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

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SUMMARY

1. Agri-environment schemes (AES) are used extensively across Europe to address biodiversity declines on farmland. In England, Environmental Stewardship (ES) was introduced in 2005 to address the shortcomings of previous schemes but, as for schemes in other countries, assessments to date have revealed little evidence for national-scale biodiversity benefits.
2. Here, we assess the efficacy of ES in driving changes in national farmland bird populations over the period 2002-2010, using BTO/JNCC/RSPB Breeding Bird Survey data. We tested for associations between ES management options, grouped into categories reflecting intended biological effects (e.g. stubble), and species' population growth rates, wherever benefits of management might be expected to occur.
3. We found strong evidence for positive effects of management that provides winter food resources (i.e. ES stubble and wild bird seed [WBS] crops) on population growth rates across multiple granivorous species, at three landscape scales. The results for management aiming to provide breeding season benefits (i.e. grassland, field margin and boundary [hedge, ditch] management) showed mixed patterns of positive and negative associations.
4. The results for stubble and WBS provide the first evidence for landscape-scale responses of biodiversity to AES management. The negative relationships also identified may show the importance of management context driving unforeseen predation or competition effects.

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

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

INTRODUCTION

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

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

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

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

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

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

METHODS

Breeding Bird Survey (BBS)

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

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

Environmental Stewardship data

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

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

Because we were interested in the effects of ES on population growth and not simply in driving aggregative responses to option presence, option quantities were matched with square-specific bird counts after time lags sufficient for influences on breeding success or over-winter survival to have affected breeding abundance. Thus, with the exception of stubbles, management had to have been in place before 1 March of the preceding year for it to have potentially affected breeding abundance in the current year. Stubble options needed to have been in place before harvest in the preceding year, so the cut-off date was 31 July.

Many granivores that breed in a focal 1km square move over larger areas in winter (Siriwardena, Setchfield & Anderson, unpublished data), so areas of ES stubble and WBS management within $9km^2$ and $25km^2$ buffers centred on $1km^2$ BBS squares, as well as within the squares themselves, were used to test effects on breeding bird counts. For these tests, landscape categorization (arable, pastoral, mixed) used the wider scales (9 or $25km^2$; N.B. correlations between classifications across scales were high [r >0.9]).

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

Statistical Analysis

We used a log-linear approach that models the change in expected abundance between consecutive years and can incorporate effects of spatio-temporal covariates, e.g. ES option quantities, on local growth rate. This approach allows maximum use of the available data by including observations from squares not surveyed, or where counts were zero, in the previous year. Fundamentally, the analyses estimated the additional effect of ES on each species' population growth rate but, importantly, growth is not thereby forced to be greatest in the years of highest management levels. The model is a multivariate extension of Freeman & Newson (2008):

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

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

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

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

Also of interest is the cumulative growth in the absence of management to year t (R'_t) and the compound effect of a single unit of management over time, which we denote α'_t. Maximum likelihood estimates of $R'_t = \sum_{j=1}^{t-1} R_j$ follow either through fitting this re-parameterisation of the model or via the standard formulae:

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

and:

$$\hat{\alpha}'_t = (t-1)\hat{\alpha} \; ; \qquad \mathrm{var}\left(\hat{\alpha}'_t\right) = (t-1)^2 \; \mathrm{var}\left(\hat{\alpha}\right) \qquad (4)$$

95% confidence intervals (CI) follow from (3) and (4) and can be back-transformed from the log scale. Note that very large CI were produced in some cases with the small sample sizes for corn bunting in pastoral landscapes, so these profoundly imprecise results are not presented.

From (4), $\hat{\alpha}'$ is the estimate of additional growth, over nine years, per unit of management (area or length under ES/CSS) per area of land. For ease of comparison across options, growth rate effects are mostly presented per 1% of land area (i.e. 1, 9 or 25ha per 1, 9 or 25km^2, respectively), or 1km of boundary (hedgerow/ditch) per 1km^2, under option management. For WBS options, which cover smaller areas (0.1-0.2% of land under ES management per km^2; Table S1), the results are reported with respect to 0.1% of the land area (i.e. 0.1, 0.9 or 2.5ha per 1, 9 or 25km^2, respectively). To aid interpretation we backtransform the estimates arising, presenting multiplicative growth rates $\exp(\hat{\alpha}')$ such that an estimate of 1.1, for example, describes growth 10% higher than the background rate at a site under a single unit of management over the period.

RESULTS

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

Stubble management

The population growth rates of corn bunting (P), goldfinch (A), linnet (A, M, P), grey partridge (P), reed bunting (A, P), skylark (M) and yellowhammer (A, P) were positively associated with the presence of ES stubble management at the 1km^2 scale (Fig. 1, Table S2). The size of the additional effect of ES management on growth rate $\exp(\hat{\alpha}')$ was large for most species/landscapes, with eight showing >10% increase in population growth rate over nine years with 1ha/km^2 under ES stubble management (Table S2). Only goldfinch (P) showed a negative association.

Wild Bird Seed (WBS) management

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

Multi-scale management of winter food options

Differences between stubble results at the 1km^2 scale and at two wider scales, 9km^2 and 25km^2, suggested variable species-specific responses to the spatial scale of food availability (Fig. 1, Table S2). Three finches (chaffinch, greenfinch and linnet) were positively associated with ES stubble management at the 25km^2 scale in pastoral squares. Linnet was also positively associated with ES stubble at the 9km^2 scale in mixed squares. Tree sparrow was significantly associated with such management at the two larger spatial scales in arable squares, whereas yellowhammer was significantly associated with stubble management in arable squares at the 1 and 25km^2 scales. Reed bunting (25km^2), stock dove (9km^2) and yellowhammer (9km^2) each showed a significant positive association with ES stubble in mixed squares at large spatial scales only. At the wider spatial scales, the significant positive values of $\exp(\hat{\alpha}')$ were >1.10, suggesting a strong effect of management on population growth rates. Only goldfinch showed a negative association at a wider spatial scale (A, 9km^2 scale), contrary to the positive association at the 1km^2 scale.

Several species were associated with ES WBS management at wider scales, but only tree sparrow (A) showed an apparent response at 1km^2 as well as both larger scales (Fig. 2, Table S3). Linnet also showed an apparent response in arable and mixed squares at both larger scales. Chaffinch, greenfinch, linnet and yellowhammer in mixed squares and skylark and stock dove in pastoral squares all showed positive associations with ES WBS at the 25km^2 scale. At the wider spatial scales, all significant positive values of $\exp(\hat{\alpha}'_9)$ were >1.10, again suggesting strong effects on population growth rates. Two significant negative associations were found with ES WBS, for corn bunting (M, 9km^2) and goldfinch (P, 9km^2).

Grassland management

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

Margin management

The population growth rates of corn bunting (P), dunnock (M), linnet (M) and turtle dove (A) were positively associated with ES arable margin management (Fig. 4, Table S5). The population growth rates of corn bunting (M), goldfinch (P) and yellow wagtail (A) showed negative results. The effect size of ($\exp(\alpha')$) for these significant results varied between -10% and +40% additional growth over nine years with 1ha/km^2 under arable margin management.

Grassland margin management (Fig. 4, Table S5) was positively associated with the population growth rates of chaffinch (A, P), dunnock (A), greenfinch (P) and whitethroat (M). The effect size for these significant results represented >7% additional growth over nine years with 1ha/km^2 under grassland margin management. There was a negative association with the growth rate of corn bunting (A), with a large effect size ($\exp(\alpha')$ = 0.46, Table S5).

Boundary management (Hedgerow & ditch options)

The population growth rates of bullfinch (M, P), house sparrow (P), reed bunting (M) and song thrush (A) were significantly positively associated with ES hedgerow management (Fig. 5, Table S6). For these significant results, effect sizes represented ≥4% additional growth over nine years with 1km/km^2 of managed boundary. Negative associations were found for goldfinch (P), tree sparrow (M, P) and yellowhammer (P), with effect sizes of ≥6% negative growth.

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

Overall response to ES management

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

DISCUSSION

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

Previous research has concluded that a shortage of winter seed drove the population declines of most granivorous farmland birds and it probably also prevents recoveries (Gillings *et al.* 2005; Siriwardena *et al.* 2000, 2007). Davey *et al.* (2010) found few clear population benefits of ES over-winter food options for granivorous species but, with multiple years per survey square, a longer survey period and more powerful analyses, we found significant positive associations between population growth rates and stubble management for three-quarters of the granivorous species tested, for one or more of three spatial scales and landscape types. The results for yellowhammer, linnet, reed bunting, grey partridge and skylark were consistent with those of Gillings *et al.* (2005) for stubble in general, and there were further positive effects on goldfinch, tree sparrow, stock dove and greenfinch. While alternative mechanisms for population limitation have been proposed for some of these species, winter seed availability is at least a strong candidate for all of them. The only negative associations found were for goldfinch (pastoral, 1km^2, and arable, 9km^2). This species is a partial migrant and even 'resident' birds move large distances between seasons, so local winter habitat may be only a weak influence on local breeding birds, but there is no clear explanation for these results.

ES wild bird seed crops provide higher seed resource densities than stubbles and supply winter food effectively in some contexts (e.g. Field *et al.* 2011). We found positive associations between several species' population growth rates and WBS management at all spatial scales, again suggesting that increased seed availability relaxes population limits on many granivorous species. It is unsurprising that various species responded differently to stubble and WBS management because seed type and context of seed delivery (e.g. vegetation height, distance from cover) affect attractiveness to different species (Siriwardena & Stevens 2004). Significant negative associations were found for one landscape/scale combination for four species expected to benefit from WBS crops, chaffinch, corn bunting, goldfinch and tree sparrow. It may be that, especially where seed resources are rare, such as in pastoral and mixed landscapes, smaller species are attracted to a food source but then are excluded competitively by dominant species, such as greenfinch and woodpigeon (Krams 2001). This could become critical during poor weather, when there may be insufficient time to locate alternative habitats. Another possibility is that concentrations of birds in seed-rich habitats lead to concentrations of predation pressure and a net negative effect on the survival of vulnerable species (Bro *et al.* 2004). Such contextual effects could explain contrasting results for a species between landscape contexts, such as the tree sparrow response to WBS management (1km scale) which was positive in arable landscapes and negative in mixed. A management solution to either problem would be to increase the number or diversity of WBS patches in an ES agreement in order to reduce concentrations of dominant or predatory species.

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

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

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

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

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

Synthesis and Applications

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

The results are not definitive about the value of other ES management, which often (partly) targets other taxa, resource protection or landscape character (e.g. Fuentes-Montemayor, Goulson & Park 2010). Also, low uptake prevented testing of some options, such as skylark plots. Further, management enhancing bird breeding habitats could be valuable in providing resources to support species' future recoveries and could also benefit local breeding populations, even if national effects are small.

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

Overall, this study shows that ES winter seed provision is producing some desired changes in landscape-scale population trends, but that increased option uptake, probably with improved management, will be required to produce national increases. Recent modifications of ES option content, scheme management and farmer guidance (Winspear *et al.* 2010) have successfully encouraged in-field management uptake (Fig. S1). However, research is still needed to identify effective option revisions and it is essential that monitoring continues, with feedback into scheme design and operation (Kleijn & Sutherland 2003). The key agri-environment effects found here, such as those of overwinter seed provision, are relevant at least across Western Europe, where intensive winter cropping is the norm and farmland bird populations have declined. Moreover, many Northern European breeding populations winter further south-west, so will be influenced by farmland management there. In addition, the general principles concerning evidence-based management design apply equally to other taxa and schemes across Europe. Adopting such principles can ensure that AES represent a viable solution for addressing landscape-scale conservation priorities.

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Supporting Information

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

Table S1. Summary of broad option categories

Table S2. Population growth rates for ES stubble management

Table S3. Population growth rates for ES WBS management

Table S4. Population growth rates for ES grassland management

Table S5. Population growth rates for ES margin management

Table S6. Population growth rates for ES boundary management

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

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

Table 1. Species included in the analysis with BBS codes and broad dietary preferences; * denotes species classified as farmland (arable or pastoral) specialists and † denotes obligate summer migrants.

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

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

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.

Figure 1. Population growth rates over nine years ($\exp(\hat{R}_9)$, ○) at a) 1km^2, b) 9km^2 and c) 25km^2 spatial scales, and the additional effect ($\exp(\hat{R}_9) \times \exp(\hat{\alpha}'_9)$, ●) with 1, 9 and 25ha/km^2 under ES stubble management, respectively. A = Arable, M = Mixed and P = Pastoral landscapes, with the number of unique BBS squares in which the species occurred given adjacent. 'NA' refers to tests results not reported (see Methods). For species codes see table 1.

Figure 2. Population growth rates over nine years ($\exp(\hat{R}_9)$, ○) at a) 1km^2, b) 9km^2 and c) 25km^2 spatial scales, and the additional effect ($\exp(\hat{R}_9) \times \exp(\hat{\alpha}'_9)$, ●) with 0.1, 0.9, 2.5ha/km^2 under ES wild bird seed (WBS) management, respectively. See Fig.1 for details.

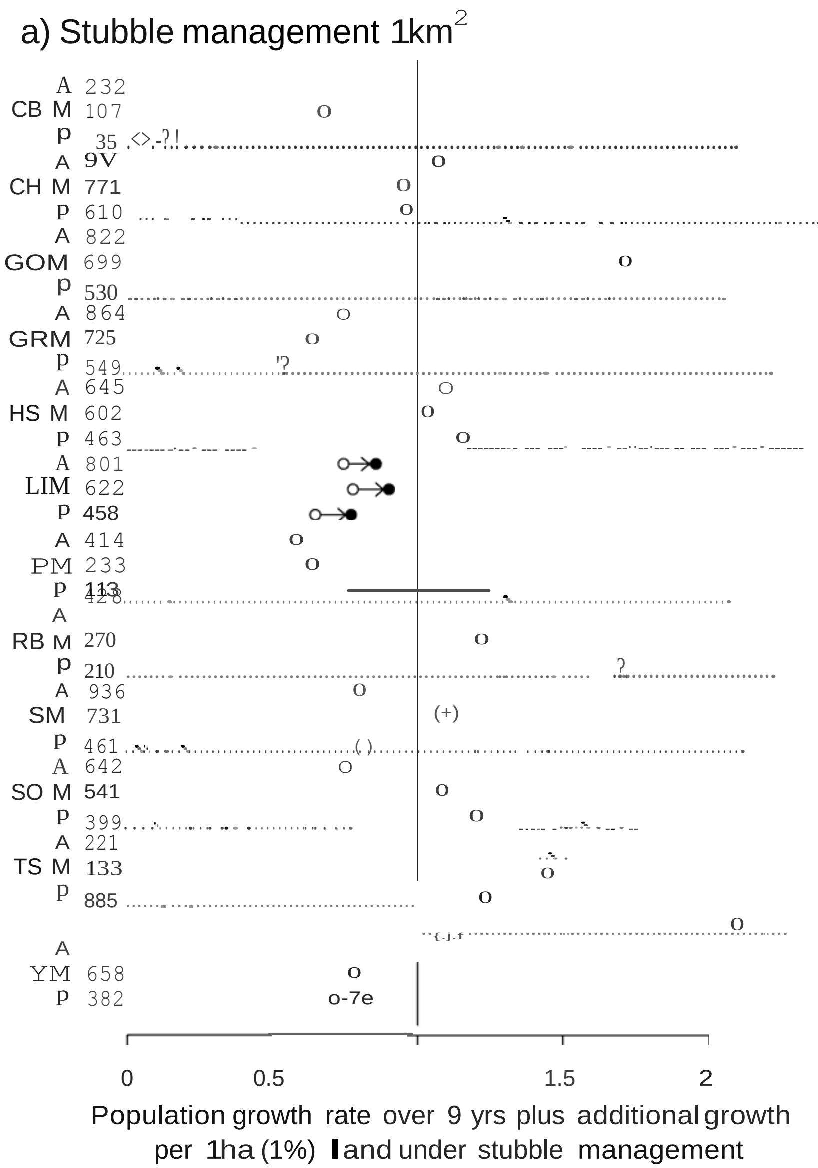
Figure 3. Population growth rates over nine years ($\exp(\hat{R}_9)$, ○) and the additional effect ($\exp(\hat{R}_9) \times \exp(\hat{\alpha}'_9)$, ●) with 1ha/km^2 under ES grassland management. See Fig.1 for details.

Figure 4. Population growth rates over nine years ($\exp(\hat{R}_9)$, ○) and the additional effect ($\exp(\hat{R}_9) \times \exp(\hat{\alpha}'_9)$, ●) with 1ha/km^2 under ES a) arable and b) grassland margin management (●). See Fig.1 for details.

Figure 5. Population growth rates over nine years ($\exp(\hat{R}_9)$, ○) and the additional effect ($\exp(\hat{R}_9) \times \exp(\hat{\alpha}'_9)$, ●) with 1km/km^2 of ES hedgerow management. See Fig.1 for details.

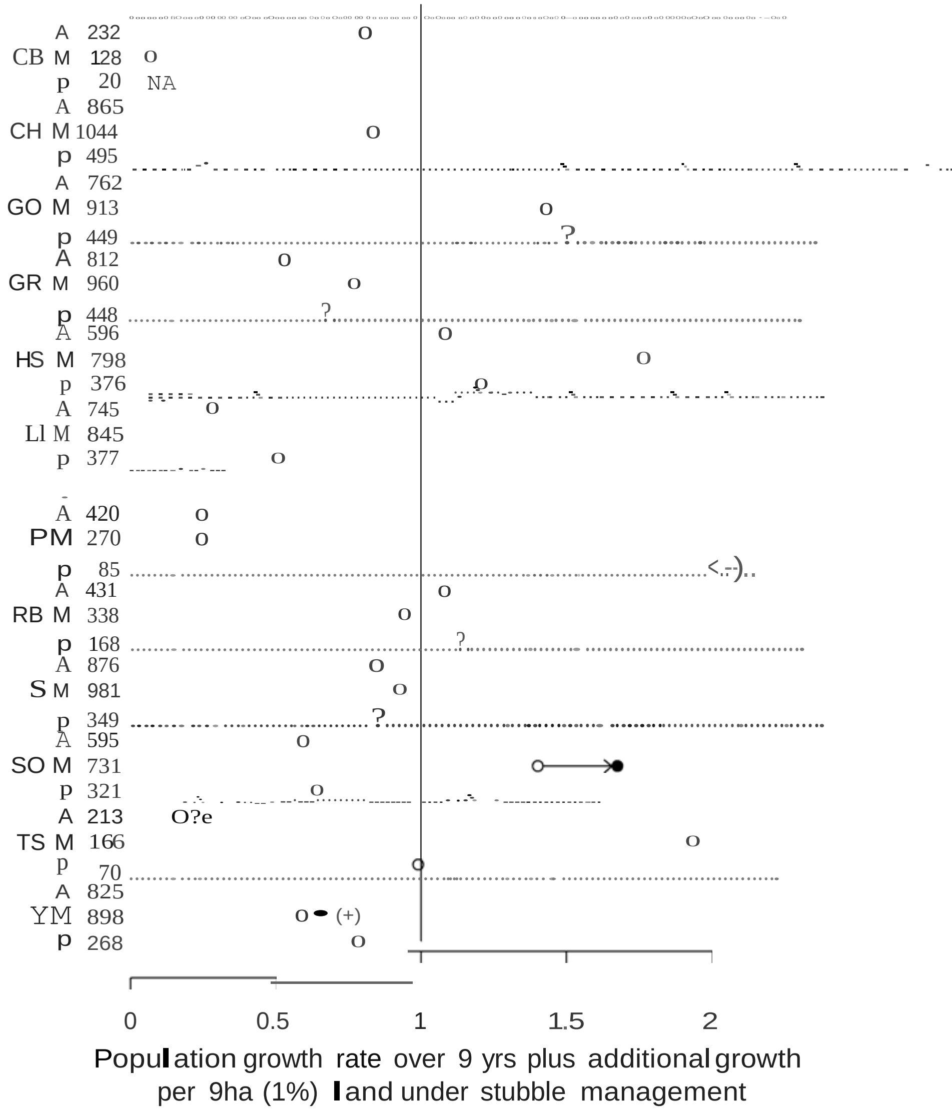
Figure 6. Population growth rates over nine years ($\exp(\hat{R}_9)$, ○) and the additional effect ($\exp(\hat{R}_9) \times \exp(\hat{\alpha}'_9)$, ●) with 1km/km^2 of ES ditch management. See Fig.1 for details.

Figure 1

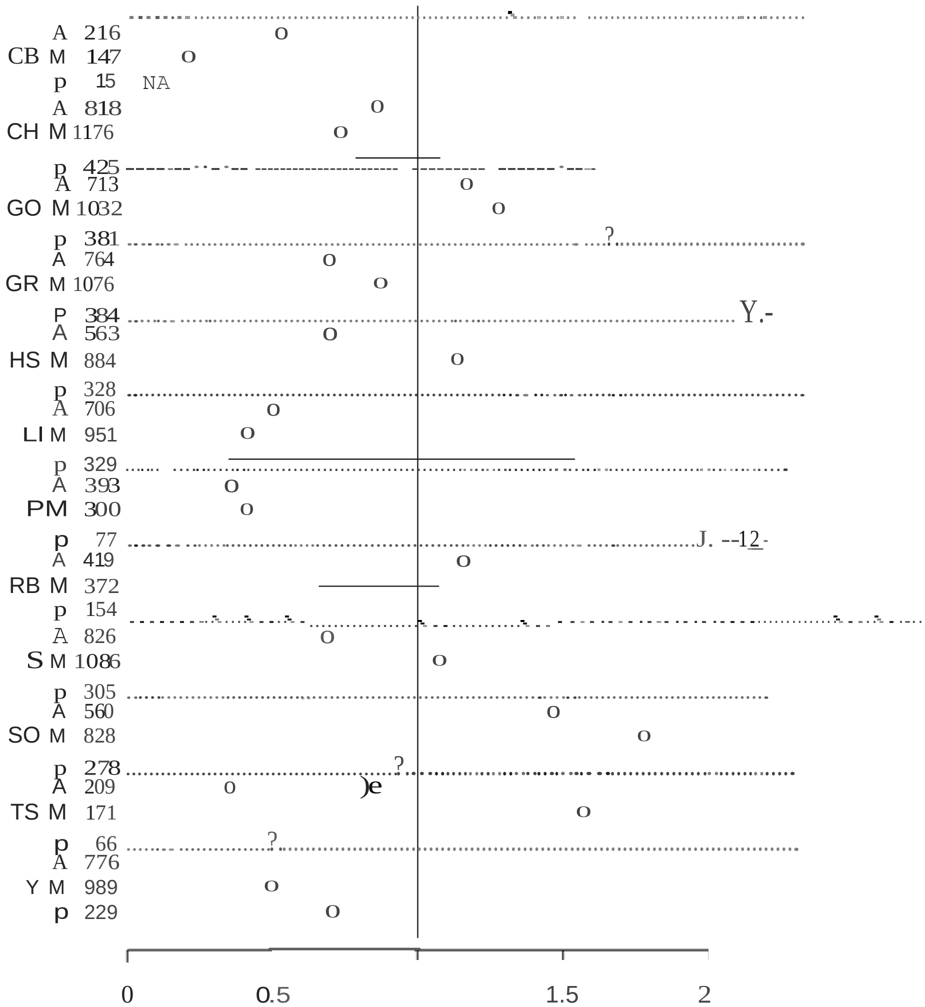


a) Stubble management 1km2
CB
CH
GOM
GRM
HS
LIM
PM
RB
SM
SO
TS
YM
0
0.5
1.5
2
Population growth rate over 9 yrs plus additional growth per 1ha (1%) land under stubble management

b) Stubble management 9km^2



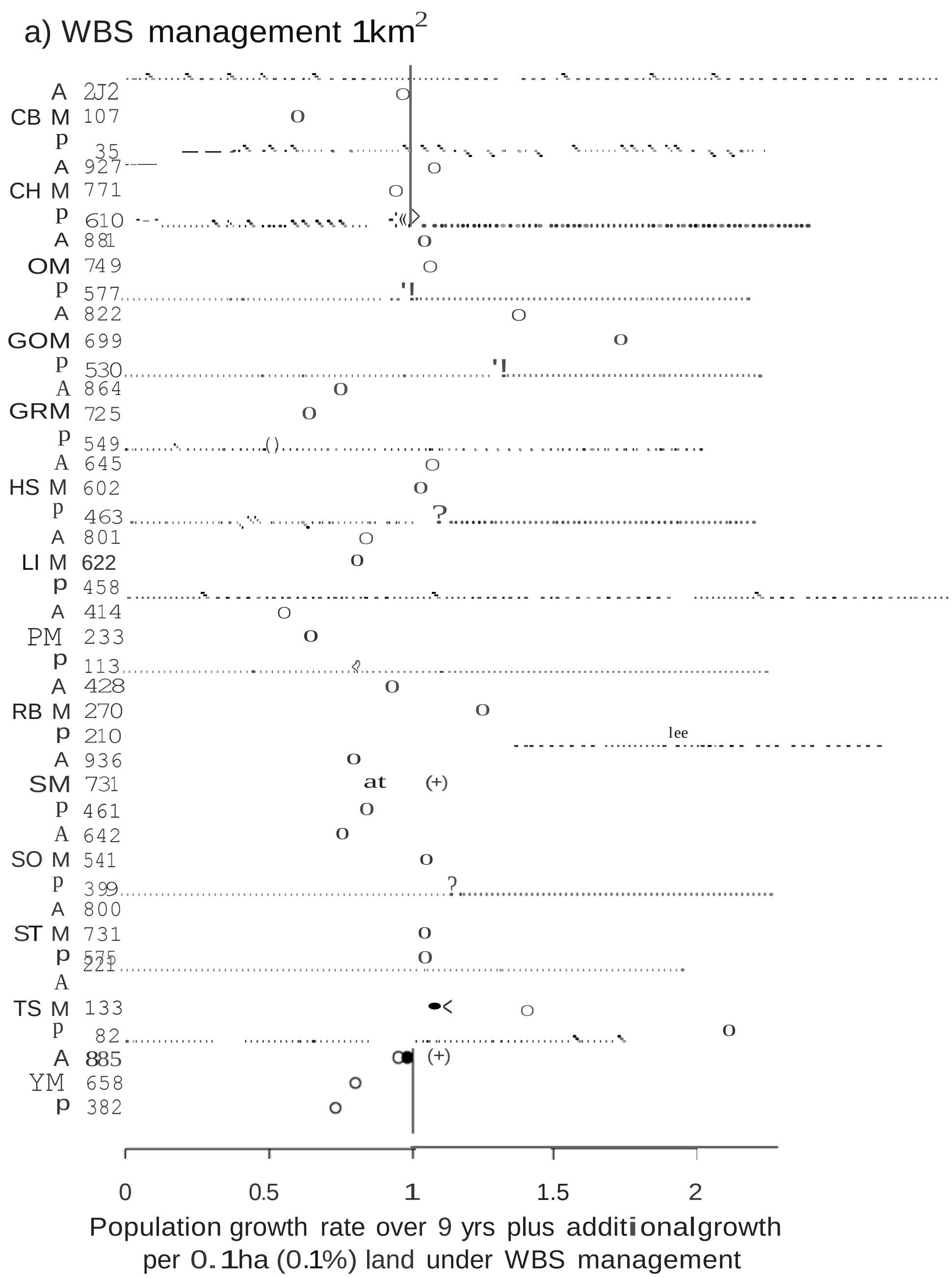
c) Stubble management 25km²



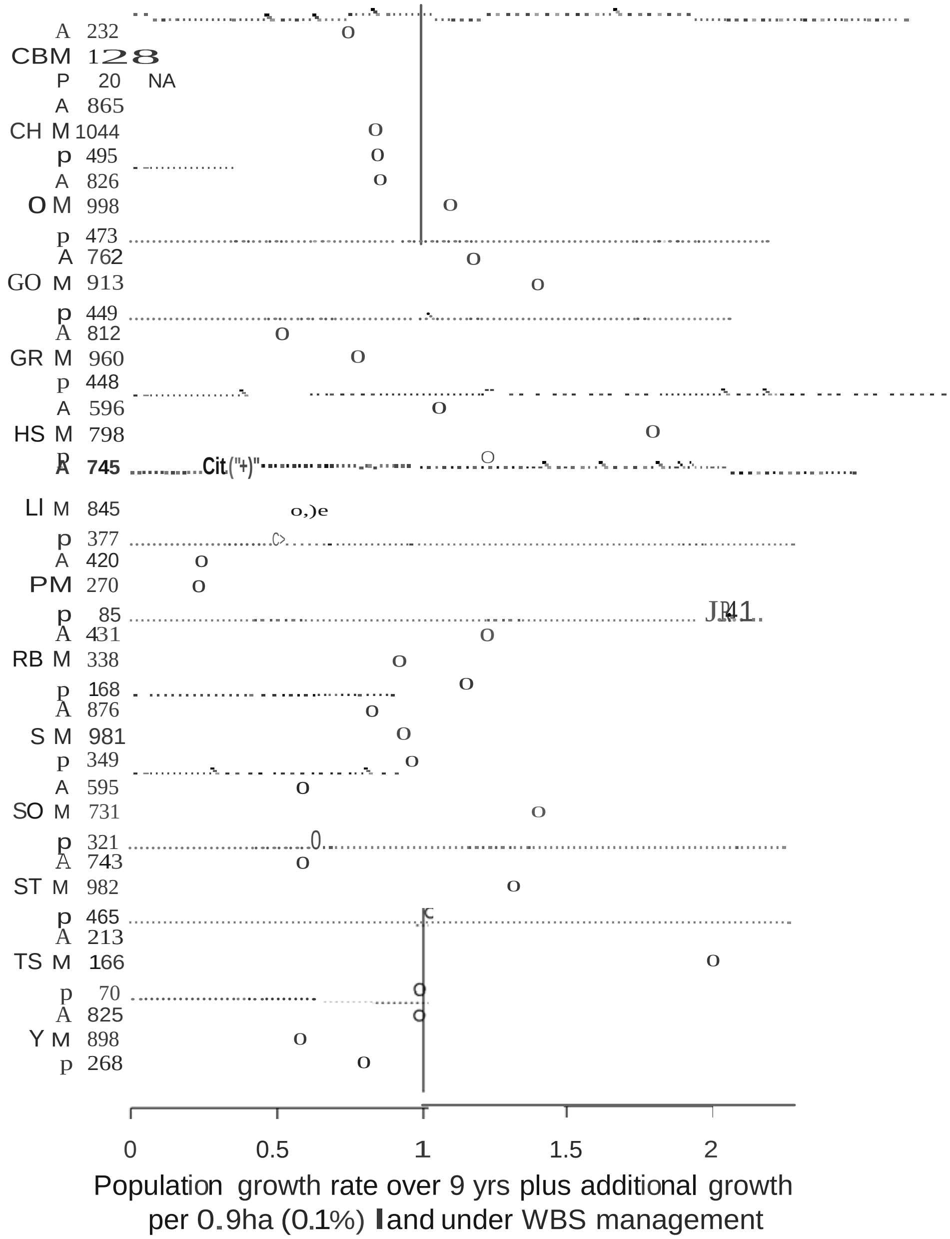
Population growth rate over 9 yrs plus additional growth per 25ha (1%) land under stubble management

691

Figure 2


a) WBS management 1km2
CB
CH
OM
GOM
GRM
HS
LI
PM
RB
SM
SO
ST
TS
YM
0
0.5
1
1.5
2
Population growth rate over 9 yrs plus additional growth per 0.1ha (0.1%) land under WBS management

b) WBS management $9km^2$



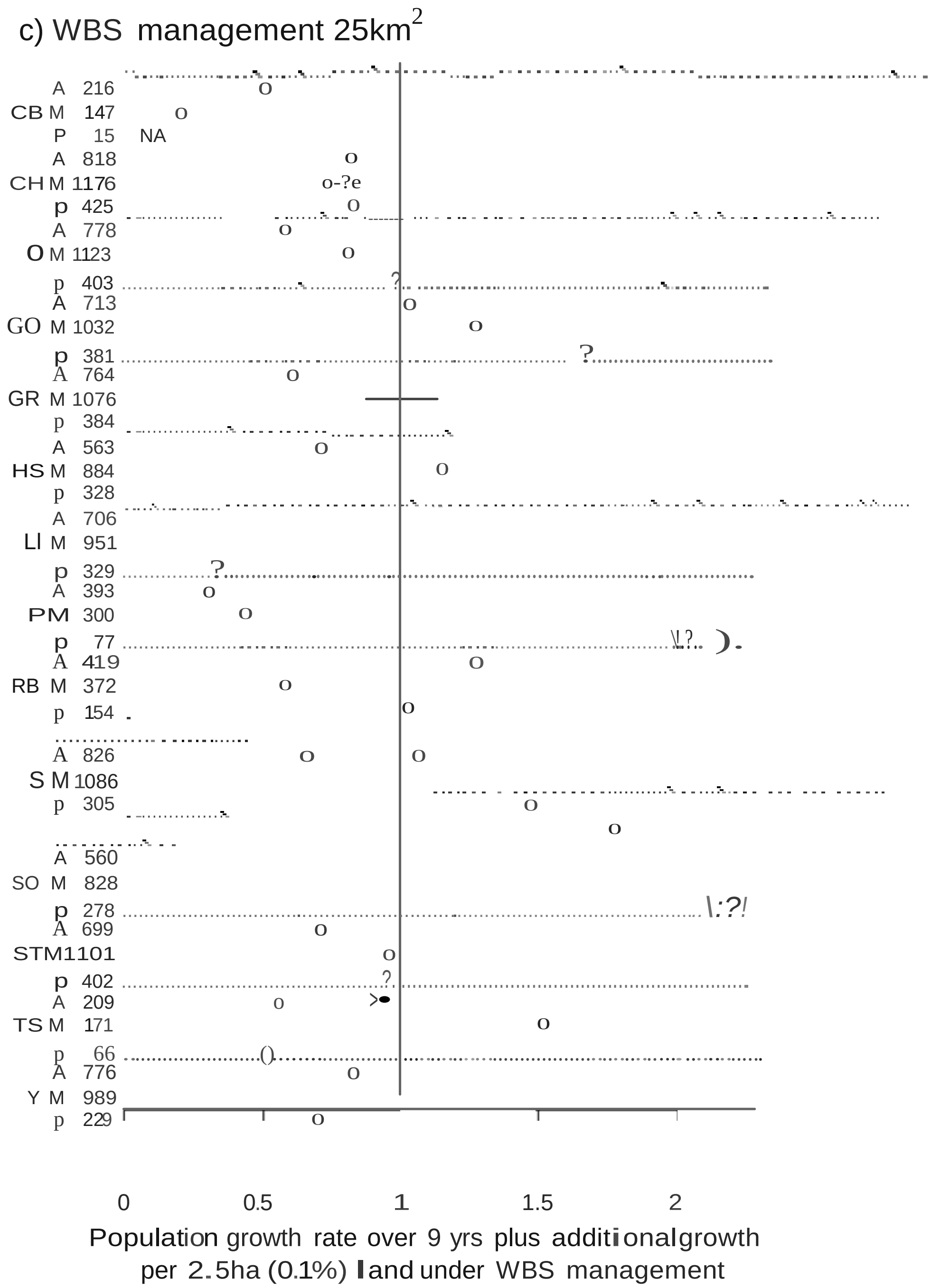

c) WBS management 25km2
A 216
CB M 147
P 15
NA
A 818
CH M 1176
p 425
A 778
M 1123
p 403
A 713
GO M 1032
p 381
A 764
GR M 1076
p 384
A 563
HS M 884
p 328
A 706
M 951
p 329
A 393
PM 300
p 77
A 419
RB M 372
p 154
A 826
S M 1086
p 305
A 560
SO M 828
p 278
A 699
STM 1101
p 402
A 209
TS M 171
p 66
A 776
Y M 989
p 229
0
0.5
1
1.5
2
Population growth rate over 9 yrs plus additional growth per 2.5ha (0.1%) land under WBS management

Figure 3

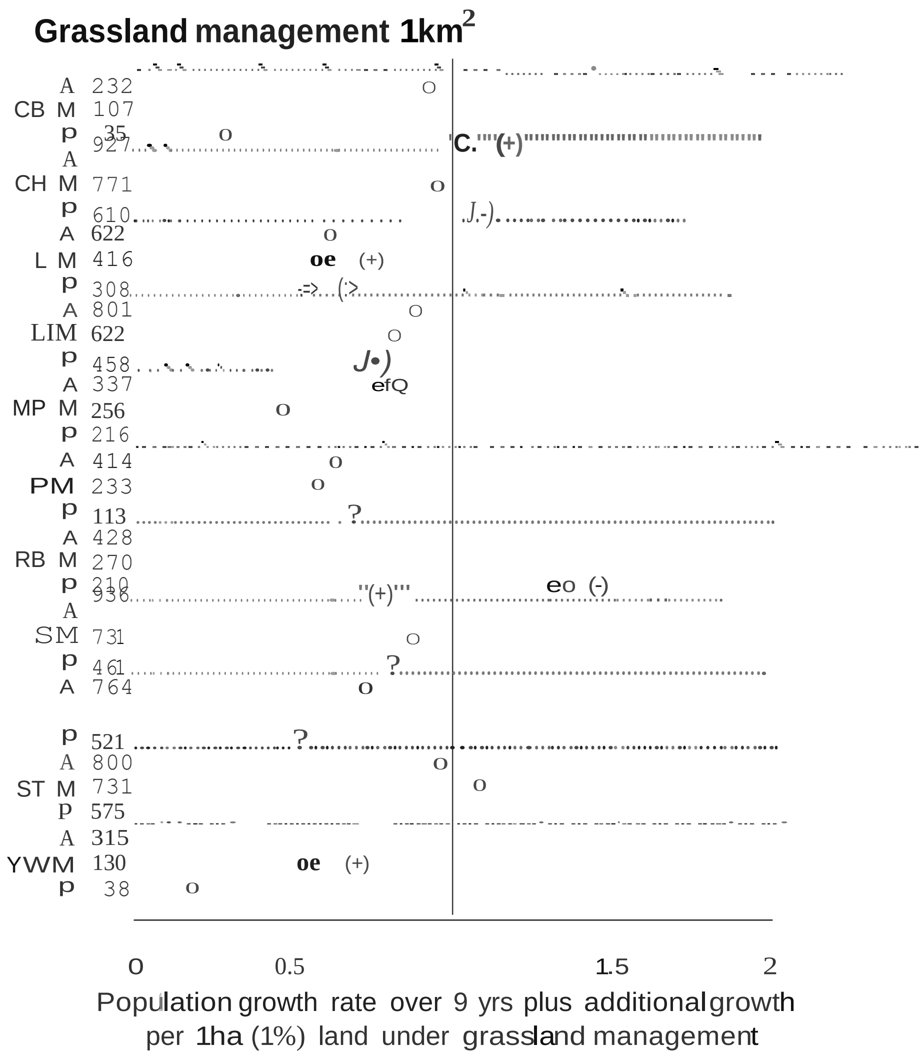
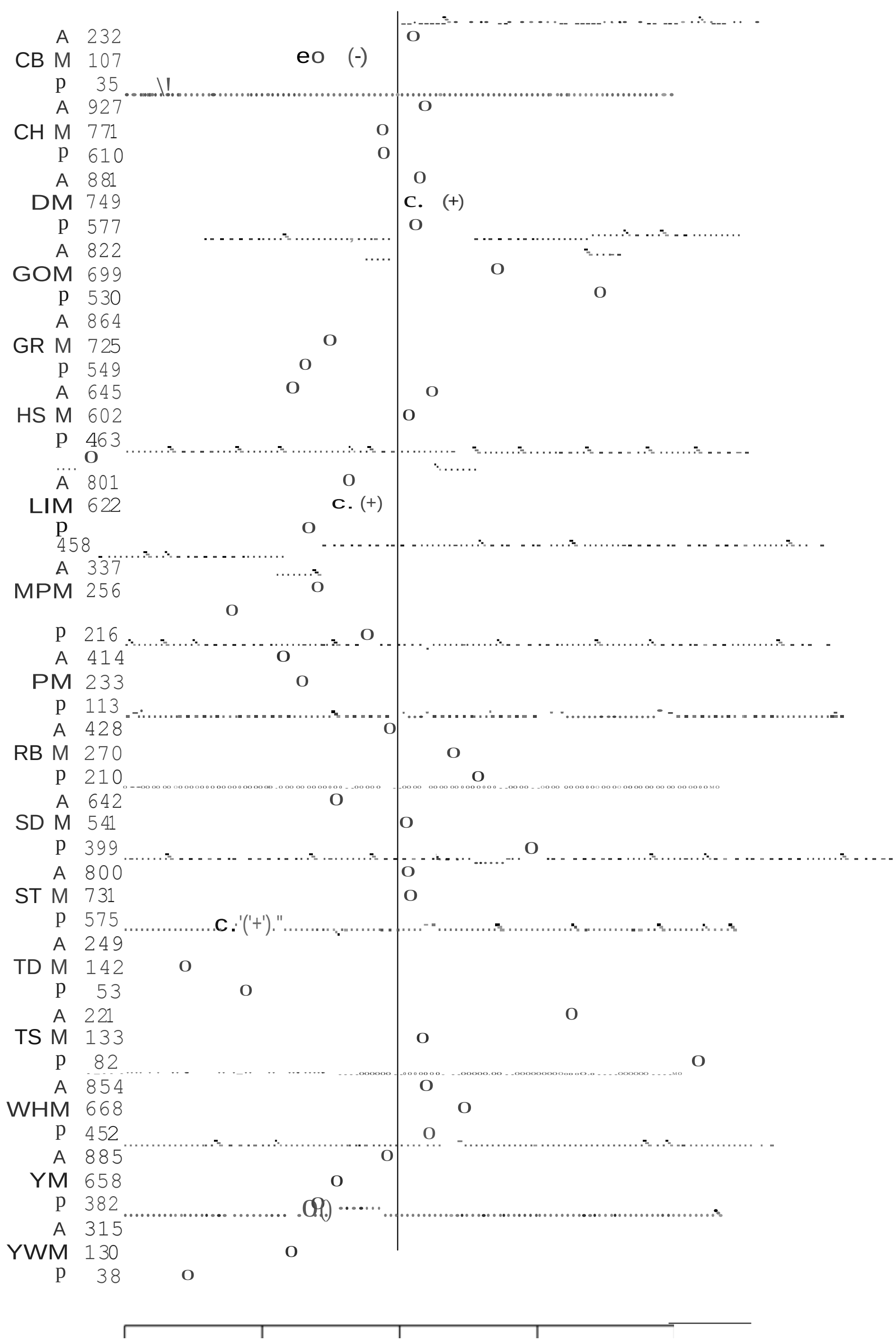

Grassland management 1km2
0
0.5
1.5
2
Population growth rate over 9 yrs plus additional growth
per 1ha (1%) land under grassland management

Figure 4

a) Arable margin management



0 0.5 rowth per 1ha (1%) land under arable margin management 1 1.5 2

Population growth rate over 9 yrs plus additional g

b) Grassland margin management

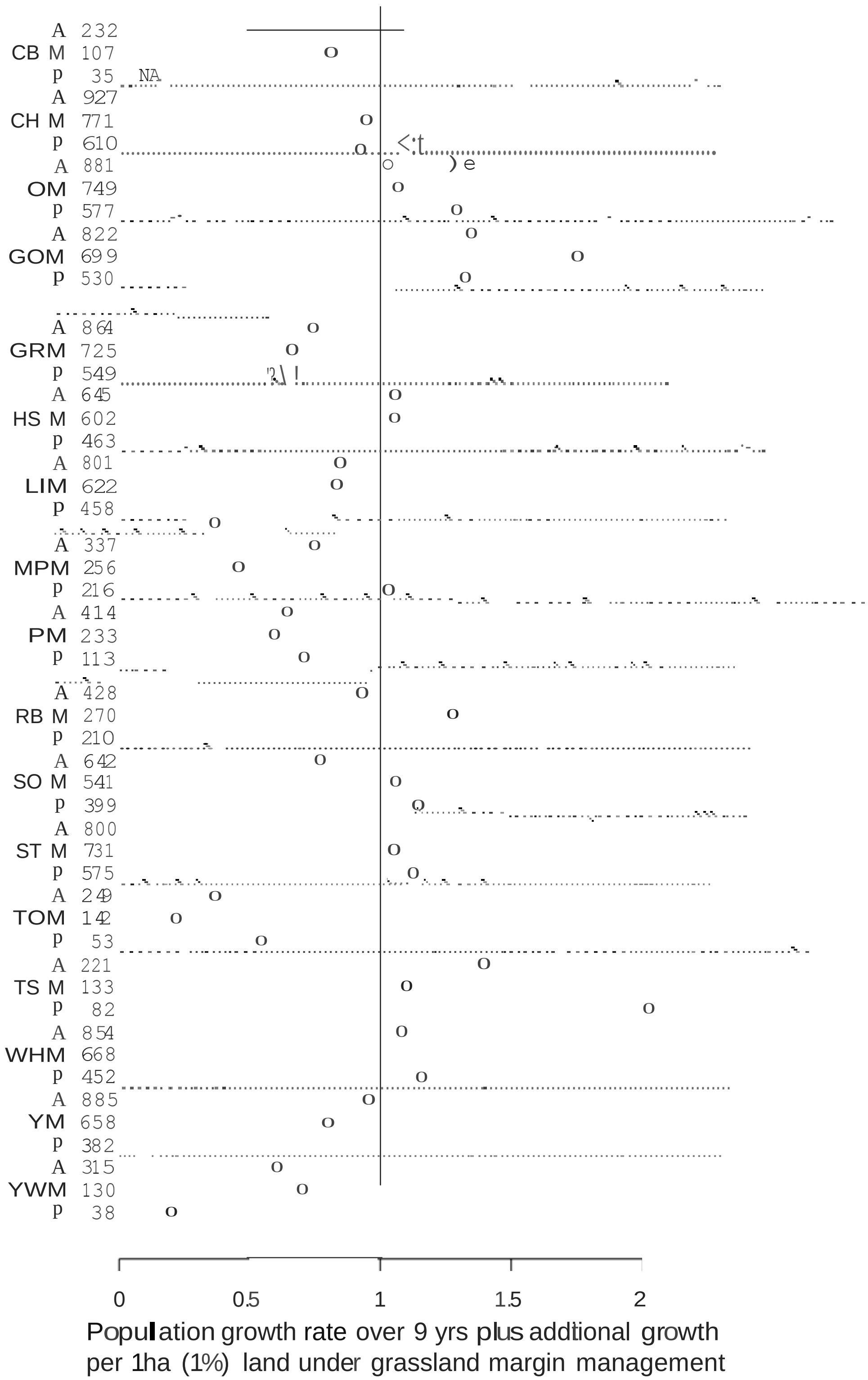


Figure 5

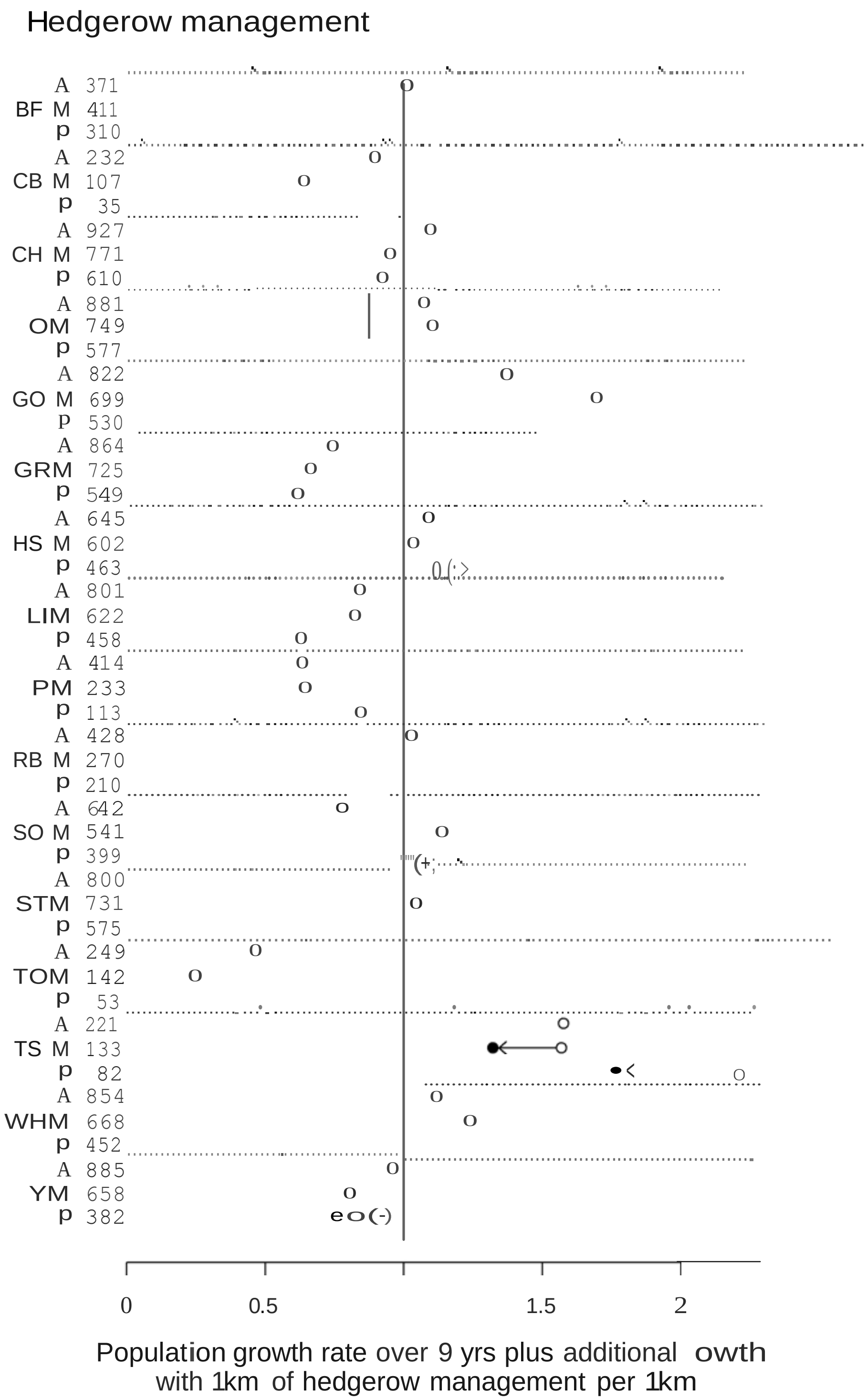
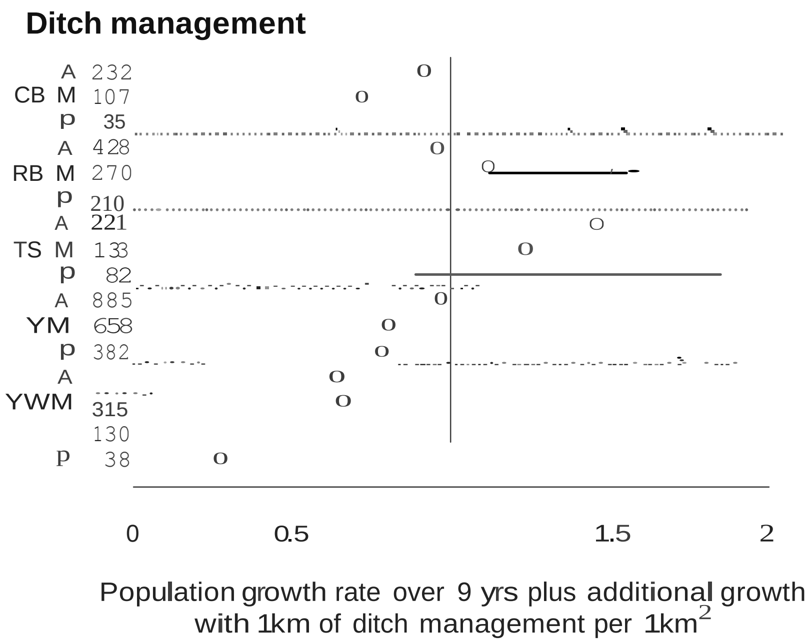

Hedgerow management
A 371
BF M 411
P 310
A 232
CB M 107
P 35
A 927
CH M 771
P 610
A 881
OM 749
P 577
A 822
GO M 699
P 530
A 864
GRM 725
P 549
A 645
HS M 602
P 463
A 801
LIM 622
P 458
A 414
PM 233
P 113
A 428
RB M 270
P 210
A 642
SO M 541
P 399
A 800
STM 731
P 575
A 249
TOM 142
P 53
A 221
TS M 133
P 82
A 854
WHM 668
P 452
A 885
YM 658
P 382
0
0.5
1.5
2
Population growth rate over 9 yrs plus additional owth
with 1km of hedgerow management per 1km

Figure 6


Ditch management
CB
RB
TS
YM
YWM
A
M
P
232
107
35
428
270
210
221
133
82
885
658
382
315
130
38
0
0.5
1.5
2
Population growth rate over 9 yrs plus additional growth with 1km of ditch management per 1km2