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16 **A role for liming as a conservation intervention? Earthworm abundance is**

17 **associated with higher soil pH and foraging activity of a threatened shorebird in**

18 **upland grasslands**

19 **Running title:** Conservation benefits of liming

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31 **Abstract**

32 The relationship between farmland bird populations and agricultural intensification has

33 been well studied. However, the impact of variation in soil conditions and soil

34 management is an exception, especially in upland (sub-alpine) farming systems. In this

35 study, we examined the relationships between liming history, soil pH and patterns of

36 foraging by Northern Lapwing, *Vanellus vanellus*, chicks in order to test the potential utility

37 of soil amendment as a conservation intervention for shorebirds nesting in agricultural

38 grasslands. Limed fields had higher soil pH than unlimed fields, and soil pH declined with

39 the number of years since a field was last limed. The most important predictor of total

40 earthworm abundance was soil organic matter with very few earthworms in peats of very

41 high organic matter content. However, there was a marked additive effect of soil pH with

42 earthworms more than twice as abundant at high (pH = 6.0) as at the low (pH = 3.5)

43 extremes of soil pH recorded in the study. Specifically, at Lapwing chick foraging

44 locations, the density of *Allolobophora chlorotica*, an acid-intolerant species of earthworm

45 found just below the surface of the soil, was significantly higher than at randomly selected

46 locations. These results suggest that liming helped to maintain breeding habitat quality for

47 Lapwings and other species dependent on earthworms. This is of conservation

48 significance in upland agricultural grasslands in the UK, where there has been a long-term

49 reduction in agricultural lime use since the mid-20th century. Field-scale trials of liming

50 would be valuable to test whether targetted amendment of soil pH in agriculturally

51 improved grasslands could retain an important role in conservation management for

52 shorebirds in upland landscapes where geology, high rainfall, and leaching tend to acidify

53 soils over time.

54 **Key words:** agriculture, grassland, lime, earthworm, lapwing, *Vanellus*, soil pH

55

56 **1 Introduction**

57 Agricultural intensification has been implicated in widespread declines in biodiversity, with

58 negative effects of agricultural change on birds in Europe particularly well documented

59 (Robinson & Sutherland, 2002, Newton, 2004, Wretenberg *et al.*, 2007, Wilson *et al.*,

60 2009). Intensification has resulted in a simplification of the farmed landscape associated

61 with reduced habitat heterogeneity and availability of nesting opportunities and food

62 sources for many farmland birds (Benton *et al.*, 2003, Tscharntke *et al.*, 2005).

63 One aspect of agricultural change which has received relatively little attention in relation to

64 farmland bird declines is soil management in upland (sub-alpine) grassland systems, and

65 especially the amendment of soil pH. This is surprising because soil invertebrates provide

66 important food resources for a wide range of farmland-feeding birds including shorebirds,

67 thrushes, starlings and corvids (Tucker, 1992, Wilson *et al.*, 2009), and the diversity and

68 abundance of many of these invertebrate groups are pH-sensitive (Edwards & Bohlen,

69 1996, Cole *et al.*, 2006).

70 Soil pH is reduced by agricultural processes such as cropping and the use of nitrogenous

71 fertilisers, but also naturally through leaching of calcium and other base cations from the

72 soil and has been further lowered in some areas by anthropogenic atmospheric acid

73 deposition (Rowell & Wild, 1985). Natural leaching of calcium is faster in areas with

74 higher rainfall, especially where acidic underlying geology and peat formation result in low

75 buffering capacity. These conditions describe agriculturally marginal, upland grasslands

76 over much of the UK. Such landscapes are now an internationally important stronghold

77 for populations of breeding shorebirds of several species (e.g. Eurasian Curlew,

78 *Numenius arquata*; Brown *et al.*, 2015). Yet even in these environments, they are

79 declining rapidly (Balmer *et al.*, 2013, Brown *et al.*, 2015) having already suffered

80   catastrophic declines in lowland agricultural systems (Wilson *et al.,* 2005, Lawicki *et al.*,

81   2011).

82   The effects of soil acidification are widely counteracted through agricultural liming to raise

83   soil pH (MAFF, 1969, Wilkinson, 1998, Spaey *et al.*, 2012). In the UK, agricultural lime

84   sales peaked in the 1950s and '60s under a Government subsidy which persisted into the

85   1970s (Figure 1), but have since declined steadily to pre-subsidy levels. Low soil pH and

86   declines in pH occurred between the 1970s and 2001, particularly in western and northern

87   areas that are dominated by livestock farms in higher altitude, higher rainfall environments

88   (Baxter *et al.,* 2006). By 2007, there was some evidence that this trend was being

89   reversed, perhaps due to the declining impacts of acid deposition from industrial pollution

90   (Emmett *et al.* 2010).

91   Earthworms comprise around 75% of soil fauna biomass in temperate grasslands

92   (Bardgett & Cook, 1998), play a key role in maintaining soil fertility and constitute a prey

93   resource for a number of birds that are associated with farmland, including shorebirds,

94   gulls and corvids (Barnard & Thompson 1985, Wilson *et al.*, 2009). Earthworms are

95   sensitive to soil pH and very few earthworms occur in soils below pH 4.3 (Edwards &

96   Bohlen, 1996). Because lime is applied as a surface dressing, it has a greater effect on

97   epigeic and endogeic (surface and near-surface dwelling) than anecic (burrowing)

98   earthworm species, with reported increases in earthworm abundance following liming

99   being mainly in epigeic species (Deleport & Tillier, 1999, Bishop, 2003, Potthoff *et al.*,

100   2008). Accordingly, Brandsma (2004) identified an increase in field use by both Northern

101   Lapwings *Vanellus vanellus* (henceforth 'Lapwings') and Black-tailed Godwits *Limosa*

102   *limosa* following increases in earthworm abundance that occurred after liming.

103   In this study we use upland agricultural grassland with a known liming history to test the

104   impact of lime use on prey resources and foraging habitat use by Lapwings, for whom

105   earthworms are an important component of the diet, including during chick development

106   (Beintema *et al.,* 1991, Sheldon, 2002). Specifically we addressed the following questions:

107

108   1) How long does the positive effect of liming on soil pH last?

109   2) How is earthworm abundance related to soil pH, soil moisture and soil organic matter?

110   3) Do locations selected by foraging Lapwing chicks have a higher abundance of epigeic

111   or endogeic earthworms than randomly selected locations?

112

113   **2 Methods**

114   *2.1 Study area*

115   The study took place from 2009 – 2011 on upland grassland in central Scotland (56°

116   4'40.06"N 4° 0'45.00'"W), covering three livestock farms (Townhead, Muirpark and

117   Lochend) and a total area of 685 ha. The underlying geology is basalt, overlain by glacial

118   tills, and peat. The average annual precipitation within the area is 1020 mm. The three

119   farms all produce beef cattle and sheep and range from 140 m to 340 m above sea level.

120   Field types in marginal agricultural areas such as this are split into two types; 'in-bye'

121   (enclosed fields used for either arable or sown grass production), and 'out-bye' (semi-

122   natural grass and dwarf shrub 'moorland' vegetation cover used for rough grazing only

123   (Gray 1996).

124   *2.2 Soil pH and earthworm sampling*

125   Soil properties and earthworm abundance were assessed in 19 fields which had

126   undergone differing numbers of lime application within the preceding 10 years (Table 1).

127   Around 50ha of the in-bye land at Townhead had been used to grow a brassica fodder

128   crop in the preceding ten years (McCallum, 2012). This provided a contrast between

129   fields that had undergone fodder crop management and had received two or three lime

130   applications (5 tonnes ha^{-1} annum^{-1}, applied as a surface dressing of calcium carbonate

131   dust) in the preceding 10 years, and fields that had not undergone this cropping

132   management, and had received either no or just one lime application during this period.

133   Because liming occurred at the time of fodder crop management and this was rotated

134   round fields, the number of years since the last lime application varied between fields. In-

135   bye fields at the other two study farms had not experienced fodder crop management.

136   Those at Muirpark had received no lime during the preceding 10 years, whereas fields at

137   Lochend had received one or two lime applications. Out-bye fields had received no lime

138   within the preceding 10 years.

139   Soil cores (10cm depth x 10.5 cm diameter) were collected from nine random locations

140   (generated using the sampling tool extension, Finnen & Menza, 2007, within ArcGIS 9.2)

141   within each field between 19 April and 11 May, and were used to measure soil pH, soil

142   organic matter and earthworm abundance. For fields with high variability in earthworm

143   abundance between the samples, an additional five samples were collected. Two soil

144   moisture measurements were taken in the field within 15cm of each soil core. In 2009 this

145   was done with a theta probe (ML2, Delta-T Devices, Cambridge, England) and in 2010

146   with a soil moisture metre (HH2 moisture metre, SM200 moisture sensor, Delta-T

147   Devices, Cambridge, England).

148   Soil was air-dried for a minimum of two weeks then sieved to < 2 mm prior to carrying out

149   soil analysis. Soil pH was measured using a digital pH meter (pH209, Hanna Instruments,

150   Woonsocket, Rhode Island, USA), calibrated using buffers of pH 7 and pH 4. Soil pH was

151   tested on 10 g of air dried, sieved soil, mixed with 25 ml distilled water, once the solution

152   had been left to settle for a minimum of 10 minutes. Soil organic matter was calculated as

153   the percentage of weight lost by burning sieved soil in a furnace at 425°C overnight (i.e

154   weight loss on ignition). The soil was prepared by drying at 105°C for a minimum of four

155   hours and then weighed both before and after burning.

156   Earthworms were sampled using the same cores used to assess soil properties, with soil

157   cores hand sorted in the laboratory within four days of collection (Edwards & Bohlen,

158   1996, Laidlaw, 2008). To avoid double counting of broken earthworms, only those with

159   heads were counted. Earthworms were identified to species level (Sims & Gerard, 1985),

160   with the exception of juveniles of either *Lumbricus* species or *Apporrectodea caliginosa*

161   and *A. rosea*, which were assigned to one of these two groups based on colour,

162   prostomium shape and spacing of chaetae.

163   ***2.3 Field observations of foraging Lapwing chicks***

164   To test whether chick foraging location (hereafter termed chick location) was related to

165   earthworm abundance, 19 lapwing chicks (10 in 2010, 9 in 2011) from separate broods

166   were fitted with Pip3Ag376 backpack mounted radio-tags (Biotrack Ltd, Dorset, UK). All

167   chicks within a brood were also ringed using British Trust for Ornithology metal rings,

168   above the knee. Coloured insulating tape was used on the ring to provide each brood with

169   a temporary unique colour marker. Radio-tagged chicks were re-captured at

170   approximately weekly intervals in order that tags that were beginning to come loose could

171   be re-glued.

172   Chick locations were estimated using triangulation by taking the bearing of the strongest

173   signal from the chick's radio-tag (using a Sika receiver and three-element flexible Yagi

174   antennae – Biotrack Ltd, Dorset, UK) from a minimum of three locations in succession

175   (White & Garrot, 1990, Kenward, 2001). Estimated chick locations and the associated

176   error ellipses (50% confidence) were calculated using Lenth's maximum likelihood

177   estimator (White & Garrot, 1990), using Location of a Signal 4.0.3.7 (Ecological Software

178   Solutions LLC, 2010). Error ellipses incorporated antenna error, which was established

179   from a number of test triangulations carried out at the study site (standard deviation 11.5).

180   Chicks were located by triangulation every one to three days. In addition to triangulated

181   locations (22 locations), some radio-tagged chicks were sighted using direction of the

182   strongest signal to guide where to look for the chick (9 observations). Fields were also

183   searched visually (with a telescope) for non radio-tagged chicks, using clues from adult

184   behaviour to concentrate on areas in which chicks were likely to be located (8

185   observations). Visual searches for chicks were carried out no more than once per day for

186   each field. Where chick location was estimated by triangulation, chick foraging was not

187   confirmed as it was not possible to see chicks. Lapwing chicks spend most of the time

188   either foraging or being brooded (Beintema & Visser, 1989) so it was likely that chicks

189   would be located in areas where they were foraging.

190   At each chick location four soil cores were collected, and four randomly located soil cores

191   were also taken from the same field. Soil moisture and earthworm abundance were

192   measured as described above.

193   **2.4 Data analysis**

194   *2.4.1. The relationship between soil properties and liming history*

195   To determine whether liming had the agriculturally desired impacts on soil pH, we tested

196   the relationship between soil pH and whether or not a field had received lime in the

197   preceding 10 years, using a linear mixed effects model (LMM). This model included data

198   from 12 fields across the three farms, but excluded seven fields which had received either

199   no or one lime application during the preceding 10 years, but could not be formally

200   assigned as 'limed' or 'unlimed' in the preceding decade. An additional LMM was run

201   using in-bye fields at Townhead only (n = 13), comparing those that had two or three lime

202   applications (i.e. had been subjected to the fodder crop management regime) with those

203   that had received one or none, as a binary fixed factor. In both models, the response

204 variable, pH, was measured at the soil core scale, with field identity included as a random

205 (grouping) factor within the model, and year included as a fixed effect. The first model

206 also included farm as a fixed effect. These models were also run using percentage soil

207 organic matter as the response variable to test whether this differed between the

208 treatment groups. Finally, a third LMM was implemented including only fields that had

209 been limed two or three times within the preceding 10 years. This model tested whether

210 soil pH was related to the number of years (covariate) since the last lime application, and

211 was also implemented with soil core as the replicate ($n = 58$) and field ($n = 6$) fitted as a

212 random effect.

213 *2.4.2. The relationship between soil properties and earthworm abundance*

214 GLMMs were used to test the relationship between earthworm abundance and soil

215 properties. The response variable, total earthworm abundance (and, in separate models

216 the abundance of the three most numerous species or groups of earthworms:

217 *Aporrectodea rosea / caliginosa*, *Allolobophora chlorotica* and *Lumbricus* spp.), was

218 measured on the soil core scale, with field identity included as a random factor. The

219 explanatory variables were soil pH, soil organic matter and soil moisture, and their

220 quadratic terms were also included because earthworms are not tolerant of extreme soil

221 conditions (Edwards & Bohlen, 1996). Explanatory variables were checked for collinearity

222 prior to analysis, and because no correlations exceeded 0.5, collinearity was not

223 considered to compromise inference. Farm and year were also included as fixed effects.

224 These models used data from all 19 fields assessed across the three farms.

225 *2.4.3. Differences between chick and random locations*

226 GLMMs were used to test whether earthworm abundance differed between chick foraging

227 locations and random locations, whilst accounting for soil moisture. Mean earthworm

228 abundance was calculated from the four soil cores collected at a chick location. However,

229   because the four random cores were collected from separate locations, data from these

230   were not pooled. Total earthworm abundance and the abundance of *A. chlorotica* (the

231   individual species with the biggest overall difference between foraging and random

232   locations in the raw data) were each modelled as the response variable with location

233   (chick foraging or random) and soil moisture as predictor variables. Sample identity (chick

234   foraging and the four random locations) nested within chick identity was included as a

235   random factor to account for non-independence of samples (i.e. each chick location is

236   spatially associated with random locations within the same field) and repeated sampling

237   involving the same chick. Because triangulation error meant that associated errors for

238   chick locations were variable, the inverse of the area of the error ellipse was included as a

239   case weight (Crawley, 2007) within the GLMMs, with weights calculated using the formula:

240    $(1/Area_i) / \Sigma (1/ Area)$

241   where $Area_i$ is the area of the 50% confidence ellipse for the individual triangulated chick

242   location, and $\Sigma (1/ Area)$ is the sum of 1/Area for all triangulated chick locations. Direct

243   observations of chick locations and random locations were given a case weight of 1.

244   All statistical analyses were performed with R version 2.15.0 (R Development Core Team

245   2012). All LMMs and GLMMs were conducted using glmmPQL from the MASS package

246   (Venables & Ripley, 2002). Covariates were standardised prior to analysis (Schielzeth,

247   2010).

248   Models where the response variable was a count were implemented with Poisson errors

249   and log link and were corrected for over-dispersion. Models where the response variable

250   was a percentage were implemented with binomial error structure and logit link. For all

251   other models Gaussian error structure and identity link, were specified. Model residuals

252   were checked graphically for normality and homogeneity of variance (Zuur *et al.*, 2007).

253   Minimum adequate models were obtained using stepwise backwards selection, retaining

254   all variables that were significant at the 5% level and fixed factors that accounted for the

255   study design. Model fit was assessed by calculating pseudo r^2 (from now on referred to

256   as r^2), the square of the correlation between the predicted values and the observed data

257   (Zuur *et al.*, 2009).

258   **3. Results**

259   ***3.1 The relationship between soil properties and liming history***

260   Between individual samples, soil pH ranged from pH 3.5 to 6.0. On average pH was

261   highest in fields at Lochend where fields had received 1 or 2 lime applications in the

262   preceding 10 years, and lowest for out-bye fields at Townhead (and in-bye fields at

263   Muirpark) where no liming had occurred within the preceding 10 years (Table 1). Soil

264   organic matter ranged from 5 to 90%, on average being lowest in fields at Townhead that

265   had been limed two or three times in the preceding 10 years and highest on fields at

266   Muirpark Farm which had received no lime within the preceding 10 years.

267   Soil pH was significantly higher (by 0.8 pH units) in soil that had been limed than that

268   which had not in the preceding 10 years (Table 2, Figure 2a). However, soil organic

269   matter was significantly lower in limed soil compared to un-limed soil (Table 2, Figure 2b),

270   indicating that differences in pH were the result of intrinsic differences in soil properties

271   combined with differences in liming history. Soil pH was higher (0.3 pH units) in soil that

272   had been limed two or three times within the preceding 10 years, in comparison to 0 or 1

273   times (Table 2, Figure 2c). Soil organic matter was not significantly different between

274   these two groups (Table 2, Figure 2d), indicating that differences in soil pH on

275   agriculturally improved 'in-bye' land were probably due to liming rather than difference in

276   the nature of the soil. Soil pH declined by around 0.07 pH units with every year since

277   liming (t = -2.4, p = 0.022, n=58; r^2 = 0.50; Figure 3).

278   *3.2 The relationship between soil properties and earthworm abundance*

279   Across the three farms and the two years of the study, 516 earthworms were collected of

280   which 75% were *Apporectodea caliginosa /rosea*, 9% were *A. chlorotica*, and 8% were

281   *Lumbricus* spp. (Appendix A).

282   There was weak evidence of an increase in total earthworm abundance with soil pH, and

283   a decline at high levels of soil organic matter (i.e. in the context of this study, peat-rich

284   soils), but there was no relationship with soil moisture (Table 3, Figure 4a & b). The

285   model predicted earthworm density of close to 390 earthworms m^{-2} (in the top 10 cm of

286   soil) at pH 6.0, in comparison to just 190 earthworms m^{-2} at pH 4.0. Differences with

287   change in soil organic matter were even greater with close to 650 earthworms per m^{-2}

288   predicted at 10% soil organic matter, in comparison to just 25 earthworms per m^{-2} in very

289   peaty conditions at 90% soil organic matter ($r^2 = 0.31$).

290   *Apporectodea caliginosa / rosea* exhibited a weak quadratic relationship with soil pH and

291   declined with increasing soil organic matter (Table 3, Figure 4c & d). Abundance peaked

292   at around 250 earthworms m^{-2} at pH 5.4, over 3 times as many as occurred at pH 4.0 (70

293   earthworms m^{-2}). Again the change with increasing soil organic matter was more

294   substantial, with close to 540 earthworms m^{-2} predicted at 10% organic matter in

295   comparison to just 10 earthworms m^{-2} at 80% organic matter ($r^2 = 0.27$).

296   *Allolobophora chlorotica* abundance also had a quadratic relationship with soil pH, but this

297   relationship was stronger and abundance of this species was not correlated with soil

298   organic matter, and weakly with soil moisture (Table 3, Figure 4e). Abundance peaked at

299   around pH 5.2 at a predicted density of around 40 earthworms m^{-2}, and this species was

300   not found below pH 4.5 ($r^2 = 0.39$).

301   *Lumbricus* spp. abundance was not related to soil pH or soil moisture but declined with

302   increasing soil organic matter (Table 3, Figure 4f), although we note that the r^2 for this

303   model was very low at 0.14.

304   ***3.3 Differences between chick and random locations?***

305   A total of 263 earthworms was found across 39 chick foraging locations that occurred

306   within 13 fields at the study site, with 189 in total at random locations. The most abundant

307   earthworm species group across both chick and random locations was *A. caliginosa* / *A.*

308   *rosea* (57% of total), with *A. chlorotica* accounting for 21%, and *Lumbricus* spp. 13%.

309   Total earthworm abundance was not related to chick foraging location, but was higher

310   when soil moisture was higher (r^2 = 0.40; Table 4). The abundance of *A. chlorotica* was

311   significantly higher at chick foraging locations than random locations, with the model

312   predicting over twice as many *A. chlorotica* at chick foraging compared to random

313   locations (39 earthworms m^{-2} at chick foraging locations, compared to 15 earthworms m^{-2}

314   at random locations; Figure 5). *Allolobophora chlorotica* was also significantly more

315   abundant when soil moisture was higher (r^2 = 0.27).

316   **4. Discussion**

317   In the UK, agricultural lime use has declined by over 70% in the past 50 years. We found

318   higher soil pH in fields that had received more lime applications in the preceding decade

319   and a decline in soil pH with the number of years since a field had last been limed. This

320   supports the hypothesis that a reduction in lime use may have contributed to declining soil

321   pH in upland grassland areas. Total earthworm abundance was strongly related to soil

322   organic matter with very few earthworms in soils with high organic content. In this

323   environment, this means very peaty soils, where the high soil moisture, low soil pH and

324   poor quality of organic matter combine to make conditions generally unsuitable for

325   earthworms (Edwards & Bohlen, 1996). In addition, total earthworm abundance increased

326   with increasing soil pH and earthworm densities were very low in soils below pH 4.5 which

327   accounted for almost 20% of our samples. *Allolobophora chlorotica* exhibited the

328   strongest relationship with soil pH of the three earthworm groups tested and was the only

329   one for which soil organic matter content was unimportant. This species of earthworm

330   was over twice as abundant (after correcting for soil moisture) at Lapwing chick foraging

331   locations than random locations. In this study, most liming was associated with

332   establishment of a fodder crop which involved shallow cultivation. Given that cultivation is

333   known to reduce earthworm densities (Curry *et al.*, 2002), this suggests that the beneficial

334   impacts of liming were more than sufficient to outweigh any initial cultivation impact.

335   Overall, our results suggest that the long-term reduction in lime use in upland grassland

336   areas could have led to a decline in earthworm abundance, due to lower soil pH, therefore

337   reducing foraging opportunities for Lapwing chicks and other shorebird species that occur

338   within this habitat and are dependent upon earthworms as a key prey item.

339   Substantial declines in shorebirds in Europe are primarily due to poor breeding

340   productivity, with reproductive success insufficient to replace losses due to adult mortality

341   (Roodbergen *et al.*, 2012). Whilst predation is a key limiting factor, poor chick growth in

342   sub-optimal habitats is likely to contribute to poorer chick survival in these environments

343   (Kentie *et al.*, 2013). Lapwing chick condition is positively associated with the number of

344   earthworm chaetae within their faeces, indicating the importance of this prey type in

345   Lapwing chick development (Sheldon, 2002). The low densities of earthworms in soils

346   with high organic matter and / or low soil pH within this study, suggest that these soil

347   conditions may result in poor foraging opportunities for breeding shorebirds and thus limit

348   the numbers and breeding success of these species in these areas. This is further

349   supported by a Scotland-wide study which showed an additive effect of soil conditions on

350   breeding Lapwing densities such that densities were highest when soil pH was relatively

351   high and organic matter relatively low (McCallum *et al.,* 2015); in other words soils which

352   we find here to support high earthworm densities.

353   *Allolobophora chlorotica* was only found in soils between pH 4.7 and 5.7, towards the

354   upper end of soil pH in this study. This species is intolerant of acidic soil conditions

355   (Satchell, 1955) and has previously been shown to respond positively to liming (Bishop,

356   2003). Lapwing chick foraging location was associated with *A. chlorotica* density

357   suggesting that this may be a favoured prey resource. *Allolobophora chlorotica* is

358   generally found in the upper 5 cm of soil amongst the grass roots (Gerard, 1967), which is

359   also where Lapwing chicks find food resources (Benteima *et al.,* 1991). *Apporectodea*

360   *caliginosa* and *rosea*, the most abundant species group within this study may be lower in

361   the soil profile (within the top 10 cm; Gerard, 1967) and consequently may not be as

362   accessible to Lapwing chicks. Soil conditions suitable for *A. chlorotica* occurred more

363   frequently in fields that had undergone liming at least once within the past 10 years

364   indicating that liming could increase this species abundance and therefore prey resources

365   for breeding Lapwings.

366   *4.1 Conclusions*

367   Our results highlight the importance of lime use in maintaining soil pH in upland grassland

368   areas. Declining soil pH associated with a reduction in lime use on agricultural grasslands

369   is likely to have led to declines in earthworm abundance and reduced foraging habitat

370   quality for birds reliant on earthworms as prey, especially where underlying geology has

371   poor buffering capacity and rainfall levels are high enough to reduce soil pH through

372   leaching. We found that Lapwing chick foraging location was associated with higher

373   densities of one particular earthworm species, *A. chlorotica,* which only occurred within a

374   narrow range of soil pH, and further work to identify if this earthworm species contributes

375   more substantially to Lapwing chick diet than others would be valuable.

376   We suggest that field scale trials of lime use within upland grassland agricultural areas

377   would be useful to test whether liming could be used as a conservation measure for

378   farmland birds where earthworms constitute a major component of their diet. Application

379   of agricultural lime does lead to some carbon dioxide emissions from soil, although these

380   emissions may be lower than assumed by modelling studies (West & McBride, 2005, Biasi

381   *et al.*, 2008) and this, along with quarrying and transport of lime, mean that use of

382   agricultural liming as a bird conservation intervention in upland areas would need to be

383   carefully targetted. This would entail a focus on existing sown and agricultural improved

384   grasslands of low biodiversity interest that are topographically suited to settlement by

385   breeding shorebirds (McCallum *et al.*, 2015), and where soil pH has fallen below that

386   recommended for agricultural grass production.

387

388   **Acknowledgements**

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527 **Tables**

528 Table 1 Mean ± standard error of field soil pH (raw data) for each farm showing fields

529 grouped by history of liming.

Farm	Field Type	Lime applications in preceding 10 years	No. of fields	Mean soil pH	Mean soil organic matter (%)
Townhead	In-bye	2 or 3	6	5.1 ± 0.10	21 ± 3
Townhead	In-bye	0 or 1	7	5.0 ± 0.10	30 ± 2
Townhead	Out-bye	0	2	4.5 ± 0.33	33 ± 3
Muirpark	In-bye	0	2	4.6 ± 0.003	37 ± 1
Lochend	In-bye	1 or 2	2	5.3 ± 0.16	26 ± 5

530

531 Table 2 Statistical summary for LMMs testing the relationship between liming history and

532 soil pH for Lime Model 1 (comparison of limed fields v non-limed fields) and Lime Model 2

533 (comparison of fields receiving 2/3 lime applications within the past 10 years to those that

534 received 0/1). The same models were repeated using soil organic matter as the response

535 variable to test whether this differed between the two pairs of treatment groups, and the

536 statistical summaries are also presented here. The sample size for Lime Model 1 was

537 138 across 12 fields, and for Lime Model 2 was 115 across 13 fields.

	Soil pH			Soil Organic Matter		
	DF	F	p-value	DF	F	p-value
Lime Model 1						
Lime	1	50.2	0.0001	1	9.6	0.015
Year	1	32.2	<0.0001	1	2.05	0.15
Farm	2	1.1	0.39	2	1.76	0.23
Lime Model 2						
Lime	1	10.5	0.008	1	2.29	0.16
Year	1	35.9	<0.0001	1	3.38	0.07

538

539

540

541   Table 3 Statistical summary for GLMMs testing the relationship between (i) total

542   earthworm, (ii) *Apporectodea caliginosa / rosea,* (iii) *Allolobophora chlorotica* and (iv)

543   *Lumbricus* spp. abundance and soil properties, showing the minimum adequate model.

544   Sample size was 190 soil cores across 19 fields.

	DF	Parameter estimate ± SE	Statistic	p-value
Total earthworm				
Soil pH	1	0.21 ± 0.11	t = 2.0	0.051
Soil organic matter	1	-0.55 ± 0.12	t = -4.5	<0.0001
Farm	2	-	F = 0.18	0.83
Year	1	-	F = 1.8	0.18
Apporectodea caliginosa / rosea				
Soil pH	1	0.29± 0.12	t = 2.38	0.018
Soil pH^2	1	-1.17 ± 0.08	t = -1.88	0.061
Soil organic matter	1	-0.67 ± 0.13	t = -5.12	<0.0001
Farm	2	-	F = 1.08	0.36
Year	1	-	F = 2.09	0.15
Allolobophora chlorotica				
Soil pH	1	1.33± 0.39	t = 3.44	0.0007
Soil pH^2	1	-1.77 ± 0.43	t = -4.16	0.0001
Soil moisture	1	0.47 ± 0.24	t = 1.94	0.054
Farm	2	-	F = 0	1
Year	1	-	F = 0.25	0.61
***Lumbricus* spp.**				
Soil organic matter	1	-0.65 ± 0.25	t = -2.63	0.0093
Farm	2	-	F = 0.17	0.84
Year	1	-	F = 0.26	0.61

545

546

547

548

549 Table 4 Statistical summary for GLMMs testing whether earthworm abundance (total and

550 *A. chlorotica*) differed with foraging location (chick compared to random location) and soil

551 moisture; minimum adequate models are presented. The sample size was 195 soil cores,

552 accounted for by 39 sample groups (including 1 chick location with 4 cores and 4 random
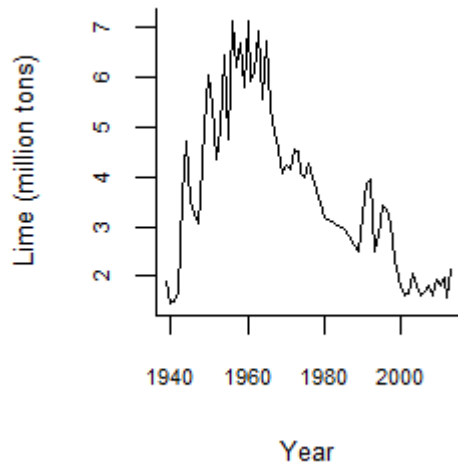
553 locations with 1 core), for 22 chicks.

	DF	Parameter estimate ± SE	t	p-value
Total earthworm				
Soil moisture	1	0.26 ± 0.11	2.31	0.0223
Allolobophora chlorotica				
Foraging location (CvR)	1	0.89 ± 0.30	3.01	0.0031
Soil moisture	1	0.62 ± 0.19	3.33	0.0011

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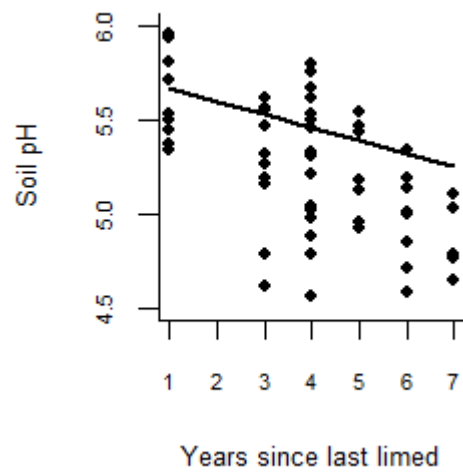
557   **Figures**

558

559   Figure 1 The quantity of lime sold in Great Britain for agricultural purposes, annually since
560   1939: data sources: 1939 – 1976, Agricultural Lime Producers Council (1977), 1980 –
561   1989, Wilkinson (1998), 1990 – 2000, Hillier *et al*. (2003), 2001 – 2013, Bide *et al*. (2015).
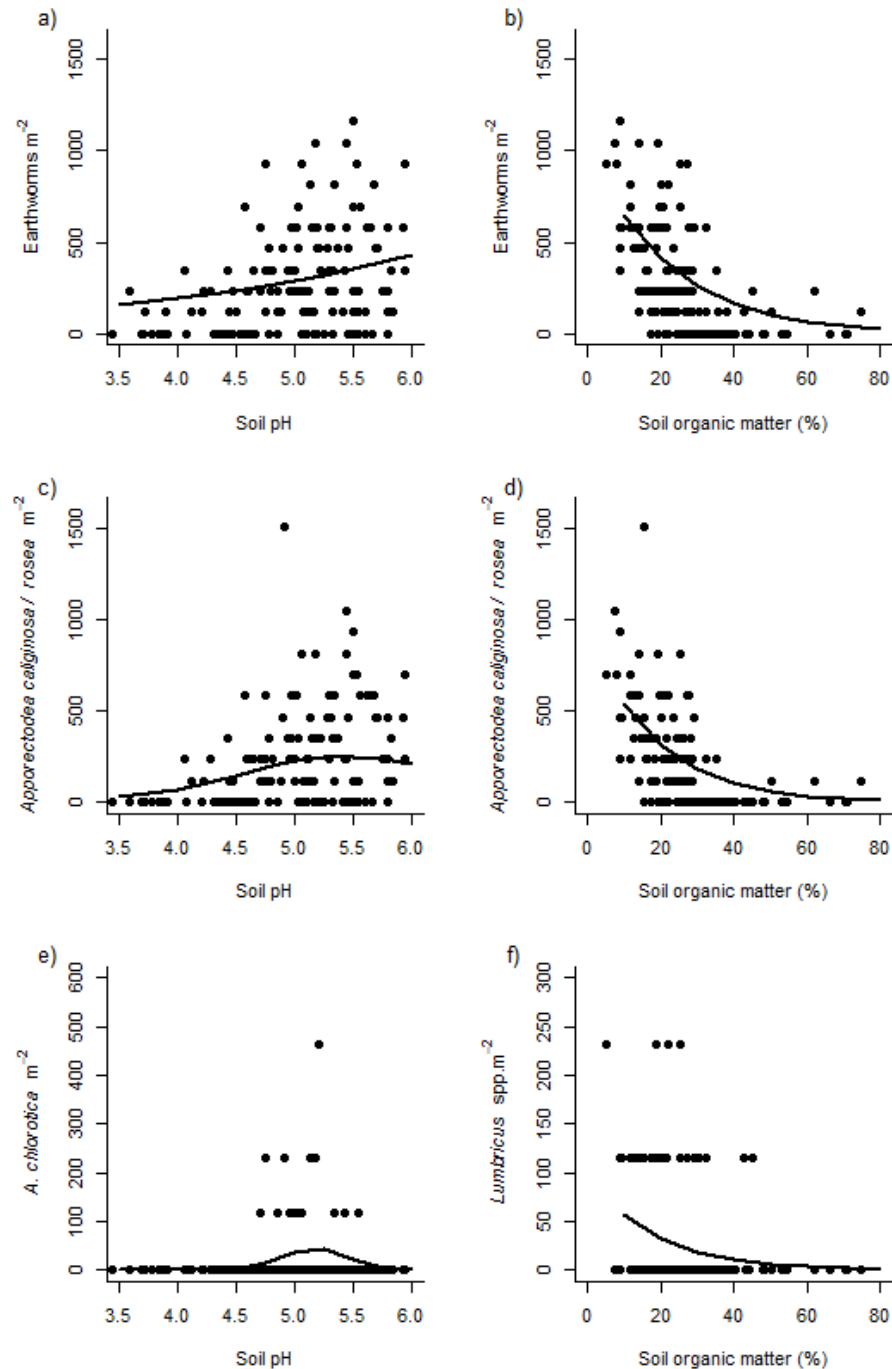
562

Figure 2a) Modelled values of soil pH ± standard errors in fields (n=12) which had been limed compared to those that had not, within the preceding 10 years, b) Modelled values of percentage soil organic matter ± standard errors in fields (n=12) which had been limed compared to those that had not, within the preceding 10 years, c) Modelled values of soil pH ± standard errors in fields (n=13; Townhead only) which had undergone 2 or 3 lime applications in the preceding 10 years, compared to those that had undergone 0 or 1, d) Modelled values of percentage soil organic matter ± standard errors in fields (n=13; Townhead only) which had undergone 2 or 3 lime applications in the preceding 10 years, compared to those that had undergone 0 or 1.
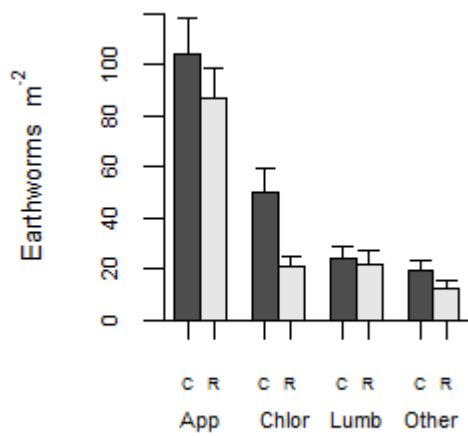
572

573   Figure 3 Modelled decline in soil pH with number of years since last lime application
574   compared to the raw data of soil pH (solid circles) verses number of years since last
575   limed. Each point represents one soil core (n = 58 from six fields).

576

577

Figure 4 The relationship between a) total earthworm abundance and soil pH, b) total earthworm abundance and soil organic matter, c) *Apporectodea caliginosa / rosea* abundance and soil pH d) *Apporectodea caliginosa / rosea* abundance and soil organic matter, e) *Allolobophora chlorotica* and soil pH and f) *Lumbricus* spp. And soil organic matter, showing the predicted earthworm abundance with varying soil pH or organic matter generated from GLMMs, with raw data represented by closed circles. Each point represents the number of worms in a single core multiplied up to per m² value to enable direct comparisons to other studies.

586

587 Figure 5 Mean earthworm density, and standard error, at chick (C) compared to random

588 (R) locations, showing the 3 main species groups *Apporectodea caliginosa / rosea* (App),

589 *Allolobophora chlorotica* (Chlor), *Lumbricus* spp. (Lumb), and all other species (other).

590 Densities to a depth of 10 cm.