1 Changing cultures, changing environments: a novel means of investigating the effects of introducing 2 non-native species into past ecosystems

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8

9 **Abstract**: Descended from junglefowl of Asia and South-east Asia, the chicken was introduced into Europe 10 during the first millennium BCE. As one of the most recently domesticated species, it makes an excellent case 11 study for investigating the consequences of such introductions to past ecological communities. We present a 12 unique application of a novel ecological method to explore multiple past interspecies relationships. Analysing the 13 faunal record using a Bayesian belief network, which allows for the analysis of multiple interspecies relationships 14 simultaneously, indicates that the chicken has more affinity with other domestic birds rather than domestic 15 mammals in terms of species interactions. We find that the introduction of the chicken affected fox, partridge, 16 pigeon and rat, but the success of the chicken was most affected by responses to abiotic variables, rather than 17 biotic interactions. As the method is not limited to environmental variables, we also examined the effect of 18 recovery method and demonstrate that sieving would enhance the frequency of small animal remains recovered 19 from archaeological sites.

20

21 **1. Introduction**: Relationships between different species, otherwise termed inter-specific interactions, can be 22 both positive and negative. Interactions usually take the form of competition, predation, herbivory, and symbiosis 23 (Lang and Benbow 2013). Symbiosis, literally meaning 'living-together', encompasses commensalism, 24 amensalism, parasitism and mutualism, whereby only the latter is a mutually beneficial relationship and is not 25 necessarily equally so (Parmentier and Michel 2013). Within ecological communities these relationships become 26 established over time but can be disrupted by environmental change or by the introduction of non-native species. 27 Introducing non-native species into a new environment can cause dramatic changes in both the invader and the 28 native populations within a very short period (as little as fifty years (approximately 100 chicken generations)) 29 (Mooney and Cleland 2001). Niche displacement, hybridisation and reorganisation of mutual relationships can all 30 be consequences of such an introduction. Investigation of past ecological communities has identified unusual 31 compositions of species assemblages compared to what might be expected today, which may cause 32 evolutionary change (Stewart 2009).

33

34 As a bird that has descended from junglefowl of Asia and Southeast Asia, and then been transported to Europe 35 by people, the chicken successfully acclimated to different environments (Pitt et al. 2016). The subsequent effect 36 of this has not been studied, making the chicken an interesting case study for evaluating the impact of

37introducing non-native species into new environments. Analysing changes in interactions between species found 38together in the faunal record over time enables us to examine the effect of the introduction of the chicken on its 39ecosystem. Investigating responses to various factors can help determine whether changes in communities 40occurred because of human intervention or natural change. Examination of species interactions is not new to 41archaeology, but investigation usually focuses primarily on human use of animals as a product, rather than how 42species affect one another. It is usually limited to the primary domestic species, and often only mammals.

43

44Yet the presence of humans and the animals they keep has an effect beyond the domestic sphere, directly and 45indirectly. O'Connor (1993) discussed the displacement of certain groups of birds by facultative carnivores and 46carrion-feeders, particularly those which rely on other live species for food or have specific dietary needs. The 47consequence is that certain species should be expected to be encountered in faunal remains, and where this 48pattern is not found, then other factors must be responsible. Synanthropic species benefit from association with 49humans but usually have habitats outside of human settlements. Synurbanisation is defined as the 'highest level 50of synanthropisation' (Boev 1993, 145) and includes species which nest in human settlements. Human 51perception of synanthropic, and particularly commensal species, varies greatly. Commensal species are drawn 52to human habitations for food and shelter, and might be enjoyed, reviled, tolerated or hunted (O'Connor 2013a).

53

54Understanding complex networks of species interactions related to other species or to changing environments is 55challenging. One of the oft-noted issues in ecological studies is the lack of incorporation of biotic relationships as 56opposed to models based purely on abiotic variables (Pearson and Dawson 2003; Baselga and Araújo 2009; 57Soberón and Nakamura 2009; Wisz et al. 2013). Ecological 'community models' attempt to incorporate multiple 58biotic species interactions to address fine scale variability (McInerny and Purves 2011; Kissling et al. 2012; 59Araújo and Rozenfeld 2014; Pollock et al. 2014). Such models could be beneficial to archaeological 60interpretation. Rather than using them to predict where species might occur, as with ecological applications, it is 61the interaction itself which is of most interest to archaeology.

62

63Bayesian Belief Network models (Stafford et al. 2015; Spiers et al. 2016) offer an effective means of 64understanding complex networks of species interactions. The model predicts how changes in certain variables, 65for example an increase in frequency of chicken, would affect other species, for example, other edible birds, 66other fighting birds, predators and commensal species. The method is not limited to environmental factors, and 67can also be used to investigate more practical aspects of archaeology, such as how archaeological recovery 68methods affect the retrieval of small animal bones. It is generally assumed that sieving will result in greater 69recovery of small animal bones (Wilkinson 2007, 87; Davis 2012, 29); however, there are instances where 70sieving has produced limited or no additional results (Zeiler and de Vries 2008; Elevelt 2012). Given additional 71costs (time and financial) associated with this process it is important to understand how useful it might be. We 72present a methodology for adapting archaeological data for use in a BBN, and use the technique to assess

73whether introducing the chicken into a new ecosystem had an impact on other species, whether other species or
74abiotic variables influenced the success of the introduction of chicken, and whether the method can be used to
75identify recovery biases.

76

77**2. Materials and Methods:** We performed four different models using specific variables. The first two models
78use only biotic (species) variables, the second considers biotic and abiotic variables, including climate, location,
79and site type, and the final model addresses recovery method on species frequency.

80

81Matrices of faunal assemblages, including species found together, date, site-type, number of identified
82specimens (NISP), recovery and bone condition were extracted from a pan-European database of assemblages
83containing bird bones (Pitt 2017; Pitt and Stewart in press). The dataset includes sites from ca. 3000 BCE to 500
84CE (Figure 1). For clarity of interpretation, assemblages from site phases dating from ca. 3000 - 800 BCE are
85referred to as 'period 1'; '800 BCE – 0/42 CE' as 'period 2'; and '1 - 500 CE' as 'period 3'. The dates broadly
86correspond with the Bronze Age, Iron Age and Roman periods in Europe, but it is recognised that the Bronze
87Age ended at different times in different parts of Europe, that the Greek civilisation and Roman Republic fall
88within the time frame of 'period 2', and not all phases in Europe in 'period 3' were occupied by the Romans.
89Period 2 includes sites from the United Kingdom up until 42 CE, due to the later arrival of the Romans in this
90region.
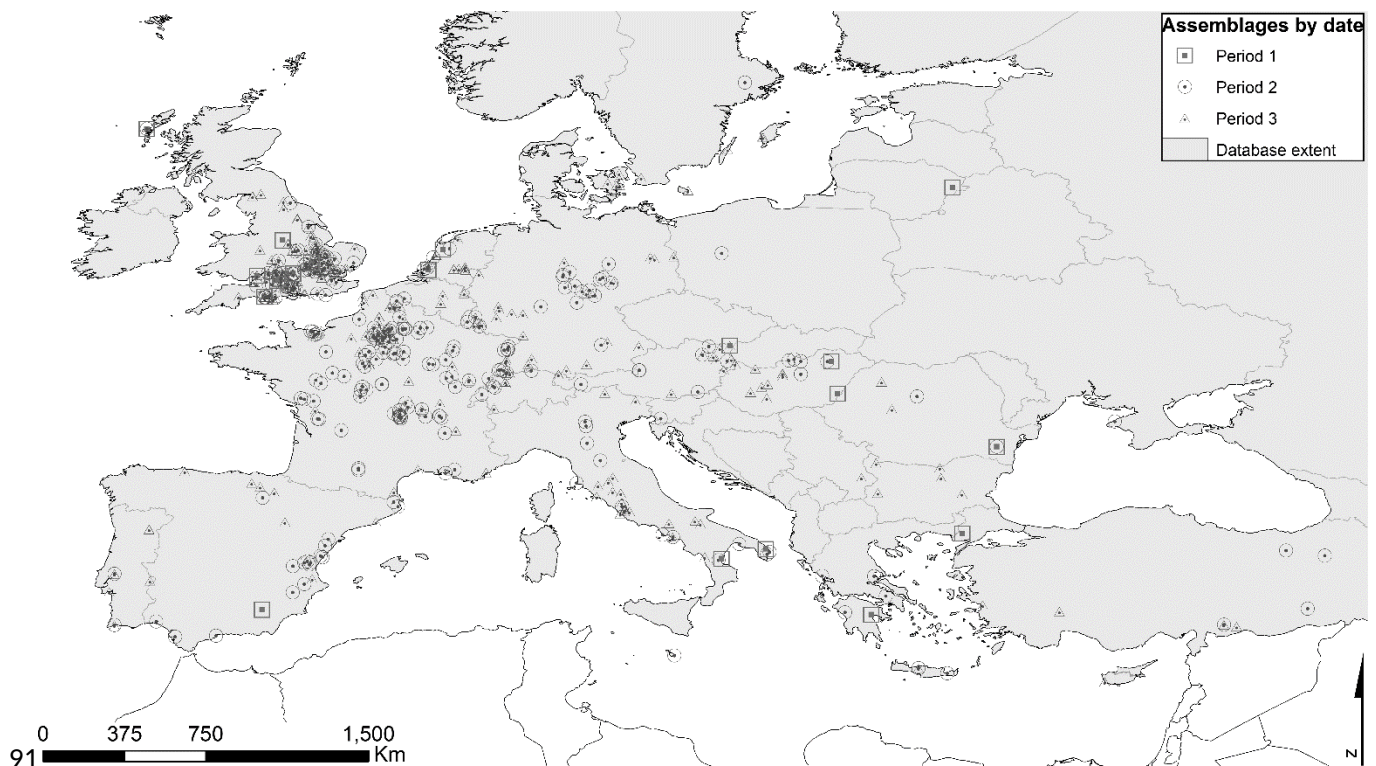
92*Figure 1 Location of assemblages*

3

93As many animal bones cannot be reliably, confidently or consistently identified to species (Pitt and Stewart in
94press), genus level data was used. 'Species' is used in this study as a general term meaning 'type', and includes
95multiple genera where applicable. Assemblages containing only one of the selected species were excluded for
96most analyses because they offer no insights into species relationships. This resulted in a dataset containing
97824 archaeological assemblages. Analysis of recovery method included all assemblages which provided
98information on bone condition (n=340) and whether sieving had taken place (n=454).

99

1004000 BCE bioclim layers (Hijmans et al. 2005) and comparable 4050 BCE Mauri et al (2015) layers (Pitt 2017)
101were used to downscale 2150 BCE layers (Mauri et al. 2015), for period 1, and 'Iron Age' and 'Roman' (Büntgen
1022011) layers for periods 2 and 3 respectively from modern bioclim (Hijmans et al. 2005) layers, assuming no
103change in the spatial distribution of weather patterns. This increased resolution to 2.5 arc-minutes, or approx.
1045km at the equator. A 90m digital elevation model (CGIAR Consortium for Spatial Information 2008) provided
105altitude information. These variables were extracted at assemblage locations using ArcGIS (v.10.2.2).

106

107The community modelling method uses a Bayesian Belief Network (BBN) in the form of a Microsoft® Excel
108spreadsheet, developed by Stafford et al. (2015). This method has only previously been applied to ecological
109research but can be adapted to inform archaeological interpretation. The principal difference is that ecological
110studies use prediction of change to model a future outcome, while an archaeological study will use the known
111outcome to model a prediction of change, thus enabling identification or exclusion of the factors which have most
112likely shaped the archaeological record. Bayesian statistics use 'prior beliefs', which, in an ecological BBN,
113represent the belief that a given species may increase or decrease in the future, based on expert available
114knowledge. For example, there is a belief that Species A will increase if climate change causes temperatures to
115rise, based on expert knowledge. The ecologist wants to predict how that will affect increase or decrease of
116interacting species, given their relationships with one another. The changing factor is known (an increase in
117Species A). The aim is to predict the outcome, i.e. does the model predict that an increase in Species A will lead
118to an increase or decrease in Species B and C?

119

120When used in archaeological studies, the prior beliefs predict increase or decrease in frequency of species
121based on known changes in the past. Information present in the dataset provides parameters which are used to
122predict how a combination of multiple variables should affect species frequency. Comparison with the known
123record, specifically increases or decreases in species, explains whether the factors modelled are resulting in the
124observed changes over time. If the models fail to predict the known outcome, then other factors must explain the
125differences. For example, Species A is known to have increased in frequency in the Roman period, but it is not
126known how this may this have affected increase or decrease of interacting species, given their relationships with
127one another. The archaeologist knows which other species increased or decreased over the same time period
128and needs to establish whether these changes are connected. If Species B is known from the archaeological

129record to have increased and the model predicts that an increase in Species A will result in an increase in
130Species B, then it is possible that the increase in both species may be more than coincidence. If the model
131predicts that an increase in Species A will result in a decrease in Species B, then it is unlikely that the increase in
132Species B was related to the increase in Species A and other variable changes can then be modelled to find a
133better match for the outcome (increase in species B).

134

135There are three stages in a BBN:

136   1.   An interaction matrix explaining the strength of any interaction between two variables

137   2.   An interaction matrix containing whether an interaction is present

138   3.   Prior beliefs (see above)

139

140

141Stage 1: We calculated a value between 0-1 representing the strength of the relationship between two variables.
142This reflects the probability of increase or decrease of pairs of variables, whereby a value of 0.5 represents no
143relationship, a value of 1 indicates that variable A would increase with variable B, and a value of 0 would indicate
144that variable A would decrease with variable B. This was established for each pair of variables by calculating how
145the relationships compare to what would be expected by chance:

146

147 $$x = \frac{\sum variable\,A\,e.g.\,chicken\,bones \times \sum variable\,B\,e.g.\,duck\,bones}{\sum total\,of\,all\,variables(e.g.\,total\,bones)}$$

148for variables based on frequency (e.g. species or site type); or

149 $$x() = \frac{\sum variable\,A(e.g.\,elevation)}{n()(number\,of\,assemblages)}$$

150for variables based on averages (e.g. climate or elevation), where x represents the expected value;

151

152and then establishing how far this interaction differs from a value of 0.5, representing no relationship:

153 $$y = \sigma \dot{\iota} \frac{\sum variable\,A}{)}$$

154where y represents standard deviation

155 $$z = (variable\,A() - x) \div y$$

156where z represents the difference between the observed and expected totals

157 $$BBN\,value = \left(\frac{z}{sd}\right) + 0.5(value\,of\,no\,relationship)\,,$$

158where sd represents the number of standard deviations required to scale the data to a value between 0 and 1,
159with a minimum value of $sd = 3$.

160

161Stage 2: If an interaction (positive or negative) was present, this was input into the second stage of the BBN. 162Based on the formula above, relationships of 0.55 or above and 0.45 or below were interpreted as interactions. 163As 0.5 represents no change, the range between 0.45 and 0.55 is unlikely to represent a meaningful 164relationship.

165

166Stage 3: We then adjusted the prior beliefs.. The model uses Bayesian inference to assess how changes, based 167on observations from the archaeological record (e.g. an increase in chicken), would affect the other variables in 168the study, based on their interactions with one another. Where a known increase or decrease occurred, albeit 169limited by caveats associated with archaeological excavation (Pitt and Stewart in press), the prior belief was 170adjusted to 1 or 0 respectively.

171

172Species were selected based on association with chicken within specific spheres of interest (Table 1). The 173chicken is found in the domestic sphere, along with the other primary domestic animals, dog, horse, pig, 174sheep/goat, and the domestic birds, duck, goose and pigeon. Cattle were not selected for this analysis, as it has 175been noted that comparison of cattle with other primary mammals and with birds is problematic, due to disposal 176practices, recovery and preservation issues (Maltby 1997; Maltby 2010). It should be noted that duck, goose or 177pigeons found on archaeological sites are not necessarily domestic but may have been merely tamed (Albarella 1782005), or may represent other duck species (Parker 1988). Many of the selected domestic species are also 179edible, as are partridge and quail, although partridge and quail are additionally of interest for their use as fighting 180birds (Jennison 1937; Gal 2008).

	Genera
Chicken	Gallus
Dog	Canis
Duck	Anas, Aythya
Fox	Vulpes
Goose	Anser, Branta
Horse	Equus
Marten	Martes
Mouse	Apodemus, Mus, Micromys
Partridge	Alectoris, Perdix
Pig	Sus
Pigeon	Columba
Quail	Coturnix
Rat	Rattus
Sheep/goat	Capra, Ovis
Sparrow	Passer
Weasel/stoat	Mustela

181*Table 1 Selected species.*

182

1833. Results and discussion

184 3.1 Analysis of changes in the faunal record

185 The known outcome from the archaeological data forms the prior beliefs and allows interpretation of the 186 Bayesian belief models. This study is concerned with understanding how known increases in chicken affected 187 other species with which it is associated, and whether changes in the frequency of those species may have 188 contributed to the increase in frequency of chicken found on archaeological sites. The data were analysed to 189 establish how species populations changed over time (Table 2).

	Period 1 (to 800 BCE)		Period 2 (800 BCE - 0/42 CE)		Period 3 (1/43 - 500 CE)			
	NISP	No. of sites	NISP	No. of sites	NISP	No. of sites	Total NISP	Total Sites
Chicken	16	2	4157	221	90040	468	94213	**691**
Dog	1087	23	21336	237	39903	356	62326	**616**
Duck	106	8	360	74	3415	197	3881	**279**
Fox	152	14	952	70	495	51	1599	**135**
Goose	44	6	308	59	4697	169	5049	**234**
Horse	542	17	42164	237	42881	398	85587	**652**
Marten	263	6	72	9	16	12	351	**27**
Mouse	0	0	215	16	906	44	1121	**60**
Partridge	20	4	39	12	598	32	657	**48**
Pig	7084	27	302716	275	216385	445	526185	**747**
Pigeon	3	2	515	26	799	104	1317	**132**
Quail	0	1	7	5	37	6	44	**12**
Rat	23	2	84	2	264	24	371	**28**
Sheep/goat	14524	27	341695	277	273019	446	629238	**750**
Sparrow	0	0	50	7	69	12	119	**19**
Weasel/stoat	6	3	46	18	209	29	261	**50**
Total	**23870**	**28**	**714716**	**292**	**673733**	**504**	**1412319**	824
Database Total (all mammals and birds)	**105888**	**647**	**1002702**	**3242**	**1164718**	**7520**	**2273308**	**11409**

190 *Table 2. NISP and frequency of occurrence on sites*

191 Domestic animals dominate the evidence in all periods, with bones of pig and sheep/goat recovered in greatest 192 frequency. Chicken is present in small numbers by period 2. By period 3 it is widespread with larger populations. 193 The change in frequency of chicken is paralleled by other species, including duck, goose, mouse, partridge, 194 quail, rat and weasel/stoat. Sparrow and pigeon also increase in frequency in period 3, but are present in 195 reasonable numbers in period 2. The increase in evidence of chicken in period 3 coincides with decreases in fox, 196 marten, pig and sheep/goat. The primary edible mammals experience minor population decreases in period 3, 197 but horse and dog continue to increase. Marten decrease over both periods.

198

199 3.2 Bayesian belief network analyses

## 200*3.2.1: Biotic interactions*

201A species relationship matrix was calculated using the formula in Section 2 (Table 3). In terms of the effect of the 202chicken on other species, the results show that assemblages containing chicken are more likely to contain dog, 203duck, goose, horse, partridge, pig, pigeon, and rat than expected by chance. They are less likely to contain fox 204and marten. In terms of species affecting the chicken, chicken is more likely to occur with goose, mouse, pigeon, 205quail, sheep/goat and sparrow, and less likely to occur with dog, duck, fox, horse, pig, and weasel/stoat. The 206domestic mammals are largely unaffected by other species and, where they have a relationship with other 207animals, then it is another domesticate. The domestic birds are affected by a mix of wild and domestic species, 208both positively and negatively.

	Chicken	Dog	Duck	Fox	Goose	Horse	Marten	Mouse	Partridge	Pig	Pigeon	Quail	Rat	Sheep/goat	Sparrow	Weasel/stoat
Chicken	0.50	0.56	0.60	0.39	0.71	0.58	0.27	0.47	0.56	0.57	0.64	0.49	0.58	0.54	0.53	0.53
Dog	0.40	0.50	0.46	0.57	0.36	0.57	0.61	0.48	0.40	0.55	0.39	0.44	0.54	0.55	0.46	0.51
Duck	0.44	0.51	0.50	0.44	0.77	0.47	0.61	0.51	0.44	0.51	0.65	0.53	0.34	0.51	0.51	0.27
Fox	0.35	0.48	0.38	0.50	0.41	0.53	0.66	0.25	0.41	0.52	0.41	0.34	0.35	0.50	0.41	0.31
Goose	0.64	0.46	0.59	0.42	0.50	0.48	0.33	0.42	0.50	0.53	0.47	0.55	0.34	0.46	0.37	0.25
Horse	0.42	0.59	0.48	0.58	0.36	0.50	0.63	0.48	0.38	0.57	0.34	0.42	0.30	0.56	0.48	0.31
Marten	0.50	0.49	0.54	0.52	0.55	0.49	0.50	0.62	0.63	0.51	0.53	0.46	0.46	0.49	0.44	0.45
Mouse	0.58	0.53	0.50	0.46	0.51	0.49	0.48	0.50	0.43	0.47	0.49	0.44	0.69	0.52	0.64	0.76
Partridge	0.50	0.48	0.58	0.54	0.54	0.49	0.51	0.64	0.50	0.49	0.70	0.80	0.62	0.51	0.46	0.74
Pig	0.89	0.85	0.80	0.85	0.67	0.84	0.85	0.82	0.81	0.50	0.75	0.78	0.86	0.87	0.83	0.82
Pigeon	0.66	0.54	0.61	0.48	0.63	0.44	0.43	0.57	0.68	0.48	0.50	0.44	0.41	0.50	0.58	0.39
Quail	0.55	0.48	0.53	0.50	0.55	0.49	0.51	0.43	0.56	0.49	0.53	0.50	0.58	0.51	0.45	0.74
Rat	0.51	0.49	0.55	0.50	0.55	0.49	0.51	0.69	0.64	0.50	0.55	0.50	0.50	0.50	0.45	0.75
Sheep/goat	0.97	0.92	0.88	0.92	0.73	0.91	0.61	0.90	0.91	0.91	0.90	0.87	0.94	0.50	0.90	0.89
Sparrow	0.59	0.51	0.49	0.56	0.52	0.50	0.49	0.45	0.46	0.47	0.47	0.69	0.51	0.52	0.50	0.46
Weasel/stoat	0.43	0.47	0.42	0.46	0.43	0.51	0.41	0.40	0.39	0.51	0.40	0.37	0.57	0.50	0.53	0.50

209*Table 3 Matrix of inter-species relationships, whereby the species in the row affects the species in the column. Light grey* 210*represents a positive relationship, dark grey represents a negative relationship and white indicates no relationship.*

211

212For the first model (Figure 1), using biotic variables only, the intention is to determine the effect of the chicken on 213other species. The species interactions (Table 3) were used for stages one and two of the BBN, and the prior for 214chicken in the third stage was altered from 0.5 (no change) to 1 (increase), based on the known increase in 215chicken in both periods evident in the archaeological record (Table 2).
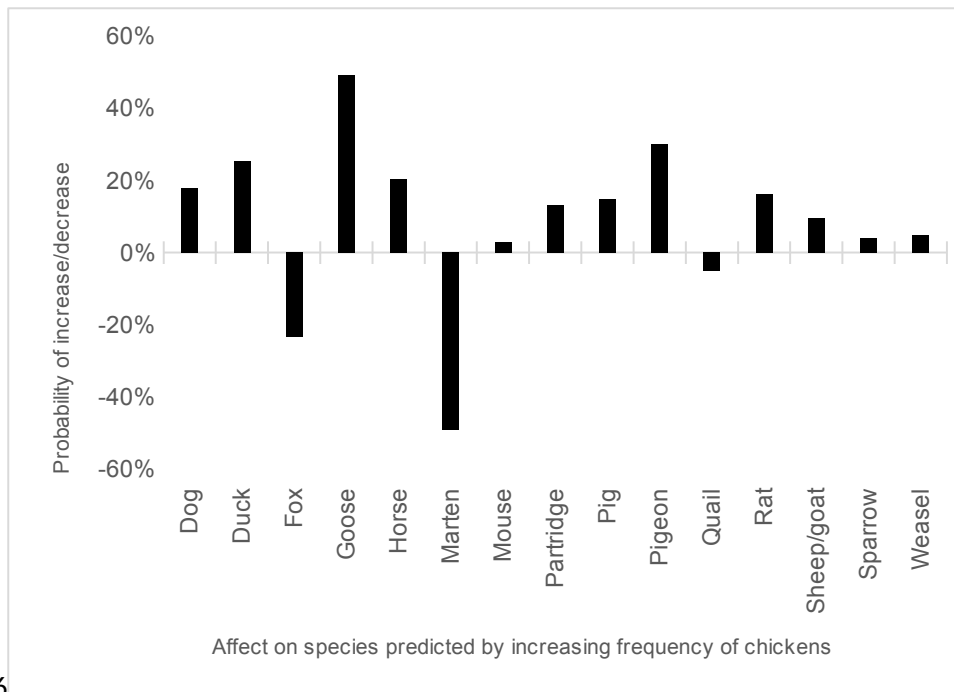
216

218 The results show that when the relationships of the other species with each other are considered, an increase in 219 chicken is predicted to have a negative impact on fox, marten and quail. Its increase should coincide with 220 increases in all other species. Fox and quail increase in period 2 despite increase in chicken, suggesting that 221 chicken is not likely to be an over-riding factor. Decrease in marten coincides with increase in chicken, and so 222 chicken is not excluded as a factor. However, only limited increase in chicken in period 2 makes it difficult to 223 draw firm conclusions. In period 3, a relatively large increase in chicken corresponds with the patterns seen for 224 all species except quail, pig and sheep/goat. Increase in chicken, therefore, is unlikely to have affected quail, pig 225 and sheep/goat.

226

227 The prior beliefs of the species 'affecting' the chicken were altered in turn in the third stage of the model (Figure 228 2). Periods 2 and 3 were modelled separately due to some of the interacting species increasing in one period 229 (value=1), but decreasing (value=0) in another (Table 2).
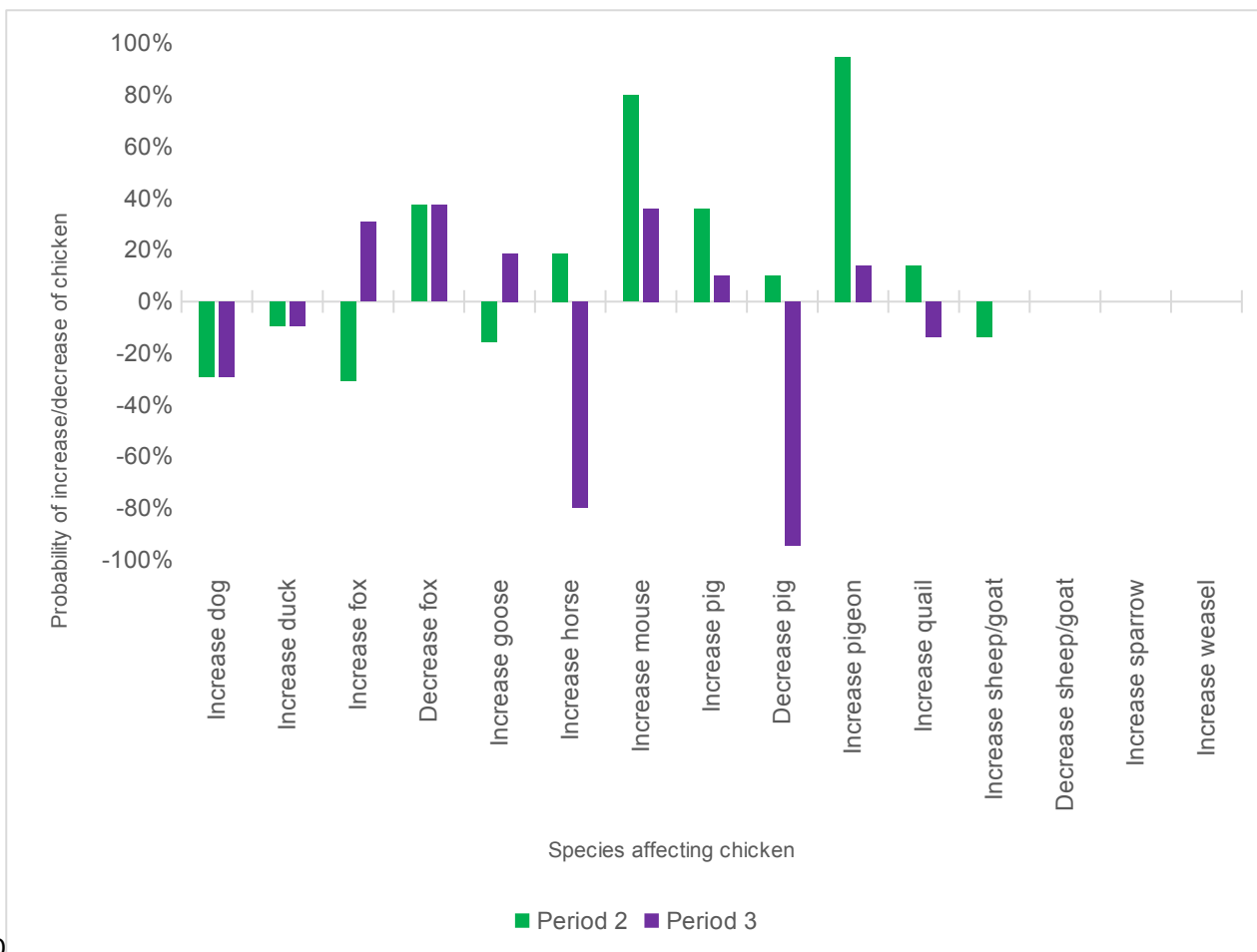
Figure 2. BBN model prediction for changes in chicken frequency caused by changes in frequency of species affecting chicken.

Limited increase in chicken in period 2 could be explained by dog, duck, fox, horse and weasel/stoat inhibiting increase, or goose, mouse, pig, pigeon, quail, sheep/goat and sparrow aiding it. Given the relatively large increase of chicken in period 3, predictions of dog, duck, pig, sheep/goat and weasel/stoat causing decrease in chicken suggests that these species are not influencing factors. Conversely, decrease in fox and increase in goose, mouse, pigeon, quail, and sparrow in period 3 parallel the archaeological record and cannot be excluded.

3.2.2: Biotic and abiotic interactions

Abiotic variables provide information regarding factors outside of the ecological community which could have caused the changes observed in the archaeological record. We included site type, climate and elevation variables. Religious sites are sites with a primary function of ritual, religious, or funerary use, including ritual feasting, temples, sanctuaries, cult sites, and cemeteries. Rural sites are permanent settlements associated with rural activity or comprising a series of dwellings in insufficient number to be defined as urban. Urban sites are permanent settlements with a high density of dwellings and other buildings. If these factors do not better explain

247the observed changes, then they are unlikely to be major driving factors. The relationships between the abiotic
248variables and both the chicken and the species affected by chicken (Table 4), were calculated as per the method
249in Section 2.

	Chicken	Dog	Duck	Fox	Goose	Horse	Marten	Partridge	Pig	Pigeon	Rat
Religious	0.65	0.45	0.5	0.43	0.5	0.5	0.5	0.5	0.5	0.58	0.61
Rural	0.5	0.56	0.5	0.63	0.5	0.5	0.65	0.5	0.5	0.45	0.86
Urban	0.39	0.5	0.55	0.44	0.5	0.5	0.39	0.55	0.5	0.5	0.03
Elevation	0.46	0.40	0.27	0.47	0.29	0.41	0.83	0.91	0.43	0.58	0.61
Temperature	0.5	0.43	0.38	0.5	0.4	0.42	0.5	0.94	0.5	0.5	0.62
Precipitation	0.4	0.38	0.43	0.21	0.3	0.39	0.43	0.94	0.43	0.76	0.68

250*Table 4. Matrix of species relationships with climate and environment variables, whereby the variable in the row affects the*
251*species in the column. Light grey represents a positive relationship, dark grey represents a negative relationship and white*
252*indicates no relationship.*

253

254The abiotic variable relationships were added to stages one and two of the model. The inter-species
255relationships were retained. The prior beliefs of each of the abiotic variables were altered in the third stage of the
256model to reflect known changes (Figure 3), as observed in historical records (climate) or derived from the
257dataset (elevation at site locations and site type). Known changes in period 2, compared to period 1, include a
258decrease in religious sites; and increase in rural and urban sites. The average height of a site above sea level
259increases, as does annual rainfall. In period 3, urban sites increase at the expense of rural sites; sites are
260located at lower elevation, and annual rainfall decreases slightly, compared to period 2.
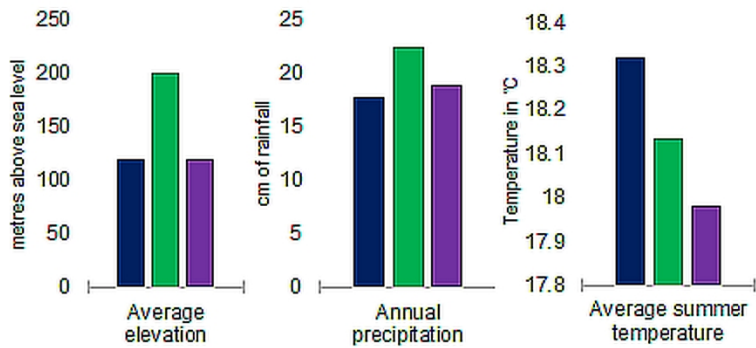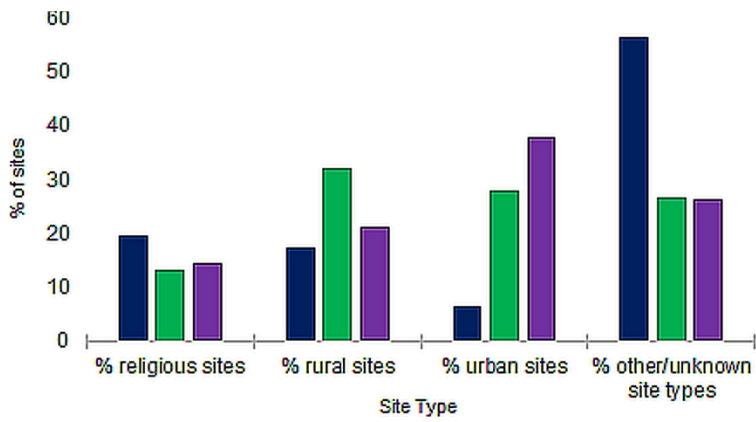
261 ■ Period 1 (to 800 BCE) ■ Period 2 (800 BCE – 0/42 CE) ■ Period 3 (1/43 – 500 CE)

262 *Figure 3. Changes in abiotic variables between periods 1-3.*

263 The results (Figure 4) show that increase in religious sites, decrease in precipitation and a move to lower 264 elevations may help to explain the rise in chicken numbers. The increase in urban spread, which is predicted to 265 negatively affect the chicken is due, in part, to high frequency of chicken bones found at religious sites (Table 5). 266 Greater human occupation provides convincing reasons for the decline of the marten in both periods 2 and 3, 267 due to negative responses to increased rural settlements (the reverse of the chart in period 2) and increase in 268 urban settlements in period 3, which also tend to occupy lower elevations. The abiotic variables do not explain 269 the patterns seen for pigeon, partridge, rat or fox, suggesting other factors are affecting these species.

270
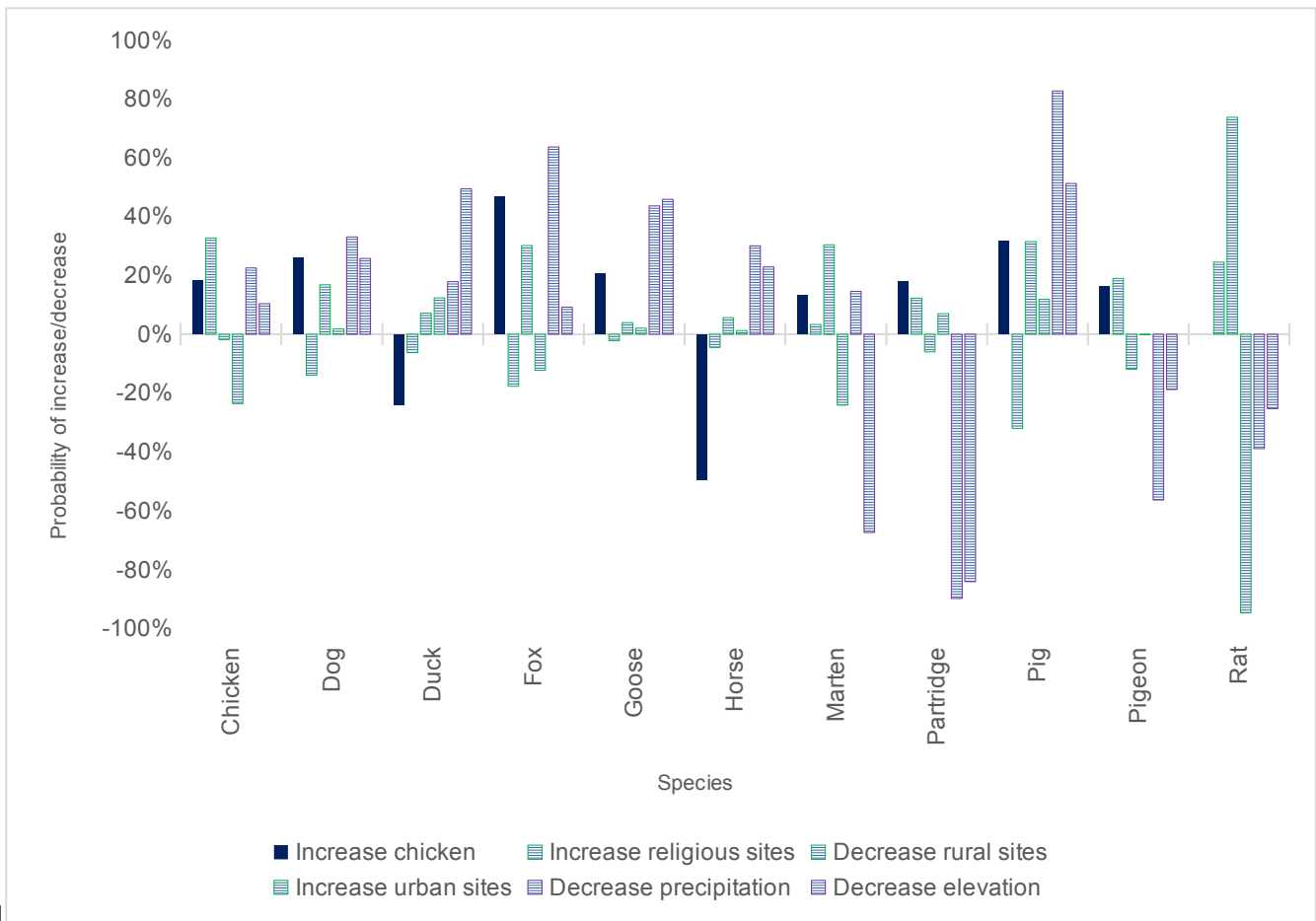
272 *Figure 4. BBN model prediction for response of chicken and species affected by chicken to climate and environmental* 273 *variables.*

Species	Frequency on religious sites (n=131)
Pig	119
Chicken	114
Sheep/goat	108
Dog	74
Horse	71
Goose	39
Duck	34
Pigeon	25
Fox	18
Mouse	16
Partridge	9
Weasel/stoat	6
Rat	5
Sparrow	4
Marten	2
Quail	2

274 *Table 5. Species occurrence on religious sites.*

275

276 3.2.3 Recovery methods

277 One of the main benefits of this kind of model is that it is not limited to purely environmental variables. This 278 allows testing of a further theory- that the frequency of small animals is affected by excavation recovery 279 methods. Larger bones are easier to detect during hand excavation, and smaller ones more likely to be missed 280 unless contexts are sieved (Payne 1972; Sapir-Hen et al. 2017). Other factors influence whether sieving is part 281 of the excavation methodology, and these were included in the models. Type of site was included because 282 religious sites, particularly burials and cremations, are more likely to be sieved. This was confirmed by the 283 relationship calculation (Table 6 and 7), after the method presented in Section 2. The type of excavation, whether 284 commercial, rescue or research can influence the type of site excavated and whether sieving is performed. Bone 285 condition also affects whether more bones are recovered by sieving, and sieving was calculated to procure 286 greater numbers of bones in poor condition.

	Chicken	Dog	Duck	Fox	Goose	Horse	Marten	Mouse	Partridge	Pig	Pigeon	Quail	Rat	Sheep/goat	Sparrow	Weasel/stoat
Hand excavated	0.33	0.5	0.5	0.3	0.5	0.5	0.5	0.01	0.52	0.54	0	0.39	0.29	0.31	0.51	0.43
Sieved	0.67	0.5	0.5	0.7	0.5	0.5	0.5	0.99	0.48	0.46	1	0.61	0.71	0.69	0.49	0.57
Good condition	0.34	0.5	0.5	0.4	0.5	0.5	0.36	0.32	0.54	0.51	0.02	0.55	0.42	0.51	0.52	0.55
Poor condition	0.68	0.5	0.5	0.43	0.56	0.5	0.64	0.69	0.46	0.5	0.58	0.47	0.43	0.48	0.5	0.46
Commercial	0.45	0.88	1	0.58	0.69	0.51	0.44	0.48	0.45	0.47	0.44	0.42	0.71	0.52	0.48	0.46
Rescue	0.67	0.43	0	0.49	0.5	0.44	0.79	0.3	0.27	0.36	0.32	0.3	0.18	0.64	0.8	0.27
Research	0.38	0.19	0	0.43	0.31	0.55	0.27	0.72	0.78	0.67	0.74	0.78	0.61	0.34	0.23	0.77
Religious	0.7	0.43	0.5	0.4	0.5	0.5	0.5	0.5	0.45	0.47	0.58	0.44	0.62	0.49	0.48	0.45
Rural	0.44	0.56	0.5	0.61	0.44	0.5	0.69	0.5	0.47	0.49	0.39	0.46	0.8	0.52	0.7	0.7
Urban	0.38	0.5	0.57	0.43	0.5	0.5	0.37	0.28	0.58	0.55	0.39	0.56	0.03	0.48	0.34	0.34

287 *Table 6. Matrix of species and recovery method variables relationships, whereby the variable in the row affects the species in* 288 *the column. Light grey represents a positive relationship, dark grey represents a negative relationship and white indicates no* 289 *relationship.*

290

	Hand excavated	Sieved	Poor condition	Religious	Rural	Urban
Hand excavated	0.5	0.5	0.5	0.38	0.5	0.5
Sieved	0.5	0.5	0.5	0.62	0.5	0.5
Good condition	0.5	0.5	0.5	0.5	0.5	0.5
Poor condition	0.5	0.5	0.5	0.5	0.5	0.5
Commercial	0.5	0.5	0.5	0.5	0.5	0.5
Rescue	0.5	0.5	0.5	0.5	0.5	0.5

Research	0.76	0	0.5	0.5	0.5	0.5
Religious	0.43	0.73	0.5	0.5	0.5	0.5
Rural	0.5	0.44	0.5	0.5	0.5	0.5
Urban	0.55	0.33	0.5	0.5	0.5	0.5

291 *Table 7. Matrix of recovery method variables relationships, whereby the variable in the row affects the variable in the column.*
292 *Light grey represents a positive relationship, dark grey represents a negative relationship and white indicates no relationship.*

293

294 These relationships were used in stages one and two of the BBN to assess the predicted increase in NISP if
295 more sieving is done (value=1 in stage three) (Figure 5). Inter-species relationships were not included as they
296 are not relevant to this analysis. The model predicts that nine of the species in this study are likely to benefit from
297 more sieving, especially mouse and pigeon. Sieving would not decrease recovery of any of these species.
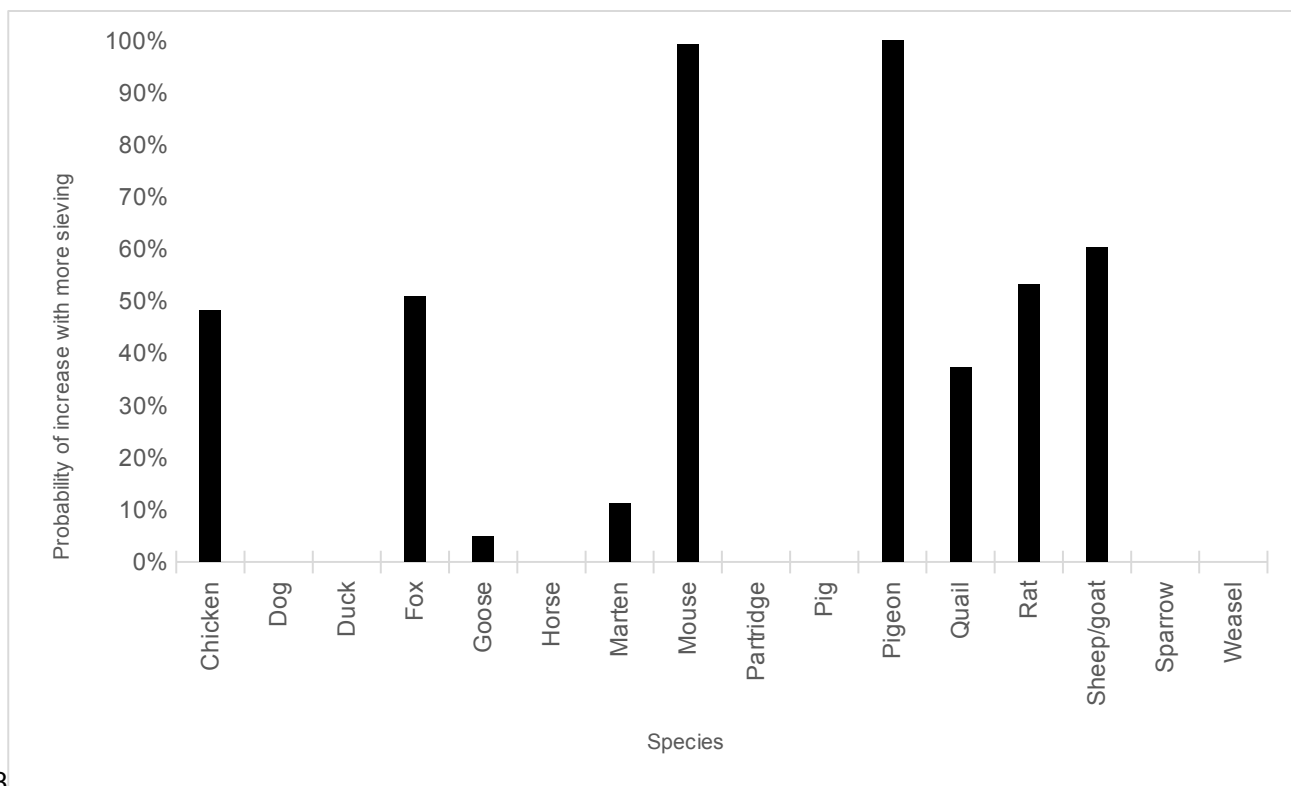
298

299 *Figure 5. BBN model prediction for recovery of animal bones with more sieving.*

300

301 **4. Discussion:** Analysis of presence on archaeological sites shows that increase in chicken occurs at the same
302 time as changes in other species related to the chicken in various spheres of influence. Decreases in pig and
303 sheep/goat and only minimal increase in horse in period 3 suggests that observed increase of other species is
304 not merely because of population size increases. The largest percentage change observed is the chicken in
305 period 3. This large increase of chicken also coincides with increases in duck, goose, mouse, partridge, quail, rat
306 and weasel/stoat and decreases in fox and marten. As a predator species, which is known to steal eggs, the

307fortune of the weasel/stoat contrasts with that of the fox and marten. This raises interesting observations for
308further analysis. Does the chicken affect the increase of weasel/stoat and cause fox and marten to decline?
309Perhaps the weasel/stoat is perceived differently by humans (after O'Connor 2013a)? Does the presence of
310other domestic species cause higher occurrence of chicken, and vice versa? Or does the increasing popularity of
311the chicken in period 3 cause proportional decreases in the primary domesticates? Does the method of feeding
312chickens enhance populations of commensal species such as mouse, rat, feral pigeon and sparrow? Are other
313factors causing these changes instead?

314

315Calculating the relationships for the Bayesian belief network inter-species model identified that the ecosystem
316dynamics are different for domestic birds compared to domestic mammals, and, given the wide range of species
317that affect or are affected by chicken, the chicken belongs in a domestic sphere influenced by the other domestic
318birds. The models predicted that chicken neither influenced, nor was influenced by, the primary domestic
319mammals. Changing dietary patterns between periods 2 and 3 (King 1999) and particularly the varied diet
320enjoyed by the Romans (Rowan 2017), at least on some sites, might offer a good explanation for the increase in
321birds, and slight decrease in domestic mammals. The models predict that goose and pigeon are most likely to
322increase chicken. This may be due to their position within the domestic sphere. Goose husbandry is well
323established by the Roman period, but duck domestication appears to be in its infancy, based on ancient literature
324(Albarella 2005). Positive association of duck with urban settlements and lower elevations may, therefore, be
325explained by importation into towns (after Parker 1988). Association with religious sites, consistent with the
326findings of King (2005), is predicted to be the abiotic variable most affecting chicken.

327

328Chickens are, however, known to be frequently found in towns (Maltby 1997). As common quail prefer open,
329agricultural habitats (BirdLife International 2016), it might be expected that they should not be found associated
330with chicken. Yet, an increase in quail is predicted to increase chicken populations. An increase in chicken,
331however, is predicted to reduce numbers of quail. The known evidence suggests otherwise. They are both
332fighting, edible birds and quail could be imported to towns for these purposes. The same is true for partridge, the
333other fighting bird, which is predicted to increase with increased numbers of chicken. Environmental variables
334cannot explain what is seen in the faunal record. This suggests that the increase of the chicken is not to the
335detriment of the other potential fighting birds.

336

337Environmental variables, particularly the spread of urbanisation, deforestation, and construction of settlements at
338lower elevations explain the reduction of marten in the archaeological record better than the influence of chicken,
339although exacerbation by increase of chicken in period 3 is not discounted. The models show that the effect of
340the chicken on the other egg-thief, weasel/stoat is little more than expected by chance, and that the weasel/stoat
341does not, in fact, affect chicken. Of the predators, fox matches the pattern seen in the archaeological data, with

342its increase perhaps inhibiting numbers of chicken initially and then experiencing population decline as chicken 343appears more frequently in the archaeological record.

344

345The other small birds, sparrow and pigeon, along with mouse and rat, are predicted to increase with increased 346numbers of chicken, and thus the introduction of the chicken may have benefited these species. These species 347are all small and recovery is likely to have been a major issue. Mouse, pigeon and rat were all shown to benefit 348from more sieving. This suggests that the frequency of small mammals and birds present was, in all likelihood, 349higher, but that they were not recovered. With the exception, perhaps, of pigeon, they are all also species which 350have less direct human interaction and so their presence on archaeological sites is opportunistic. Their remains 351are more likely to be found where humans have chosen to deposit their refuse, rather than in the main centres of 352human activity (O'Connor 2013b) and so are likely to be underrepresented in the archaeological literature.

353

354There is another explanation, not accounted for in the models, which could apply to rat and to fox. These two 355species are a problem for chicken keepers because foxes can decimate a flock, while rats can contaminate feed 356and water and cause disease in humans (Graham 2015). Both animals would thrive around chickens, and eat 357their eggs, were it not for humans, who will take measures to protect their flock from them. This offers a good 358explanation for the predicted and observed results for fox, which increases in period 2 while chicken is present, 359but only in low frequency and has been newly introduced. It decreases in period 3 when chicken increases 360dramatically and humans are likely to have developed better means of protecting them. This is consistent with a 361study of Anglo-Saxon fauna, which identified no direct correlation between chicken and fox (Poole 2015). Poole 362(2015) suggested that, in these instances, humans may have been reducing the fox population as a threat to 363human infant burials.

364

365**5. Conclusions**: The impact of the chicken on its environment and of the environment on the chicken was 366examined using a novel method to identify and exclude potential causes and effects. Analysis of the 367relationships and associations between species found in similar spheres of human activity, and their responses 368to external environmental factors, allows us to establish which of the many possible correlations are likely to 369have contributed to, or been most affected by, the success of the chicken in Europe. The results show that 370chicken demonstrate most affinity with the other domestic birds. Where chicken is found, goose and pigeon are 371more likely to be found, and, indirectly, duck via a positive mutual relationship between duck and goose. Its 372introduction and success did not affect the primary domestic mammals, nor the other fighting birds, quail and 373partridge, possibly due to their use as food also.

374

375The introduction of the chicken was shown to most affect fox, partridge and pigeon. Increase in chicken, directly 376or indirectly, provides the best explanation for the decrease of fox, having established that environmental

377changes in period 3 should have led to increases in fox numbers. While the chicken may have contributed to the

378decline of marten, external environmental factors, particularly the spread of urbanisation, offer a better

379explanation. Increase in chicken may have aided increases in mouse, quail and rat; although models suggest

380that recovery of these species, which are present in low numbers in the dataset, are affected by retrieval

381methods and may be under-represented. Recovery models find that sieving would enhance recovery of nine of

382the sixteen species assessed (over 50%), making it a worthy endeavour for small animal assemblages.

383

384The results are model predictions and must be interpreted as such. In this study, interpretation is restricted to

385better understanding of the information present in the data. For future work, if two independent datasets were

386available, this would enable the user to establish the prior beliefs from one dataset, and use this information to

387test hypotheses from another dataset. This would facilitate testing of site scale hypotheses as well as those at

388larger regional scales. Local or regional study of detailed recovery techniques may also provide interesting

389results. This study presents a method which can be easily applied to any archaeological dataset. It demonstrates

390how an inter-disciplinary approach, using novel ecological techniques, offers an efficient means of comparing

391various inter-related aspects of large quantities of data and can help to better interpret the archaeological record.

392

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