# A new framework of spatial targeting for single-species conservation planning

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## Abstract

*Context*

Organisations acting to conserve and protect species across large spatial scales prioritise to optimise use of resources. Spatial conservation prioritization tools typically focus on identifying areas containing species groups of interest, with few tools used to identify the best areas for single-species conservation, in particular, to conserve currently widespread but declining species.

*Objective*

A single-species prioritization framework, based on temporal and spatial patterns of occupancy and abundance, was developed to spatially prioritise conservation action for widespread species by identifying smaller areas to work within to achieve predefined conservation objectives.

*Methods*

We demonstrate our approach for 29 widespread bird species in the UK, using breeding bird atlas data from two periods to define distribution, relative abundance and change in relative abundance. We selected occupied 10-km squares with abundance trends that matched species conservation objectives relating to maintaining or increasing population size or range, and then identified spatial clusters of squares for each objective using a Getis-Ord-Gi* or near neighbour analysis.

*Results*

For each species, the framework identified clusters of 20-km squares that enabled us to identify small areas in which species recovery action could be prioritised.

*Conclusions*

Our approach identified a proportion of species' ranges to prioritize for species recovery. This approach is a relatively quick process that can be used to inform single-species conservation for any taxa if sufficiently fine-scale occupancy and abundance information is available for two or more time periods. This is a relatively simple first step for planning single-species focussed conservation to help optimise resource use.

Keywords: Spatial conservation prioritization · Conservation intervention · Widespread species · Isolated population · Bird atlas· Abundance

## Introduction

Conservation resources are limited and need to be used efficiently and where they can be most effective. To help achieve this many frameworks for spatial prioritization have been developed and implemented across ecological systems (Moilanen et al. 2008; Moilanen et al. 2009; Winiarski et al. 2014). Spatial conservation prioritization (SCP) frameworks typically concern the identification of priority areas to guide conservation resource allocation and are most commonly applied to identify areas for protection and habitat restoration, or to avoid and mitigate the negative impacts of economic development. Areas for prioritization are usually identified by using groups of particular species or habitats, typically based on threat or taxonomic classification and complementarity (although see Beger et al. 2010). SCP most commonly uses data describing species distributions, habitat types and connectivity to derive decisions, but can incorporate other types of data.

SCP methods are infrequently applied to guide the allocation of conservation resources for single species (although see Sirkia et al. 2012; Wan et al. 2014), despite sharing the same principles and the suitability of software tools such as Marxan (Watts et al. 2009) and Zonation (Moilanen et al. 2005). This may arise because SCP tends to focus on identifying areas that contain the greatest richness in biodiversity or groups of species of particular interest, thereby potentially providing a greater return on investment. Consequently, much SCP is based upon complementarity mapping, identifying hotspots of overlapping interest which may then enable protection or restoration through conservation networks and/or protected areas (Moilanen et al. 2009; Wilson et al. 2011; Wilson et al. 2007). At the same time however, many conservation organisations invest in single-species programmes (Young et al. 2014), but very few have used SCP to inform resource allocation formally.

Many species identified as conservation priorities are rare and localised in distribution, and thus there is less need for SCP; it is relatively easy to identify areas containing the most important populations and ranges are often small enough for entire populations to be the focus of conservation efforts. However, there is growing awareness of steep declines in species which remain relatively common and widespread. Range-wide declines of such species are becoming evident worldwide, for example, in many birds (Hoffmann et al. 2018; Inger et al. 2015) and invertebrates (Conrad et al. 2006; Van Dyck et al. 2009). Conserving common and widespread species may be critical as they have a greater biomass and importance in terms of ecosystem function compared to rare species (Gaston and Fuller 2007), and even small reductions in these species results in large losses in the total number of individuals. For widespread but declining species, deciding where resources are best allocated spatially can be more difficult and will be more important when whole-range action is not feasible. Site-based actions, for example in protected areas, are only likely to influence relatively small proportions of such populationsand so landscape-scale interventions, such as those provided through Agri-Environment Schemes (AES) in Europe, are required. These must be applied over a sufficient area to benefit a high proportion of the target species' population to enable impact at the population level (Kleijn et al. 2011).

The fundamental outcomes of species conservation are usually expressed in terms of species population size or density and range extent. Targets may include preventing further loss of numbers or range in declining species, maintaining numbers and range, and increasing numbers and range of species depleted following previous declines. Population size and range extent are not independent, and tend to be positively correlated, but the form of this relationship varies between species (Gaston et al. 2000). These multiple conservation aims are reflected in targets set by biodiversity frameworks such as the Aichi biodiversity targets (CBD 2010) and species Favourable Conservation Status, as set out under the EU Habitats Directive (Mehtälä and Vuorisalo 2007). These frameworks are often underpinned by assessments of species extinction risk, as defined by the IUCN Red List, which considers both range and population size in red-listing criteria (IUCN 2012). Whether conservation action should primarily aim to maintain or increase the range of a given priority species, or to maintain or increase the population size, or both, will be dependent on drivers of decline, prior and current status, available resources and the tractability of implementing conservation solutions.

Decisions on where to focus conservation interventions can be informed by using spatial and temporal trends in abundance (Johnston et al. 2015). Species abundance, and abundance change over time, vary spatially due to landscape variation in habitat availability and quality, climate, elevation, and in intra- and interspecific competition mediated survival and demography (Newton 1988). In addition, we might expect different population-level responses to conservation interventions depending on where they are applied within a species' range, for example, where existing abundance is high or low, and where the temporal abundance trend is increasing or decreasing. Although evidence of spatial variation in the success of species' conservation interventions is almost totally lacking (Murdoch et al. 2007), SCP can use spatially explicit abundance information to identify priorities according to species conservation objectives, namely those focussed on maintaining or increasing population size or range extent.

Here we illustrate a pragmatic single-species SCP framework. The framework aims to prioritise conservation action for relatively widespread declining bird species by identifying smaller areas to work within to achieve predefined conservation objectives. Our framework first defines conservation need for a species by assessing its stage along a theoretical 'species recovery curve' and then identifies and maps potential target areas for conservation action, based on spatial and temporal patterns in abundance.

## Species selection

A species prioritisation approach based on the Birds of Conservation Concern assessment process (BoCC, Eaton et al. 2015) is used by the Royal Society for the Protection of Birds (RSPB), a large nature conservation organisation in the UK. BoCC is a well-established, objective assessment of the status of all bird species in the UK, Channel Islands and Isle of Man, placing each species on a Red, Amber or Green list of conservation concern, with Red-listed species being of the highest concern.

We test and illustrate our framework with 29 bird species of conservation concern in the UK, all either Red or Amber listed in the latest BoCC assessment. From the complete UK Red (67 species) and Amber (96 species) list, we used breeding season data from a bird atlas conducted in Britain and Ireland during 2008–11 (Balmer et al. 2013) to exclude species that did not breed in the UK and those with a coastal breeding distribution. From the remaining 115 species, we next selected the 71 that were considered breeding in 7% or more 10-km squares throughout Britain and Ireland, with these species defined for our study as widespread species for which targeting the whole of the UK is impractical. We excluded Red grouse as most grouse populations are managed for commercial shooting and two species (Bullfinch and Reed bunting) that although listed by BoCC, have more recently seen an increase in population trend and so are not of immediate conservation concern. Finally, we reduced our species list further by selecting species for which reasons for decline were at least partly known and resulted from factors acting from within the UK, as these are the species for which evidence-based conservation interventions can be implemented within the UK breeding range.

## Stages of species recovery

A managed process of species recovery can be described as following a series of stages, depicted as a theoretical 'species recovery curve' (Fig. 1). This approach is based on similar use in human healthcare, has been used by the RSPB and other conservation organisations (Moorhouse et al. 2015) and is similar to one described by Westwood et. al. (2014). This species recovery curve is a simple means of representing hypothetical steps to restore the favourable status of a species. There are four distinct stages; 1) **diagnostic research** - determining the causes of poor conservation status; 2) **testing solution research** - development and testing of practical management solutions; 3) **recovery management** - the deployment of identified solutions and evaluation of species response, and 4) **sustainable management** of the recovered population. Species are allocated to curve stages based on best available evidence by RSPB staff and annually reviewed. Species can be considered to be at multiple stages of the recovery curve because of differing progress in different habitats or areas, between which drivers of change, and/or conservation interventions, may differ.

Species recovery is achieved by progress through the recovery curve through a range of mechanisms, including dedicated intervention projects, site acquisition and management, land and sea management advocacy, site protection and influencing government policies, e.g. on land management and the marine environment. Species recovery is a long-term process and it is important to continue with a recovery programme until the target population has reached a self-sustaining level, meaning it will remain with a stable or increasing population without the requirement for specific interventions.

## Deciding species conservation objectives

While it is self-evident that clear objectives are required from the outset of species recovery projects, we question whether these are always sufficiently well-defined and articulated. Here we define four sequential objectives, based on improvements in species status as measured by population size and range extent (Table 2). Species conservation Objective 1 is to stop ongoing population decline, i.e. maintain current population size or population density. Objective 2 is to reverse previous population decline, i.e. increase population size. Once a population is increasing in number, Objective 3 would then secure (maintain) the current range, if this has not been achieved already. Population increases may not necessarily be accompanied by range expansion and may even occur despite continuing range loss, particularly if delivered through spatially targeted conservation action within the existing range. Finally, Objective 4 would be to increase the range, most obviously (although not necessarily) back into areas previously occupied. There may be cases where maintaining and increasing population size objectives may be acted upon simultaneously, for example through a single intervention. In our example, conservation objectives were defined for species based on their stage on the species recovery curve (Fig. 1).

## Identifying priority target areas for species

### Species data

Species breeding ranges were defined by the occupancy of 10-km squares using breeding season data from a bird atlas conducted in Britain and Ireland during 2008–11 (Balmer et al. 2013). Although we were only interested in identifying areas for targeting in the UK for our example, our analyses included the Republic of Ireland as patterns of abundance and distribution there could influence the identification of squares for targeting within Northern Ireland; although squares identified in the Republic of Ireland were excluded from the final stage and so were not displayed in the final maps. Changes in species abundance were approximated using changes in relative abundance between the 2008–11 atlas (atlas 2) and the preceding atlas (atlas 1), for which fieldwork was undertaken during 1988–91 (Gibbons et al. 1993). Both atlases generated relative abundance maps using species lists from two 1-hour field surveys conducted in each of a minimum of eight 'tetrads' (2×2-km squares) per 10-km square between 1 April and 31 July. We used relative abundance maps generated by the method of Balmer et al. (2013). Relative abundance estimates for species for each 10-km square (relative to all other squares) were calculated from the standardized tetrad visits by one of three methods depending on species, with the most refined approach used that the data for a species permitted. These three methods either map actual counts in each square, smooth data with square values adjusted according to counts in adjacent squares, or use predictive models that include variables such as habitat. For our analysis the resulting maps were then summarised and displayed to a 20x20-km square resolution.

## Identifying priority target areas

Deciding which areas to prioritise depends on the aim of the intervention. If the aim is to maintain the population size of a declining population (Objective 1), we suggest that remaining areas of high relative density should be targeted to conserve remaining populations and reduce further loss. In contrast, if the aim is to increase population size (Objective 2), we propose to focus effort on areas that have undergone recent declines in abundance, on the basis that these areas could, with suitable conservation intervention, have the capacity to return a species to a higher density. Where lost recently, dependent on the reason for loss which first needs addressing, areas that have experienced a relatively recent decline are more likely to have retained the same environmental conditions and habitats compared to areas where species have been in decline over a longer period. Areas where populations have been in decline over longer periods of time are more likely to require interventions which take longer to achieve and are more costly, such as through habitat creation, or because species' life histories result in both slow decline and recovery, such as long-lived species with low fecundity where individuals continue to breed but with low breeding success causing decline, in conjunction with having a relatively late recruitment age, resulting in slow population recovery (Jenouvrier et al. 2009; Sæther and Bakke 2000). Objectives 3 and 4 for species' range might be best met by targeting action in areas of lower density to prevent local extinction (in order to maintain range) due to small populations being at a greater risk of extinction (Purvis et al. 2000), or targeting action in areas where a species has gone extinct recently if there is evidence that conservation interventions could increase range, i.e. if suitable habitat and conditions remain and reasons for loss has been adequately addressed.

Priority areas for targeting conservation action were identified by a map-based analysis (Fig. 2). For the species conservation Objectives 1-3, target areas were identified using spatial cluster analysis on subsets of occupied 10-km squares. Cluster analysis identifies groupings that share characteristics. We used the Getis-Ord Gi* statistic calculated within ArcMap 10.5 (ESRI, 2016), a statistic typically used for identifying clusters of events (Baruch-Mordo et al. 2008), but also for guiding species prioritization (Kober et al. 2012). The Getis-Ord Gi* statistic assesses clustering and provides information about local high and low clustering across a study extent. In our framework this tested, for each species separately, the degree to which each square where a species was present was surrounded by squares with similarly high or low clustering within a specified geographical distance. Our specified distance was a minimum fixed (Euclidean) distance band, the minimum distance that ensured every square where a species was present had at least one other occupied square to make clustering assessments with. A Z-score and P value were returned for each square, which indicate whether spatial clustering is more pronounced than expected in a random distribution. To identify priority areas, we ordered squares by Z-score, in ascending or descending order according to species conservation objective, and the number of targeting squares we selected for the final stage was predetermined for each species based on the number of occupied 10-km squares in atlas 2. For species found in 7-20% of 10-km squares in atlas 2 (including Republic of Ireland), we selected the top 40% of 10-km squares, for species found in 20-40% of 10-km squares in atlas 2, we selected the top 30%, and for species found in 40-100% of 10km atlas squares, we selected the top 20%. This approach aimed to ensure that target areas covered an area that could be affordable and practical to work within.

The Getis-Ord Gi* equation used in the ArcMap tool is:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[ n \sum_{j=1}^{n} w_{i,j}^2 - \left( \sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}$$

where $x_j$ is the attribute value for feature $_j$, $w_{i,j}$ is the spatial weight between locations of $_i$ relative to $_j$, $n$ is equal to the number of features and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\bar{X}\right)^2}$$

For species conservation Objective 1 'maintain population size', a Getis-Ord Gi* analysis was run on the relative abundance value of occupied squares using atlas 2 data. Squares were then ranked in descending order by Z-score and the number of squares selected for targeting based was 20, 30 or 40% of species range according to the total number of 10-km squares occupied by the species in atlas 2.

For species conservation objective 2 'increase population size', first a map layer that only included occupied squares that had declines in relative abundance between the two atlases was selected. The Getis-Ord Gi* analysis was run for this subset of squares, using values of absolute change in relative abundance between atlas 1 and atlas 2. Squares were then ranked in ascending order by Z-score and the number of squares selected for targeting based was 20, 30 or 40% of species range according to the total number of 10-km squares occupied by the species in atlas 2.

For species conservation objective 3 'maintain range', a Getis-Ord Gi* analysis was run on the relative abundance value of occupied squares using atlas 2 data. Squares were then ranked in ascending order by Z-score and the number of squares selected for targeting based was 20, 30 or 40% of species range according to the total number of 10-km squares occupied by the species in atlas 2, which represented spatial clusters of squares that showed the lowest abundance.

For species conservation objective 4 'increase range', squares that had no recorded occupancy in atlas 2, but that did have occupancy recorded in atlas 1, were identified. We calculated the distance between squares where the species was found in atlas 2 with squares where the species had been lost between atlas 1 and atlas 2. From these squares, we then only selected the squares that were within 50km of a square occupied in atlas 2 for targeting.

For our illustration, we sought to prioritize species conservation work within ten UK operational areas used by the RSPB. Each area has a work programme revised every five years guided by a national organisational strategy. These operational areas defined the spatial units used for our final assessment.

Operational areas containing >30% of identified target squares were defined as the highest priority for the stated objective (Target Area 1), those containing 10-30% of target squares as medium priority (Target Area 2) and those containing <10% of target squares as lower priority (Target Area 3). We calculated Target Area category values within the GIS using the 'Frequency' and 'Field Calculator' tools. Finally, all resulting maps were converted to a raster map, to a 20-km resolution summarising by the mean Target Area category. We intentionally produced maps at the 20-km scale to avoid over-interpretation by end-users to specific sites or populations, but maps could be generated at any spatial scale equal to or larger than the occupancy and abundance data available.

## Target areas identified

Maps for all 29 species (Online Resource, Fig. S1), over all relevant species conservation objectives, identified a mean of 87.6 20-km squares per species in which to target species recovery work (Table 3), from which one (for 25 species) or two (for three species) operational areas per species were identified as being of the highest priority for targeting (Target Area 1). For the species conservation Objective 1 'maintain population size', the 26 species for which this was mapped had a mean of 87.5 20-km squares identified (range 22-181) over a mean of 4.3 operational areas (range 1-9). For Objective 2, 'increase population size' the 10 species maps had a mean of 113.1 20-km squares (range 6-181) and identified a mean of 5.5 operational areas (range 2-7). For Objective 3 'maintain range' the four maps had a mean of 60.5 20-km squares (range 8-118) and identified a mean of 5.3 operational areas (range 2-9). Although none of the 29 species reached Objective 4 'increase range' on the recovery curve, we did map this for two species, Corncrake *Crex crex* because this species has been subject to a previous reintroduction programme to England (Carter and Newbery 2004), and Nightjar *Caprimulgus europaeus* because if the recent increasing population trend continues but range remains static, this could be a realistic objective in the near future. These two 'increase range' maps had a mean of 15.5 20-km squares (range 14-17) and four operational areas (range 3-5) identified (Fig. S1).

Of the 11 species which had more than one species' conservation objective mapped, eight resulted in different operational areas being identified as the highest priority for different conservation objectives. While this is expected where objectives oppose each other, for example high versus low abundance, this is an important because it suggests that areas selected for conservation intervention by SCP will in most cases vary according to the conservation objective. Although not examined in our single-species approach, this pattern is also likely to apply if multi-species congruence type approaches of SCP based on abundance trends are used. This reinforces the recognised need to set very clear objectives for species recovery programmes, as well as for SCP (Jones et al. 2018; Lehtomäki and Moilanen 2013), whether applying single-species or multi-species approaches, and revising the objectives as species recover.

## Discussion and conclusions

Ecological assessments to inform where to target conservation resources are important as these resources are finite and need to be used wisely. We illustrate a relatively simple framework to help guide spatial targeting using existing data on species abundance and distribution. While the methods that we use to identify spatial aggregation are not new, their application to inform the spatial targeting of single-species conservation programmes is more novel. Our framework resulted in identifying a single area to our highest priority targeting category for most species (93%), and generally suggested clear spatial priorities in respect of individual species and objectives defined by the species' conservation objectives we used. This should therefore allow for a more efficient and successful approach to conservation planning.

For most species, target areas identified by our framework differed according to the species conservation objective. These objectives will themselves be influenced by the current trend and status of a species, and both these may change as a species responds to conservation intervention. Therefore, assessments of these should be made a-priori and either the mapping exercise repeated as circumstances change, or all the objectives should be mapped for each species to aid planning ahead. For example, where to target conservation effort for a species based on a 'maintain range' objective map might be influenced by where effort is recommended based on the 'increase range' objective map, or versa visa. This may avoid the possibility that as a species progresses through the recovery stages work is stopped in one area and started in another.

Our framework could be applied to any species of flora or fauna for which trends in distribution and abundance are well known across the entire area of interest. Birds in the UK have been particularly well monitored for decades and so our example was able to use high quality data for the whole of the area at a relatively fine spatial resolution. However, monitoring schemes for other taxa (Schmeller et al. 2009), and for birds in previously less well monitored areas (Underhill et al. 2017;

Wotton et al. 2018), are becoming established in many parts of the world and will provide future opportunities for similar prioritization exercises. Advances in estimating abundance (Dennis et al. 2013) and new methods of monitoring at large spatial extents (Biggs et al. 2015) further increase the availability of suitable data for a range of taxa. For many taxa, prioritization exercises may still be meaningful at smaller spatial scales, so a national monitoring scheme is not a prerequisite.

There are a number of ways our framework could be improved. For example, our targeting maps only take into account the extent and location of suitable available habitat or elevation/climatic conditions (i.e. a species' climatic niche) via the actual species' distributions. Our framework does not consider how species might respond to future climatic change, both in terms of potential range shift to include new areas and the loss of other areas (Gillings et al. 2015), or in terms of how climatic change may spatially alter species abundance (Stephens et al. 2016).

Different approaches may need to be considered for certain species groups. Atlas data are potentially less accurate, especially in mapping abundance, for species poorly detected by generic atlas survey methods, such as nocturnal or cryptic species (including Nightingale *Luscinia megarhynchos* and Woodcock *Scolopax rusticola*, which we included in our illustration). For such species, data from repeated single-species surveys with tailored methodology to maximise detection, could be used in a similar way to that described here. Also it should be borne in mind that our example is dependent on interventions made within the breeding range being successful in effecting recovery. While this is likely to be true for most of the species we selected, as the reasons for decline are at least partly known, for other species conservation interventions may be required to address drivers acting upon populations in the non-breeding season. For example, some resident UK species' breeding populations are influenced by factors that occur during the winter (Siriwardena et al. 2006). Migratory species have multiple life stages in which factors can influence population dynamics and many species show spatial variation in population trends (Morrison et al. 2013). Conserving mobile and migratory species is a challenge for SCP generally (Runge et al. 2014), although most migratory birds tend to show high between-year site philopatry (Paradis et al. 1998), meaning species' ranges and priority areas will not differ between years, unless undergoing rapid contraction or expansion. Most seabirds and some other highly colonial nesting species may also require a different approach because the locations needed to implement conservation interventions could be marine foraging areas or breeding colonies, and because breeding distributions are often exclusively coastal.

Finally, pragmatically, resource allocation is not decided purely based upon species biology. Many economic, political, social and logistical considerations that we did not include also need consideration (Mazor et al. 2014; Naidoo et al. 2006). A parallel framework, or second stage assessment, could incorporate such non-biological factors along with the recommendations resulting from our spatial framework.

There are also broader issues concerning SCP. We still lack a comprehensive understanding of where to target conservation action within species ranges in order to achieve particular objectives, including maintaining or increasing population size and range. For example, it is not known whether it is better to target conservation action in the core of species' ranges or at the edge, in areas of high or low abundance, or in areas where populations are currently stable or decreasing, and optimal targeting is likely to vary between species and circumstances.

Optimisation methods are commonly used to prioritize populations in a metapopulation context (Moilanen and Cabeza 2002), and Spatially Explicit Population Models (SEPMs, e.g. Dunning et al. 1995) incorporating abundance data are used to prioritize habitats or habitat patches to direct single-species work within (e.g. Conlisk et al. 2014; Minor and Urban 2007). Where spatially explicit information exists for a species' metapopulation dynamics, habitat availability and quality, and connectivity (Hodgson et al. 2011), SEPMs should provide better guidance on where to work than our simple framework. However, such methods will frequently identify priority populations or habitats that are scattered spatially; our framework is designed to identify one or few relatively small areas. Furthermore, the highly detailed level of information required for SEPMs is often not known or available, and SEPMs usually only address one conservation objective. Our basic framework requires less information about a species and can be used for multiple and dynamic objectives.

For single-species SCP, spatial targeting based on multi-species complementarity hotspot approaches is unlikely to be the most effective in delivering conservation action. Approaches that encapsulate spatial and temporal variation in abundance, ecological traits and demography across distributions are required. Our simple and adaptable framework incorporates one of these, abundance. As we gain a more complete knowledge of a species' metapopulation dynamics and of spatial variation in species' demography and effectiveness of conservation interventions, it should be possible to include these in more complex frameworks. Once the spatial prioritization process has been completed for a species, congruence approaches can then be used to identify overlap in priority areas across groups of species; this would be particularly valuable when there is overlap or synergy between the conservation actions required. Conservation planning is an on-going process in which current decisions set the stage for those to be made in the future (Costello and Polasky 2004; Murdoch et al. 2007). Our simple framework is a starting point that can be built on or tailored to suit other taxa, spatial scale or conservation strategy.

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## Open access

The bird atlas data used in this study is available from the British Trust for Ornithology upon request (http://www.bto.org/research-data-services/data-services/data-request-system).

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| Species recovery stage actions | Species recovery objective |
|---|---|
| Diagnostic research (D): Undertake research to understand cause of decline. | Maintain population size, while diagnosing causes of decline. |
| Trial solution research (T): Undertake and assess trial management until it provides evidence that management interventions are effective. | Maintain population size, while devising management solution. |
| Recovery management (R): Conservation interventions adopted across the species' range which enable achievement against population/range targets with continued conservation intervention. | Maintain population size while solutions become adopted. Increase population size once solutions adopted range wide. Maintain range once population has increased above predetermined threshold.<br>Consider increasing range where recovered populations are at risk from stochastic events. |
| Sustainable management (S): Continued management through conservation interventions until evidence that population/range targets are being achieved and can be sustained with little or no conservation intervention. | Maintain population size and maintain range. Consider reducing conservation intervention resource. |

**Table 1.** Description of each stage of a hypothetical species recovery curve, and corresponding species recovery objective.

| Objective | Aim | Method |
|---|---|---|
| 1)<br>Maintain population size | Prevent further population decline, by targeting effort at remaining higher abundance areas where this will act upon a relatively large proportion of the remaining population | Spatial cluster analysis using relative abundance in atlas 2. Target identified squares with the highest relative abundance |
| 2)<br>Increase population size | Target effort in areas where declines in abundance have been most severe but species is still present, and thus has the potential to recover to previous levels | Restrict analysis to only squares that saw declines in abundance between atlas's. Spatial cluster analysis using change in relative abundance in atlas 2. Target identified squares with the lowest relative abundance |
| 3)<br>Maintain range | Target effort in areas where species is still present but at low density, where local extinction (and hence range loss) is most likely | Spatial cluster analysis, using relative abundance in atlas 2. Target squares with the lowest relative abundance |
| 4)<br>Increase range | Target areas from which the species has been lost but which were occupied in previous assessment – areas where a species has been lost from relatively recently are most likely to be reoccupied. | Squares that had no recorded occupancy in atlas 2 but that did have occupancy recorded in atlas 1 were identified. Target all identified squares that were within a distance of 50km from squares occupied in atlas 2 |

**Table 2.** Species conservation objectives, their aims and the methods used to create targeting maps for each objective.

|  |  | 1) Maintain population size |  |  | 2) Increase population size |  |  | 3) Maintain range |  |  | 4) Increase range |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Recovery curve stage(s) | Target 20-km squares | Number of operational areas identified | Number of operational areas containing Target Area 1 | Target 20-km squares | Number of operational areas identified | Number of operational areas containing Target Area 1 | Target 20-km squares | Number of operational areas identified | Number of operational areas containing Target Area 1 | Target 20-km squares | Number of operational areas identified | Number of operational areas containing Target Area 1 |
| Black grouse | T and R | 36 | 2 | 2 |  |  |  |  |  |  |  |  |  |
| Corn bunting | T and R | 72 | 5 | 1 | 72 | 6 | 1 |  |  |  |  |  |  |
| Corncrake | T and R |  |  |  | 6 | 2 | 1 | 9 | 3 | 1 | 17 | 3 | 2 |
| Cuckoo | D | 132 | 4 | 1 |  |  |  |  |  |  |  |  |  |
| Curlew | T | 113 | 4 | 1 |  |  |  |  |  |  |  |  |  |
| Grasshopper warbler | T | 22 | 1 | 2 |  |  |  |  |  |  |  |  |  |
| Grey partridge | R | 99 | 4 | 1 | 99 | 6 | 1 |  |  |  |  |  |  |
| Hen harrier | T | 45 | 4 | 1 |  |  |  |  |  |  |  |  |  |
| House sparrow | D and R | 148 | 7 | 1 | 181 | 6 | 1 |  |  |  |  |  |  |
| Lapwing | T and R | 136 | 6 | 1 | 136 | 4 | 1 |  |  |  |  |  |  |
| Linnet | D and R | 111 | 9 | 1 |  |  |  |  |  |  |  |  |  |
| Marsh tit | T | 89 | 5 | 1 |  |  |  |  |  |  |  |  |  |
| Nightingale | D | 37 | 6 | 2 |  |  |  |  |  |  |  |  |  |
| Nightjar | D and R |  |  |  |  |  |  | 8 | 2 | 1 | 14 | 5 | 0 |
| Oystercatcher | D and T | 122 | 4 | 1 |  |  |  |  |  |  |  |  |  |
| Redshank | D and S | 107 | 7 | 1 | 116 | 6 | 2 | 118 | 9 | 0 |  |  |  |
| Ring ouzel | T | 46 | 4 | 1 |  |  |  |  |  |  |  |  |  |
| Skylark | T and R | 181 | 8 | 1 | 99 | 5 | 1 |  |  |  |  |  |  |
| Snipe | T | 46 | 2 | 2 |  |  |  |  |  |  |  |  |  |
| Song thrush | R | 74 | 5 | 2 | 181 | 7 | 1 |  |  |  |  |  |  |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Swift | D and T | 153 | 5 | 3 | | | | | | |
| Tree sparrow | R | | | | 113 | 6 | 1 | 107 | 7 | 1 |
| Turtle dove | T | 64 | 2 | 1 | | | | | | |
| Twite | D and T | 62 | 3 | 1 | | | | | | |
| Whinchat | D | 84 | 4 | 1 | | | | | | |
| Willow tit | D and T | 63 | 4 | 1 | | | | | | |
| Woodcock | D | 35 | 4 | 2 | | | | | | |
| Yellowhammer | R | 130 | 7 | 1 | 128 | 7 | 0 | | | |
| Yellow wagtail | T | 67 | 4 | 1 | | | | | | |

**Table 3.** Recovery curve stage and summary of mapping results for all 29 species analysed. For each of the four species conservation objectives that are relevant to the conservation objectives of each species, the number of 20-km squares resulting from analysis are shown together with the number of operational areas they occurred in and the number of Target Areas with the highest priority that were identified. Shaded areas indicate targeting maps that were produced for each species, with blank areas meaning that no assessment was made for that species and objective because species recovery objectives were not applicable based on their species recovery curve stage. Species recovery curve stages are explained in Table 1, with 13 species having multiple stages as these differed between habitat types or geographical areas.

**Fig. 1.** Theoretical species recovery curve. Species recovery actions undertaken at each stage D (diagnostic research), T (trial solution research), R (recovery management) and S (sustainable management) are described in Table 1.

**Fig. 2.** Stages of target map creation, using the priority area map to maintain population size for Curlew *Numenius arquata* as an example. Stages of map creation from left to right show a) relative abundance, b) result of Getis-Ord Gi* analysis with all occupied 567 10-km squares displayed by Z-Score, c) selection of the 113 10-km squares with the higest Z-Score from the Getis-Ord Gi* analysis, and d) the final targeting map. The ten operational areas (spatial units used) are shown in all maps.

**Fig. 3.** Example maps for a) Grey partridge *Perdix perdix*, b) Redshank *Tringa totanus*, c) Tree sparrow *Passer montanus*, d) Ring ouzel *Turdus torquatus* and e) Swift *Apus apus*. Column 1 shows relative abundance, column 2 change in relative abundance between atlas 1 (1988-91) and atlas 2 (2007-11), column 3 priority area map to maintain population size, column 4 priority area map to increase population size and column 5 priority area map to maintain range. For these species no priority area map to increase range was created because this objectives was not applicable based on species recovery curve stage. The ten operational areas (spatial units used) are shown in all maps.

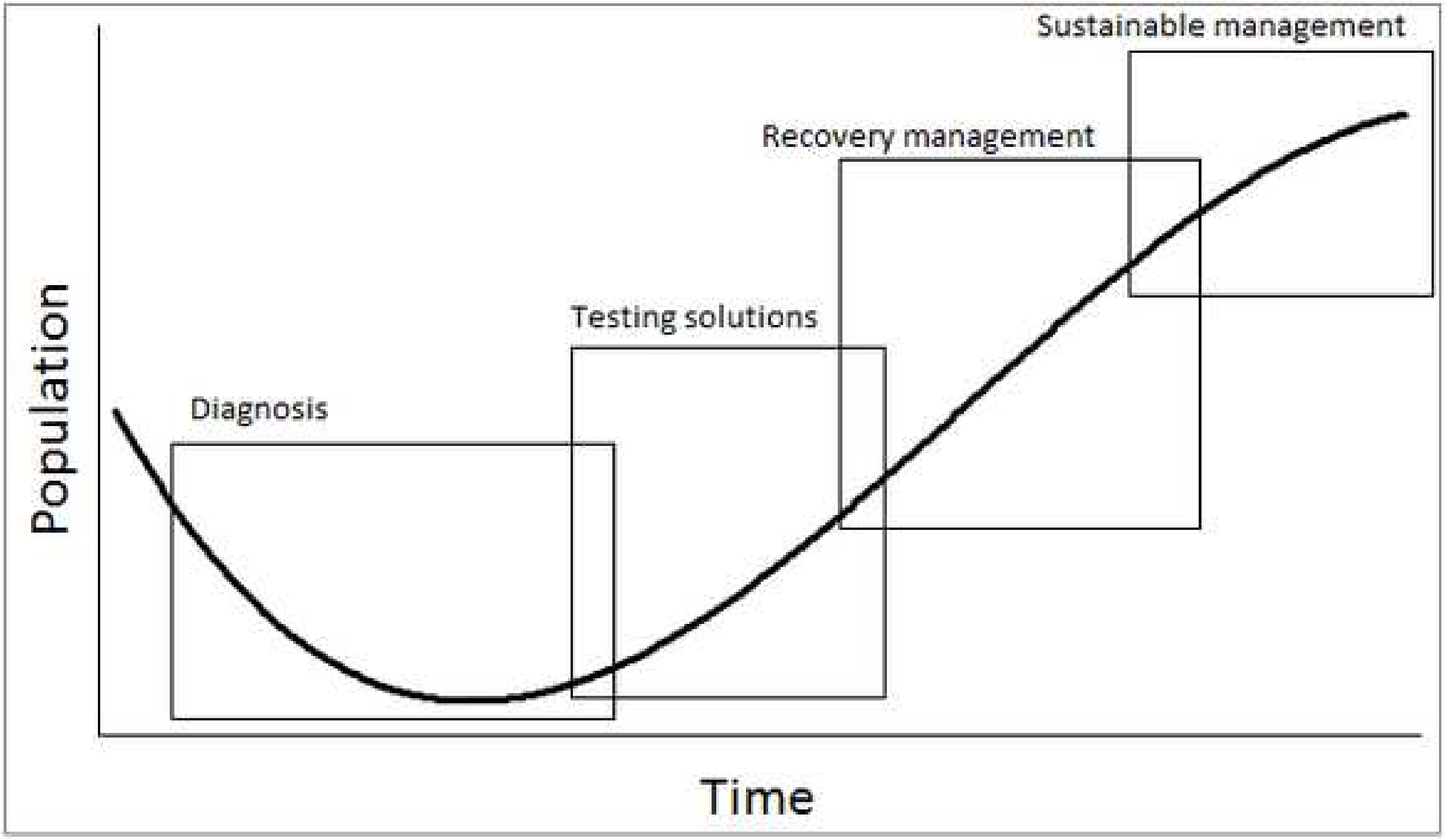
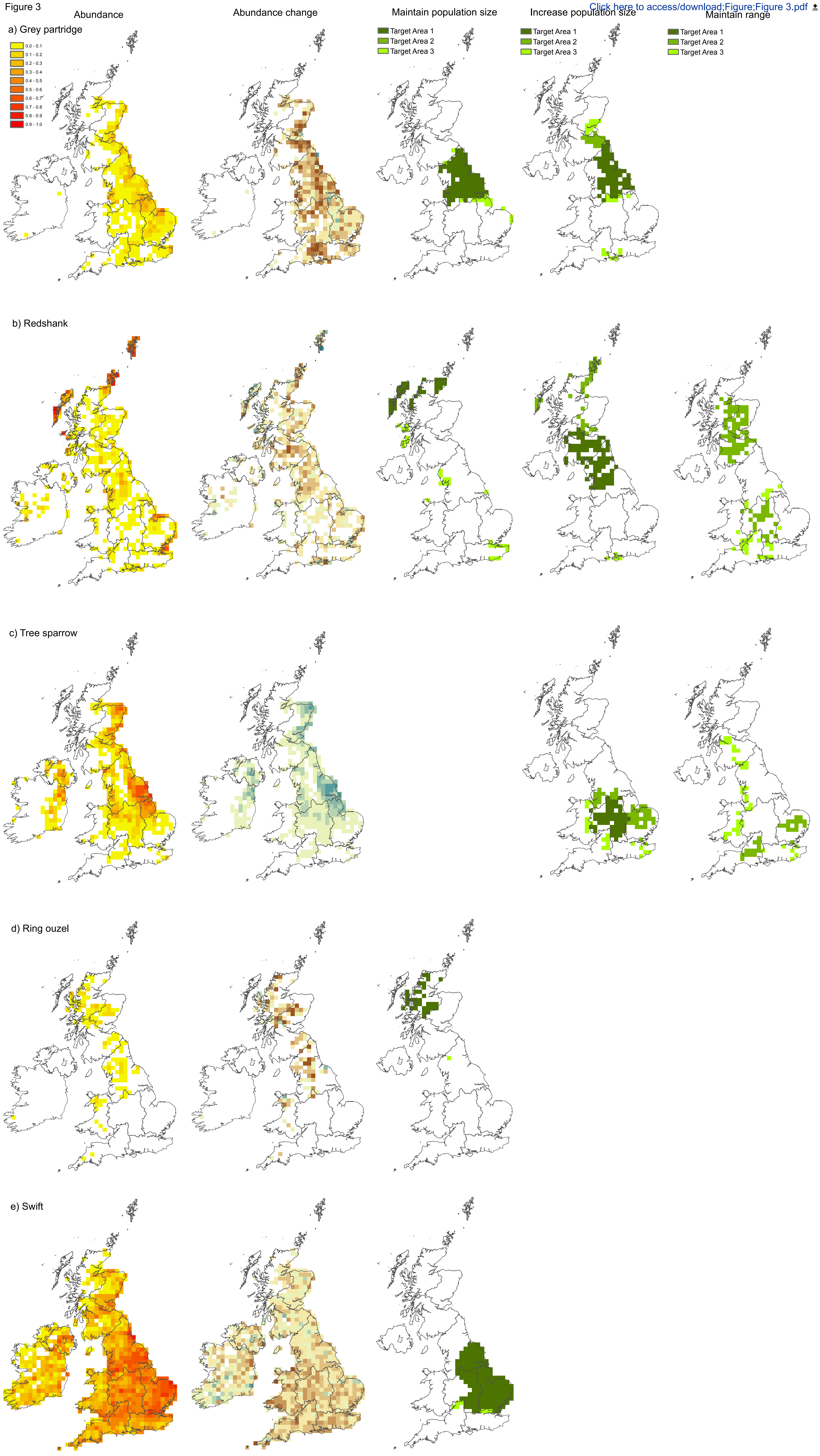

Sustainable management
Recovery management
Testing solutions
Diagnosis
Population
Time

Figure 2


a)
Relative abundance
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
b)
Z score
-4 - -2
-2 - 0
0. - 2
2 - 4
4 - 6
6 - 8
8 - 10
c)
Highest ranked Z-Score
d)
Target Area 1
Target Area 2
Target Area 3

Figure 3


Abundance
Abundance change
Maintain population size
Increase population size
Maintain range
a) Grey partridge
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
Target Area 1
Target Area 2
Target Area 3
Target Area 1
Target Area 2
Target Area 3
Target Area 1
Target Area 2
Target Area 3
b) Redshank
c) Tree sparrow
d) Ring ouzel
e) Swift

Supplementary figure 1a

Supplementary figure 1b

Supplementary figure 1c

Supplementary figure 1d

Supplementary figure 1e

Supplementary figure 1f