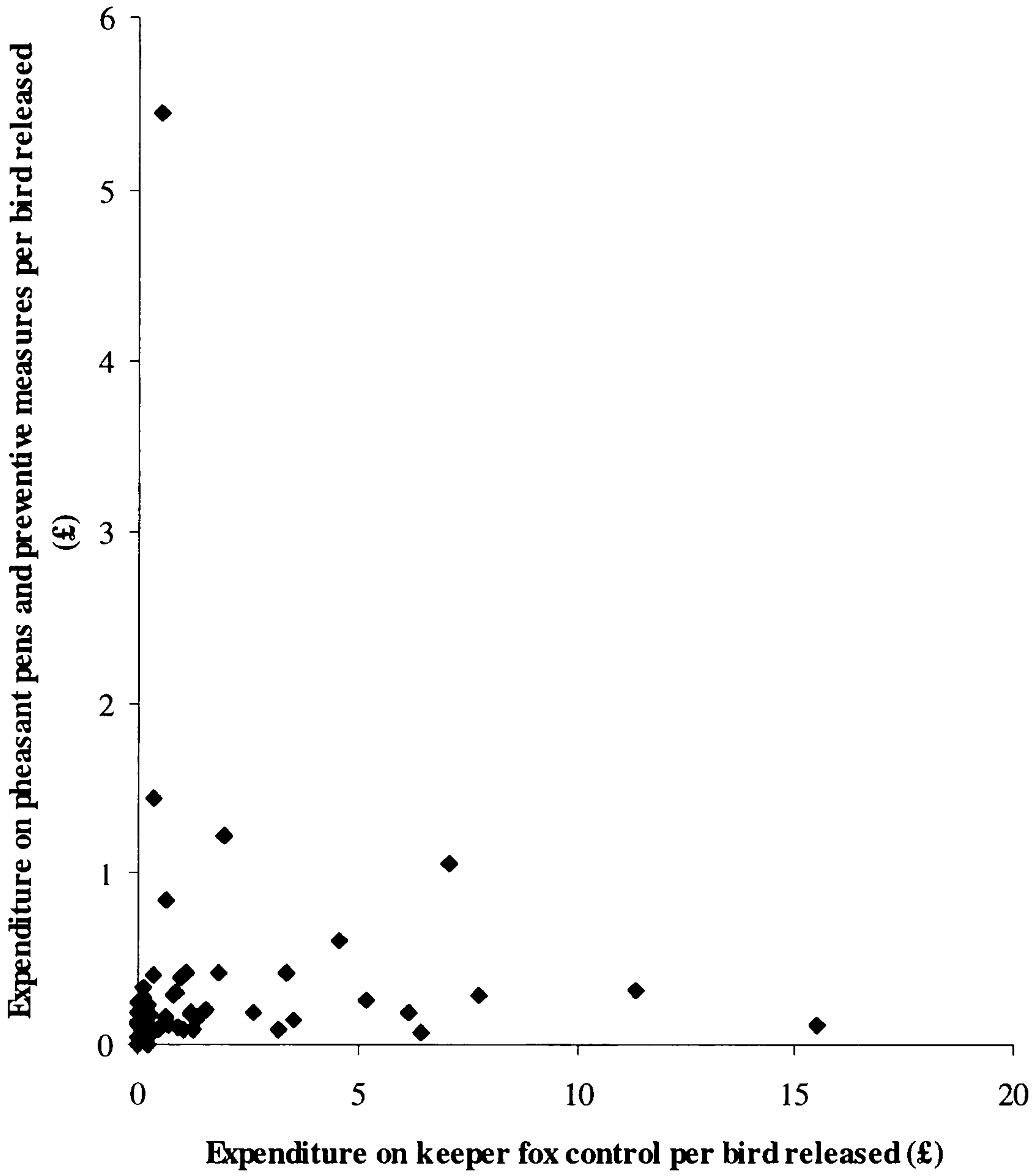


Figure 7.6: Comparison of expenditure on the two preventive measures considered (pheasant pens and associated preventive measures and fox control) [n = 45]

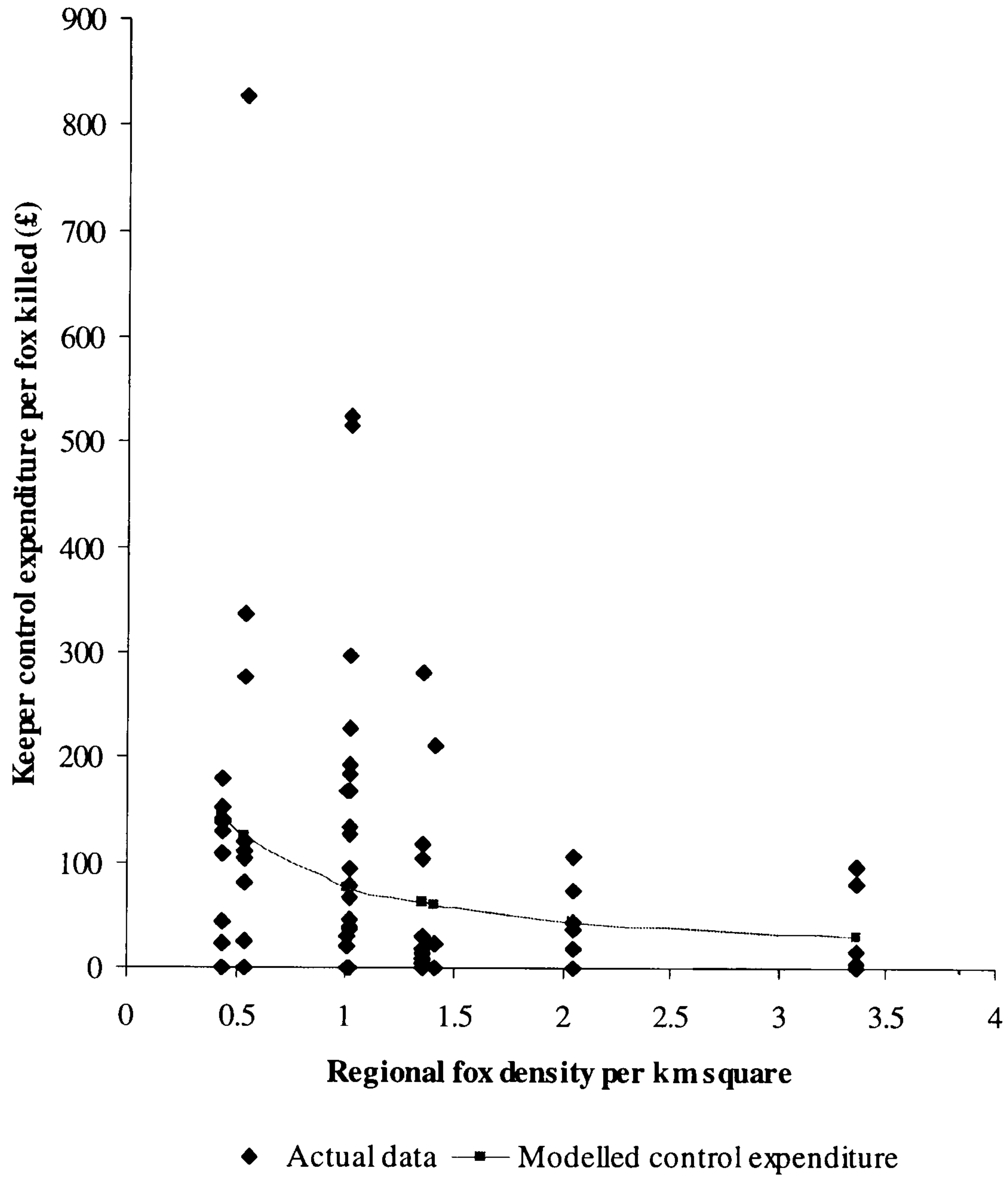


Figure 7.7: Association between keeper control expenditure per fox killed and regional fox density both for actual data and relationship modelled with regression analysis [n = 53]

CHAPTER 8

OVERALL DISCUSSION AND CONCLUSIONS

The aims of this thesis were to assess the impacts of foxes on agricultural interests in Britain, to identify the factors influencing them and to analyse the costs of foxes with regard to these impacts in an economic framework through financial analyses.

8.1. PREDATION LOSSES TO FOXES

In terms of livestock, poultry and pheasant losses to foxes, the over-riding trend was one of the majority of holdings reporting low levels of fox predation and a few individuals reporting significant losses due to foxes. Such variation in depredation levels associated with various factors, such as farm characteristics and predator control, has also been observed for other livestock predators by Nass *et al.* (1984), Cozza *et al.* (1996), Knowlton *et al.* (1999), Landa *et al.* (1999), Vos (2000) and Stahl *et al.* (2001). Some of the high loss figures may be attributed to overestimation by respondents to the survey and specific figures at the top end of losses may be inaccurate. However, the fact that this overall pattern of few high loss figures was similar across all the producer types indicates that it is genuine. The best data set in terms of sample size was that for sheep producers, the sample size being a reflection of the higher number of sheep producers in Britain relative to the other groups surveyed. Because this data set was the largest, it was possible to undertake more thorough analyses on it than the other data sets and the results obtained from analyses are likely to be more robust.

8.1.1. Factors influencing fox predation

There was a wide range in reported losses due to fox predation and in all cases a significant proportion of respondents reported no fox predation. It appeared that the processes determining the occurrence and scale of fox predation differed, possibly because the mechanisms determining whether a predator starts to hunt at a site differ from those that make it rewarding to kill prey there (Kenward *et al.* 2001). Therefore, analyses were split to assess factors influencing the occurrence of fox predation and those influencing the scale of predation on farms where it was reported to have occurred. Such predation impacts are often influenced by a combination of factors (Stahl *et al.* 2001) and the analyses performed here illustrated the importance of using multivariate techniques when investigating influences on predation to avoid inappropriate management recommendations. In several cases, most notably lamb predation, a number of factors that appeared important in univariate analyses were not so when other effects were accounted for.

Flock or herd size is an important influence on variation in predation by vertebrate species other than foxes (for example, Nass *et al.* 1984; Landa *et al.* 1999; Mech *et al.* 2000; Vos 2000) and for all the producer interests surveyed here, the numbers of animals potentially available to be predated upon or the number dying of other causes were associated with perceived fox predation. In the case of the occurrence of reported fox predation, these associations were positive, indicating either that foxes are more attracted to holdings with larger numbers of potential prey or simply that with a larger number of stock available the probability of at least one being predated is increased.

Positive associations between total losses and flock or herd size can be explained by the functional response of the predator to prey density. However, flock size was taken into account here in the loss data prior to analysis (i.e. all figures were per ewe, per sow, etc.) because it is the loss relative to flock size rather than total losses that is important to producers. Therefore an association between losses and flock or herd size indicates whether losses tend to be proportional to flock size or not. In the case of sheep, they were not, with foxes tending to take fewer lambs per ewe on larger farms. Losses were also disproportionate to flock size for pheasants (if the number of birds dying from other causes can be taken as a proxy for the number available to kill), but in this case more pheasants were lost where there were more birds. This difference is probably due to the fact that a fox is likely to kill only one lamb at a given predation event, but it may kill a large number of pheasants due to the phenomenon of surplus killing. That foxes kill proportionally more pheasants when there are more of them available may be due to an increased likelihood of repeat visits when there are a large number of pheasants.

In the cases of predation of chickens and predation of pheasants, an alternative explanation for the positive associations between predation and losses to other causes is that holdings where overall losses were high tended to experience high fox predation losses or were more likely to experience predation. This indicates that husbandry and management factors may be involved in determining the occurrence or levels of fox predation, even for these producer types for which no such influences were demonstrated.

Regional differences in perceptions of fox predation were evident in all cases, except for poultry, where differences between producer types were more important in explaining variation between holdings. Generally, the occurrence and scale of reported fox predation mirrored relative fox abundance amongst regions, being high in the Southwest and low in North and East England.

The identification of factors influencing fox predation enables the targeting of both measures to alleviate problems and future research into management options for damage limitation to the areas and situations where damage is most significant (Moore *et al.* 1999; Stahl *et al.* 2001; Tourenq *et al.* 2001). This study identified effective preventive measures for fox predation in two cases: indoor housing for sheep and electric fencing for pigs. The reasons behind the influence of non-management factors on predation should also be investigated to determine whether they could be manipulated by changes in husbandry or control techniques. Losses of livestock, poultry and game are likely to be a function of a number of variables that are very specific to individual farms and could not be assessed here, such as the skill of individual stockmen and gamekeepers. This is one reason why there was so much unexplained variation in the data sets.

8.1.2. Fox control, abundance and predation

The reactive nature of fox control in Britain to livestock losses has been noted by other researchers, including Baker and Macdonald (2000) and Heydon and Reynolds (2000b). With the exception of the game estates surveyed, which all carried out fox control, all the producer groups surveyed here were more likely to have experienced loss of stock to foxes if they carried out fox control and there was a positive association between pheasant losses and fox kills on game estates. If the aim of population control is to reduce livestock losses, these associations between fox culling and losses appear counter-intuitive. One problem with citing reactive control as the reason for these positive associations between control and predation losses is that in most cases fox control data were given for the same year as loss data. It is not known what the level of predation would be without fox control, but it is possible that the disruption of fox populations by fox control results in a higher likelihood of predation of livestock and game. The 'sink' created by local fox control tends to draw in immigrants (Reynolds *et al.* 1993; Tapper *et al.* 1996) and these immigrants may be less able to target their natural prey because they are in an unfamiliar environment and are therefore more likely to prey upon livestock.

Macdonald *et al.* (2000) suggest that farmers' objectives with regard to fox control are driven by the amount of damage that it is perceived would occur in the absence of control. As indicated earlier, since perceptions tend to be the determinants of actions, the cause and effect behind these links between carrying out fox control and the number of foxes killed and perceptions of the fox as a pest can not be determined for these data.

Only for the sheep producer data were there associations between fox kills and fox abundance and between fox abundance and lamb losses, which could explain these counter-intuitive relationships in terms of more foxes being killed where they are more abundant and, in turn, more lambs being killed by foxes where there are higher numbers of foxes. The fact that the data are perceived losses also complicates this relationship, as perceptions of the fox as a problem are also likely to be linked to the number of foxes there are. As discussed earlier (Chapter 1), there is a lack of data in the literature linking predator abundance and damage caused. Therefore, it is not unexpected that such links were only observed here in one data set, especially given the fact that the fox population data were not holding-specific. It should be noted that, because associations were not found between predation of these species and fox abundance, it does not mean such associations do not exist. However, without these damage-density relationships, an analysis of the effectiveness of fox control was not possible for predation of pigs, poultry and pheasants.

It is widely believed that specific individuals or 'rogue' foxes are the cause of much of the predation of lambs (Chadwick *et al.* 1997; Burns *et al.* 2000), but there is little evidence to back up this belief (Rowley 1970). 'Problem individuals' have been cited as the cause of livestock predation hotspots by a number of authors, e.g. Mizutani (1993) and Sacks *et al.* (1999), but there is debate as to whether such individuals actually exist (Linnell *et al.* 1999). If such a phenomenon does occur the indiscriminate culling of foxes to reduce their abundance is unlikely to be effective in reducing damage and it will be changes in the numbers of these 'rogue' individuals rather than in total fox numbers that influence predation (Greentree *et al.* 2000). It can be hypothesised, however, that the number of 'problem' individuals is positively related to overall fox abundance. If so, as long as fox control is effective in reducing fox abundance, it will be effective in reducing the number of 'problem' individuals, if these individuals are as susceptible to culling techniques as other foxes (but 'problem' coyotes, for example, often are not, Knowlton *et al.* 1999). The control of itinerant foxes is more difficult to deal with, as the abundance of such foxes is unlikely to be related to overall fox density, although it may well be linked to the level of control (i.e. disturbance).

8.2. COSTS OF FOX PREDATION

The costs of fox predation to agricultural producers and game interests in Britain comprise both those directly associated with loss of stock and the cost of preventive measures, including fox control, if this can be considered effective at preventing damage. Only in two cases, outdoor pig and sheep producers, were preventive measures associated with lower losses of stock, as hypothesised. In these cases, it was possible to look at the total costs of predation and to assess how predation might be managed more efficiently in financial terms. The analyses indicated that it was not economically worthwhile for producers to eliminate predation losses from their farms completely and that losses should be tolerated to a certain extent, as farmers and consumers did with pest damage in general in the early 1900s (Fall & Jackson 1998). The analyses illustrated the importance of assessing a pest's impact in terms of avoidable costs. If it is not possible to reduce predation to zero, a total cost figure for predation losses alone is of limited use for informing management decisions. In the cases of both the indoor housing of sheep and fencing for pigs, the increment in the benefits of expenditure on these preventive measures decreased steeply with increasing expenditure and it was only worthwhile for the farmer to spend a small amount specifically to limit fox predation.

It was only possible to assess the costs of fox control and the link between fox control and predation for sheep producers, where the model indicated that additional fox control was only worthwhile financially on small farms or those with certain specific characteristics. In addition, the indication was that housing ewes indoors was an economically more efficient strategy for reducing lamb loss than was additional fox control to that already carried out. As discussed previously, the data collected here did not enable the drawing of management guidelines specific enough to aid individual producers, but the framework developed for these analyses could be usefully applied to other vertebrate pest species, as well as for future analyses of fox impacts with other data sets. It should be noted that, as the aim of the economic analyses was to identify the best strategy to deal with predation and not to calculate the exact monetary value of predation losses, the use of imperfect data does not necessarily detract from the results (Morris 1999).

One of the hypotheses tested here was that spending more on preventive measures results in reduced losses due to predation, which appeared not to be the case for fox predation of poultry and game. More expensive fencing is not necessarily more effective at preventing predation and a number of other factors, such as the level of maintenance, are likely to also be important. Perhaps the main difficulty with assessing preventive measures for fox predation is that these measures tend to have multiple uses, including preventing predators other than foxes and losses in general. Whilst the total cost approach taken here was the most appropriate, given the limitations of available data and the fact that the aim of the thesis was to concentrate on fox predation solely, it is likely that focusing on the production side of the system would provide further insight into the association between predation and prevention. There will also be economic effects (from the farmer's point of view) of having other livestock on farms, for example, on a mixed farm a producer may carry out fox control to protect his chickens which has the knock-on effect of also preventing predation of lambs. A whole farm approach would capture such effects, but would not only require a complex modelling approach (because of the many interactive components of agricultural systems, Mizutani 1999), but also a large amount of data from individual farms.

8.3. DATA RELIABILITY

8.3.1. Questionnaire survey data

All analyses were based on the use of questionnaire data. The drawbacks of using such data have been outlined elsewhere in the thesis, the major ones being related to response biases in the sample population and errors and unreliability in the data provided. Determining whether fox predation was the cause of death for livestock or game animals is generally difficult even for experts in this field and a number of respondents to the surveys carried out here indicated that figures for losses due to predation were completely unknown. The accuracy of producer-recorded causes of death has been brought into question by studies on piglet mortality (Vaillancourt *et al.* 1990; Christensen & Svensmark 1997). Moore *et al.* (1999) ground-truthed a sample of badger damage reports from a questionnaire survey in England and Wales and found information on damage to be generally accurate, except in the case of alleged predation incidents. In these cases, the ground-truthing proved difficult and in the majority of cases there was only circumstantial evidence that badgers were to blame for livestock deaths. Other authors have outlined the difficulties of finding animals that have been predated and the fact that even when found their state often makes it impossible to determine the cause of death with certainty (Lloyd 1980; Hewson 1984b; Edwards *et al.* 1994; Landa *et al.* 1999; White *et al.* 2000b).

Further uncertainty in determining the impact of fox predation lies in whether animals that were killed by foxes would have died later from another cause (Greentree *et al.* 2000) and therefore whether fox predation has a compensatory or additive effect overall with regard to other mortality. In the case of red grouse, a study in the late 1950s indicated that it was 'surplus' birds without territories that were most vulnerable to predation (Jenkins *et al.* 1964). However, such an effect may well not be standard across all prey species, nor across holdings with livestock or game vulnerable to fox predation. For example, two studies on predation of grouse with caecal nematode infections produced opposite results, one arguing that grouse with higher worm burdens were more likely to be predated than those with low burdens (Hudson *et al.* 1992) and the other indicating the opposite (Moss *et al.* 1990).

The contentiousness of the issue of fox management in Britain at this time resulted in difficulties in undertaking the questionnaire surveys and is likely to have been a further influence on responses. However, the resource costs and limited geographical ranges of other techniques for studying predation, such as field post-mortem studies (Hone 1994; Knowlton *et al.* 1999), meant that, despite its drawbacks, the questionnaire survey approach was the most appropriate one to use for this study, given that data from a relatively large number of holdings was required.

8.3.2. Fox population density estimates

As indicated by the discussion in Chapter 1, there is a lack of data available on fox population densities across Britain. In addition, the techniques used to determine fox abundance (and canid population numbers in general), which are generally based on relative density indices, have their inherent problems (Harris & Saunders 1993). Macdonald *et al.* (1998) recommended that the monitoring of fox populations in Britain would be best achieved through the use of standardised spotlight counts. However, there are a number of difficulties associated with applying this method on a large scale, not least the resource cost and the fact that such a technique is unsuitable for unskilled volunteers, whose help is essential in carrying out a national survey (Webbon 2002). Webbon (2002) therefore chose the faecal count technique as the most appropriate for collecting information on fox densities across Britain. In that it directly provides a relative fox density estimate, there is no problem in assessing the association between predation and population density using faecal count data. However, the difficulty in using the data here lies in the fact that it was only possible to base estimates on a small number of region or land class groups and that data had to be aggregated. Ideally, a fox population density estimate would be available for every holding for which data were collected in order that the two might be directly referenced to one another. However, there was not a more specific and accurate fox population density data set than the one used available for Britain.

8.4. WIDER ECONOMIC IMPACTS OF FOX PREDATION

In addition to the costs considered here, foxes also have beneficial impacts on British agricultural interests. Potentially, they are pest controllers for arable farmers and foresters, since rabbits and rodents are important components of fox diet and also significant pests (Hewson & Leitch 1983; Macdonald 1984; Harris & Lloyd 1991; Kolb 1994; McKillop *et al.* 1996; Chadwick *et al.* 1997). Despite the large numbers of rabbits that are killed by foxes, it is unlikely that foxes have a significant impact on rabbit populations or the damage they cause, except where rabbit numbers are already low (Trout & Tittensor 1989; Newsome 1990; Pech *et al.* 1992). Nevertheless, foxes may prevent dramatic increases in rabbit abundance (Banks *et al.* 1998; Banks 2000; Trout *et al.* 2000). The impacts of fox predation on populations of other pest species are uncertain.

To those that engage in fox hunting, the fox is a quarry and its pursuit provides them with a benefit through enjoyment of the sporting activity. In addition, the activity provides social contacts both for those involved and those who let the hunt on their land, usually farmers, as well as the collection and disposal of fallen livestock by hunt kennels, often carried out free or at a subsidised price (Baines *et al.* 1995).

The effects of fox predation are not only felt by agricultural producers and game interests. Through predation on species of conservation importance, especially ground-nesting birds, foxes can also be considered to be a pest to conservation interests. Examples include golden plover (Parr 1993), ringed plover (Pienkowski 1984), avocets (Chadwick *et al.* 1997), eider duck (Wilson 1990), curlews (Bealey *et al.* 1999; Grant *et al.* 1999) and terns (Kruuk 1972; Patterson 1977), but fox predation of lapwings was not considered a significant mortality factor in two studies (Baines 1990; Seymour 1999). In addition to ground-nesting birds, fox predation may be important in determining hare population sizes (Reynolds & Tapper 1995; Tapper *et al.* 1996).

Fox control is carried out on many coastal nature reserves to safeguard vulnerable bird populations (Reynolds 1998). However it is difficult to separate out the effects of foxes and other factors on wild animal populations (White *et al.* 2000a). Foxes are unlikely to have an effect on robust populations, i.e. they probably would not cause an initial decline in a species, but may affect it significantly once this decline has occurred (Newsome 1990; Smith 1999). Although long-term bird breeding numbers tend not to experience increases following predator control actions (Côté & Sutherland 1997), the effectiveness of fox control in realising conservation benefits is uncertain and the actions of a number of predator species tends to complicate the conclusions of predator exclusion experiments with regard to fox predation alone.

8.5. FUTURE WORK

There are a number of different areas in which this work could be extended: different specifications could be tried for the models; the analyses and framework developed here could be applied elsewhere; further data on fox population dynamics and the effects of fox population management could be collected; other aspects of management and farmer behaviour could be considered; and the wider economic impacts of foxes assessed.

The likelihood of predation occurring and the scale of predation when it did occur were considered as separate processes for the analysis of the costs of lamb predation by foxes. However, due to the small sample sizes for the other producer types, one analysis was used to look at the scale of losses when assessing the trade-off between losses and preventive expenditure for these other data. A useful extension of these analyses would be to model the occurrence of predation separately for these data sets too. Comparing the output of such a model with that produced here would enable us to ascertain whether different mechanisms determine the likelihood and scale of predation. However, larger data sample sizes than those available for this study would be desirable for the application of such an analysis.

The models developed in Chapters 3 and 4 could be used to assess the management of vertebrate pest populations other than foxes. Their data requirements are relatively low, but they are potentially applicable to a range of situations where either optimal management strategies or the avoidable costs of pest actions need to be identified. The analyses could also be extended to consider other forms of preventive measure for fox predation, as well as to assess the relative cost-effectiveness of different forms of fox control, if it were possible to collect data on these.

Given less constrained resource funding, the impact of foxes on agricultural interests in Britain could be more accurately assessed and subsequent analyses of such data would enable robust strategies for the management of fox predation to be identified. Additional field studies to those already carried out on lamb predation in Scotland (Hewson 1984b; White *et al.* 2000b) would enable the collection of accurate data on fox predation. Nevertheless, unless a large number of holdings across different regions of Britain were involved, it would be difficult to make broad-scale management recommendations from such data. Large-scale manipulative experiments over several geographical regions are desirable to evaluate fox control and its impact on fox abundance and predation (Greentree *et al.* 2000; Macdonald *et al.* 2000; White *et al.* 2000a). However, a scientifically rigorous assessment of this type would be unfeasible in Britain because of the large number of replicates it would require (Greentree *et al.* 2000; Macdonald *et al.* 2000), whilst it would be difficult to account for the effects of immigration. Data on the dynamics of rural fox populations and the effect of population management on these dynamics are generally lacking and even small-scale studies would provide a useful advancement of our knowledge in this area.

In addition to information on the impacts of fox control on fox abundance and damage, alternatives to lethal control should also be considered. Potential alternatives include reproductive control (discussed by Artois 1997; Bradley *et al.* 1997; Pech *et al.* 1997; McLeod and Saunders 2001; Marks *et al.* 2001 and Saunders *et al.* 2002) and the manipulation of the behaviour that brings the fox into conflict with man (Putman 1989), through conditioned taste aversion, supplementary or diversionary feeding and habitat management, for example (Van Vuren & Smallwood 1996; Baker & Macdonald 1999; White *et al.* 2000a). Given the controversial nature of the use of lethal control for foxes in Britain, research into alternatives should be encouraged. However, there are ethical, technical and legal problems associated with fertility control, in particular, and none of these non-lethal control methods have yet been successfully used to reduce wild fox populations or predation. White *et al.* (2000a) outline some of the difficulties associated with using these techniques in the field.

To individual livestock holders the relative risk of the adverse effects of action (or inaction) is usually an important component of decision-making in addition to economic criteria (Norton 1976; Pannell 1990; Morris 1999; Chilonda & Van Huylenbroeck 2001). In fact, pest control is sometimes undertaken without any regard for the economics of the situation and it is often perceptions rather than the actual situation that determine actions (Mumford 1981a; Mumford 1981b; Mumford & Norton 1984; Allen & Sparkes 2001). It is therefore important to take these attitudes to risk into account when assessing preventive and control actions (Chilonda & Van Huylenbroeck 2001). Risk and decision models have been applied to crop pest management, e.g. Rossing *et al.* (1994), but neglected for the analysis of vertebrate pest control. The fact that many farmers seem to adopt a fixed control strategy with regard to foxes indicates that behavioural decision models may provide a more appropriate economic model than one of cost-minimisation only.

Foxes are not the only predators of livestock, poultry and game in Britain and a number of the techniques used to manage fox predation will also effectively prevent predation by some of these other species. Therefore predation management should not focus solely on foxes and an overall assessment of control should include the effects of all the predators that cause losses. The results of studies by Dion *et al.* (1999) and Risbey *et al.* (2000) illustrate how concentrating control on certain predator species may not solve (and can exacerbate) a predation problem. It is also important to consider the spatial effects of any control action and the effects that an action on one farm has on those surrounding it (Bicknell 1993). It would be interesting to consider how group management systems (i.e. several landowners acting together) would affect predation impacts, e.g. Bhat *et al.* (1996). The temporal distribution of losses due to fox predation should also be assessed in order to determine whether producers experience the same levels of losses over time (Knowlton *et al.* 1999).

An overall assessment of fox management, its effectiveness and worth, should take into account all the costs and benefits of fox predation and fox activity to society in Britain. Such benefits include the non-use and existence values the fox has to those whose lives would be less satisfying if foxes were not present (as discussed for wildlife in the U.S. by Conover, 1997a & b). A full economic analysis would necessitate a large amount of data collection and the quantification of all these benefits and costs. Messmer (2000) outlines the inadequacy of data available to assess the social and economic losses caused by wildlife. Even when only considering the costs of fox predation to agriculture, an economic analysis would investigate the effects of these on society in general, including the externality effects of fox control actions, rather than solely focusing on the costs to farmers. The humaneness and acceptability of control actions (both lethal and non-lethal) are also important issues (Reynolds & Tapper 1996; Reiter *et al.* 1999; Heydon & Reynolds 2000; Macdonald *et al.* 2000; White *et al.* 2000a). Bicknell (1993) argues that individual, self-interested behaviour by landowners is unlikely to provide pest management services at a level that is acceptable to society, due to externalities and the fact that pest management has some public-good properties, in that the benefits and costs that arise from it often accrue to individuals other than those paying for it. She also outlines the facts that pest management actions may impact on markets for agricultural products and that the benefits of pest control to conservation interests are extremely difficult to quantify in monetary terms.

A further problem is that the costs and benefits of wildlife impacts are not distributed evenly across different sectors of society and the burden of dealing with costly impacts tends to fall to a great extent on the agricultural community (Messmer 2000). This necessitates the transfer of the economic benefit of wildlife from the national to the local scale where the loss is incurred, as discussed by Vickery *et al.* (1994) with regard to brent goose management in Britain. However, there is often little support amongst the general public for compensating individuals and companies that suffer wildlife damage (Reiter *et al.* 1999). Vickery *et al.* (1994) along with other authors have also intimated that the problem of brent goose management is largely political rather than ecological or economic, which is also likely to be the case for foxes in Britain.

The fox has interactions with a number of different economic sectors in Britain and, as a top carnivore and generalist predator, ecological interactions with many species. Assessing the overall costs and benefits of fox management to society is a fundamental step to achieving efficient management strategies and is especially important given the controversy and differing opinions surrounding fox management in this country and the diversity of stakeholders involved.

APPENDIX A

Questionnaire form for sheep producer survey

IMPACT OF FOXES ON SHEEP FARMING

GENERAL

1. **What is the total area of your farm?** ☐ hectares (OR) ☐ acres

2. **What percentage of this area is used for the following types of farming?**
Sheep ☐ Dairy cattle ☐ Beef cattle ☐ Arable ☐ Other ☐

3. **How many paid employees are there on your farm?**
Full-time ☐ Part-time (less than 16 hours a week) ☐ Casual (less than 6 months of year) ☐

4. **Please rate the following land uses from 0 to 5, according to how much of the land surrounding your farm they take up** (**0** = none of the surrounding land, **5** = all of the surrounding land). You may give the same rating to more than one land use.
Arable ☐ Livestock ☐ Game rearing ☐ Forestry ☐
Village ☐ Urban ☐ Rough grazing ☐
Other ☐ Please state: ☐

5. **Is your farm hill, upland or lowland?** Please tick one box.
Hill ☐ Upland ☐ Lowland ☐

6. **What breed(s) are your sheep?** ☐

7. **How many ewes and shearlings (gimmer hoggs) were there on your holding in October 1999?** ☐

AT YOUR MOST RECENT LAMBING:

8. **On what date did lambing begin?** Day/Month/Year ☐ ☐ ☐

9. **How many ewes were lambing?** ☐

10. **a) Did you lamb your ewes indoors?**
Yes, all ewes ☐ Yes, but only some ewes ☐ ⇒ **Please answer (b)** No ☐
b) If only some, how many and why these ewes?
Number ☐ (OR) % ☐ Why? ☐

11. **How many days were ewes and lambs kept indoors for after lambing?** ☐ days

12. **a) Did you lamb your ewes in lambing pens?**
Yes, all ewes ☐ Yes, but only some ewes ☐ ⇒ **Please answer (b)** No ☐
b) If only some, how many and why these ewes?
Number ☐ (OR) % ☐ Why? ☐

13. **How many ewes had multiple births?** Number ☐ (OR) % ☐

14. **Did ewes with multiple lambs receive supplementary feeding during pregnancy?** Yes ☐ No ☐

15. **How many lambs were born alive?** Number ☐

16. (Please only include losses of live sheep and estimate numbers if you do not know exact figures)

Between birth and weaning, how many lambs:	Number	(OR)	Percentage (of those born alive)
were killed by predators (including foxes)?	☐		☐
were killed just by foxes?	☐		☐
died from other causes?	☐		☐

17. **Please tick the appropriate box to rate between 1 and 5 how reliable you believe the above figures for lamb losses to be (1 = guess, 3 = estimate, 5 = accurate figures):**

1	2	3	4	5
☐	☐	☐	☐	☐

18. **How does the number of lambs lost to foxes this year compare to losses in a typical year on your farm?**
Below average ☐ Average ☐ Above average ☐

Please turn over

19. Has there been a change in the number of lambs killed by foxes over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

20. How much do you consider losses to foxes cost you at this most recent lambing? £ ☐

FOX CONTROL MEASURES

(Including shooting and lamping, trapping, terriers and spades, snaring and hunting with hounds)

21. How many foxes, if any, were killed on your farm in the last 12 months? ☐ foxes

22. Has there been a change in the number of foxes killed on your farm over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

23. What was the cost of all your predator control in the last year? £ ☐ (OR) days ☐

24. What proportion of this was spent on fox control? % ☐

25. Has the amount you spend on fox control changed over the past five years?

Decreased ☐ No change ☐ Increased ☐ Don't know ☐

26. Have you seen signs of any of the following animals (other than your own) **on your farm over the last 12 months?** (Please tick.)

Stoats/weasels ☐ Mink ☐ Badgers ☐ Foxes ☐ Cats ☐ Dogs ☐

PRODUCTION ON YOUR FARM IN 1999

All figures will remain totally confidential.

27. How many of the following sheep and how much wool have you sold in the past 12 months?

Finished lambs ☐ Stores ☐ Draft ewes ☐ Culls ☐

Ewe lambs for breeding (at 6 months old) ☐ Ewe lambs for breeding (at 1 year old) ☐

Wool (kg) ☐

28. What was the average liveweight of your finished lambs? ☐ kg

29. How many sheep qualified for the Hill Livestock Compensatory Allowance (HLCA)? ☐

30. How many sheep qualified for the Sheep Annual Premium (SAP)? ☐

31. Please tick if you are in a Less Favoured Area (LFA) and/or qualify as Severely Disadvantaged.

LFA (Less Favoured Area) ☐ Severely Disadvantaged ☐

32. Do you pay rent or grazing costs? Yes ☐ No ☐

33. What percentage of your farm income comes from sheep farming? (Please tick one box)

Less than 25% ☐ Around 25% ☐ Around 50% ☐ Around 75% ☐ 100% ☐

34. If you are able, please supply me with figures for the following, even approximate, for your farm in **1999.** These will help me estimate the costs of sheep production for the economic side of my research into fox impacts.

Total annual farm overheads £ ☐

Number of replacement ewes and shearlings/gimmer hoggs purchased Number ☐

Amount of concentrates used (please specify units, e.g. £, kg, lb) ☐

Amount of bought forage used (please specify units) ☐

Amount of fertiliser used (please specify units) ☐

Vet and medical expenses £ ☐

If you would be willing to answer some more detailed questions for my study, please tick this box ☐

Please give me your name, telephone number and postcode in case I need to contact you about your form. I will not pass this information on to anyone else. If you prefer to remain anonymous (unless you ticked the box above), please give just your **postcode** and **parish** (if known) so I can check the rough location of your farm.

Name ________________________ **Telephone number** ________________________

Postcode ________________________ **Parish** ________________________

Thank you very much for your help. Please send this form back in the enclosed FREEPOST envelope, or to my address on the letter, and feel free contact me if you have any comments or queries.

APPENDIX B

Summary of the variables and codes used in Chapters 2, 3 and 4 analyses

Variable	**Description**
Occurrence of perceived predation	Binary response variable, coded 0 for farms where no fox predation of lambs was reported and 1 for farms where at least one lamb was reported killed by foxes
Number of lambs perceived killed by foxes per ewe	Continuous dependent variable, reported number of lambs killed by foxes on farms where at least one lamb was reported killed, divided by the number of lambing ewes and ln-transformed
Country	Single digit code: 1 = England, 2 = Wales, 3 = Scotland
Region	Single digit code for region according to postcode (Table 1): 1 = Southwest, 2 = South, 3 = Southeast, 4 = Midlands, 5 = Wales, 6 = Northwest, 7 = Northeast, 8 = Anglia, 9 = Scotland
Farm type	Single digit code: 1 = lowland, 2 = upland, 3 = hill
England	Dummy variable, coded 1 for farms in England
Wales	Dummy variable, coded 1 for farms in Wales
Scotland	Dummy variable, coded 1 for farms in Scotland
Southwest	Dummy variable, coded 1 for farms in the Southwest postcode region
South	Dummy variable, coded 1 for farms in the South postcode region
Southeast	Dummy variable, coded 1 for farms in the Southeast postcode region
Midlands	Dummy variable, coded 1 for farms in the Midlands postcode region
Northwest	Dummy variable, coded 1 for farms in the Northwest postcode region
Northeast	Dummy variable, coded 1 for farms in the Northeast postcode region
Anglia	Dummy variable, coded 1 for farms in the East Anglia postcode region
Hill	Dummy variable, coded 1 for hill farms
Upland	Dummy variable, coded 1 for upland farms
Lowland	Dummy variable, coded 1 for lowland farms
Total area of farm	Continuous variable, area of farm in hectares

Area of land used for sheep farming	Continuous variable, area of land on farm devoted to sheep farming, in hectares
Lambs born	Continuous variable, number of lambs born on farm at most recent lambing, ln-transformed
Lambing ewes	Continuous variable, number of ewes lambing at most recent lambing, ln-transformed
Lambs born per ewe	Continuous variable, number of lambs born on farm at most recent lambing per lambing ewe
More than 250 ewes	Dummy variable, coded 1 for farms with more than 250 ewes
Ewe stocking density	Continuous variable, number of ewes per hectare of land used for sheep farming
Arable a	Score on scale of 0 to 5 for amount of land in surroundings of farm taken up by arable land-uses (0 = none of the surrounding land, 5 = all of the surrounding land)
Livestock a	Score on scale of 0 to 5 for amount of land in surroundings of farm used for livestock (0 = none of the surrounding land, 5 = all of the surrounding land)
Game rearing a	Score on scale of 0 to 5 for amount of land in surroundings of farm used for game rearing (0 = none of the surrounding land, 5 = all of the surrounding land)
Forestry a	Score on scale of 0 to 5 for amount of land in surroundings of farm used for forestry (0 = none of the surrounding land, 5 = all of the surrounding land)
Village a	Score on scale of 0 to 5 for amount of land in surroundings of farm taken up by village land-uses (0 = none of the surrounding land, 5 = all of the surrounding land)
Urban a	Score on scale of 0 to 5 for amount of land in surroundings of farm taken up by urban land-uses (0 = none of the surrounding land, 5 = all of the surrounding land)
Rough grazing a	Score on scale of 0 to 5 for amount of land in surroundings of farm used for rough grazing (0 = none of the surrounding land, 5 = all of the surrounding land)
Arable b	Dummy variable, coded 1 for farms with arable land in their surroundings
Livestock b	Dummy variable, coded 1 for farms with land used for livestock in their surroundings
Game rearing b	Dummy variable, coded 1 for farms with land used for game rearing in their surroundings

Forestry b	Dummy variable, coded 1 for farms with land used for forestry in their surroundings
Village b	Dummy variable, coded 1 for farms with village(s) in their surrounding land
Urban b	Dummy variable, coded 1 for farms with urban land-uses in their surroundings
Rough grazing b	Dummy variable, coded 1 for farms with land used for rough grazing in their surroundings
Percentage of ewes lambed indoors	Continuous variable, percentage of ewes lambed indoors out of all ewes lambing, arcsine transformed
Percentage of ewes lambed in lambing pens	Continuous variable, percentage of ewes lambed in pens out of all ewes lambing, arcsine transformed
Percentage of ewes with multiple births	Continuous variable, percentage of ewes that had multiple births out of all ewes lambing, arcsine transformed
Indoor lambing	Dummy variable, coded 1 for farms where all ewes were lambed indoors
Days in	Continuous variable, number of days for which ewes and lambs kept in after lambing
Supplementary feeding	Dummy variable, coded 1 for farms where ewes with multiple lambs received supplementary feeding during pregnancy
Month of lambing	Single digit code for month in which lambing took place: 1 = January, 2 = February, 3 = March, 4 = April, 5 = May to November, 6 = December (some months pooled to increase sample sizes and no farms lambed in June, July or August)
Mountain and Moorland	Dummy variable, coded 1 for farms with mountain and moorland sheep breed(s)
Grass Hill	Dummy variable, coded 1 for farms with grass hill sheep breed(s)
Longwool	Dummy variable, coded 1 for farms with longwool sheep breed(s)
Terminal Sire	Dummy variable, coded 1 for farms with terminal sire sheep breed(s)
Halfbred	Dummy variable, coded 1 for farms with halfbred sheep breed(s)
Scottish Blackface	Dummy variable, coded 1 for farms with Scottish Blackface sheep
Number of lambs reported lost to causes other than predation	Continuous variable

Number of lambs reported lost to causes other than predation per lambing ewe	Continuous variable, number of lambs reported lost to causes other than predation divided by number of lambing ewes
Number of foxes killed on farm in last year	Continuous variable
Number of foxes killed per hectare in last year	Continuous variable, number of foxes killed on farm in last year divided by area of farm (in hectares)
Fox control carried out	Dummy variable, coded 1 for farms where foxes were killed by various control measures
Region-based relative fox density	Continuous variable with 9 levels
Land class-based relative fox density	Continuous variable with 7 levels

APPENDIX C

Questionnaire forms for free-range poultry producer surveys

IMPACT OF FOXES ON TURKEY PRODUCERS

GENERAL

1. How large is the turkey range area on your farm? ☐ hectares (OR) ☐ acres

2. How many paid employees are there on your farm?

Full-time ☐ Part-time ☐ (less than 16 hours a week) Casual ☐ (less than 6 months of year)

3. Please rate the following land uses from 0 to 5, according to how much of the land surrounding your farm they take up (0 = none of the surrounding land, 5 = most of the surrounding land). You may give the same rating to more than one land use.

Arable ☐ Livestock ☐ Game rearing ☐ Forestry ☐

Village ☐ Urban ☐

Other ☐ Please state: ☐

4. How many turkeys were there on your farm in August 1998? ☐

HUSBANDRY

5. Do you have fixed or mobile housing for your turkeys? Fixed ☐ Mobile ☐

6. Is housing available at all times or only at night? All times ☐ Night only ☐

7. What proportion of a 24 hour day are the turkeys outside for, on average? (Please tick most appropriate box)

0-25% ☐ 26-50% ☐ 51-75% ☐ 76-100% ☐

8. How long do you grow your turkeys for? ☐ weeks

9. In what month did you buy your poults in 1998? ☐

FENCING

10. How effective is the fence surrounding your turkey range area at:	Very effective	Somewhat effective	Ineffective
i) preventing foxes from getting into the range area?	☐	☐	☐
ii) preventing all unwanted animals from getting into the area?	☐	☐	☐
iii) preventing turkeys from escaping?	☐	☐	☐

11. What type of fence surrounds your turkey range area? Please tick all that apply. If none of the below, please state any alternative method you use to prevent turkey losses.

Permanent perimeter fence ☐ (OR) Mobile ☐

Electric ☐ (OR) Wire and post ☐ (OR) Flexinet ☐

Alternative ☐

12. In what year was the fence first used? ☐

13. How much did the fence cost when first purchased? £ ☐

14. What length is the fence? ☐ metres

15. How much does maintenance of the fence cost per year? £ ☐

16. Have you seen signs of any of the following animals (other than your own) on your farm over the last 12 months? (Please tick.)

Stoats/weasels ☐ Mink ☐ Badgers ☐ Foxes ☐ Cats ☐ Dogs ☐

PREDATION BY FOXES ON YOUR FARM IN 1998 (Please only include losses of live turkeys)

17. How many turkeys:	Number (OR)	Percentage (of turkeys on farm)
were killed by predators (including foxes)?		
were killed by foxes?		
died from other causes?		

18. Please tick the most appropriate box to rate between 1 and 5 how reliable you believe the above figures for losses to be (1 = guess, 3 = estimate, 5 = accurate figures):

1	2	3	4	5
☐	☐	☐	☐	☐

19. During which month(s) were turkeys killed (please tick)?

Jun	Jul	Aug	Sept	Oct	Nov	Dec
☐	☐	☐	☐	☐	☐	☐

20. Has there been a change in the number of turkeys killed by foxes over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

21. On how many occasions did turkeys experience stress due to fox activity in 1998? ☐

22. How much do you consider that foxes cost you in 1998:

In terms of turkeys killed? £ ☐

In terms of meat deterioration caused by stress? £ ☐

23. How do these costs compare to those of a typical year on your farm?

Below average ☐ Average ☐ Above average ☐

INFORMATION ON FOX CONTROL MEASURES
(Including shooting and lamping, trapping, terriers and spades, snaring and hunting with hounds)

24. How many foxes, if any, were killed on your farm in 1998? ☐ foxes

25. Has there been a change in the number of foxes killed on your farm over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

26. What was the cost of all your predator control in 1998? £ ☐ (OR) days ☐

27. What proportion of this was spent on fox control? % ☐

28. Has the amount you spend on fox control changed over the past five years?

Decreased ☐ No change ☐ Increased ☐ Don't know ☐

TURKEY PRODUCTION ON YOUR FARM IN 1998 (All supplied figures will remain totally confidential.)

29. How many turkeys were sold at Christmas and at what average market price each?

Number sold ☐ Average market price £ ☐

30. What was the average liveweight of turkeys sold? ☐ lb (OR) ☐ kg

31. How many chicks did you buy from breeders and at what average price each?

Number bought ☐ Average price £ ☐

If you would be willing to answer some more detailed questions for my study, please tick this box ☐

Please give me your name in case I need to contact you about your form. I will not pass this information onto anyone else. If you prefer to remain anonymous (unless you ticked the box above), please just give your **postcode** and **parish** (if known) so I can check the rough location of your farm.

Name ______________________________

Postcode ______________________________ **Parish** ______________________________

Thank you very much for your help. Please send this form back in the FREEPOST envelope enclosed or to my address below and feel free contact me if you have any comments or queries.

Rebecca Moberly, Environment Department, University of York, FREEPOST NEA8324, York YO10 5ZZ

IMPACT OF FOXES ON GOOSE PRODUCERS

GENERAL

1. How large is the area of goose paddocks on your farm? ☐ hectares (OR) ☐ acres

2. How many paid employees are there on your farm?

Full-time ☐ Part-time ☐ (less than 16 hours a week) Casual ☐ (less than 6 months of year)

3. Please rate the following land uses from 0 to 5, according to how much of the land surrounding your farm they take up (0 = none of the surrounding land, 5 = all of the surrounding land). You may give the same rating to more than one land use.

Arable ☐ Livestock ☐ Game rearing ☐ Forestry ☐

Village ☐ Urban ☐

Other ☐ Please state: ☐

4. How many geese were there on your farm in August 1999? ☐

HUSBANDRY

5. Do you have fixed or mobile housing for your geese? Fixed ☐ Mobile ☐

6. Is housing available at all times or only at night? All times ☐ Night only ☐

7. What proportion of a 24 hour day are the geese outside for, on average? (Please tick most appropriate box)

0-25% ☐ 26-50% ☐ 51-75% ☐ 76-100% ☐

8. In what month did you buy your geese in 1999? ☐

9. How long do you grow your geese for? ☐ weeks

PREDATION BY FOXES ON YOUR FARM IN 1999 (Please only include losses of live geese)

10. How many geese:	Number	(OR)	Percentage (of geese on farm)
were killed by predators (including foxes)?	☐		☐
were killed by foxes?	☐		☐
died from other causes?	☐		☐

11. Please tick the most appropriate box to rate between 1 and 5 how reliable you believe the above figures for losses to be (1 = guess, 3 = estimate, 5 = accurate figures):

1	2	3	4	5
☐	☐	☐	☐	☐

	Jun	Jul	Aug	Sept	Oct	Nov	Dec
12. During which month(s) were geese killed (please tick)?	☐	☐	☐	☐	☐	☐	☐

13. Has there been a change in the number of geese killed by foxes over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

14. On how many occasions did geese experience stress due to fox activity in 1999? ☐

15. How much do you consider that foxes cost you in 1999:

In terms of geese killed? £ ☐

In terms of meat deterioration caused by stress? £ ☐

16. How do these costs compare to those of a typical year on your farm?

Below average ☐ Average ☐ Above average ☐

17. Have you seen signs of any of the following animals (other than your own) on your farm over the last 12 months? (Please tick.)

Stoats/weasels ☐ Mink ☐ Badgers ☐ Foxes ☐ Cats ☐ Dogs ☐

INFORMATION ON FOX CONTROL MEASURES

(Including shooting and lamping, trapping, terriers and spades, snaring and hunting with hounds)

18. How many foxes, if any, were killed on your farm in 1999? ☐ foxes

19. Has there been a change in the number of foxes killed on your farm over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

20. What was the cost of all your predator control in 1999? £ ☐ (OR) days ☐

21. What proportion of this was spent on fox control? % ☐

22. Has the amount you spend on fox control changed over the past five years?

Decreased ☐ No change ☐ Increased ☐ Don't know ☐

FENCING

23. How effective is the fence surrounding your goose paddocks at:	Very effective	Somewhat effective	Ineffective
i) preventing foxes from getting into the paddocks?	☐	☐	☐
ii) preventing all unwanted animals from getting in?	☐	☐	☐
iii) preventing geese from escaping?	☐	☐	☐

24. What type of fence surrounds your goose paddocks? Please tick all that apply. If none of the below, please state any alternative method you use to prevent goose losses.

Permanent perimeter fence ☐ Mobile ☐

Electric ☐ Wire and post ☐ Flexinet ☐

Alternative ☐

25. In what year was the fence first used? ☐

26. How much did the fence cost when first purchased? £ ☐

27. What length is the fence? ☐ metres

28. How much does maintenance of the fence cost per year? £ ☐

GOOSE PRODUCTION ON YOUR FARM IN 1999 If you are able, please supply me with figures for the following, even approximate. These will help with the economic side of my research into fox impacts. All figures will remain totally confidential.

29. How many geese were sold at Michelmas and at what average market price each and liveweight?

Number sold ☐ Average market price £ ☐ Average liveweight ☐ lb

30. How many geese were sold at Christmas and at what average market price each and liveweight?

Number sold ☐ Average market price £ ☐ Average liveweight ☐ lb

31. How many chicks were bought and at what average price each?

Number bought ☐ Average price £ ☐

32. How much feed did you buy in 1999 and/or how much do you spend on feed?

Amount of feed (please state lb/kg/ton) ☐ Cost of feed £ ☐

33. What proportion of the total annual costs on your farm are spent in goose production? % ☐

If you would be willing to answer some more detailed questions for my study, please tick this box ☐ and write your name and telephone number below.
Otherwise, please just tell me what parish your farm is in (if known) so I can check its rough location.

Name ______________________ **Telephone number** ______________________

Parish ______________________

Thank you very much for your help. Please send this form back in the enclosed FREEPOST envelope, or to my address below, and feel free to contact me if you have any comments or queries.

Rebecca Moberly, Environment Department, University of York, FREEPOST NEA8324, York YO10 5ZZ
Tel. 01904 434074 Fax. 01904 432998 Email: RLM106@york.ac.uk

IMPACT OF FOXES ON FREE-RANGE CHICKEN GROWERS

GENERAL

1. **What is the area of chicken pasture on your farm?** ☐ hectares (OR) ☐ acres

2. **How many paid employees are there on your farm?**

Full-time ☐ Part-time ☐ (less than16 hours a week) Casual ☐ (less than 6 months of year)

3. **Please rate the following land uses from 0 to 5, according to how much of the land surrounding your farm they take up (0 =** none of the surrounding land, **5 =** most of the surrounding land). You may give the same rating to more than one land use.

Arable ☐ Livestock ☐ Game rearing ☐ Forestry ☐

Village ☐ Town ☐ City ☐

Other ☐ Please state: ☐

4. **How many chickens were there on your farm, on average, in 1998?** ☐ chickens

HUSBANDRY

5. **Is indoor housing for your chickens available at all times or only at night?**

All times ☐ Night only ☐

6. **What proportion of a 24 hour day are the chickens outside for, on average?** (Please tick most appropriate box)

0-25% ☐ 26-50% ☐ 51-75% ☐ 76-100% ☐

7. **How long do you grow your chickens for?** ☐ weeks

8. **At what age are chickens given access to free range?** ☐ weeks

9. **What is the average liveweight of your chickens when fully grown?** ☐ lb

10. **When did your most recent completed growing period end?** Day/Month/Year ☐ ☐ ☐

FENCING

11. **How effective is the fence surrounding your chicken pasture at:**	Very effective	Somewhat effective	Ineffective
i) preventing foxes from getting into the pasture?	☐	☐	☐
ii) preventing all unwanted animals from getting into the pasture?	☐	☐	☐
iii) preventing chickens from escaping?	☐	☐	☐

12. **What type of fence surrounds your chicken pasture? Please tick all that apply. If none of the below, please state any alternative method you use to prevent hen losses.**

Permanent perimeter fence ☐ Mobile ☐

Electric ☐ Wire and post ☐ Flexinet ☐

Alternative ☐

13. **In what year was the fence first used?** ☐

14. **How much did the fence cost when first purchased?** £ ☐

15. **What length is the fence?** ☐ metres

16. **How much does maintenance of the fence cost per year?** £ ☐

17. **Have you seen signs of any of the following animals** (other than your own) **on your farm over the last 12 months?** (Please tick.)

Stoats/weasels ☐ Mink ☐ Badgers ☐ Foxes ☐ Cats ☐ Dogs ☐

PREDATION BY FOXES ON YOUR FARM (Please only include losses of live chickens)

18. During the most recent finished growing period, how many chickens:	Number (OR)	% (of chickens on farm)
were killed by predators (including foxes)?	☐	☐
were killed by foxes?	☐	☐
died from other causes?	☐	☐

19. Please tick the most appropriate box to rate between 1 and 5 how reliable you believe the above figures for losses to be (1 = guess, 3 = estimate, 5 = accurate figures):

1	2	3	4	5
☐	☐	☐	☐	☐

20. Has there been a change in the number of chickens killed by foxes over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

21. On how many occasions did chickens experience stress due to fox activity, during the most recent growing period? ☐

22. How much do you consider that foxes cost you during the most recent growing period:

In terms of chickens killed? £ ☐

In terms of meat deterioration caused by stress? £ ☐

23. How do these costs compare to those of a typical growing period on your farm?

Below average ☐ Average ☐ Above average ☐

INFORMATION ON FOX CONTROL MEASURES

(Including shooting and lamping, trapping, terriers and spades, snaring and hunting with hounds)

24. How many foxes, if any, were killed on your farm in 1998? ☐ foxes

25. Has there been a change in the number of foxes killed on your farm over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

26. What was the cost of all predator control in 1998? £ ☐ (OR) days ☐

27. What proportion of this was spent on fox control? % ☐

28. Has the amount you spend on fox control changed over the past five years?

Decreased ☐ No change ☐ Increased ☐ Don't know ☐

CHICKEN PRODUCTION ON YOUR FARM

This information will be useful for the economic side of my research.

29. How many chickens were sold at the end of the most recent growing period? ☐

30. What percentage of these received bonus payments for reaching weight and feed conversion targets? % ☐

If you would be willing to answer some more detailed questions for my study, please tick this box ☐

Please give me your name, telephone number and postcode in case I need to contact you about your form. I will not pass this information on to anyone else. If you prefer to remain anonymous (unless you ticked the box above), please give just your **postcode** and **parish** (if known) so I can check the rough location of your farm.

Name ____________________ Telephone number ____________________

Postcode ____________________ **Parish** ____________________

Thank you very much for your help. Please send this form back in the enclosed FREEPOST envelope and feel free contact me if you have any comments or queries.

Rebecca Moberly, Environment Department, University of York, FREEPOST NEA8324, York YO10 5ZZ
Tel. 01904 434074 Fax. 01904 432998 Email: RLM106@york.ac.uk

THE IMPACT OF FOXES ON FREE RANGE EGG PRODUCERS

GENERAL

1. How large is the area of chicken pasture on your farm? hectares (OR) acres

2. How many paid employees are there on your farm?

Full-time ☐ Part-time (less than 16 hours a week) ☐ Casual (less than 6 months of year) ☐

3. Please rate the following land uses from 0 to 5, according to how much of the land surrounding your farm they take up (0 = none of the surrounding land, **5 =** all of the surrounding land). You may give the same rating to more than one land use.

Arable ☐ Livestock ☐ Forestry ☐ Game rearing ☐

Village ☐ Urban ☐ Other ☐ Please state:

4. How many laying hens were there on your unit at the start of the last laying cycle?

5. What type of outlet do you supply your eggs to? (Please tick all that apply.)

Packing station ☐ Wholesalers ☐ Retailers/caterers ☐

Direct to consumers (i.e. employees and general public) ☐ Other (e.g. sales to processors) ☐

HUSBANDRY

6. Do you have fixed or mobile housing for your hens? Fixed ☐ Mobile ☐

7. Is housing available at all times or only at night? All times ☐ Night only ☐

8. What proportion of a 24 hour day are the hens outside for, on average? (Please tick most appropriate box)

0-25% ☐ 26-50% ☐ 51-75% ☐ 76-100% ☐

9. What is your average number of eggs per hen housed per year? eggs

10. How often do you replace your hen stock? Every weeks

11. How many weeks do your hens lay for? weeks

12. How long is your turn-around period between production cycles? weeks

13. When did your most recent laying cycle finish? Day/Month/Year

FENCING

14. How effective is the fence surrounding your chicken pasture at:	Very effective	Somewhat effective	Ineffective
i) preventing foxes from getting into the pasture?	☐	☐	☐
ii) preventing all unwanted animals from getting into the pasture?	☐	☐	☐
iii) preventing hens from escaping?	☐	☐	☐

15. What type of fence surrounds your chicken pasture? Please tick all that apply. If none of the below, please state any alternative method you use to prevent hen losses.

Permanent perimeter fence ☐ Mobile ☐

Electric ☐ Wire and post ☐ Flexinet ☐

Alternative

16. In what year was the fence first used?

17. How much did the fence cost when first purchased? £

18. What length is the fence? metres

19. How much does maintenance of the fence cost per year? £

20. Have you seen signs of any of the following animals (other than your own) **on your farm over the last 12 months?** (Please tick.)

Stoats/weasels ☐ Mink ☐ Badgers ☐ Foxes ☐ Cats ☐ Dogs ☐

PREDATION BY FOXES ON YOUR FARM (Please only include losses of live hens)

21. When did your most recent (finished) laying cycle start? Day/Month/Year ☐ ☐ ☐

22. During the most recent finished laying cycle, how many hens:

	Number (OR)	Percentage (of hens on farm)
were killed by predators (including foxes)?	☐	☐
were killed by foxes?	☐	☐
died from other causes?	☐	☐

23. Please tick the most appropriate box to rate between 1 and 5 how reliable you believe the above figures for losses to be (1 = guess, 3 = estimate, 5 = accurate figures):

1	2	3	4	5
☐	☐	☐	☐	☐

24. Has there been a change in the number of chickens killed by foxes over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

25. On how many occasions did hens experience stress due to fox activity, during the last laying cycle? ☐

26. How much do you consider that foxes cost you during this most recent laying cycle in terms of financial loss of eggs laid? £ ☐

27. How do these costs compare to those of a typical laying cycle on your farm?

Below average ☐ Average ☐ Above average ☐

INFORMATION ON FOX CONTROL MEASURES
(Including shooting and lamping, trapping, terriers and spades, snaring and hunting with hounds)

28. How many foxes, if any, were killed on your farm in the last 12 months? ☐ foxes

29. Has there been a change in the number of foxes killed on your farm over the past five years?

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

30. What was the cost of all your predator control in the last year? £ ☐ (OR) days ☐

31. What proportion of this was spent on fox control? % ☐

32. Has the amount you spend on fox control changed over the past five years?

Decreased ☐ No change ☐ Increased ☐ Don't know ☐

EGG PRODUCTION ON YOUR FARM

If you are able, please supply me with figures for the following, even approximate. These will help with the economic side of my research into fox impacts. All figures will remain totally confidential.

33. How many eggs were sold in the last 12 months and at what average market price per dozen?

Number sold ☐ Average market price per dozen £ ☐

34. How many replacement pullets did you buy in the last 12 months and at what average price each?

Number bought ☐ Average price each £ ☐

35. How much feed did you buy in the last 12 months and/or how much do you spend on feed?

Amount of feed (please state lb/kg/tonnes) ☐ Cost of feed £ ☐

36. What proportion of the total annual costs on your farm are spent in egg production? % ☐

If you would be willing to answer some more detailed questions for my study, please tick this box ☐

Please give me your name, telephone number and postcode in case I need to contact you about your form. I will not pass this information on to anyone else. If you prefer to remain anonymous (unless you ticked the box above), please give just your **postcode** and **parish** (if known) so I can check the rough location of your farm.

Name ____________________ Telephone number ____________________

Postcode ____________________ **Parish** ____________________

Thank you very much for your help. Please send this form back in the enclosed FREEPOST envelope, or to my address below, and feel free to contact me if you have any comments or queries.

Rebecca Moberly, Environment Department, University of York, FREEPOST NEA8324, York YO10 5ZZ
Tel. 01904 434074 Fax. 01904 432998 Email: RLM106@york.ac.uk

APPENDIX D

Summary of the variables and codes used in Chapter 5 logistic regression analyses for chicken and egg producer data

Variable	Description
Range area	Continuous variable, area of chicken pasture, in hectares
Flock size	Continuous variable, number of birds on farm, for chicken producers: average number of chickens in 1999; for egg producers: number of laying hens at start of last laying cycle
Stocking density	Continuous variable, number of birds per hectare of chicken pasture
Arable b	Dummy variable, coded 1 for farms with arable land in their surroundings
Livestock b	Dummy variable, coded 1 for farms with land used for livestock in their surroundings
Game rearing b	Dummy variable, coded 1 for farms with land used for game rearing in their surroundings
Forestry b	Dummy variable, coded 1 for farms with land used for forestry in their surroundings
Village b	Dummy variable, coded 1 for farms with village(s) in their surrounding land
Urban b	Dummy variable, coded 1 for farms with urban land-uses in their surroundings
Rough grazing b	Dummy variable, coded 1 for farms with land used for rough grazing in their surroundings
Fixed housing	Dummy variable, coded 1 for producers with fixed housing for chickens
Housing available at all times	Dummy variable, coded 1 for producers with housing available at all times, rather than at night only
Time outside	Single digit code for proportion of a 24 hour day chickens are outside for on average, 1 = 0-25%, 2 = 26-50%, 3 = 51-75%, 4 = 76-100%
Permanent	Dummy variable, coded 1 for producers with permanent perimeter fence round chicken pasture
Mobile	Dummy variable, coded 1 for producers with mobile fencing round chicken pasture
Electric	Dummy variable, coded 1 for producers with electric fencing round chicken pasture

Flexinet	Dummy variable, coded 1 for producers with Flexinet fencing round chicken pasture
Wire and post	Dummy variable, coded 1 for producers with wire and post fencing round chicken pasture
Electric only	Dummy variable, coded 1 for producers only with electric fencing round chicken pasture
Flexinet only	Dummy variable, coded 1 for producers only with Flexinet fencing round chicken pasture
Wire and post only	Dummy variable, coded 1 for producers only with wire and post fencing round chicken pasture
Number of chickens reported lost to causes other than predation (square-root transformed)	Continuous variable, number of chickens reported lost to causes other than predation, square-root transformed to reduce right skew of original variable
Proportion of chickens reported lost to causes other than predation	Continuous variable, number of chickens reported lost to causes other than predation divided by flock size, arcsine-transformed
Number of foxes killed on farm in last year	Continuous variable, number of foxes killed in 1998 for chicken producers, number of foxes killed in last 12 months for egg producers
Fox control carried out	Dummy variable, coded 1 for farms where foxes were killed by various control measures
Region-based relative fox density	Continuous variable with 9 levels
Land class-based relative fox density	Continuous variable with 7 levels

APPENDIX E

Questionnaire form for outdoor pig producer survey

IMPACT OF FOXES ON OUTDOOR PIG PRODUCTION

GENERAL

1. **How large is the area of your pig paddocks?** hectares (or) acres

2. **How many paid employees are there on your farm?**

Full-time

Part-time (less than 16 hours a week)

Casual (less than 6 months of year)

3. **Please rate the following land uses from 0 to 5, according to how much of the land surrounding your pig paddocks they take up (0 =** none of the surrounding land, **5 =** most of the surrounding land). You may give the same rating to more than one land use.

Arable

Livestock

Game rearing

Forestry

Village

Urban

Other

Please state:

4. **How many sows (including served gilts) are there, on average, on your holding?** sows

HUSBANDRY

5. **How many times a year, on average, does each of your sows farrow?** times

6. **How many sows farrow per week, on average?** sows

7. **How many piglets are born alive per sow, on average?** piglets

8. **Are sows and piglets shut in their arks overnight for the first 48 hour period after farrowing?** Yes ☐ No ☐

9. **Are piglets retained by fenders in front of the arks prior to weaning?** Yes ☐ No ☐

10. **Do arks have plastic flaps over their entrances?** Yes ☐ No ☐

11. **What percentage of your sow stock do you replace per year?** %

12. **What percentage of your boar stock do you replace per year?** %

BOUNDARY FENCING

13. **How effective is the fence surrounding your paddocks at:**

	Very effective	Somewhat effective	Ineffective
i) preventing foxes from getting into the paddocks?	☐	☐	☐
ii) preventing all unwanted animals from getting in?	☐	☐	☐
iii) preventing pigs from escaping?	☐	☐	☐

14. **a) Do you use a specialist fox fence?** Yes ☐ ⇒ **please answer (b) and (c)** No ☐ ⇒ **please answer (d)**

b) What is the height of the fence? metres/centimetres (or) feet/inches

c) How many strands does it have? strands

d) What other type of boundary fence surrounds your paddocks? Please tick all that apply. If none of the below, please state any alternative method you use to prevent pig losses.

Permanent perimeter fence ☐ Mobile ☐

Electric ☐ Wire and post ☐ Flexinet ☐

Alternative:

15. **In what year was the fence first used?**

16. **How much did the fence cost when first purchased?** £

17. **What length is the fence?** metres

18. **How much does maintenance of the fence cost per year?** £

IN THE PAST YEAR:

19. In the past year, how many piglets have been born on your farm? ☐ piglets

(Please only include losses of live pigs)

20. Between farrowing and weaning, how many piglets:

	Number (or)	Percentage (of those born alive)
died, in total?	☐	☐
were killed by predators (including foxes)?	☐	☐
were killed by foxes?	☐	☐
died due to fox disturbance of a sow?	☐	☐

21. Please tick the most appropriate box to rate between 1 and 5 how reliable you believe the above figures for piglet losses to be (1 = guess, 3 = estimate, 5 = accurate figures):

1	2	3	4	5
☐	☐	☐	☐	☐

22. During which month(s) were pigs killed by foxes? (Please circle)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

23. How much do you consider losses to foxes cost you in the last year? £ ☐

24. Has there been a change in the number of piglets killed by foxes over the past five years?
A decrease ☐ No change ☐ An increase ☐ Don't know ☐

25. Have you seen signs of any of the following animals (other than your own) **on your farm over the last 12 months?** (Please tick.)
Stoats/weasels ☐ Mink ☐ Badgers ☐ Foxes ☐ Cats ☐ Dogs ☐

INFORMATION ON FOX CONTROL MEASURES

(Including shooting and lamping, trapping, terriers and spades, snaring and hunting with hounds)

26. How many foxes, if any, were killed on your farm in the last year? ☐ foxes

27. Has there been a change in the number of foxes killed on your farm over the past five years?
A decrease ☐ No change ☐ An increase ☐ Don't know ☐

28. What was the cost of all your predator control in the last year? £ ☐ (or) days ☐

29. What proportion of this was spent on fox control? % ☐

30. Has the amount of time and money you spend on fox control changed over the past five years?
Decreased ☐ No change ☐ Increased ☐ Don't know ☐

PIG PRODUCTION ON YOUR FARM

If you are able to, please supply me with figures for the following, even approximate. These will help with the economic side of my research into fox impacts. All figures will remain totally confidential.

31. How many of the following pigs did you sell over the last 12 months and at what average liveweight?

Weaners (at weaning)	☐	Average liveweight kg	☐
Stores	☐	Average liveweight kg	☐
Finishers	☐	Average liveweight kg	☐
Boars for cull	☐	Sows for cull	☐

32. How much feed did you buy in the last 12 months and/or how much did you spend on feed?
Amount of feed (**please state lb/kg/ton**) ☐ Cost of feed £ ☐

33. What proportion of the total annual costs on your farm are spent in pig production? % ☐

LOCATION

34. Please give me the postcode and parish of your farm (if known) so I can check its rough location:
Postcode ☐ Parish ☐

Thank you very much for your help. Please send this form back in the FREEPOST envelope, or to my address:
Rebecca Moberly, Environment Department, University of York, FREEPOST NEA8324, York YO10 5ZZ

APPENDIX F

Summary of the variables and codes used in Chapter 6 regression analyses

Variable	**Description**
Total number of sows (ln-transformed)	Continuous variable, number of sows (including served gilts) on holding on average, ln-transformed to reduce right skew of original variable
Stocking density	Continuous variable, average number of sows per hectare of paddock, calculated by dividing number of sows by the area of the paddocks in hectares
Number of piglets born (ln-transformed)	Continuous variable, number of piglets born on holding in last year, ln-transformed to reduce right skew of original variable
Number of piglets born per sow	Continuous variable, number of piglets born on holding in last year divided by number of sows on holding
Arable b	Dummy variable, coded 1 for holdings with arable land in their surroundings
Livestock b	Dummy variable, coded 1 for holdings with land used for livestock in their surroundings
Game rearing b	Dummy variable, coded 1 for holdings with land used for game rearing in their surroundings
Forestry b	Dummy variable, coded 1 for holdings with land used for forestry in their surroundings
Village b	Dummy variable, coded 1 for holdings with village(s) in their surrounding land
Urban b	Dummy variable, coded 1 for holdings with urban land-uses in their surroundings
Rough grazing b	Dummy variable, coded 1 for holdings with land used for rough grazing in their surroundings
North Scotland	Dummy variable, coded 1 for holdings in North Scotland region (Table 2.3)
North England	Dummy variable, coded 1 for holdings in North England region (Table 2.3)

East England	Dummy variable, coded 1 for holdings in East England region (Table 2.3)
Midlands	Dummy variable, coded 1 for holdings in Midlands region (Table 2.3)
Southwest England	Dummy variable, coded 1 for holdings in Southwest England region (Table 2.3)
South England	Dummy variable, coded 1 for holdings in South England region (Table 2.3)
Wales	Dummy variable, coded 1 for holdings in Wales region (Table 2.3)
Land class 1	Dummy variable, coded 1 for holdings with central farm buildings in land class group 1 (Table 2.4)
Land class 2	Dummy variable, coded 1 for holdings with central farm buildings in land class group 2 (Table 2.4)
Land class 3	Dummy variable, coded 1 for holdings with central farm buildings in land class group 3 (Table 2.4)
Land class 4	Dummy variable, coded 1 for holdings with central farm buildings in land class group 4 (Table 2.4)
Land class 5	Dummy variable, coded 1 for holdings with central farm buildings in land class group 5 (Table 2.4)
Land class 6	Dummy variable, coded 1 for holdings with central farm buildings in land class group 6 (Table 2.4)
Specialist fox fence	Dummy variable, coded 1 for holdings with a specialist fox fence surrounding pig paddocks
Permanent	Dummy variable, coded 1 for producers with permanent perimeter fence surrounding pig paddocks
Mobile	Dummy variable, coded 1 for producers with mobile fencing surrounding pig paddocks
Electric	Dummy variable, coded 1 for producers with electric fencing surrounding pig paddocks

Flexinet	Dummy variable, coded 1 for producers with Flexinet fencing surrounding pig paddocks
Wire and post	Dummy variable, coded 1 for producers with wire and post fencing surrounding pig paddocks
Shut in arks overnight	Dummy variable, coded 1 for producers that shut sows and piglets in arks overnight for first 48 hour period after farrowing
Retaining fenders	Dummy variable, coded 1 for producers with piglets retained by fenders in front of arks prior to weaning
Plastic flaps on ark entrances	Dummy variable, coded 1 for producers with plastic flaps over ark entrances
Number of piglets reported died in total (ln-transformed)	Continuous variable, number of piglets reported died in total between birth and weaning, ln-transformed to reduce right skew of original variable
Number of piglets reported died in total per sow	Continuous variable, number of piglets reported died in total between birth and weaning divided by the number of sows on holding
Fox control carried out	Dummy variable, coded 1 for farms where foxes were killed by various control measures
Number of foxes killed on farm in last year	Continuous variable, number of foxes killed in the last year
Region-based relative fox density	Continuous variable with 9 levels
Land class-based relative fox density	Continuous variable with 7 levels

APPENDIX G

Questionnaire form for survey of game interests

IMPACT OF FOXES ON GAME INTERESTS

GENERAL

1. **What is the area of your shoot?** ☐ hectares (or) ☐ acres

2. **Please rate the following land uses from 0 to 5, according to how much of the land surrounding your shoot they take up (0** = none of the surrounding land, **5** = most of the surrounding land). You may give the same rating to more than one land use.

Arable ☐ Livestock ☐ Game rearing ☐ Forestry ☐

Village ☐ Urban ☐

Other ☐ Please state: ☐

3. **How many of the following birds were shot in the last year?**

Pheasant ☐ Grey Partridge ☐ Red Grouse ☐

Duck ☐ Geese ☐ French (Red-leg) Partridge ☐

4. **What type(s) of shoot do you run?** (Please tick)

Driven ☐ Walked-up ☐ Dogging ☐ Duck-flighting ☐

INFORMATION ON FOX CONTROL MEASURES

5. **How many foxes were killed on your shoot in the last year?** ☐ foxes

6. **How many or what percentage of these foxes were killed by each of the following methods in the last year?**

	Number	(or)	%	
Lamping (shooting at night)	☐		☐	
Shooting by day	☐		☐	-- with rifles ☐ (and/or) shotguns ☐ (Please tick)
Snaring	☐		☐	
Digging out with terriers	☐		☐	
Trapping	☐		☐	
Hunting with hounds	☐		☐	-- Mounted ☐ (and/or) Foot pack ☐ (Please tick)
Other	☐		☐	

Please state 'other' method: ☐

7. **What percentage of the fox kills were made in each of these seasons last year?**

Spring (March-May) ☐ Summer (June-August) ☐ Autumn (September-November) ☐ Winter (December-February) ☐

8. **Has there been a change in the number of foxes killed on your shoot over the past five years?**

A decrease ☐ No change ☐ An increase ☐ Don't know ☐

9. **How many gamekeepers are employed on the shoot?** (Please include yourself, if applicable.)

Full-time ☐ Part-time (less than16 hours a week) ☐ Casual (less than 6 months of year) ☐

10. **How much of their time do the keepers spend on fox control?** % ☐

11. **Has the amount of time spent on fox control changed over the past five years?**

Decreased ☐ No change ☐ Increased ☐ Don't know ☐

12. **Do you shoot ground game on shoot days?** Yes ☐ No ☐

Please turn over

PHEASANT RELEASE PENS

13. How many pheasant release pens do you have? pens

14. How effective are the release pens at:

	Very effective	Somewhat effective	Ineffective
i) preventing foxes from getting into the pens?	☐	☐	☐
ii) preventing all unwanted animals from getting into the pens?	☐	☐	☐

15. What measures do you employ to prevent foxes from entering pens? (Please tick)

Overhanging anti-fox fringe ☐ Electric fencing ☐ Fox grids over entrances ☐

Dug-in or pegged down netting ☐ Snare walls ☐ Flashing lights (scarers) ☐

Others (please state)

16. What length of perimeter netting do you allow per bird? metres (or) yards

17. How long do you expect your pens to last? years

PREDATION BY FOXES OF PHEASANTS IN RELEASE PENS THIS YEAR
(Please only include losses of live pheasants)

18. How many pheasants were released into pens? pheasants

19. How old were the pheasants when released into pens? weeks

20. How many pheasants in the release pens:

	Number (or)	% (of pheasant chicks)
died, in total?		
were killed by predators (including foxes)?		
were killed by foxes?		

21. Please tick the most appropriate box to rate between 1 and 5 how reliable you believe the above figures for losses to be (1 = guess, 3 = estimate, 5 = accurate figures):

1	2	3	4	5
☐	☐	☐	☐	☐

22. Has there been a change in the number of pheasants killed by foxes in release pens over the past five years? A decrease ☐ No change ☐ An increase ☐ Don't know ☐

FURTHER INFORMATION

23. Do you sell your shooting by bird or by day? (Please tick) By bird ☐ By day ☐

24. How many shooting days do you have a year? days

25. How many guns do you have per shoot day? guns

26. What proportion of the estate or holding's revenue is accounted for by shooting? (Please tick one box)

Less than 25% ☐ Around 25% ☐ Around 50% ☐ Around 75% ☐ 100% ☐

27. Please give the estate or holding's **postcode** and **parish** (if known) so I can check its rough location.

Postcode **Parish**

28. Please tick this box if you have long-term records on fox control and/or pheasant losses you would be willing to let me use for my study ☐

Thank you very much for your help. Please send this form back in the enclosed FREEPOST envelope or to my address below and feel free contact me if you have any comments or queries.

Rebecca Moberly, Environment Department, University of York, FREEPOST NEA8324, York YO10 5ZZ
Tel. 01904 434074 Fax. 01904 432998 Email: RLM106@york.ac.uk

APPENDIX H

Summary of the variables and codes used in Chapter 7 regression analyses

Variable	**Description**
Number of pheasants released (square-root-transformed)	Continuous variable, number of pheasants released into release pens in 2000, square-root-transformed to reduce right skew of original variable
Number of release pens	Continuous variable, number of pens into which pheasants were released
Pheasants per pen	Continuous variable, average number of pheasants in each release pen on shoot, calculated by dividing number of pheasant released by number of release pens
Age at release	Continuous variable, age of pheasants at release, in weeks
Arable b	Dummy variable, coded 1 for shoots with arable land in their surroundings
Livestock b	Dummy variable, coded 1 for shoots with land used for livestock in their surroundings
Game rearing b	Dummy variable, coded 1 for shoots with land used for game rearing in their surroundings
Forestry b	Dummy variable, coded 1 for shoots with land used for forestry in their surroundings
Village b	Dummy variable, coded 1 for shoots with village(s) in their surrounding land
Urban b	Dummy variable, coded 1 for shoots with urban land-uses in their surroundings
Rough grazing b	Dummy variable, coded 1 for shoots with land used for rough grazing in their surroundings
North Scotland	Dummy variable, coded 1 for shoots in North Scotland region (Table 2.3)
South Scotland	Dummy variable, coded 1 for shoots in South Scotland region (Table 2.3)
North England	Dummy variable, coded 1 for shoots in North England region (Table 2.3)
East England	Dummy variable, coded 1 for shoots in East England region (Table 2.3)

Midlands	Dummy variable, coded 1 for shoots in Midlands region (Table 2.3)
Southwest England	Dummy variable, coded 1 for shoots in Southwest England region (Table 2.3)
South England	Dummy variable, coded 1 for shoots in South England region (Table 2.3)
Wales	Dummy variable, coded 1 for shoots in Wales region (Table 2.3)
Land class 1	Dummy variable, coded 1 for shoots in land class group 1 (Table 2.4)
Land class 2	Dummy variable, coded 1 for shoots in land class group 2 (Table 2.4)
Land class 3	Dummy variable, coded 1 for shoots in land class group 3 (Table 2.4)
Land class 4	Dummy variable, coded 1 for shoots in land class group 4 (Table 2.4)
Land class 5	Dummy variable, coded 1 for shoots in land class group 5 (Table 2.4)
Land class 6	Dummy variable, coded 1 for shoots in land class group 6 (Table 2.4)
Land class 7	Dummy variable, coded 1 for shoots in land class group 7 (Table 2.4)
Anti-fox fringe	Dummy variable, coded 1 for shoots using overhanging anti-fox fringes on pens
Electric fencing	Dummy variable, coded 1 for shoots using electric fencing on pens
Fox grids	Dummy variable, coded 1 for shoots using fox grids over pen entrances
Dug-in netting	Dummy variable, coded 1 for shoots using dug-in or pegged down netting for pens
Snare walls	Dummy variable, coded 1 for shoots using snare walls round pens
Scarers	Dummy variable, coded 1 for shoots using flashing lights or scarers by pens
Radio	Dummy variable, coded 1 for shoots using radios as scarers near pens
Number of preventive measures used on pens	Continuous variable, number of different measures employed to prevent foxes from entering release pens

Number of pheasants reported died from causes other than predation (square-root-transformed)	Continuous variable, number of pheasants reported died from causes other than predation, square-root-transformed to reduce right skew of original variable
Percentage of pheasants reported died from causes other than predation (arcsine-transformed)	Continuous variable, percentage of pheasants reported died from causes other than predation out of the total released, arcsine-transformed
Percentage of pheasants reported killed by predators (arcsine-transformed)	Continuous variable, percentage of pheasants reported killed by predators out of the total released, arcsine-transformed
Number of foxes killed on shoot in last year	Continuous variable, number of foxes killed in the last year
Foxes killed per hectare in last year	Continuous variable, number of foxes killed in the last year divided by shoot area
Region-based relative fox density	Continuous variable with 9 levels
Land class-based relative fox density	Continuous variable with 7 levels

REFERENCES

Abbott, T. A., Hunter, E. J. & Guise, H. J. (1996). Survey of management and welfare in outdoor pig production systems. *Applied Animal Behaviour Science* **49**: 96-97.

Abenspergtraun, M. (1991). Survival strategies of the echidna *Tachyglossus aculeatus* Shaw 1792 (Monotremata, Tachyglossidae). *Biological Conservation* **58**: 317-328.

Acharya, G. (1998). Valuing the environment as an input: the production function approach. *Environmental Valuation, Economic Policy and Sustainability*, M. Acutt & P. Mason (Eds.), pp. 63-78. Edward Elgar, Cheltenham.

Adams, R. M., Crocker, T. D. & Thanavibulchai, N. (1982). An economic assessment of air pollution damages to selected annual crops in southern California. *Journal of Environmental Economics and Management* **9**: 42-58.

Adams, R. M., Hamilton, S. A. & McCarl, B. A. (1986). The benefits of pollution control: the case of ozone and US agriculture. *American Journal of Agricultural Economics* **68**: 886-893.

Adams, R. M. & McCarl, B. A. (1985). Assessing the benefits of alternative ozone standards on agriculture: the role of response information. *Journal of Environmental Economics and Management* **12**: 264-276.

Andelt, W. F. & Hopper, S. N. (2000). Livestock guard dogs reduce predation on domestic sheep in Colorado. *Journal of Range Management* **53**(3): 259-267.

Allen, L. R. & Sparkes, E. C. (2001). The effect of dingo control on sheep and beef cattle in Queensland. *Journal of Applied Ecology* **38**: 76-87.

Anderson, R. M., Jackson, H. C., May, R. M. & Smith, A. M. (1981). Population dynamics of fox rabies in Europe. *Nature* **289**: 765-771.

Andrew, J. & Robottom, I. (2001). Science and ethics: some issues for education. *Science Education* **85**(6): 769-780.

Anon (1993). The Field survey of predation on lambs by foxes. *The Field*. **April:** 56-60.

Anon (1997). *The Pheasant*. The Game Conservancy Trust, Fordingbridge, Hampshire.

Armitage, P. & Berry, G. (1994). *Statistical Methods in Medical Research*. Blackwell Science Ltd, Oxford.

Artois, M. (1997). Managing problem wildlife in the 'Old World': a veterinary perspective. *Reproduction, Fertility and Development* **9**: 17-25.

Artois, M., Lemaire, M., George, J., Demerson, J. M. & Jacquemet, J. (1987). Les fèces du Renard (*Vulpes vulpes*) comme indice de consommation ou de préférence alimentaire et d'activité. *Cahiers d'Ethologie Appliquée* **7**(3): 275-286.

Artois, M., Delahay, R., Guberti, V. & Cheeseman, C. (2001). Control of infectious diseases of wildlife in Europe. *Veterinary Journal* **162**(2): 141-152.

Aubert, M. F. A. (1999). Costs and benefits of rabies control in France. *Revue Scientifique et Technique de l'Office International des Epizooties* **18**(2): 533-543.

Baines, R., Baker, S., Hallett, J. & Macdonald, D. (1995). *The impact of foxes and fox hunting on the management of Wiltshire County Farms Estate. Centre for Rural Studies Occasional Paper No. 22.* Centre for Rural Studies, Cirencester.

Baines, D. (1990). The roles of predation, food and agricultural practice in determining the breeding success of the lapwing (*Vanellus vanellus*) on upland grasslands. *Journal of Animal Ecology* **59**: 915-929.

Baines, D. (1996). The implications of grazing and predator management on the habitats and breeding success of black grouse *Tetrao tetrix. Journal of Applied Ecology* **33**(1): 54-62.

Baker, P. J., Funk, S. M., Harris, S. & White, P. C. L. (2000). Flexible spatial organization of urban foxes, *Vulpes vulpes*, before and during an outbreak of sarcoptic mange. *Animal Behaviour* **59**: 127-146.

Baker, S. E. & Macdonald, D. W. (1999). Non-lethal predator control: exploring the options. *Advances in vertebrate pest management*, D. P. Cowan & C. J. Feare (Eds.), pp. 251-266. Filander Verlag, Fürth.

Baker, S. E. & Macdonald, D. W. (2000). Foxes and foxhunting on farms in Wiltshire: a case study. *Journal of Rural Studies* **16**: 185-201.

Balharry, E. A. & Macdonald, D. W. (1999). Cost-effective electric fencing for protecting gamebirds against Pine Marten *Martes martes* predation. *Mammal Review* **29**: 67-72.

Banks, P. B. (2000). Can foxes regulate rabbit populations? *Journal of Wildlife Management* **64**(2): 401-406.

Banks, P. B., Dickman, C. R. & Newsome, A. E. (1998). Ecological costs of feral predator control: foxes and rabbits. *Journal of Wildlife Management* **62**: 766-772.

Barbier, E. B., Acreman, M. & Knowler, D. (1997). *Economic Valuation of Wetlands.* Ramsar Convention Bureau, Switzerland.

Barnett, V. (1991). *Sample Survey: Principles and Methods.* Edward Arnold, London.

Barr, C. J., Bunce, R. G. H., Clarke, R. T., Fuller, R. M., Furse, M. T., Gillespie, M. K., Groom, G. B., Hallam, C. J., Hornung, M., Howard, D. C., *et al.* (1993). *Countryside Survey 1990: Main Report.* HMSO, London.

Bealey, C. E., Green, R. E., Robson, R., Taylor, C. R. & Winspear, R. (1999). Factors affecting the numbers and breeding success of stone curlews *Burhinus oedicnemus* at Porton Down, Wiltshire. *Bird Study* **46**(2): 145-156.

Begon, M., Harper, J. L. & Townsend, C. R. (1996). *Ecology: Individuals, Populations and Communities*. Blackwell Science, Oxford.

Beltrán, J. F., Delibes, M. & Rau, J. R. (1991). Methods of censusing red fox (*Vulpes vulpes*) populations. *Hystrix* **3**: 199-214.

Bennett, R. M., Christiansen, K. & Clifton-Hadley, R. S. (1999). Direct costs of endemic diseases of farm animals in Great Britain. *The Veterinary Record* **145**: 376-377.

Bhat, M. G., Huffaker, R. G. & Lenhart, S. M. (1996). Controlling transboundary wildlife damage: modelling under alternative management scenarios. *Ecological Modelling* **92**: 215-224.

Bicknell, K. (1993). Cost-benefit and cost-effectiveness analyses in pest management. *New Zealand Journal of Zoology* **20**: 307-312.

Bingham, D. (1993). The price of a wild pheasant. *The Field*. **March 1993:** 48-49.

Birley, M. H. (1979). The theoretical control of seasonal pests. *Mathematical Biosciences* **43**: 141-157.

Blanco, J. C., Reig, S. & Delacuesta, L. (1992). Distribution, status and conservation problems of the wolf *Canis lupus* in Spain. *Biological Conservation* **60**: 73-80.

Boatfield, G. (1994). *Farm Livestock*. Farming Press, Ipswich.

Bradley, M. P., Hinds, L. A. & Bird, P. H. (1997). A bait-delivered immunocontraceptive vaccine for the European red fox (*Vulpes vulpes*) by the year 2002? *Reproduction, Fertility and Development* **9**: 111-116.

Brent, R. J. (1997). *Applied Cost-Benefit Analysis*. Edward Elgar, Cheltenham.

Brochier, B. (1989). Emplacement et densité des terriers de mise-bas du renard roux (*Vulpes vulpes* L.) en périphérie bruxelloise. *Cahiers d'Ethologie Appliquée* **9**: 495-508.

Bryson, T. (1984). *The Sheep Housing Handbook*. Farming Press, Ipswich.

Bunce, R. G. H. (1992). *The Distribution and Aggregation of ITE Land Classes*. Institute of Terrestrial Ecology, Merlewood, Grange-over-Sands, Cumbria.

Burns, L., Edwards, V., Marsh, J., Soulsby, L. & Winter, M. (2000). *The Final Report of the Committee of Inquiry into Hunting with Dogs in England and Wales*. The Stationery Office Limited, Norwich.

Burrows, R. (1968). *Wild Fox*. David and Charles, Newton Abbot.

Butler, J. R. A. (2000). The economic costs of wildlife predation on livestock in Gokwe communal land, Zimbabwe. *African Journal of Ecology* **38**: 23-30.

Caughley, G. & Sinclair, A. R. E. (1994). *Wildlife Ecology and Management*. Blackwell Scientific, Boston, MA.

Cavallini, P. (1994). Faeces count as an index of fox abundance. *Acta Theriologica* **39**: 417-424.

Cavallini, P. & Santini, S. (1996). Reproduction of the red fox *Vulpes vulpes* in Central Italy. *Annales Zoologici Fennici* **33**: 267-274.

Chadwick, A. H., Hodge, S. J. & Ratcliffe, P. R. (1997). *Foxes and Forestry*. Forestry Commission, Edinburgh.

Chautan, M., Pontier, D. & Artois, M. (2000). Role of rabies in recent demographic changes in Red Fox (*Vulpes vulpes*) populations in Europe. *Mammalia* **64**(4): 391-410.

Cherrett, J. M., Ford, J. B., Herbert, I. V. & Probert, A. J. (1971). *The Control of Injurious Animals*. English Universities Press, London.

Chilonda, P. & Van Huylenbroeck, G. (2001). A conceptual framework for the economic analysis of factors influencing decision-making of small-scale farmers in animal health management. *Revue Scientifique et Technique de l'Office International d'Epizooties* **20**: 687-700.

Choquenot, D., Lukins, B. & Curran, G. (1997). Assessing lamb predation by feral pigs in Australia's semi-arid rangelands. *Journal of Applied Ecology* **34**: 1445-1454.

Choquenot, D. & Parkes, J. (2001). Setting thresholds for pest control: how does pest density affect resource viability? *Biological Conservation* **99**: 29-46.

Choquenot, D. & Hone, J. (unpublished). Using bioeconomic models to maximise benefits from vertebrate pest control: lamb predation by feral pigs.

Christensen, J. & Svensmark, B. (1997). Evaluation of producer-recorded causes of preweaning mortality in Danish sow herds. *Preventive Veterinary Medicine* **32**: 155-164.

Cobham Resource Consultants (1983). *Countryside Sports: Their Economic Significance. Main Report prepared for The Standing Conference on Countryside Sports*. Cobham Resource Consultants, Oxford.

Collins, A. R., Workman, J. P. & Uresk, D. W. (1984). An economic analysis of black-tailed prairie dog (*Cynomys ludovicianus*) control. *Journal of Range Management* **37**(4): 358-361.

Coman, B. J. (1985). Australian predators of livestock. *World Animal Science. Part B. Vol 2. Parasites, Pests and Predators*, S. M. Gaafar, W. E. Howard & R. E. Marsh (Eds.), pp. 411-425. Elsevier, Amsterdam.

Committee on Animal Nutrition, N. R. C. (1985). *Nutrient Requirements of Sheep, Sixth Revised Edition*. National Academy Press, Washington DC.

Conover, M. R. (1997a). Monetary and intangible valuation of deer in the United States. *Wildlife Society Bulletin* **25**: 298-305.

Conover, M. R. (1997b). Wildlife management by metropolitan residents in the United States: practices, perceptions, costs, and values. *Wildlife Society Bulletin* **25**: 306-311.

Conover, M. R., Pitt, W. C., Kessler, K. K., DuBow, T. J. & Sanborn, W. A. (1995). Review of human injuries, illnesses and economic losses caused by wildlife in the United States. *Wildlife Society Bulletin* **23**: 407-414.

Conway, G. (1981). Man versus pests. *Theoretical Ecology*, R. M. May (Ed.) pp. 356-386. Blackwell Scientific Publications, Oxford.

Côté, I. M. & Sutherland, W. J. (1997). The effectiveness of removing predators to protect bird populations. *Conservation Biology* **11**: 395-405.

Cottle, P. & Cottle, S., Eds. (1998). *Outsider's Guide to Animal Production.* Outsider's Guide, Lincoln.

Cowan, P. E. & Tyndale-Biscoe, C. H. (1997). Australian and New Zealand mammal species considered to be pests or problems. *Reproduction, Fertility and Development* **9**: 27-36.

Cozza, K., Fico, R., Battistini, M-L. & Rogers, E. (1996). The damage-conservation interface illustrated by predation on domestic livestock in central Italy. *Biological Conservation* **78**: 329-336.

Dasgupta, A. K. & Pearce, D. W. (1978). *Cost-Benefit Analysis: Theory and Practice.* Macmillan Press, London.

DEFRA (2000). *Eggs and Poultry Facts and Statistics www.defra.gov.uk/foodrin/poultry/flow4.htm.* Department for Environment, Food and Rural Affairs, London.

DEFRA (2001). *The Welfare of Hens in Free Range Systems.* Department for Environment, Food and Rural Affairs, London.

Dickman, C. R., Pressey, R. L., Lim, L. & Parnaby, H. E. (1993). Mammals of particular conservation concern in the western division of New South Wales. *Biological Conservation* **65**: 219-248.

Dion, N., Hobson, K. A. & Larviere, S. (1999). Effects of removing duck-nest predators on nesting success of grassland songbirds. *Canadian Journal of Zoology* **77**: 1801-1806.

Duncan, J. S., Reid, H. W., Moss, R., Phillips, J. D. P. & Watson, A. (1979). Ticks, louping ill and red grouse on moors in Speyside, Scotland. *Journal of Wildlife Management* **43**: 500-505.

Edwards, S. A., Smith, W. J., Fordyce, C. & MacMenemy, F. (1994). An analysis of the causes of piglet mortality in a breeding herd kept outdoors. *Veterinary Record* **135**: 324-327.

Ellis, G. M. & Fisher, A. C. (1986). Valuing the environment as input. *Journal of Environmental Management* **25**: 149-156.

Enemark, H. L., Bjorn, H., Henriksen, S. A. & Nielsen, B. (2000). Screening for infection of *Trichinella* in red fox (*Vulpes vulpes*) in Denmark. *Veterinary Parasitology* **88**: 229-237.

Failu, L. & Griess, D. (1974). Essai d'alimentation de renards roux à l'aide d'un aliment composé complet sec pour le chien. *Revue de Medecine Véterinaire* **125**(10): 1215-1224.

Fall, M. W. & Jackson, W. B. (1998). A new era of vertebrate pest control? An introduction. *International Biodeterioration and Biodegradation* **42**: 85-91.

Fankhauser, S. (1995). Protection versus retreat: the economic costs of sea-level rise. *Environment and Planning A* **27**: 299-319.

FAWC (1997). *Report on the Welfare of Laying Hens.* Farm Animal Welfare Council (FAWC), Surbiton, Surrey.

FAWC (1996). *Report on the Welfare of Pigs Kept Outdoors.* Farm Animal Welfare Council (FAWC), Surbiton, Surrey.

Forchhammer, M. C. & Asferg, T. (2000). Invading parasites cause a structural shift in red fox dynamics. *Proceedings of the Royal Society, London B* **267**: 779-786.

Forster, J. A. (1975). Electric fencing to protect sandwich terns against foxes. *Biological Conservation* **7**: 85.

Freeman, A. M. (1993). *The Measurement of Environmental and Resource Values - Theory and Methods.* Resources for the Future, USA.

Game Conservancy (1983). *Pheasant Rearing and Releasing.* The Game Conservancy, Fordingbridge, Hampshire.

Game Conservancy Trust (1996). *Gamebird Releasing.* The Game Conservancy Trust, Fordingbridge, Hampshire.

Gefen, E. & Macdonald, D. W. (2001). Foxes. *The New Encyclopedia of Mammals*, D. W. Macdonald (Ed.) pp. 54-61. Oxford University Press, Oxford.

Grant, M. C., Orsman, C., Easton, J., Lodge, C., Smith, M., Thompson, G., Rodwell, S. & Moore, N. (1999). Breeding success and causes of breeding failure of curlew *Numenius arquata* in Northern Ireland. *Journal of Applied Ecology* **36**: 59-74.

Greentree, C., Saunders, G., McLeod, L. & Hone, J. (2000). Lamb predation and fox control in south-eastern Australia. *Journal of Applied Ecology* **37**(6): 935-943.

Gujarati, D. N. (1995). *Basic Econometrics.* McGraw-Hill, New York.

Hanley, N., Shogren, J. F. & White, B. (2001). *Introduction to Environmental Economics.* Oxford University Press, Oxford.

Harding, E. K., Doak, D. F. & Albertson, J. D. (2001). Evaluating the effectiveness of predator control: the non-native red fox as a case study. *Conservation Biology* **15**: 1114-1122.

Harris, S. (1989). When is a pest a pest? *New Scientist* **121**(1654, 4 March 1989): 49-51.

Harris, S. & Lloyd, H. G. (1991). Fox *Vulpes vulpes. The Handbook of British Mammals*, G. B. Corbet & S. Harris (Eds.), pp. 351-367. Blackwell Science Publications, Oxford.

Harris, S., Morris, P., Wray, S. & Yalden, D. (1995). *A Review of British Mammals: Population Estimates and Conservation Status of British Mammals other than Cetaceans.* JNCC, Peterborough.

Harris, S. & Rayer, J. M. V. (1986). Urban fox (*Vulpes vulpes*) population estimates and habitat requirements in several British cities. *Journal of Animal Ecology* **55**: 575-91.

Harris, S. & Saunders, G. (1993). The control of canid populations. *Symposium of the Zoological Society of London* **65**: 441-464.

Harris, S. & Smith, G. C. (1987a). Demography of two urban fox (*Vulpes vulpes*) populations. *Journal of Applied Ecology* **24**: 75-86.

Harris, S. & Smith, G. C. (1987b). The use of sociological data to explain the distribution and numbers of urban foxes in England and Wales. *Symposium of the Zoological Society of London* **58**: 313-328.

Harris, S. & White, P. C. L. (1994). *The Red Fox.* The Mammal Society, London.

Harris, S. & Woollard, T. (1988). Bristol's foxes. *Proceedings of the Bristol Naturalists' Society* **48**: 3-15.

Headley, J. C. (1972). Defining the economic threshold. *Pest Control Strategies for the Future*, pp. 100-108. National Academy of Sciences, Washington DC.

Hewson, R. (1984a). Changes in the numbers of foxes (*Vulpes vulpes*) in Scotland. *Journal of Zoology, London* **204**: 561-569.

Hewson, R. (1984b). Scavenging and predation upon sheep and lambs in west Scotland. *Journal of Applied Ecology* **21**: 843-868.

Hewson, R. (1985). Lamb carcasses and other food remains at fox dens in Scotland. *Journal of Zoology, London* **206**: 291-296.

Hewson, R. (1986). Distribution and density of fox breeding dens and the effects of management. *Journal of Applied Ecology* **23**: 531-538.

Hewson, R. & Kolb, H. H. (1973). Changes in the numbers and distribution of foxes (*Vulpes vulpes*) killed in Scotland from 1948-1970. *Journal of Zoology, London* **171**: 345-365.

Hewson, R. & Leitch, A. F. (1983). The food of foxes (*Vulpes vulpes*) in Scottish forests. *Journal of Zoology, London* **176**: 287-292.

Heydon, M. J. & Reynolds, J. C. (2000a). Demography of rural foxes (*Vulpes vulpes*) in relation to cull intensity in three contrasting regions of Britain. *Journal of Zoology, London* **251**: 265-276.

Heydon, M. J. & Reynolds, J. C. (2000b). Fox (*Vulpes vulpes*) management in three contrasting regions of Britain, in relation to agricultural and sporting interests. *Journal of Zoology, London* **251**: 237-252.

Heydon, M. J., Reynolds, J. C. & Short, M. J. (2000). Variation in abundance of foxes (*Vulpes vulpes*) between three regions of rural Britain, in relation to landscape and other variables. *Journal of Zoology, London* **251**: 253-264.

Hill, D. & Robertson, P. (1988). *The Pheasant: Ecology, Management and Conservation.* BSP Professional, Oxford.

Hillebrandt, P. M. (1960). The economic theory of the use of pesticides. Pt. 1. The dosage response curve, the rate of application and the area to be treated. *Journal of Agricultural Economics* **13**: 464-472.

Hoare, R. E. (1992). Present and future use of fencing in the management of larger African mammals. *Environmental Conservation* **19**: 160-164.

Hone, J. (1994). *Analysis of Vertebrate Pest Control.* Cambridge University Press, Cambridge.

Honeyman, M. S., Roush, W. B. & Penner, A. D. (1999). *1999 Swine Research Report, Management and Economics. Piglet Mortality in Various Hut Types for Outdoor Farrowing.* Iowa State University Extension, Ames.

Hosmer, D. W. & Lemeshow, S. (1989). *Applied Logistic Regression.* John Wiley & Sons, New York.

Hudson, P. J. (1992). *Grouse in Space and Time - the Population Biology of a Managed Game Bird.* The Game Conservancy, Fordingbridge, Hampshire.

Hutchings, M. R. & Harris, S. (1996). *The Current Status of the Brown Hare (*Lepus europaeus*) in Britain.* Joint Nature Conservation Committee, Peterborough.

Insley, H. (1977). An estimate of the population density of the red fox (*Vulpes vulpes*) in the New Forest, Hampshire. *Journal of Zoology, London* **183**: 549-553.

Jenkins, D., Watson, A. & Miller, G. R. (1964). Predation and red grouse populations. *Journal of Applied Ecology* **1**: 183-195.

Judenko, E. (1973). *Analytical method for assessing yield losses caused by pests on cereal crops with and without pesticides.* Centre for Overseas Pest Research, London.

Kauhala, K. (2001). *Red fox and grouse populations in Finland: is the fox threatening grouse populations?* Canid Biology and Conservation Conference, Oxford.

Kauhala, K., Helle, P. & Helle, E. (2000). Predator control and the density and reproductive success of grouse populations in Finland. *Ecography* **23**(2): 161-168.

Kenward, R. E. (1977). Predation on released pheasants (*Phasianus colchicus*) by goshawks (*Accipiter gentilis*) in central Sweden. *Swedish Game Research* **10**: 79-112.

Kenward, R. E., Hall, D. G., Walls, S. S. & Hodder, K. H. (2001). Factors affecting predation by buzzards *Buteo buteo* on released pheasants *Phasianus colchinus. Journal of Applied Ecology* **38**: 813-822.

Kinnear, J. E., Onus, M. L. & Bromilow, R. N. (1988). Fox control and rock-wallaby population dynamics. *Australian Wildlife Research* **15**: 435-450.

Kirby, D. K. (2000). *An ecological economic approach to upland heather moorland management.* PhD Thesis, Environment Department, University of York.

Knight, J. D. (1997). The role of decision support systems in integrated crop protection. *Agriculture, Ecosystems and Environment* **64**: 157-163.

Knowlton, F. F., Gese, E. M. & Jaeger, M. M. (1999). Coyote depredation control: an interface between biology and management. *Journal of Range Management* **52**: 398-412.

Kolb, H. (1996). *Country Foxes.* Whittet, London.

Kolb, H. (1994). Rabbit *Oryctolagus cuniculus* populations in Scotland since the introduction of myxomatosis. *Mammal Review* **24**: 41-48.

Kolb, H. H. & Hewson, R. (1980). A study of fox populations in Scotland from 1971 to 1976. *Journal of Applied Ecology* **17**: 7-19.

Kropff, M. J., Teng, P. S. & Rabbinge, R. (1995). The challenge of linking pest and crop models. *Agricultural Systems* **49**: 413-434.

Kruuk, H. (1972). Surplus killing by carnivores. *Journal of Zoology, London* **166**: 233-244.

Landa, A., Gudvangen, K., Swenson, J. E. & Røskaft, E. (1999). Factors associated with wolverine *Gulo gulo* predation on domestic sheep. *Journal of Applied Ecology* **36**: 963-973.

Leckie, F. M., Thirgood, S. J., May, R. & Redpath, S. M. (1998). Variation in the diet of red foxes on Scottish moorland in relation to prey abundance. *Ecography* **21**: 599-604.

Lever, C. (1985). *Naturalized mammals of the world.* Longman, Harlow, Essex.

Lever, R. J. A. W. (1959). The diet of the fox since myxomatosis. *Journal of Animal Ecology* **28**: 359-375.

Lindblad, M. (2001). Development and evaluation of a logistic risk model: predicting frit fly infestation in oats. *Ecological Applications* **11**: 1563-1572.

Lindström, E. R. (1989). Food limitation and social regulation in a red fox population. *Holarctic Ecology* **12**: 70-79.

Lindström, E. R., Andrén, H., Angelstam, P., Cederlund, G., Hörnfeldt, B., Jäderberg, L., Lemnell, P., Martinsson, B., Sköld, K. & Swenson, J. E. (1994). Disease reveals the predator: sarcoptic mange, red fox predation, and prey populations. *Ecology* **75**(4): 1042-1049.

Linnell, J. D. C., Odden, J., Smith, M. E., Aanes, R. & Swenson, J. E. (1999). Large carnivores that kill livestock: do "problem individuals" really exist? *Wildlife Society Bulletin* **27**: 698-705.

Lloyd, D. E. B. (1975). Avian predation on reared pheasants. *Game Conservancy Annual Review* **7**: 65-66.

Lloyd, H. G. (1980). *The Red Fox.* Batsford, London.

Lockie, J. D. (1959). The estimation of the food of foxes. *Journal of Wildlife Management* **23**: 67-77.

Lovari, S. & Parigi, L. (1995). The red fox as a gamebird killer or a considerate parent? *Mammalia* **59**: 455-459.

Love, R. A., Webbon, C., Glue, D. E. G. & Harris, S. (2000). Changes in the food of British Barn Owls (*Tyto alba*) between 1974 and 1997. *Mammal Review* **30**: 107-129.

Macdonald, D. W. (1980). *Rabies and Wildlife: a Biologist's Perspective.* Oxford University Press, Oxford.

Macdonald, D. W. (1984). A questionnaire survey of farmers' opinions and actions towards wildlife on farmlands. *Agriculture and the Environment*, D. Jenkins (Ed.) pp. 171-177. Institute of Terrestrial Ecology, Cambridge.

Macdonald, D. W. (1987). *Running with the Fox.* Unwin Hyman, London.

Macdonald, D. W., Bunce, R. G. H. & Bacon, P. J. (1981). Fox populations, habitat characterization and rabies control. *Journal of Biogeography* **8**: 145-151.

Macdonald, D. W. & Johnson, P. J. (1996). The impact of sport hunting: a case study. *The Exploitation of Mammal Populations*, V. J. Taylor & N. Dunstone (Eds.), pp. 160-207. Chapman and Hall, London.

Macdonald, D. W., Mace, G. & Rushton, S. (1998). *Proposals for future monitoring of British mammals.* Department of the Environment, Transport and the Regions, London.

Macdonald, D. W., Mace, G. M. & Barretto, G. R. (1999). The effects of predators on fragmented prey populations: a case study for the conservation of endangered prey. *Journal of Zoology, London* **247**(4): 487-506.

Macdonald, D. W., Tattersall, F. H., Johnson, P. J., Carbone, C., Reynolds, J. C., Langbein, J., Rushton, S. P. & Sirley, M. D. F. (2000). *Management and Control of*

Populations of Foxes, Deer, Hares and Mink in England and Wales, and the Impact of Hunting with Dogs: A Report to the Committee of Inquiry into Hunting with Dogs.

MacLean, D. A., Erdle, T. A., MacKinnon, W. E., Porter, K. B., Beaton, K. P., Cormier, G., Morehouse, S. & Budd, M. (2001). The spruce budworm decision support system: Forest protection planning to sustain long-term wood supply. *Canadian Journal of Forest Research* **31**: 1742-1757.

MAFF (1996). *Improving Lamb Survival (PB 2072).* Ministry for Agriculture, Fisheries and Food (MAFF), London.

MAFF (1999). *June Agricultural Census.* Ministry for Agriculture, Fisheries and Food (MAFF), London.

Mäler, K. G. (1992). Production function approach in developing countries. *Valuing Environmental Benefits in Developing Countries: Conference Proceedings*, J.R. Vincent, E.W. Crawford & J.P. Hoehn (Eds.). Michigan State University, East Lansing.

Manley, W., Hallett, J., Nixon, J. & Baines, R. (1999). *Economic, Social and Environmental Aspects of Hunting with Hounds in West Somerset and Exmoor.* Centre for Rural Studies, Cirencester.

Marchant, J. N., Broom, D. M. & Corning, S. (2001). The influence of sow behaviour on piglet mortality due to crushing in an open farrowing system. *Animal Science* **72**: 19-28.

Marks, C. A., Jalkanen, L., Savolainen, R. & Short, R. V. (2001). Control of red fox (*Vulpes vulpes*) fertility with cabergoline: dose response and timing of intervention. *Reproduction* **122**: 147-154.

Märcstrom, V., Kenward, R. E. & Engren, E. (1988). The impact of predation on boreal tetranoids during vole cycles: an experimental study. *Journal of Animal Ecology* **57**: 859-872.

McDonald, R., Baker, P. & Harris, S. (1997). *Is the Fox a Pest? The Ecological and Economic Impact of Foxes in Britain.* Elektra Publishing, Cheddar.

McDonald, R. A. & Harris, S. (1999). The use of trapping records to monitor populations of stoats *Mustela erminea* and weasels *M. nivalis*: the importance of trapping effort. *Journal of Applied Ecology* **36**: 679-688.

McGill (1999). *Pheasant Rearing Techniques in the UK, France and the USA - in particular focusing on methods of controlling cannibalism.* Nuffield Farming Scholarships Trust, Uckfield.

McInerney, J. & Kooij, D. (1997). Economic analysis of alternative AD control programmes. *Veterinary Microbiology* **55**: 113-121.

McInerney, J. P. (1987). An economist's approach to estimating disease losses. *Disease in Farm Livestock: Economics and Policy*, K. S. Howe & J. P. McInerney (Eds.). pp. 35-60. Commission of European Communities, Exeter.

McInerney, J. P. (1996). Old economics for new problems - livestock disease: presidential address. *Journal of Agricultural Economics* **47**(3): 295-314.

McInerney, J. P., Howe, K. S. & Schepers, J. A. (1992). A framework for the economic analysis of disease in farm livestock. *Preventive Veterinary Medicine* **13**: 137-154.

McKillop, I. G. & Silby, R. M. (1988). Animal behaviour at electric fences and the implications for management. *Mammal Review* **18**: 91-103.

McKillop, I. G., Fox, S. M., Pugh, B. D., Langton, S. D. & Sylvester-Bradley, R. (1996). Developing a model to predict yield loss of winter wheat due to grazing by European wild rabbits. *Brighton Crop Protection Conference - Pests and Diseases - 1996*, pp. 145-151. British Crop Protection Council, Surrey.

McLeod, S. R. & Saunders, G. R. (2001). Improving management strategies for the red fox by using projection matrix analysis. *Wildlife Research* **28**: 333-340.

McNeill, P. (1990). *Research Methods*. Routledge, London.

McOrist, S., Smith, S. H. & Green, L. E. (1997). Estimate of direct financial losses due to porcine proliferative enteropathy. *Veterinary Record* **140**: 579-581.

Meadows, L. E. & Knowlton, F. F. (2000). Efficacy of guard llamas to reduce canine predation on domestic sheep. *Wildlife Society Bulletin* **28**(3): 614-622.

Mech, L. D., Harper, E. K., Meier, T. J. & Paul, W. J. (2000). Assessing factors that may predispose Minnesota farms to wolf depredations on cattle. *Wildlife Society Bulletin* **28**: 623-629.

Messmer, T. A. (2000). The emergence of human-wildlife conflict management: turning challenges into opportunites. *International Biodeterioration and Biodegradation* **45**: 97-102.

Mizutani, F. (1993). Home range of leopards and their impact on livestock on Kenyan ranches. *Mammals as Predators, Proceedings of the 65th Symposium*, N. Dunstone & M. L. Gorman (Eds.), pp. 425-439. Zoological Society of London, Oxford.

Mizutani, F. (1999). Impact of leopards on a working ranch in Laikipia, Kenya. *African Journal of Ecology* **37**: 211-225.

MLC (1997). *Pig Yearbook*. Meat and Livestock Commission, Milton Keynes.

Moore, N., Whiterow, A., Kelly, P., Bishop, J., Langton, S. & Cheeseman, C. (1999). Survey of badger *Meles meles* damage to agriculture in England and Wales. *Journal of Applied Ecology* **36**: 974-988.

Morris, R. S. (1999). The application of economics in animal health programmes: a practical guide. *Revue Scientifique et Technique de l'Office International d'Epizooties* **18**: 305-314.

Moss, R., Trenholm, I. B., Watson, A. & Parr, R. (1990). Parasitism, predation and survival of hen red grouse (*Lagopus lagopus scoticus*) in spring. *Journal of Animal Ecology* **59**: 631-642.

Mumford, J. D. (1981a). Pest control decision making: sugar beet in England. *Journal of Agricultural Economics* **32**: 31-41.

Mumford, J. D. (1981b). A study of sugar beet growers' pest control decisions. *Annals of Applied Biology* **97**: 243-252.

Mumford, J. D. & Norton, G. A. (1984). Economics of decision making in pest management. *Annual Review of Entomology* **29**: 157-174.

Mutze, G. J., Veitch, L. G. & Miller, R. B. (1990). Mouse plagues in South Australian cereal-growing areas II. An empirical model for prediction of plagues. *Australian Wildlife Research* **17**: 313-324.

Narain, U. & Fisher, A. (1995). Modelling the value of biodiversity using a production function approach: the case of the Anolis lizard in the Lesser and Greater Antilles. *Biodiversity Conservation: Policy Issues and Options*, C. Perrings, K.-G. Mäler, C. Folke, B.-O. Jansson & C. S. Holling (Eds.), pp. 115-125. Kluwer Academic Publishers, The Netherlands.

Nash, M. L., Hungerford, L. L., Nash, T. G. & Zinn, G. M. (1996). Risk factors for perinatal and postnatal mortality in lambs. *Veterinary Record* **139**: 64-67.

Nass, R. D., Lynch, G. & Theade, J. (1984). Circumstances associated with predation rates on sheep and goats. *Journal of Range Management* **37**(5): 423-426.

Newsome, A. (1990). The control of vertebrate pests by vertebrate predators. *Trends in Ecology and Evolution* **5**: 187-191.

NFU (2000). Game prices take a tumble. *National Farmers Union Current News,* 10th December 2000.

NFU (2001). *Poultry and Eggs.* NFU Information Leaflet. National Farmers Union, London.

Nix, J. (1999). *Farm Management Pocketbook 30th edition (2000).* Wye College Press, Ashford.

Norton, G. A. (1976). Pest control decision making: an overview. *Annals of Applied Biology* **84**: 444-447.

Oli, M. K., Taylor, I. R. & Rogers, M. E. (1994). Snow leopard *Panthera uncia* predation of livestock - an assessment of local perceptions in the Annapurna Conservation Area, Nepal. *Biological Conservation* **68**: 63-68.

Oppenheim, A. N. (1992). *Questionnaire Design, Interviewing and Attitude Measurement.* Pinter, London.

Packer, J. J. & Birks, J. D. S. (1999). An assessment of British farmers' and gamekeepers' experiences, attitudes and practices in relation to the European Polecat *Mustela putorius*. *Mammal Review* **29**(2): 75-92.

Pannell, D. J. (1990). Responses to risk in weed control decisions under expected profit maximisation. *Journal of Agricultural Economics* **41**: 391-403.

Parr, R. (1993). Nest predation and numbers of golden plovers *Pluvialis apricaria* and other moorland waders. *Bird Study* **40**: 223-231.

Patterson, I. J. (1977). The control of fox movement by electric fencing. *Biological Conservation* **11**: 267-278.

Pech, R. P., Sinclair, A. R. E., Newsome, A. E. & Catling, P. C. (1992). Limits to predator regulation of rabbits in Australia: evidence from predator-removal experiments. *Oecologia* **89**: 102-112.

Pech, R., Hood, G. M., McIlroy, J. & Saunders, G. (1997). Can foxes be controlled by reducing their fertility? *Reproduction, Fertility and Development* **9**: 41-50.

Pennycott, T. W. (2000). Causes of mortality and culling in adult pheasants. *The Veterinary Record* **146**: 273-278.

Perry, B. D. & Randolph, T. F. (1999). Improving the assessment of the economic impact of parasitic diseases and of their control in production animals. *Veterinary Parasitology* **84**: 145-168.

Pienkowski, M. A. (1984). Breeding biology and population dynamics of ringed plovers *Charadrius hiaticula* in Britain and Greenland - nest predation as a possible factor limiting distribution and timing of breeding. *Journal of Zoology, London* **202**: 83-114.

Pearce, D. & Moran, D. (1994). *The Economic Value of Biodiversity*. Earthscan Publications, London.

Pimentel, D. (1986). Biological invasions of plants and animals in agriculture and forestry. *Ecology of Biological Invasions to North America and Hawaii*, H. A. Mooney & J. A. Drake (Eds.), pp. 149-162. Springer-Verlag, New York.

Poole, D. W. & McKillop, I. G. (1999). Comparison of the effectiveness of two types of electric fences to exclude badgers. *Crop Protection* **18**: 61-66.

Potter, R. (1998). Clinical conditions of pigs in outdoor breeding herds. *In Practice* **20**: 3-14.

Potts, G. R. (1986). *The Partridge: Pesticides, Predation and Conservation*. Collins, London.

Potts, G. R. & Vickerman, G. P. (1974). Studies on the cereal ecosystem. *Advances in Ecological Research* **8**: 107-197.

Produce Studies (1995). *Farmers' Attitudes to Fox Control*. Produce Studies Ltd, Newbury.

Putman, R. J. (1989). Introduction: mammals as pests. *Mammals as Pests*, R. J. Putman (Ed.) pp. 1-20. Chapman and Hall, London.

Pye-Smith, C. (1997). *Fox-hunting: beyond the propaganda.* Wildlife Network, Oakham, Rutland.

Ramirez, O. A. & Saunders, J. L. (1999). Estimating economic thresholds for pest control: an alternative procedure. *Journal of Economic Entomology* **92**(2): 391-401.

Rau, J. R. (1988). *Ecología del zorro Vulpes vulpes (L.) en la Reserva Biológica de Doñana, S.O. de España.* PhD Thesis, University of Seville.

Reiter, D. K., Brunson, M. W. & Schmidt, R. H. (1999). Public attitudes toward wildlife damage management and policy. *Wildlife Society Bulletin* **27**(3): 746-758.

Reynolds, J. C. (1998). Foxes and wildlife tourism. *The Game Conservancy Review* **29**: 86-91.

Reynolds, J. C., Angelstam, P. & Redpath, S. M. (1988). Predators, their ecology and impact on game bird populations. *Ecology and Management of Gamebirds*, P. J. Hudson & M. R. W. Rands (Eds.), pp. 72-98. BSP Professional Books, Oxford.

Reynolds, J. C., Goddard, H. N. & Brockless, M. H. (1993). The impact of local fox (*Vulpes vulpes*) removal on fox populations at two sites in southern England. *Gibier Faune Sauvage* **10**: 319-334.

Reynolds, J. C. & Tapper, S. C. (1995). Predation by foxes, *Vulpes vulpes,* on brown hares, *Lepus europaeus,* in central southern England and its potential impact on annual population growth. *Wildlife Biology* **1**: 145-158.

Reynolds, J. C. & Tapper, S. C. (1996). Control of mammalian predators in game management and conservation. *Mammal Review* **26**: 127-156.

Richards, D. F. (1977). Observations of the diet of the red fox (*Vulpes vulpes*) in South Devon. *Journal of Zoology, London* **183**: 495-504.

Richards, D. T., Harris, S. & Lewis, J. W. (1995). Epidemiological studies on intestinal helminth parasites of rural and urban red foxes (*Vulpes vulpes*) in the United Kingdom. *Veterinary Parasitology* **59**: 39-51.

Risbey, D. A., Calver, M. C., Short, J., Bradley, J. S. & Wright, I. W. (2000). The impact of cats and foxes on the small vertebrate fauna of Heirisson Prong, Western Australia. II. A field experiment. *Wildlife Research* **27**(3): 223-235.

Robel, R. J., Dayton, A. D., Henderson, F. R., Meduna, R. L. & Spaeth, C. W. (1981). Relationships between husbandry methods and sheep losses to canine predators. *Journal of Wildlife Management* **45**(4): 894-911.

Roberts, D. & Farrar, J. (1993). *The Economics of Egg Production: 1992. Special Studies in Agricultural Economics, Report No. 22.* Department of Agricultural Economics, University of Manchester.

Robertson, P. (1997). *A Natural History of the Pheasant.* Swan Hill Press, Shrewsbury.

Robertson, P. A. (1988). Survival of released pheasants, *Phasianus colchicus*, in Ireland. *Journal of Zoology, London* **214**: 683-695.

Romig, T., Bilger, B. & Mackenstedt, U. (1999). Current data on the geographical distribution and epidemiology of *Echinococcus multilocularis. Deutshe Tierarztliche Wochenschrift* **106**(8): 352-357.

Rossing, W. A. H., Daamen, R. A. & Hendrix, E. M. T. (1994). Framework to support decisions on chemical pest control under uncertainty, applied to aphids and brown rust in winter wheat. *Crop Protection* **13**: 25-34.

Rowley, I. (1970). Lamb predation in Australia: incidence, predisposing conditions and the identification of wounds. *CSIRO Wildlife Research* **15**: 79-123.

Ryszkowski, L., Wagner, C. K., Goszczynski, J. & Truszkoski, J. (1971). Operation of predators in a forest and cultivated fields. *Annales Zoologici Fennici* **8**: 160-169.

SAC (2001). *SAC Diversification Database. http://www.sac.ac.uk/management/External/diversification/Leis&rec/gameshooting.htm* Rural Development and Conservation Group, Management Division, Scottish Agricultural College, Edinburgh

Sacks, B. J., Jaeger, M. M., Neale, J. C. C. & McCullough, D. R. (1999). Territoriality and breeding status of coyotes relative to sheep predation. *Journal of Wildlife Management* **45**: 894-911.

Sargeant, A. B. (1978). Red fox prey demands and implications to prairie duck production. *Journal of Wildlife Management* **42**: 520-527.

Sargeant, A. B., Allen, S. H. & Eberhardt, R. T. (1984). Red fox predation on breeding ducks in mid-continent North America. *Wildlife Monographs* **89**: 1-41.

Sargeant, A. B., Sovada, M. A. & Shaffer, T. L. (1995). Seasonal predator removal relative to hatch rate of duck nests in waterfowl production areas. *Wildlife Society Bulletin* **23**: 507-513.

Saunders, G., Greentree, C. & McLoed, L. (1997). *Fox Predation: Impact and Management on Agricultural Land and Associated Remnant Habitats.* Vertebrate Pest Research Unit, NSW Agriculture.

Saunders, G., McIlroy, J., Berghout, M., Kay, B., Gifford, E., Perry, R. & Van de Ven, R. (2002). The effects of induced sterility on the territorial behaviour and survival of foxes. *Journal of Applied Ecology* **39**(1): 56-66.

Schmitz, R. A. & Clark, W. R. (1999). Survival of ring-necked pheasants (*Phasianus colchicus*) during spring in relation to landscape features. *Journal of Wildlife Management* **63**: 147-154.

Selhorst, T. & Müller, T. (1999). An evaluation of the efficiency of rabies control strategies in fox (*Vulpes vulpes*) populations using a computer simulation program. *Ecological Modelling* **124**: 221-232.

Seymour, A. S. (1999). *The ecology of nest predation by red foxes* Vulpes vulpes. PhD Thesis, School of Biological Sciences, University of Bristol.

Shea, K., Thrall, P. H. & Burdon, J. J. (2000). An integrated approach to management in epidemiology and pest control. *Ecology Letters* **3**: 150-158.

Sheppard, A. (1998a). *Pig Production 1996-97.* University of Exeter, Agricultural Economics Unit, Exeter.

Sheppard, A. (1998b). *The Structure of Pig Production in England and Wales: The results of the National Suvey of Pig Production Systems, 1st February 1998, Special Studies in Agricultural Economics No. 40.* University of Exeter, Agricultural Economics Unit, Exeter.

Smedshaug, C. A., Selas, V., Lund, S. E. & Sonerud, G. A. (1999). The effect of a natural reduction of red fox *Vulpes vulpes* on small game hunting bags in Norway. *Wildlife Biology* **5**(3): 157-166.

Smith, M. (1999). Natural born killers. *Biologist* **46**: 19-21.

Smith, G. C. & Harris, S. (1991). Rabies in urban foxes (*Vulpes vulpes*) in Britain - the use of a spatial stochastic simulation model to examine the pattern of spread and evaluate the efficacy of different control regimes. *Philosophical Transactions of the Royal Society of London, Series B* **334**: 459-479.

Smith, R. H., Neff, D. J. & Woolsey, N. G. (1986). Pronghorn response to coyote control: a benefit-cost analysis. *Wildlife Society Bulletin* **14**: 226-231.

Sodeikat, G., Niepel, L., Fehlberg, U. & Pohlmeyer, K. (1995). Comparative study on survival of released pheasants (*Phasianus cochicus* spec) reared in intensive and extensive animal keeping. *Deutsche Tierarztliche Wochenschrift* **102**: 112-116.

Sokal, R. R. & Rohlf, F. J. (1995). *Biometry, Third Edition.* W.H. Freeman and Company, New York.

Sommer, F. & Vasicek, L. (2000). Management and state of health in free-range poultry flocks. *Wiener Tierarztliche Monatsschrift* **87**: 202-212.

Southwood, T. R. E. & Norton, G. A. (1973). Economic aspects of pest management strategies and decisions. *Insects: Studies in Population Management*, P. W. Geier, L. R. Clark, D. J. Anderson & H. A. Nix (Eds.), pp. 168-184. Ecological Society of Australia, Canberra.

Stahl, P., Vandel, J. M., Herrenschmidt, V. & Migot, P. (2001). Predation on livestock by an expanding introduced lynx population: long-term trend and spatial variability. *Journal of Applied Ecology* **38**: 674-687.

Stenseth, N. C. & Hansson, L. (1981). The importance of population dynamics in heterogeneous landscapes: management of vertebrate pests and some other animals. *Agro-Ecosystems* **7**: 187-211.

Stern, V. M., Smith, R. F., van den Bosch, R. & Hagen, K. S. (1959). The integrated control concept. *Hilgardia* **29**: 81-101.

Stevens, D., Alexander, G. & Lynch, J. (1982). Lamb mortality due to inadequate care of twins by Merino ewes. *Applied Animal Ethology* **8**: 243-252.

Suarez, F., Yanes, M., Herranz, J. & Manrique, J. (1993). Nature reserves and the conservation of Iberian shrub-steppe passerines: the paradox of nest predation. *Biological Conservation* **64**: 77-81.

Suppo, C., Naulin, J.-M., Langlais, M. & Artois, M. (2000). A modelling approach to vaccination and contraception programmes for rabies control in fox populations. *Proceedings of the Royal Society of London, Series B* **267**: 1575-1582.

Swanson, T. M. & Barbier, E. B. (1992). *Economics for the Wilds.* Earthscan Publications, London.

Swire, P. W. (1978). Laboratory observation on the fox (*Vulpes vulpes*) in Dyfed during the winters of 1974/75 abd 1975/76. *British Veterinary Journal* **134**: 398-405.

Tapper, S. (1999). *A Question of Balance - game animals and their role in the British countryside.* The Game Conservancy Trust, Fordingbridge, Hampshire.

Tapper, S., Potts, G. R. & Brockless, M. (1996). The effect of an experimental reduction in predation pressure on the breeding success and population density of grey partridges *Perdix perdix*. *Journal of Applied Ecology* **33**: 965-978.

Tapper, S. C. (1992). *Game Heritage, an Ecological Review from Shooting and Gamekeeping Records.* The Game Conservancy, Fordingbridge, Hampshire.

Taylor, R. G., Workman, J. P. & Bowns, J. E. (1979). The economics of sheep predation in south-western Utah. *Journal of Range Management* **32**(4): 317-321.

Thornton, K. (1988). *Outdoor Pig Production.* Farming Press, Ipswich.

Tourenq, C., Aulagnier, S., Durieux, L., Lek, S., Mesleard, F., Johnson, A. & Martin, J. L. (2001). Identifying rice fields at risk from damage by the greater flamingo. *Journal of Applied Ecology* **38**: 170-179.

Trout, R. C. & Tittensor, A. M. (1989). Can predators regulate wild rabbit *Oryctolagus cuniculus* population density in England and Wales? *Mammal Review* **19**: 153-173.

Trout, R. C., Langton, S., Smith, G. C. & Haines-Young, R. H. (2000). Factors affecting the abundance of rabbits (*Oryctolagus cuniculus*) in England and Wales. *Journal of Zoology, London* **252**: 227-238.

Turner, A. J. (1965). A survey of neo-natal lamb losses in a Western district sheep flock. *Victorian Veterinary Proceedings* **23**: 439-444.

Twengström, E., Sigvald, R., Svensson, C. & Yuen, J. (1998). Forecasting Sclerotinia stem rot in spring sown oilseed rape. *Crop Protection* **17**: 405-411.

Vaillancourt, J. P., Stein, T. E., Marsh, W. E., Leman, A. D. & Dial, G. D. (1990). Validation of producer-recorded causes of pre-weaning mortality in swine. *Preventive Veterinary Medicine* **10**: 119-130.

Van Vuren, D. & Smallwood, K. S. (1996). Ecological management of vertebrate pests in agricultural systems. *Biological Agriculture and Horticulture* **12**: 39-62.

Vickery, J. A., Watkinson, A. R. & Sutherland, W. J. (1994). The solutions to the brent goose problem: an economic analysis. *Journal of Applied Ecology* **31**: 371-382.

Vos, J. (2000). Food habits and livestock depredation of two Iberian wolf packs (*Canis lupus signatus*) in the north of Portugal. *Journal of Zoology, London* **251**: 457-462.

Wagner, K. K. & Conover, M. R. (1999). Effect of preventive coyote hunting on sheep losses to coyote predation. *Journal of Wildlife Management* **63**(2): 606-612.

Warren, J. T. & Mysterud, I. (1995). Mortality of domestic sheep in free-ranging flocks in southeastern Norway. *Journal of Animal Science* **73**: 1012-1018.

Warren, J. T., Mysterud, I. & Lynnebakken, T. (2001). Mortality of lambs in free-ranging sheep (*Ovies aries*) in northern Norway. *Journal of Zoology, London* **254**: 195-202.

Webbon, C.C. (2002). *Monitoring populations of the red fox* (Vulpes vulpes) *in rural Britain.* PhD Thesis, School of Biological Sciences, University of Bristol.

Werker, A. R., Dewar, A. M. & Harrington, R. (1998). Modelling the incidence of virus yellows in sugar beet in the UK in relation to numbers of migrating *Myzus persicae. Journal of Applied Ecology* **35**: 811-818.

White, P. C. L., Baker, P. J., Newton-Cross, G. A., Smart, J., Moberly, R. L., McLaren, G., Ansell, R. & Harris, S. (2000a). *Report on Contract 5: Management of the Populations of Foxes, Deer, Hares and Mink and the Impact of Hunting with Dogs and Report on Contract 6: Methods of Controlling Foxes, Deer, Hare and Mink for Lord Burn's Committee of Inquiry into Hunting with Dogs.*

White, P. C. L., Groves, H. L., Savery, J. R., Conington, J. & Hutchings, M. R. (2000b). Fox predation as a cause of lamb mortality on hill farms. *The Veterinary Record* **147**: 33-37.

Williams, R. B. (1999). A compartmentalised model for the estimation of the cost of coccidiosis to the world's poultry industry. *International Journal for Parasitology* **29**: 1209-1229.

Wilson, W. L. (1990). Changes in the diet of foxes (*Vulpes vulpes*) on the sands of Forvie National Nature Reserve, during the eider nesting period, 1974-1988. *Journal of Zoology, London* **221**: 305-308.

Wilson, W. L., Day, K. R. & Hart, E. A. (1996). Predicting the extent of damage to conifer seedlings by the pine weevil (*Hylobius abietus* L.): a preliminary risk model by multiple logistic regression. *New Forests* **12**: 203-222.

Yalcin, C., Stott, A. W., Logue, D. N. & Gunn, J. (1999). The economic impact of mastitis-control procedures used in Scottish dairy herds with high bulk-tank somatic-cell counts. *Preventive Veterinary Medicine* **41**(2-3): 135-149.

Yamamura, K. (1999). Transformation using (x + 0.5) to stabilize the variance of populations. *Researches on Population Ecology* **41**: 229-234.

Yerli, S., Canbolat, A. F., Brown, L. J. & Macdonald, D. W. (1997). Mesh grids help protect loggerhead turtle *Caretta caretta* nests from red fox *Vulpes vulpes* predation. *Biological Conservation* **82**: 109-111.

Yuen, J., Twengström, E. & Sigvald, R. (1996). Calibration and verification of risk algorithms using logistic regression. *European Journal of Plant Pathology* **102**: 847-854.