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1 Landscape scale responses of birds to agri-environment
2 management: a test of the English Environmental Stewardship
3 scheme

4
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20

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22

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34 **SUMMARY**

35

36 1. Agri-environment schemes (AES) are used extensively across Europe to address
37 biodiversity declines on farmland. In England, Environmental Stewardship (ES)
38 was introduced in 2005 to address the shortcomings of previous schemes but, as
39 for schemes in other countries, assessments to date have revealed little evidence
40 for national-scale biodiversity benefits.

41 2. Here, we assess the efficacy of ES in driving changes in national farmland bird
42 populations over the period 2002-2010, using BTO/JNCC/RSPB Breeding Bird
43 Survey data. We tested for associations between ES management options,
44 grouped into categories reflecting intended biological effects (e.g. stubble), and
45 species' population growth rates, wherever benefits of management might be
46 expected to occur.

47 3. We found strong evidence for positive effects of management that provides winter
48 food resources (i.e. ES stubble and wild bird seed [WBS] crops) on population
49 growth rates across multiple granivorous species, at three landscape scales. The
50 results for management aiming to provide breeding season benefits (i.e. grassland,
51 field margin and boundary [hedge, ditch] management) showed mixed patterns of
52 positive and negative associations.

53 4. The results for stubble and WBS provide the first evidence for landscape-scale
54 responses of biodiversity to AES management. The negative relationships also
55 identified may show the importance of management context driving unforeseen
56 predation or competition effects.

57 5. **Synthesis and Applications.** This study demonstrates that AES management has
58 the potential to have national-scale effects on avian population growth rates,
59 although our results suggest that some components of the scheme have had little
60 effect on bird populations. Therefore, whilst this study provides the first proof-of-
61 concept for broad-and-shallow scheme impacts on biodiversity, our results
62 underline the importance of targeting towards population limiting factors, here
63 winter food resources. A combination of low uptake of key in-field options that
64 provide winter seed and a failure to cover the late winter period effectively
65 explain the lack of national population responses. Such issues need to be
66 addressed before schemes like ES will achieve their goals. This study shows the
67 value of feedback from monitoring for informing scheme design, through
68 identifying problems and testing solutions.

69

70 **Key words:** agricultural intensification, agricultural policy, farmland birds, land-use
71 change, winter seed provision.

72

73 **INTRODUCTION**

74

75 Agri-environment schemes (AES) are a key policy mechanism for stemming losses of
76 biodiversity associated with modern agricultural practices. Given the large financial
77 investment in AES (€34.5bn for 2007-2013; IEEP 2008), it is critical that they meet their
78 objectives. This is particularly important now because the European Union's (EU)
79 Common Agricultural Policy, the funding mechanism for EU AES, will be reformed in
80 2013 in the context of growing, competing demands for land and agricultural production.
81 Support for AES could fall significantly or be re-directed towards localised protected
82 areas instead of the wider landscape (Whittingham 2007). To date, evaluations of the
83 biodiversity benefits of AES from across Europe have shown mixed results for all taxa
84 (e.g. Kleijn *et al.* 2006; Batary *et al.* 2010), with most clear positive effects involving
85 intensive, 'narrow and deep' schemes targeted at local scales or range-restricted
86 populations (e.g. Perkins *et al.* 2011).

87

88 Delivering farmland biodiversity increases across whole landscapes requires a 'broad-
89 and-shallow' approach, i.e. low-level environmental enhancements through modest
90 farmer effort but, to date, there is little evidence for biodiversity benefits of large-scale
91 (e.g. national) schemes (Kleijn *et al.* 2003; Verhulst, Kleijn & Berendse 2007; Davey *et*
92 *al.* 2010). Nevertheless, schemes of this type are in place across the EU and Switzerland,
93 although they vary in the degree to which biodiversity is targeted relative to other
94 environmental priorities.

95

96 The Environmental Stewardship (ES) scheme was introduced across England in 2005. It
97 comprises 'broad-and-shallow' (Entry-Level Stewardship [ELS], open to all farmers) and
98 'narrow-and-deep' components (Higher-Level Stewardship [HLS], open to farmers in
99 target areas, who compete for funds for more intensive management). ELS and HLS
100 comprise menus of 'options' from which farmers can select management suited to local
101 conservation priorities and farming systems. Thus, it is important to distinguish effects of
102 the whole scheme and its component options. ES built on earlier schemes in England by
103 incorporating options that appeared successful in terms of environmental effect and
104 uptake by farmers, or modifying them to increase that success. Many options are
105 designed specifically to address the causes of biodiversity losses (other aims include
106 protecting soil and water resources and historic features: Natural England 2010a,b,c).
107 Some are targeted specifically at declining bird species (Wilson, Evans & Grice 2009),
108 e.g. wild bird seed (WBS) options prescribe planting crops to provide seed to granivorous
109 birds in winter. HLS agreements are tailored to individual farms under expert guidance
110 and include both ELS options and more demanding management aimed at regional
111 priorities (Natural England 2010b). There are ELS and HLS specific variants for organic
112 farms, which have the prefix 'Organic' (OELS and OHLS; Natural England 2010c).

113

114 ES is designed to benefit national biodiversity, so it is appropriate to evaluate it in terms
115 of national effects on target taxa (Kleijn *et al.* 2011). Farmland birds in England have
116 continued to decline, even after the introduction of ES in 2005, suggesting that the
117 scheme is failing (Risely *et al.* 2011). However, landscape-scale population-level
118 management effects on birds might occur, even if national abundance is still declining.

119 The BTO/JNCC/RSPB Breeding Bird Survey (BBS) is an annual (1994-present), UK-
120 wide, volunteer-based survey of randomly located 1km squares. Together, a large-scale
121 national survey and a national-scale AES provide a unique opportunity to test scheme
122 biodiversity effects. Reversing farmland bird declines is a high priority for English
123 environmental policy and ES is the principal tool, so farmland bird population responses
124 are appropriate measures of the efficacy of ES management.

125

126 Here, we assess the effects of ES on bird species that commonly use agricultural land
127 during their life-cycle (i.e. nesting and/or foraging in the breeding season and/or winter)
128 and are expected to benefit from specific ES management (Table 1 & S1). Both ELS and
129 HLS are included, but random sampling means that ELS dominates the data, reflecting
130 English farmland in general. This approach meets Kleijn & Sutherland's (2003)
131 recommendations for unbiased site selection for AES assessment and integrates four
132 years of pre-ES data. We report the effects of management at a 1km square scale (and
133 more widely for winter food resource options) separately for arable, pastoral and mixed
134 landscapes, because efficacy is likely to vary with landscape context (Robinson, Wilson
135 & Crick 2001). We discuss the results with respect to the potential for AES to deliver
136 landscape-scale benefits for farmland birds and as a contribution to the evidence for AES
137 effects on farmland biodiversity.

138

139

140 **METHODS**

141 **Breeding Bird Survey (BBS)**

142 BBS (1994-present) covers c. 2000 randomly selected lowland farmland 1km squares
143 throughout England annually. Volunteers walk two nominally parallel 1km transects
144 (500m apart) through each square twice during the breeding season. Each transect is
145 divided into five 200m sections; species-specific bird counts and habitat are recorded
146 separately in each. Annual, square-specific counts are calculated as the maximum over
147 the two visits of the total count summed across transect sections (Risely *et al.* 2011). For
148 this study, BBS squares were selected if they were in lowland farmland (CEH Land
149 Cover Map 2000 Environmental Zones) and had been surveyed in ≥ 2 years between 2002
150 and 2010. Squares comprising $< 50\%$ farmed land were omitted as non-agricultural. The
151 major landscape type for each square was categorised as arable (ratio of arable:pastoral
152 areas ≥ 2), pastoral (pastoral:arable ≥ 2) or mixed (all other squares), based on the CEH
153 Land Cover Map 2000. Analyses for each category were conducted separately.

154

155 All species analysed regularly use farmland to some extent (Table 1). For non-specialists
156 that regularly exploit non-agricultural habitats (e.g. gardens), only counts from transect
157 sections that were recorded as farmland were used for each square. For farmland
158 specialists (Table 1), data from all transect sections were included because birds in non-
159 farmland sections are likely to be influenced strongly by nearby farmland, whereas non-
160 specialists there are more likely to be influenced primarily by non-farmland factors.

161

162 **Environmental Stewardship data**

163 ES operates using five-year (ELS) or ten-year (HLS) agreements between farmers and
164 government, requiring the implementation of particular quantities of options, chosen by

165 farmers from the menus available (Table 2; Natural England 2010a,b,c). Spatial data
166 containing the ES agreement details for each holding (supplied by Natural England) were
167 used to quantify amounts of each option per BBS square per year, taking account of
168 agreement start dates (2005-2010). Although some option locations were spatially
169 referenced, many are rotational, with locations moving annually. Consequently, the
170 amount of each option per agreement and square was estimated by assuming that the
171 quantity of each option falling within each square was proportional to the whole
172 agreement area in the square. Hedgerow and ditch options (Table 2 & S1) can apply to
173 one or both sides of these features (depending on adjacent land ownership); therefore,
174 management affecting both sides was taken as double the boundary length. For all option
175 types, the total area or length per square was the sum across the agreement-specific
176 quantities present. Options were grouped into seven categories (Tables 2 & S1), based on
177 the location of management (in-field or boundary) and the mechanism through which
178 benefits to birds are expected (foraging or breeding). Grouping options with similar
179 expected effects should maximize statistical power.

180

181 The Countryside Stewardship Scheme (CSS) preceded ES, but many agreements were
182 extant after 2005, so CSS agreements were processed similarly to ES data and added to
183 appropriate option categories (Table S1).

184

185 Because we were interested in the effects of ES on population growth and not simply in
186 driving aggregative responses to option presence, option quantities were matched with
187 square-specific bird counts after time lags sufficient for influences on breeding success or

188 over-winter survival to have affected breeding abundance. Thus, with the exception of
189 stubbles, management had to have been in place before 1 March of the preceding year for
190 it to have potentially affected breeding abundance in the current year. Stubble options
191 needed to have been in place before harvest in the preceding year, so the cut-off date was
192 31 July.

193

194 Many granivores that breed in a focal 1km square move over larger areas in winter
195 (Siriwardena, Setchfield & Anderson, unpublished data), so areas of ES stubble and WBS
196 management within 9km² and 25km² buffers centred on 1km² BBS squares, as well as
197 within the squares themselves, were used to test effects on breeding bird counts. For these
198 tests, landscape categorization (arable, pastoral, mixed) used the wider scales (9 or
199 25km²; N.B. correlations between classifications across scales were high [$r > 0.9$]).

200

201 Note that some options expected to benefit farmland birds had to be excluded because
202 they were too uncommon in BBS squares for tests to be tractable (e.g. skylark plots).

203

204 **Statistical Analysis**

205 We used a log-linear approach that models the change in expected abundance between
206 consecutive years and can incorporate effects of spatio-temporal covariates, e.g. ES
207 option quantities, on local growth rate. This approach allows maximum use of the
208 available data by including observations from squares not surveyed, or where counts were
209 zero, in the previous year. Fundamentally, the analyses estimated the additional effect of
210 ES on each species' population growth rate but, importantly, growth is not thereby forced

211 to be greatest in the years of highest management levels. The model is a multivariate
 212 extension of Freeman & Newson (2008):

213

$$214 \quad \ln(\mu_{i,t+1}) = R_t + \alpha P_{i,t} + \beta Q_{i,t} + \ln(\mu_{i,t}) \quad (1)$$

215

216 where $\mu_{i,t}$ is the expected species count at site i at time t , $P_{i,t}$ is the amount of a given ES
 217 management variable in square i at time t and $Q_{i,t}$ is the percentage of arable habitat per
 218 square for all arable options (i.e. stubble, WBS, arable margins) or that of pastoral habitat
 219 per square for all pastoral options (grassland, grassland margins). $Q_{i,t}$ was mean-centred
 220 prior to fitting, and included because most ES options are targeted at either arable or
 221 pastoral farmland (e.g. stubble or grassland management), so option uptake is likely to be
 222 correlated with the balance of arable and pastoral farming in the landscape, which could
 223 influence bird population trends (e.g. Robinson, Wilson & Crick 2001). ES hedgerow and
 224 ditch options are not specific to farmland type, so here such landscape controls were
 225 unnecessary. From (1), R_t is the ‘background’ population growth rate from t to $t+1$ at a
 226 hypothetical reference site where $Q_{i,t}$ has the mean value for the landscape (arable,
 227 pastoral or mixed) and there is no management. The parameter α introduces the effect of
 228 ES management on population growth at a site, and β controls for the effect of the
 229 surrounding landscape. For fitting, we rewrite (1) as:

230

$$231 \quad \ln(\mu_{i,t+1}) = \sum_{j=1}^t R_j + \alpha \sum_{j=1}^t P_{i,j} + \beta \sum_{j=1}^t Q_{i,j} + \ln(\mu_{i,1}) + \ln(G_i) \quad (2)$$

232

233 which is a standard generalized linear model, with offset $\ln(G_i)$, where G_i is the number
 234 of transects surveyed in square i , introduced to standardise the square-specific intercepts
 235 $\mu_{i,1}$, as some squares had fewer than ten 200m sections. Models were fitted assuming a
 236 Poisson distribution for the observed BBS counts using the GENMOD procedure in SAS
 237 9.2 (SAS Institute Inc. 2008), accounting for overdispersion using Pearson's χ^2 goodness-
 238 of-fit statistic. The significance of ES effects on population growth rates was assessed
 239 using similarly adjusted likelihood-ratio test statistics of the hypothesis that $\alpha = 0$.

240

241 Also of interest is the cumulative growth in the absence of management to year t (R'_t) and
 242 the compound effect of a single unit of management over time, which we denote α'_t .

243 Maximum likelihood estimates of $R'_t = \sum_{j=1}^{t-1} R_j$ follow either through fitting this re-
 244 parameterisation of the model or via the standard formulae:

245

$$246 \quad \hat{R}'_t = \sum_{j=1}^{t-1} \hat{R}_j ; \quad \text{var}(\hat{R}'_t) = \sum_{j=1}^{t-1} \text{var}(\hat{R}_j) + 2 \sum_{j=1}^{t-1} \sum_{k=1}^{j-1} [\text{cov}(\hat{R}_j, \hat{R}_k)] \quad (3)$$

247

248 and:

249

$$250 \quad \hat{\alpha}'_t = (t-1)\hat{\alpha} ; \quad \text{var}(\hat{\alpha}'_t) = (t-1)^2 \text{var}(\hat{\alpha}) \quad (4)$$

251

252 95% confidence intervals (CI) follow from (3) and (4) and can be back-transformed from
 253 the log scale. Note that very large CI were produced in some cases with the small sample

254 sizes for corn bunting in pastoral landscapes, so these profoundly imprecise results are
255 not presented.

256

257 From (4), α'_i is the estimate of additional growth, over nine years, per unit of
258 management (area or length under ES/CSS) per area of land. For ease of comparison
259 across options, growth rate effects are mostly presented per 1% of land area (i.e. 1, 9 or
260 25ha per 1, 9 or 25km², respectively), or 1km of boundary (hedgerow/ditch) per 1km²,
261 under option management. For WBS options, which cover smaller areas (0.1-0.2% of
262 land under ES management per km²; Table S1), the results are reported with respect to
263 0.1% of the land area (i.e. 0.1, 0.9 or 2.5ha per 1, 9 or 25km², respectively). To aid
264 interpretation we backtransform the estimates arising, presenting multiplicative growth
265 rates $\exp(\alpha'_i)$ such that an estimate of 1.1, for example, describes growth 10% higher
266 than the background rate at a site under a single unit of management over the period.

267

268 **RESULTS**

269 Results are presented by landscape type, using the following abbreviations throughout: A
270 = arable, P = pastoral and M =mixed.

271

272 **Stubble management**

273 The population growth rates of corn bunting (P), goldfinch (A), linnet (A, M, P), grey
274 partridge (P), reed bunting (A, P), skylark (M) and yellowhammer (A, P) were positively
275 associated with the presence of ES stubble management at the 1km² scale (Fig. 1, Table
276 S2). The size of the additional effect of ES management on growth rate $\exp(\alpha'_i)$ was

277 large for most species/landscapes, with eight showing >10% increase in population
278 growth rate over nine years with 1ha/km² under ES stubble management (Table S2). Only
279 goldfinch (P) showed a negative association.

280

281 **Wild Bird Seed (WBS) management**

282 The population growth rates of corn bunting (P), reed bunting (P), skylark (M), tree
283 sparrow (A) and yellowhammer (A) were positively associated with the presence of ES
284 WBS management at the 1km² scale (Fig. 2, Table S3). For these results, values of
285 $\exp(\alpha')$ reflected 3 to 117% additional growth rate over nine years with 0.1ha/km²
286 under ES WBS management, suggesting moderate to strong effects of management on
287 population growth rates, although the latter estimate is imprecise. There were two
288 significant negative associations, for chaffinch (P) and tree sparrow (M).

289

290 **Multi-scale management of winter food options**

291 Differences between stubble results at the 1km² scale and at two wider scales, 9km² and
292 25km², suggested variable species-specific responses to the spatial scale of food
293 availability (Fig. 1, Table S2). Three finches (chaffinch, greenfinch and linnet) were
294 positively associated with ES stubble management at the 25km² scale in pastoral squares.
295 Linnet was also positively associated with ES stubble at the 9km² scale in mixed squares.
296 Tree sparrow was significantly associated with such management at the two larger spatial
297 scales in arable squares, whereas yellowhammer was significantly associated with stubble
298 management in arable squares at the 1 and 25km² scales. Reed bunting (25km²), stock
299 dove (9km²) and yellowhammer (9km²) each showed a significant positive association

300 with ES stubble in mixed squares at large spatial scales only. At the wider spatial scales,
301 the significant positive values of $\exp(\alpha'_i)$ were >1.10 , suggesting a strong effect of
302 management on population growth rates. Only goldfinch showed a negative association at
303 a wider spatial scale (A, 9km^2 scale), contrary to the positive association at the 1km^2
304 scale.

305

306 Several species were associated with ES WBS management at wider scales, but only tree
307 sparrow (A) showed an apparent response at 1km^2 as well as both larger scales (Fig. 2,
308 Table S3). Linnet also showed an apparent response in arable and mixed squares at both
309 larger scales. Chaffinch, greenfinch, linnet and yellowhammer in mixed squares and
310 skylark and stock dove in pastoral squares all showed positive associations with ES WBS
311 at the 25km^2 scale. At the wider spatial scales, all significant positive values of $\exp(\alpha'_i)$
312 were >1.10 , again suggesting strong effects on population growth rates. Two significant
313 negative associations were found with ES WBS, for corn bunting (M, 9km^2) and
314 goldfinch (P, 9km^2).

315

316 **Grassland management**

317 The growth rates of chaffinch (A), lapwing (M), linnet (P), skylark (A) and yellow
318 wagtail (M) all showed significant positive associations with ES grassland management
319 (Fig. 3, Table S4). There were negative associations for chaffinch (P), lapwing (P),
320 meadow pipit (A), reed bunting (P) and yellow wagtail (A). The effect size of $(\exp(\alpha'_i))$
321 varied between -14% and $+7\%$ additional growth over nine years with $1\text{ha}/\text{km}^2$ under
322 grassland management.

323

324 **Margin management**

325 The population growth rates of corn bunting (P), dunnock (M), linnet (M) and turtle dove
326 (A) were positively associated with ES arable margin management (Fig. 4, Table S5).

327 The population growth rates of corn bunting (M), goldfinch (P) and yellow wagtail (A)
328 showed negative results. The effect size of ($\exp(\alpha')$) for these significant results varied
329 between -10% and +40% additional growth over nine years with 1ha/km² under arable
330 margin management.

331

332 Grassland margin management (Fig. 4, Table S5) was positively associated with the
333 population growth rates of chaffinch (A, P), dunnock (A), greenfinch (P) and whitethroat
334 (M). The effect size for these significant results represented >7% additional growth over
335 nine years with 1ha/km² under grassland margin management. There was a negative
336 association with the growth rate of corn bunting (A), with a large effect size ($\exp(\alpha')$) =
337 0.46, Table S5).

338

339 **Boundary management (Hedgerow & ditch options)**

340 The population growth rates of bullfinch (M, P), house sparrow (P), reed bunting (M) and
341 song thrush (A) were significantly positively associated with ES hedgerow management
342 (Fig. 5, Table S6). For these significant results, effect sizes represented $\geq 4\%$ additional
343 growth over nine years with 1km/km² of managed boundary. Negative associations were
344 found for goldfinch (P), tree sparrow (M, P) and yellowhammer (P), with effect sizes of
345 $\geq 6\%$ negative growth.

346

347 The population growth rate of reed bunting (M) had a significant positive association
348 with ES ditch management; tree sparrow (P) had a negative association (Fig. 6, Table
349 S6). The effect sizes were large ($\exp(\alpha'_i) = 1.38$ and 0.49 , respectively).

350

351 **Overall response to ES management**

352 The responses to each of the seven categories of ES management described above varied
353 considerably, indicating that combining results would only tend to obscure species-
354 specific patterns within them. However, it remained possible that undetected interspecific
355 patterns could emerge if results were averaged across species, so we calculated the
356 geometric mean of $\exp(\alpha'_i)$ across all species within each broad option category,
357 including both significant and non-significant results (following Buckland *et al.* 2011).
358 Mean $\exp(\alpha'_i)$ estimates whose 95% CI (calculated by combining the species-specific
359 variances) did not include unity could reflect previously undetected interspecific
360 management effects. Such patterns were found for Ditches (A), WBS 9km² (M) and
361 Arable margins (A) (Fig. S2), the former positive and the latter two negative. The WBS
362 pattern reflected the influence of the strongly negative association for corn bunting (Fig.
363 2b, Table S3), while the Arable Margin patterns involved a mean parameter estimate very
364 close to unity (0.988), so show at most marginal effects (Fig. S2). However, the Ditch
365 result may be biologically significant, as it includes a mean effect of 1.078 across five
366 species with non-significant positive responses (Table S6).

367

368

369 **DISCUSSION**

370 Reversing landscape-scale biodiversity losses requires a management response at a
371 similar scale, which represents a long-term investment that is only justifiable if effective
372 and widespread changes in habitats are sustained. There is little previous evidence that
373 ‘broad-and-shallow’ AES are effective in restoring biodiversity (e.g. Davey *et al.* 2010)
374 and, in England, ES has not reversed the national population trends of declining farmland
375 birds (Risely *et al.* 2011). However, the present study suggests that ES stubble
376 management has had a positive effect on landscape-scale population growth rates of
377 several species of granivorous birds, including several declining species. Several
378 granivorous species also seem to have responded similarly to ES WBS crops, but
379 evidence for grassland, margin and boundary options is mixed. In general, these patterns
380 probably reflect the degree to which ES management options address the factors that limit
381 species’ populations (i.e. winter food provision vs. breeding habitat). We acknowledge
382 that this study incorporates multiple statistical tests, so it is likely that some apparent
383 effects represent Type 1 errors. However, while this may explain some of the inconsistent
384 results within species or option categories, the number of significant effects and their
385 consistency in direction indicate that the general patterns in the stubble and WBS results
386 are likely to be robust.

387

388 Previous research has concluded that a shortage of winter seed drove the population
389 declines of most granivorous farmland birds and it probably also prevents recoveries
390 (Gillings *et al.* 2005; Siriwardena *et al.* 2000, 2007). Davey *et al.* (2010) found few clear
391 population benefits of ES over-winter food options for granivorous species but, with

392 multiple years per survey square, a longer survey period and more powerful analyses, we
393 found significant positive associations between population growth rates and stubble
394 management for three-quarters of the granivorous species tested, for one or more of three
395 spatial scales and landscape types. The results for yellowhammer, linnet, reed bunting,
396 grey partridge and skylark were consistent with those of Gillings *et al.* (2005) for stubble
397 in general, and there were further positive effects on goldfinch, tree sparrow, stock dove
398 and greenfinch. While alternative mechanisms for population limitation have been
399 proposed for some of these species, winter seed availability is at least a strong candidate
400 for all of them. The only negative associations found were for goldfinch (pastoral, 1km²,
401 and arable, 9km²). This species is a partial migrant and even 'resident' birds move large
402 distances between seasons, so local winter habitat may be only a weak influence on local
403 breeding birds, but there is no clear explanation for these results.

404

405 ES wild bird seed crops provide higher seed resource densities than stubbles and supply
406 winter food effectively in some contexts (e.g. Field *et al.* 2011). We found positive
407 associations between several species' population growth rates and WBS management at
408 all spatial scales, again suggesting that increased seed availability relaxes population
409 limits on many granivorous species. It is unsurprising that various species responded
410 differently to stubble and WBS management because seed type and context of seed
411 delivery (e.g. vegetation height, distance from cover) affect attractiveness to different
412 species (Siriwardena & Stevens 2004). Significant negative associations were found for
413 one landscape/scale combination for four species expected to benefit from WBS crops,
414 chaffinch, corn bunting, goldfinch and tree sparrow. It may be that, especially where seed

415 resources are rare, such as in pastoral and mixed landscapes, smaller species are attracted
416 to a food source but then are excluded competitively by dominant species, such as
417 greenfinch and woodpigeon (Krams 2001). This could become critical during poor
418 weather, when there may be insufficient time to locate alternative habitats. Another
419 possibility is that concentrations of birds in seed-rich habitats lead to concentrations of
420 predation pressure and a net negative effect on the survival of vulnerable species (Bro *et*
421 *al.* 2004). Such contextual effects could explain contrasting results for a species between
422 landscape contexts, such as the tree sparrow response to WBS management (1km scale)
423 which was positive in arable landscapes and negative in mixed. A management solution
424 to either problem would be to increase the number or diversity of WBS patches in an ES
425 agreement in order to reduce concentrations of dominant or predatory species.

426

427 Little is known about the scales at which particular bird populations respond to habitat
428 characteristics, but there is evidence for variation with respect to species' ecology
429 (Pickett & Siriwardena 2011). Our results suggest that the spatial scale of stubble and
430 WBS delivery is important in species' responses, consistent with an influence of birds'
431 mobility across landscapes (Siriwardena 2010). ES WBS management at the 25km² scale
432 appeared to have more detectable benefits (Fig. 2c, Table S3), possibly because highly
433 mobile species are involved and because breeding populations in a focal square are
434 supported by seed resource density across a wide area.

435

436 Whilst there were significant positive associations with grassland management for several
437 species expected to benefit, e.g. lapwing (M) and skylark (A), negative associations were

438 equally common (Table S4). Lapwing showed contrary responses to ES management in
439 pastoral (-) and mixed (+) landscapes, perhaps reflecting a preference for spring tillage
440 with adjacent grassland during the breeding season (Wilson, Vickery & Browne 2001), so
441 ES grassland management only improves habitat where suitable tillage is nearby. Yellow
442 wagtail showed a negative association with grassland management in arable squares,
443 perhaps because ES management encourages nesting in grassland patches in arable-
444 dominated areas that would otherwise be unsuitable, exposing nests to trampling or
445 predation (cf Bro *et al.* 2004). Overall, the lack of consistent positive associations with
446 grassland options suggests that they do not address many species' key limiting factors,
447 which may reflect a lack of a real management effect from options such as "low input
448 grassland", which still allow up to 50kg/ha of nitrogen to be applied annually (Natural
449 England 2010a). However, it is also possible that, within farms, these options simply
450 cover areas too small to provide benefits effectively in practice because sustainable local
451 populations of the target species require larger habitat patches (Whittingham 2007).

452

453 Arable and grassland margins can provide nesting and spring foraging habitat for many
454 species (Vickery, Feber & Fuller 2009), but are unlikely to address population-limiting
455 factors. A failure of the options to deliver prey availability as well as abundance could
456 also limit their benefits. Douglas, Vickery & Benton (2009) showed that cutting patches
457 in field margins maximised benefits for birds, but only one ES option (EE3 - 6m arable
458 margin) mandates annual cutting to provide habitat heterogeneity (Natural England
459 2010a).

460

461 Similarly, ES boundary (hedgerow and ditch) options should improve breeding and
462 spring foraging habitat for birds, but these do not currently limit the populations of most
463 farmland passerines (e.g. Siriwardena *et al.* 2000), so it is unsurprising that few species
464 showed significant associations with boundary management. Bullfinch and song thrush
465 both commonly breed in thick hedgerows and were positively associated with hedgerow
466 management in one or more landscapes. It is unclear why tree sparrow might be
467 negatively affected by ES hedgerow options. Ditch management had positive associations
468 with reed bunting in mixed and (near-significantly) in arable squares (Table S6). This
469 may reflect a benefit from increased breeding habitat in arable landscapes, which also
470 contain winter seed resources.

471

472 Averaging management effects across species revealed just one emergent pattern that
473 might indicate an otherwise undetected biologically significant effect of ES, a positive
474 association with ditch management in arable landscapes (Fig. S2). This reflected non-
475 significant positive associations with corn bunting, reed bunting, and tree sparrow (Table
476 S6). The effect sizes involved suggest that this result could indicate a genuine
477 management benefit, but the lack of species-specific significance means that this result
478 should be treated with caution.

479

480 **Synthesis and Applications**

481 These results represent the first evidence that national-scale AES management has
482 positive effects on biodiversity, specifically involving management that provides winter
483 food resources for key bird species. Management to provide breeding season benefits did

484 not have clear positive effects. Despite the positive effects, national declines in the
485 species concerned continue, as most effects found were insufficient to turn population
486 declines into increases. For example, current average ES stubble areas (1-2% of the
487 cropped area; Table S1) are insufficient to reverse the average yellowhammer decline in
488 the BBS (Fig. 1). ES efficacy could be enhanced by increasing management quantity or
489 quality. Increasing the uptake of population-limiting in-field options is already a
490 successful policy priority (Fig. S1), but our results suggest that still greater uptake is
491 needed to reverse declines. Areas of management such as stubble options will have upper
492 limits within economically viable crop rotations, however, so management effectiveness
493 must also increase. One key improvement would see stubble and WBS options providing
494 more resources in late winter, when demand is highest and population bottlenecks are
495 most likely (Siriwardena 2010; Hinsley *et al.* 2010). Proposed solutions include revised
496 WBS options, incorporating crops that retain seed into spring or are supplemented with
497 additional seed, and stubbles that are retained until summer (Siriwardena 2010). Further
498 option development is required, but benefits of “set-aside” stubbles have a strong
499 evidence base (e.g. Gillings *et al.* 2010). One new ELS option from 2010 (EF22) already
500 aims to provide late-winter seed, but its impact will depend on uptake and resource
501 quantities in practice.

502

503 The results are not definitive about the value of other ES management, which often
504 (partly) targets other taxa, resource protection or landscape character (e.g. Fuentes-
505 Montemayor, Goulson & Park 2010). Also, low uptake prevented testing of some
506 options, such as skylark plots. Further, management enhancing bird breeding habitats

507 could be valuable in providing resources to support species' future recoveries and could
508 also benefit local breeding populations, even if national effects are small.

509

510 It is possible that the operation of ES, with voluntary selection of options and
511 independent, farm-specific agreements, limits the potential of some management. For
512 example, juxtaposition of different habitat management types or a critical threshold area
513 (greater than is practicable on a single farm) might be required to meet a species' nesting
514 and foraging needs, but might be rare within agreements (Whittingham 2007). Such
515 problems probably mostly apply to grassland options, because they typically cover small,
516 limited areas within farms, whereas margin, ditch and hedgerow management is typically
517 applied to all suitable field boundaries. However,, requirements for habitat juxtaposition
518 to deliver benefits via breeding success (Whittingham 2007) imply multiple breeding
519 season limiting factors, but previous evidence, supported by this study, indicates that
520 winter limitation is generally more critical.

521

522 Overall, this study shows that ES winter seed provision is producing some desired
523 changes in landscape-scale population trends, but that increased option uptake, probably
524 with improved management, will be required to produce national increases. Recent
525 modifications of ES option content, scheme management and farmer guidance (Winspear
526 *et al.* 2010) have successfully encouraged in-field management uptake (Fig. S1).
527 However, research is still needed to identify effective option revisions and it is essential
528 that monitoring continues, with feedback into scheme design and operation (Kleijn &
529 Sutherland 2003). The key agri-environment effects found here, such as those of

530 overwinter seed provision, are relevant at least across Western Europe, where intensive
531 winter cropping is the norm and farmland bird populations have declined. Moreover,
532 many Northern European breeding populations winter further south-west, so will be
533 influenced by farmland management there. In addition, the general principles concerning
534 evidence-based management design apply equally to other taxa and schemes across
535 Europe. Adopting such principles can ensure that AES represent a viable solution for
536 addressing landscape-scale conservation priorities.

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640 **Supporting Information**

641 Additional Supporting Information may be found in the online version of this article:

642

643 Table S1. Summary of broad option categories

644 Table S2. Population growth rates for ES stubble management

645 Table S3. Population growth rates for ES WBS management

646 Table S4. Population growth rates for ES grassland management

647 Table S5. Population growth rates for ES margin management

648 Table S6. Population growth rates for ES boundary management

649 Figure S1. ES option uptake in June 2009 and March 2011

650 Figure S2. The geometric mean of the $\exp(\alpha'_i)$ estimates across all species within each ES

651 management category

652 Table 1. Species included in the analysis with BBS codes and broad dietary preferences;

653 * denotes species classified as farmland (arable or pastoral) specialists and † denotes

654 obligate summer migrants.

655

Species	Code	Winter Diet	Summer Diet
Bullfinch <i>Pyrrhula pyrrhula</i>	BF	Plant	Both
Corn bunting <i>Emberiza calandra</i>	CB*	Plant	Both
Chaffinch <i>Fringilla coelebs</i>	CH	Plant	Both
Duncock <i>Prunella modularis</i>	D	Both	Animal
Goldfinch <i>Carduelis carduelis</i>	GO	Plant	Plant
Greenfinch <i>Carduelis chloris</i>	GR	Plant	Plant
House sparrow <i>Passer domesticus</i>	HS	Plant	Both
Lapwing <i>Vanellus vanellus</i>	L*	Animal	Animal
Linnet <i>Carduelis cannabina</i>	LI*	Plant	Plant
Meadow pipit <i>Anthus pratensis</i>	MP	Animal	Animal
Grey partridge <i>Perdix perdix</i>	P*	Plant	Both
Reed bunting <i>Emberiza schoeniclus</i>	RB	Plant	Both
Skylark <i>Alauda arvensis</i>	S*	Plant	Both
Stock dove <i>Columba oenas</i>	SD	Plant	Plant
Starling <i>Sturnus vulgaris</i>	SG	Plant	Animal
Song thrush <i>Turdus philomelos</i>	ST	Plant	Animal
Turtle dove <i>Streptopelia turtur</i>	TD*†	-	Plant
Tree sparrow <i>Passer montanus</i>	TS*	Plant	Both
Whitethroat <i>Sylvia communis</i>	WH*	-	Animal
Yellowhammer <i>Emberiza citrinella</i>	Y*†	Plant	Both
Yellow wagtail <i>Motacilla flava</i>	YW*†	-	Animal

656

657

658 Table 2. ES option categories with a description of the management. For details of the specific
 659 options related to each category, see Table S1; for scheme and option details, see Natural England
 660 (2010a,b,c)
 661

ES option category	Description
Stubble (km ²)	Requires stubbles to remain unploughed until at least mid-February and restricts chemical inputs. Benefit to birds: winter foraging habitat.
Wild Bird Seed (WBS) crops (km ²)	Requires the establishment of small patches (0.4-2ha) of seed rich crops in a >6m field margin that remain undisturbed until March. Benefit to birds: winter foraging habitat.
Grassland (km ²)	Requires restrictions on chemical inputs on grassland and the maintenance of a heterogeneous sward. Benefits to birds: foraging and breeding habitat.
Arable Margins (km ²)	Creates grass margins of width 2-6m adjacent to arable fields. Benefits to birds: nesting and breeding season foraging habitat.
Grassland Margins (km ²)	Creates grass margins of width 2-6m adjacent to pastoral fields. Benefits to birds: nesting and breeding season foraging habitat.
Hedgerow (Total length) (km)	Requires restrictions on the cutting of hedgerows and sets minimum dimensions to be maintained. Benefits to birds: foraging and nesting habitat.
Ditch (Total length) (km)	Requires that ditches are kept open and restricts the cutting and grazing of adjacent vegetation. Benefits to birds: foraging and nesting habitat.

662

663

664 Figure 1. Population growth rates over nine years ($\exp(R_9)$, \circ) at a) 1km², b) 9km² and c) 25km²
665 spatial scales, and the additional effect ($\exp(R_9) \times \exp(\alpha'_9)$, \bullet) with 1, 9 and 25ha/km² under
666 ES stubble management, respectively. A = Arable, M = Mixed and P = Pastoral landscapes, with
667 the number of unique BBS squares in which the species occurred given adjacent. 'NA' refers to
668 tests results not reported (see Methods). For species codes see table 1.

669

670 Figure 2. Population growth rates over nine years ($\exp(R_9)$, \circ) at a) 1km², b) 9km² and c) 25km²
671 spatial scales, and the additional effect ($\exp(R_9) \times \exp(\alpha'_9)$, \bullet) with 0.1, 0.9, 2.5ha/km² under
672 ES wild bird seed (WBS) management, respectively. See Fig.1 for details.

673

674 Figure 3. Population growth rates over nine years ($\exp(R_9)$, \circ) and the additional effect
675 ($\exp(R_9) \times \exp(\alpha'_9)$, \bullet) with 1ha/km² under ES grassland management. See Fig.1 for details.

676

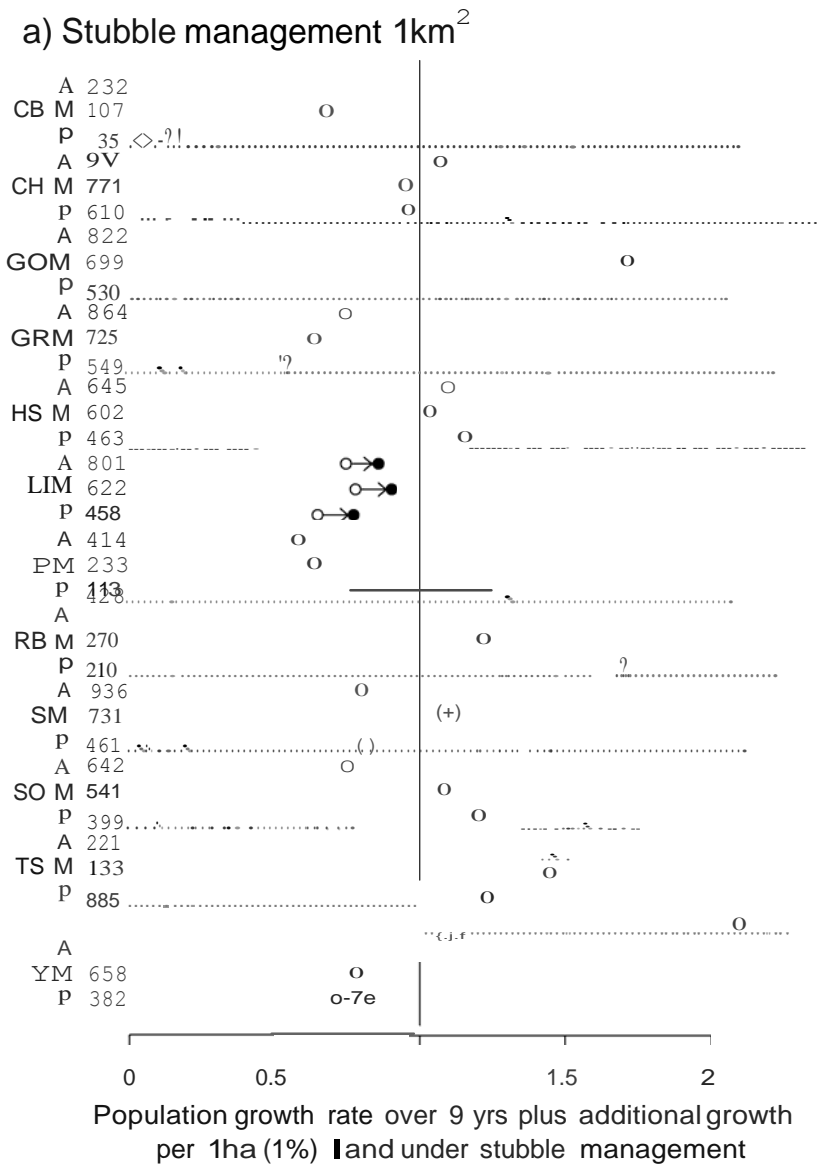
677 Figure 4. Population growth rates over nine years ($\exp(R_9)$, \circ) and the additional effect
678 ($\exp(R_9) \times \exp(\alpha'_9)$, \bullet) with 1ha/km² under ES a) arable and b) grassland margin management
679 (\bullet). See Fig.1 for details.

680

681 Figure 5. Population growth rates over nine years ($\exp(R_9)$, \circ) and the additional effect
682 ($\exp(R_9) \times \exp(\alpha'_9)$, \bullet) with 1km/km² of ES hedgerow management. See Fig.1 for details.

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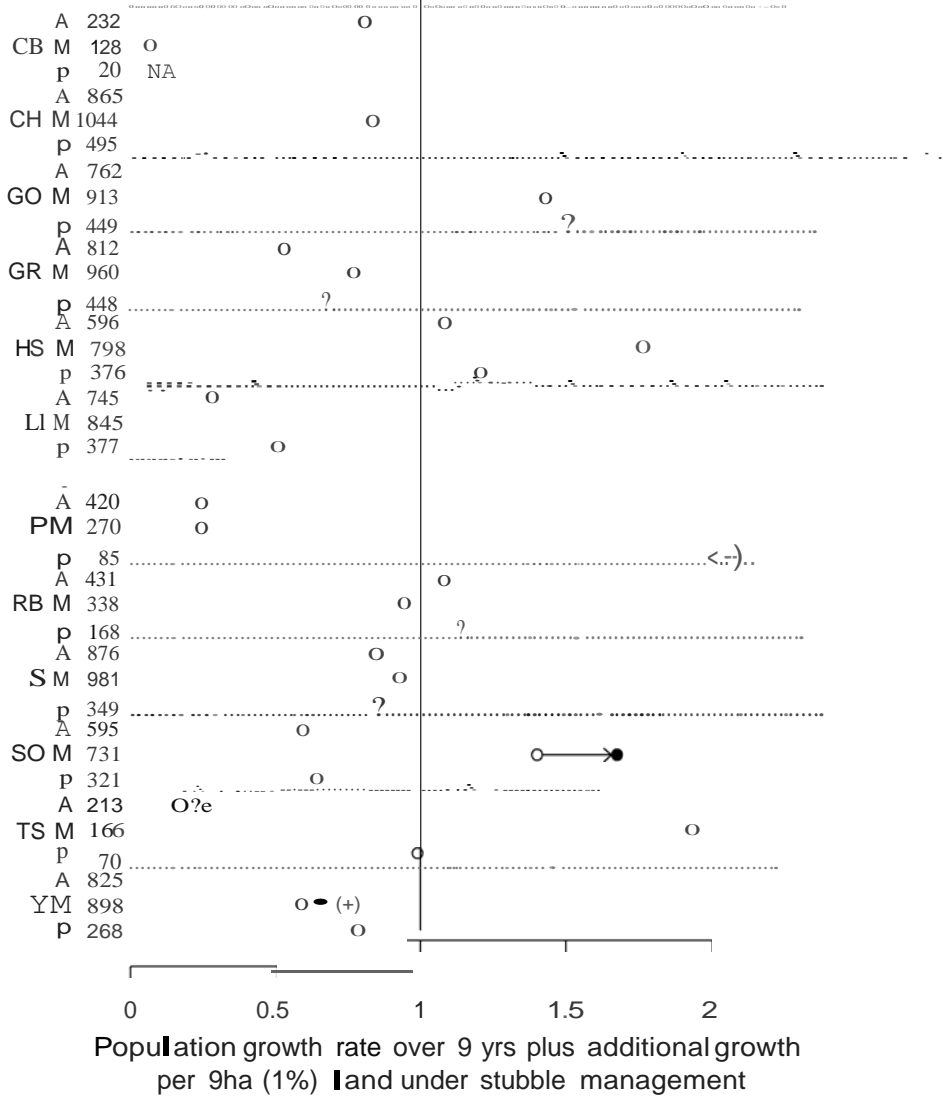
684 Figure 6. Population growth rates over nine years ($\exp(R_9)$, \circ) and the additional effect
685 ($\exp(R_9) \times \exp(\alpha'_9)$, \bullet) with 1km/km² of ES ditch management. See Fig.1 for details.



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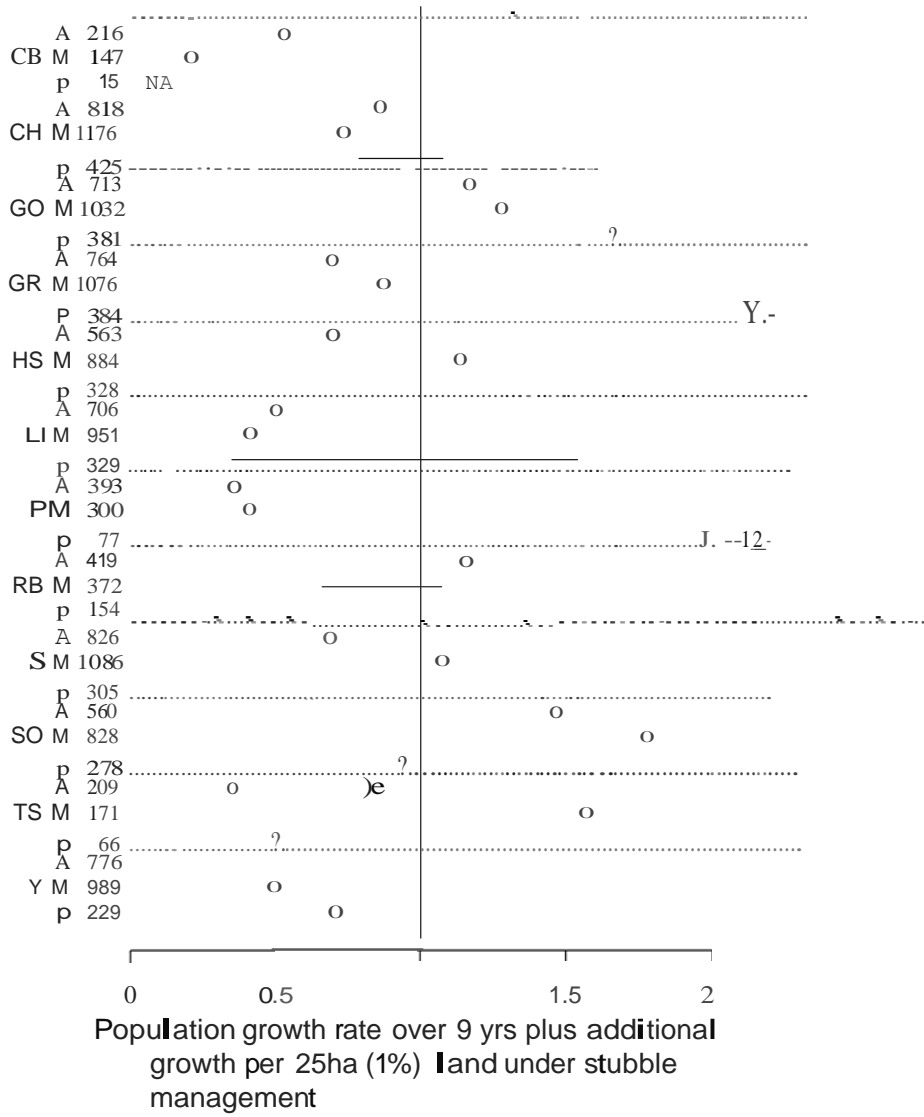
b) Stubble management 9km²

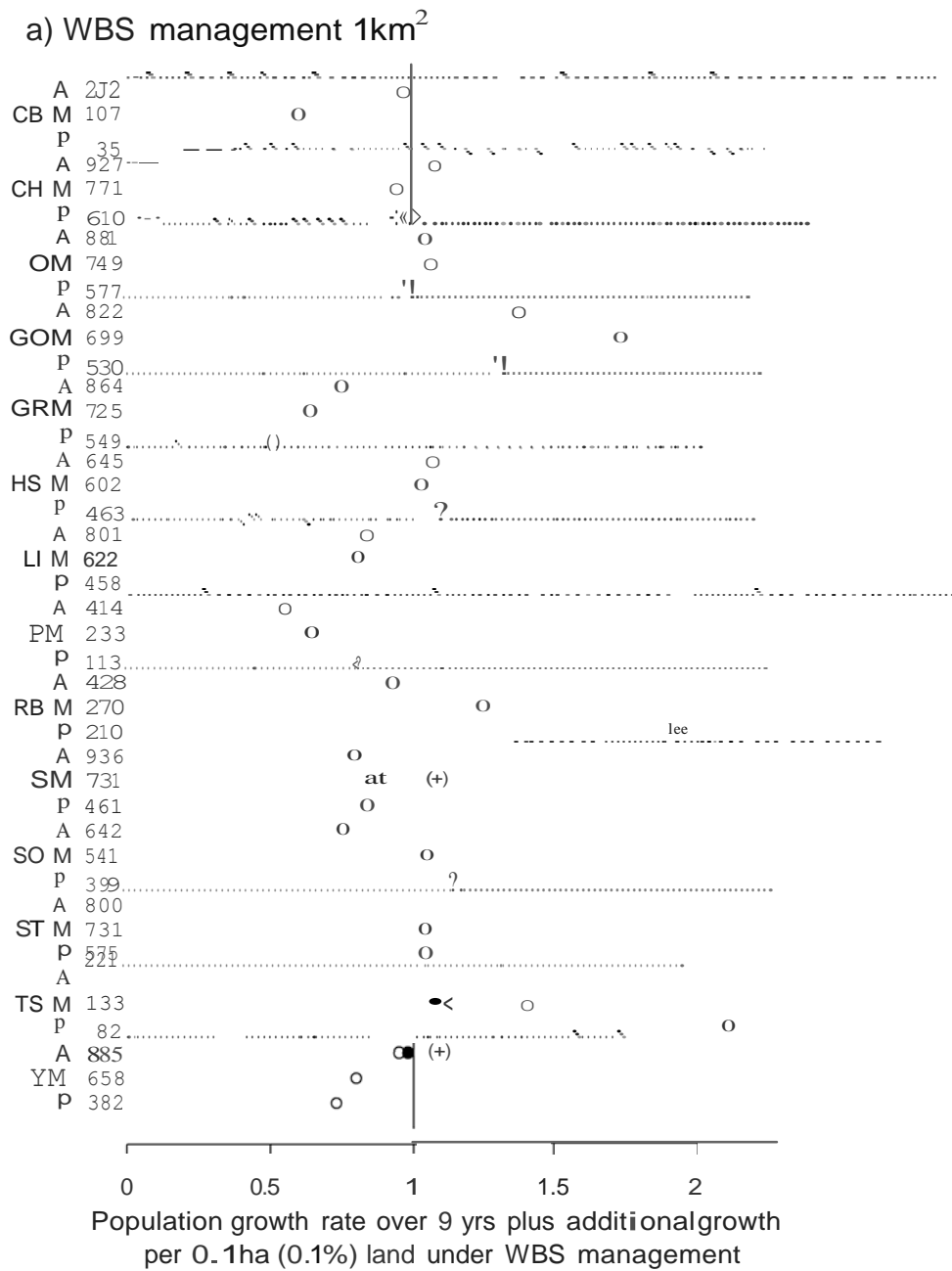


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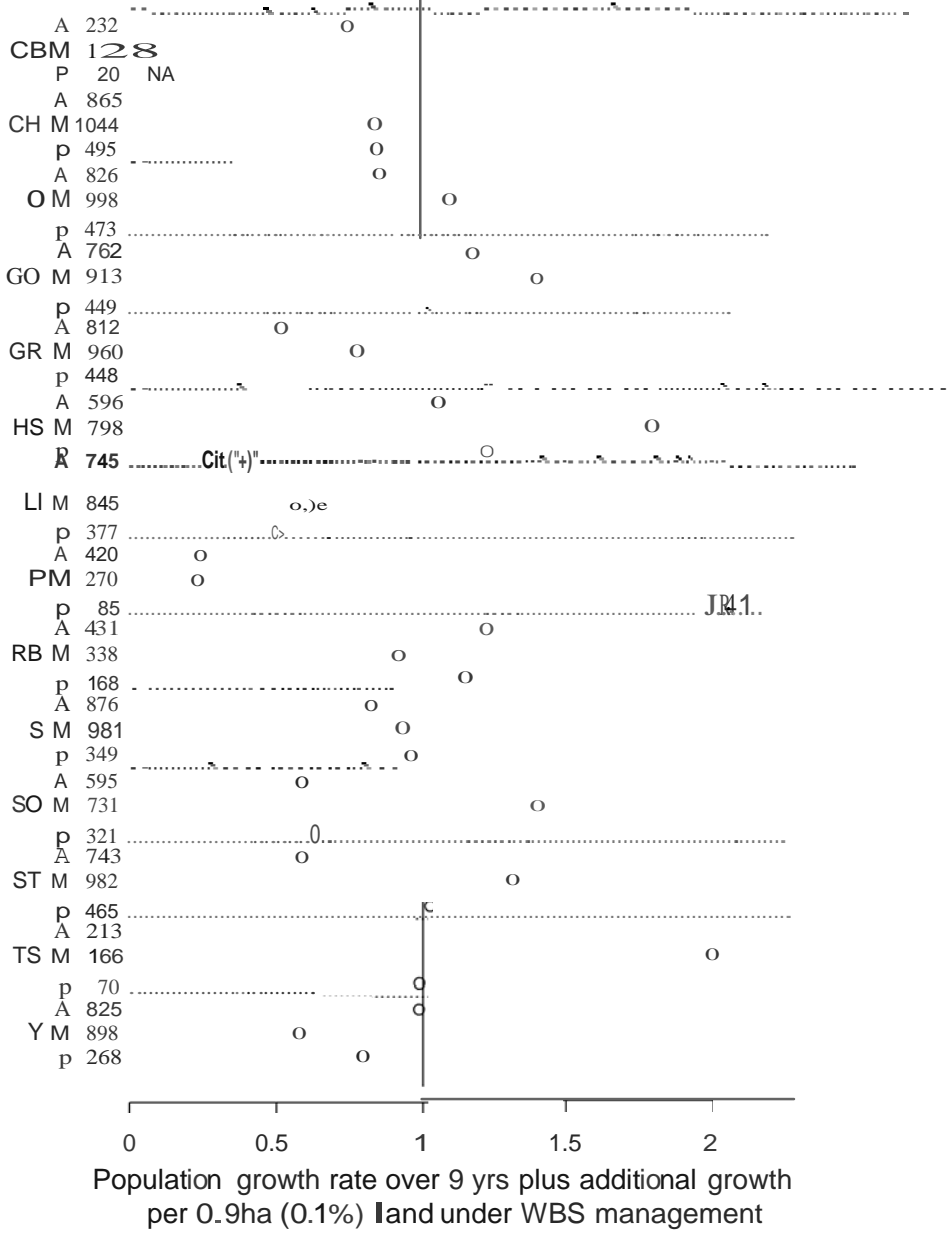
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c) Stubble management 25km²





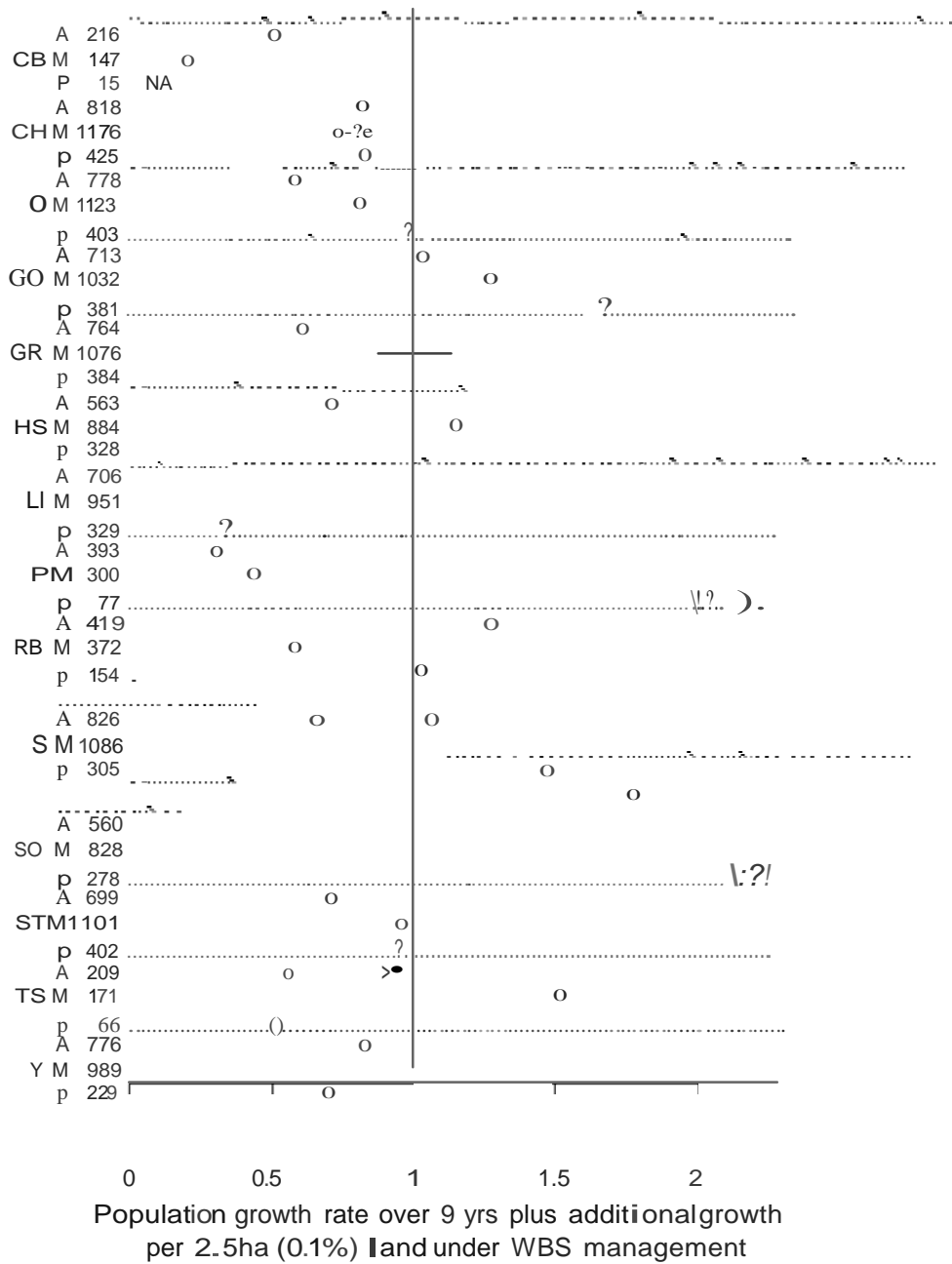
b) WBS management 9km²



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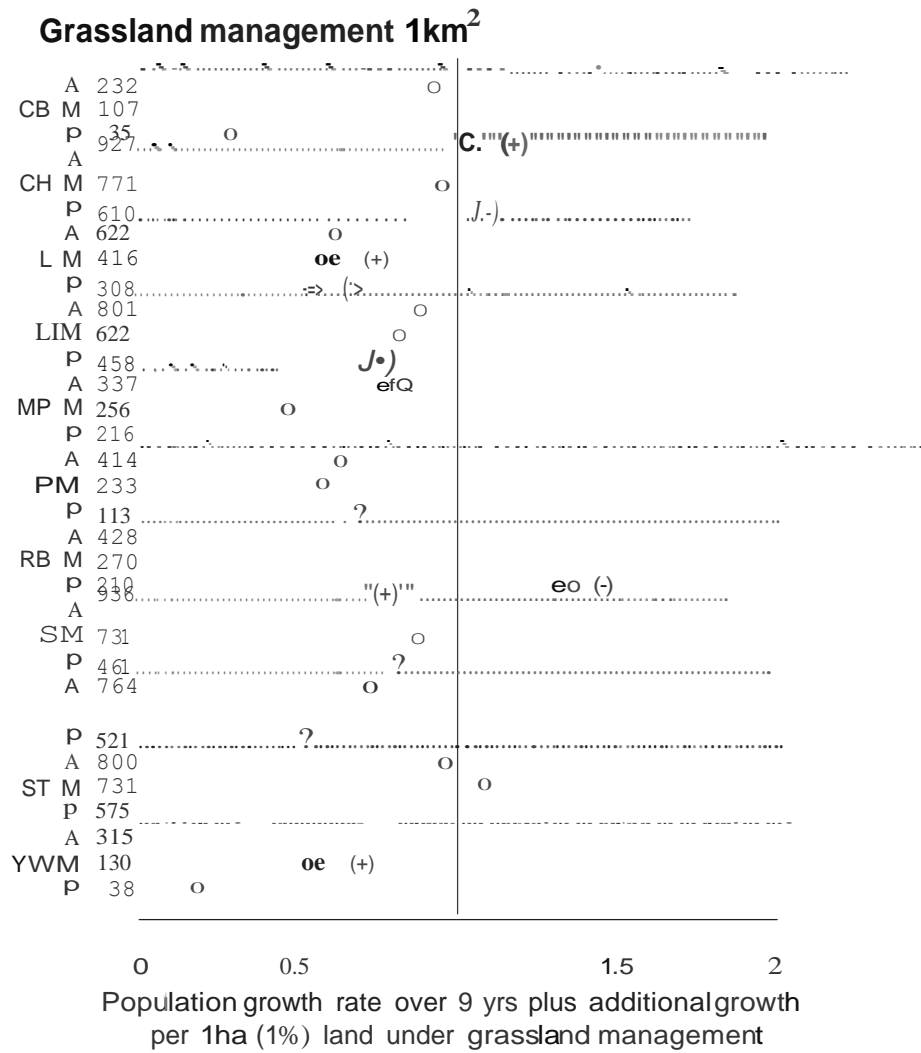
c) WBS management 25km²



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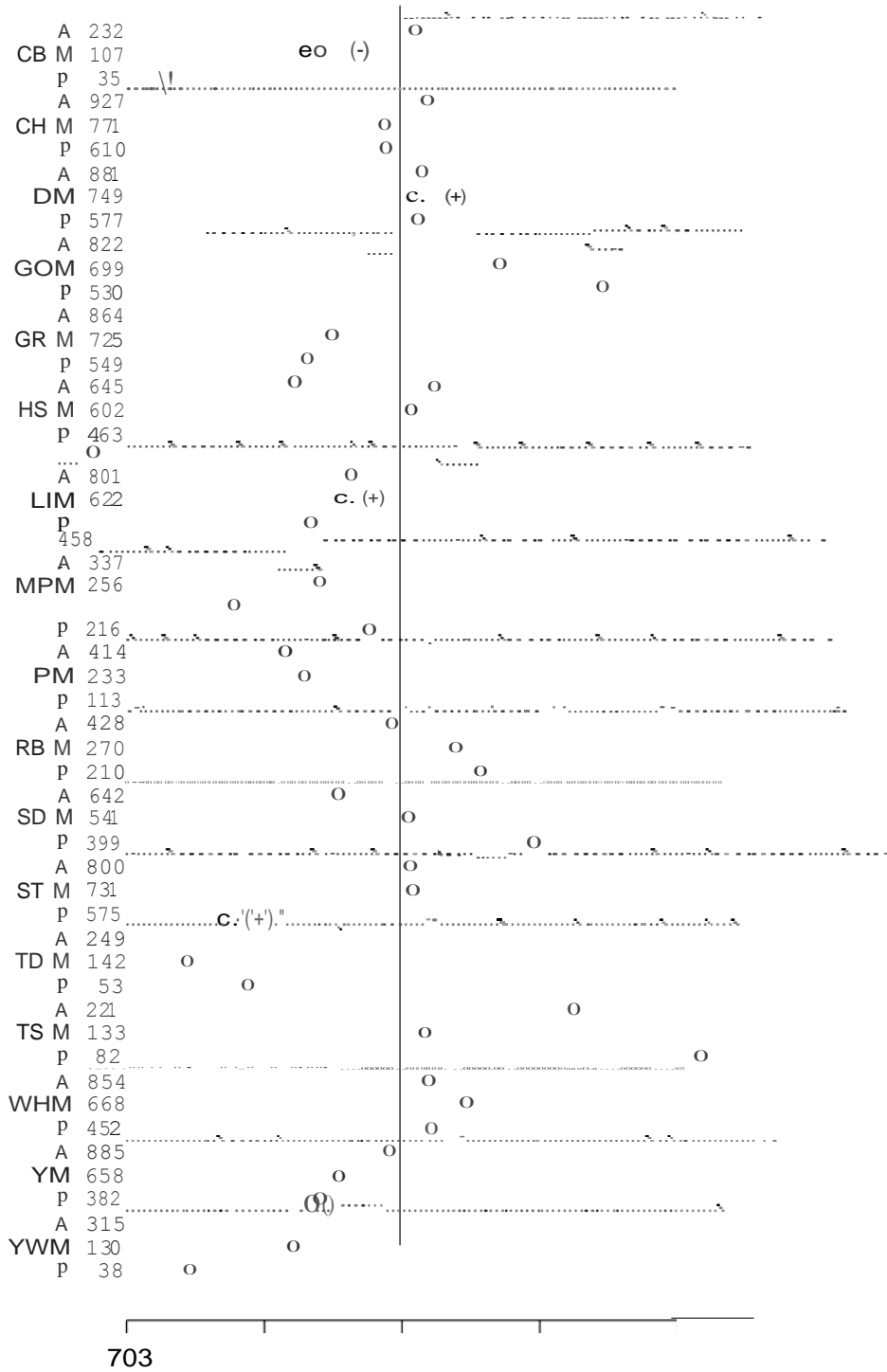
698 Figure 3



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a) Arable margin management



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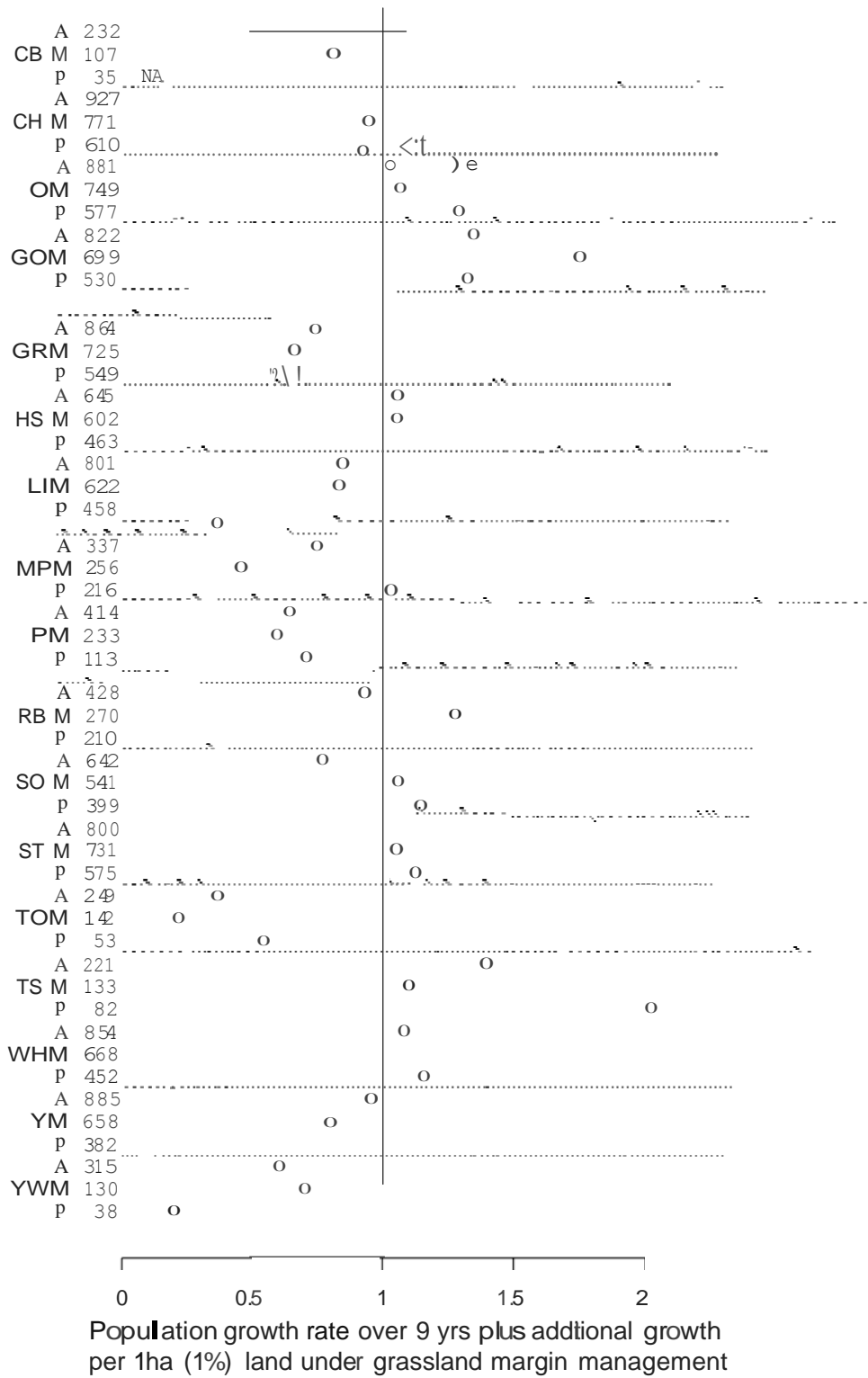
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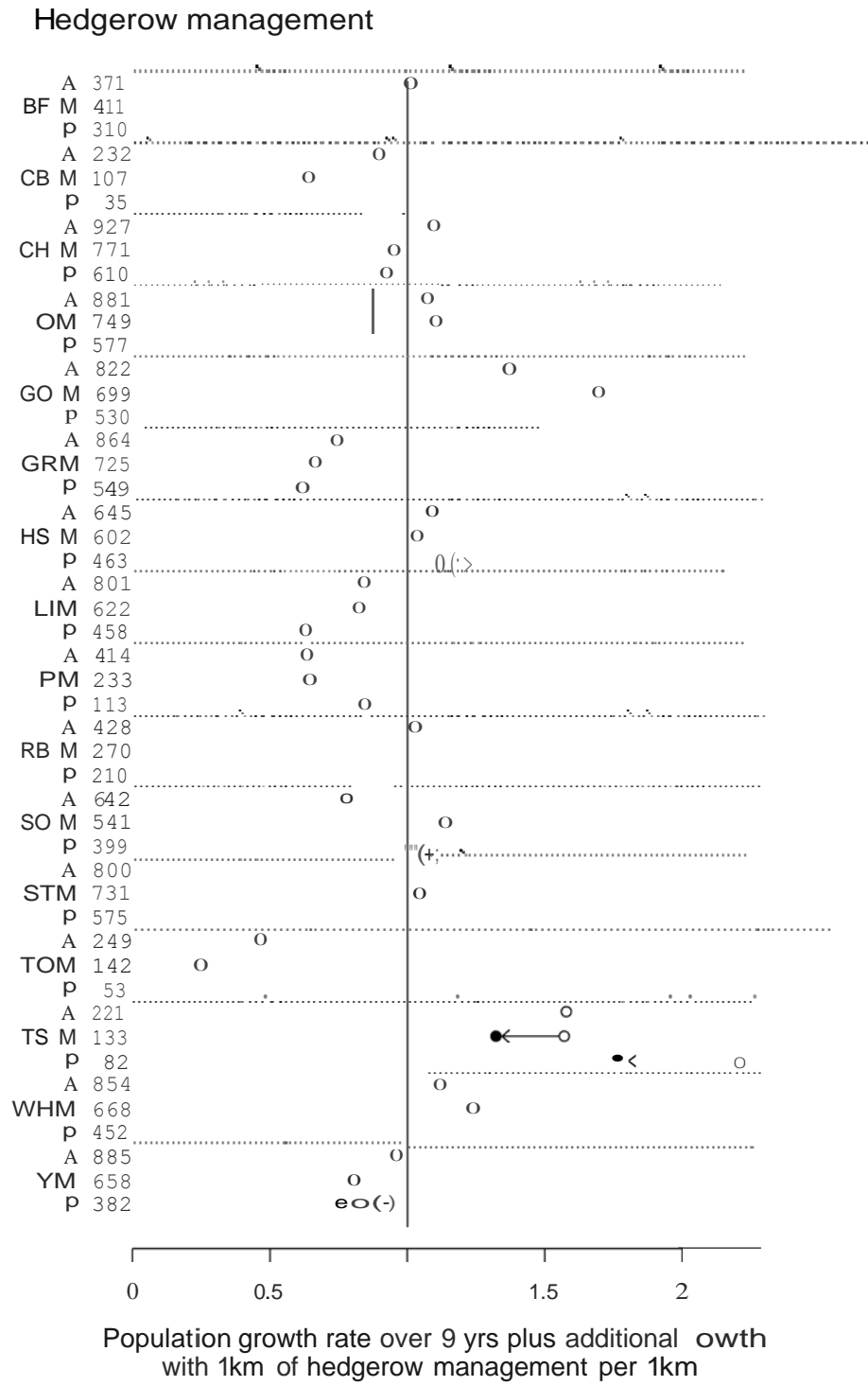
0.5 rowth per 1ha (1%⁵ land under arable margin management)

b) Grassland margin management



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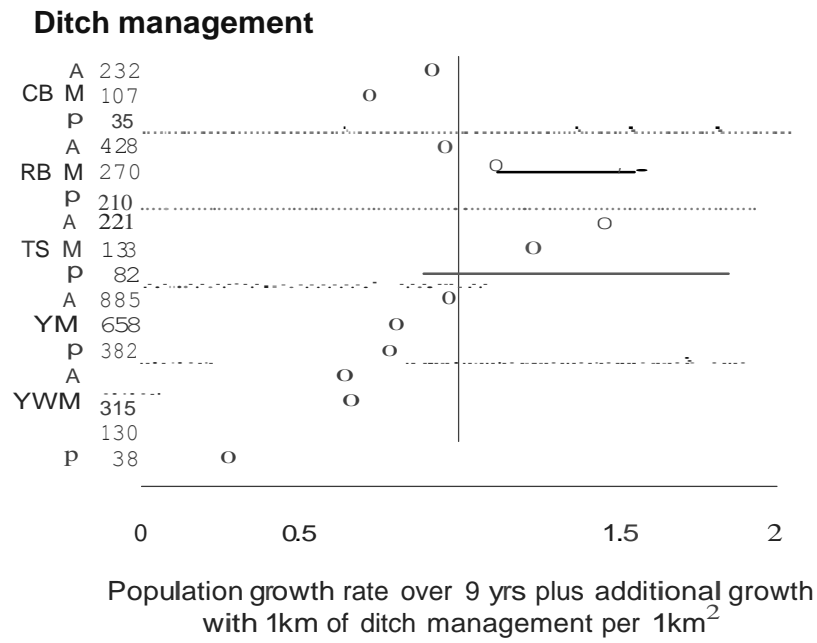
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709 Figure 6



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