Biological Conservation 269 (2022) 109524

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Conservation interventions can benefit species impacted by climate change

K.M. Bowgen [a], E.F. Kettel [a,b], S.H.M. Butchart [c,d], J.A. Carr [e], W.B. Foden [f], G. Magin [g], M.D. Morecroft [h], R.K. Smith [d], B.A. Stein [i], W.J. Sutherland [d], C.B. Thaxter [a], J.W. Pearce-Higgins [a,d,*]

[a] British Trust for Ornithology, The Nunnery, Thetford, Norfolk IP24 2PU, United Kingdom
[b] Nottingham Trent University, School of Animal, Rural and Environmental Sciences, Southwell, Nottinghamshire NG25 0QF, United Kingdom
[c] BirdLife International, David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, United Kingdom
[d] Department of Zoology, University of Cambridge, The David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, United Kingdom
[e] Sustainability Research Institute, School of Earth and Environment, Faculty of Environment, University of Leeds, LS2 9JT, United Kingdom
[f] Department of Botany & Zoology, University of Stellenbosch, Stellenbosch, Western Cape, South Africa
[g] Flora & Fauna International, David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, United Kingdom
[h] Natural England, Peasholme Green, York YO1 7PX, United Kingdom
[i] National Wildlife Federation, 1200 G Street, Suite 900, Washington, DC 20005, USA

ARTICLE INFO

Keywords:
Climate change
Adaptation
Intervention
Management
Protected area
Species conservation

ABSTRACT

There is an urgent need to quantify the potential for conservation interventions to effectively manage the impacts of climate change on species' populations and ecological communities. In this first quantitative global assessment of biodiversity conservation interventions for climate change adaptation, we identified 77 peer-reviewed studies, including 443 cases describing the response of individual species' populations or assemblages to particular interventions, whilst also accounting for responses to climate change or particular climatic variables. Eighty-two percent of studies were from Europe or North America. In 30% of reported cases, interventions were regarded as beneficial (having a significant positive impact on a population also affected by a climatic variable). However, beneficial outcomes were more likely to be reported when fewer responses were analysed, suggesting a publication bias in the reporting of beneficial responses. Management focused on particular species (e.g. targeted habitat management and species recovery interventions) was modelled to have a higher probability (73%) of being beneficial than more generic interventions such as land and water management (22%) or protection (17%). Although more data on the effectiveness of climate change adaptation for species conservation are required, the diversity of examples reviewed suggests that climate change adaptation can successfully reduce negative impacts of, or enhance positive responses to, climate change. Targeted interventions maximise the persistence of the most vulnerable populations, whilst expanding habitat management and site protection interventions may benefit the largest number of species and ecosystems. The effective monitoring and evaluation of adaptation interventions is required to improve this evidence-base for future decision-making.

1. Introduction

There is increasing evidence that climate change is affecting all components of the natural world (Scheffers et al., 2016); altering the timing of biological events (Thackeray et al., 2016), disrupting species' interactions (Ockendon et al., 2014), and changing ecological communities (Stephens et al., 2016), species' population sizes (Pearce-Higgins et al., 2015; Spooner et al., 2018) and species' distributions (Chen et al., 2011). Future impacts are projected to be much greater than those previously experienced, leading to further community disruption, range shifts and increases in species' extinction risk (Urban, 2015; Warren et al., 2018). Projections of future impacts, however, are usually made without considering the potential for conservation interventions to help species and their habitats adapt to climate change.

The Paris Agreement established a global adaptation goal and invited parties to review the effectiveness of adaptation (Dilling et al., 2019). While a range of conservation interventions for climate change adaptation have been identified (Heller and Zavaleta, 2009; Prober et al.,

---

[*] Corresponding author at: British Trust for Ornithology, The Nunnery, Thetford, Norfolk IP24 2PU, United Kingdom.
E-mail address: james.pearce-higgins@bto.org (J.W. Pearce-Higgins).

https://doi.org/10.1016/j.biocon.2022.109524
Received 22 February 2021; Received in revised form 10 March 2022; Accepted 17 March 2022
Available online 30 March 2022
0006-3207/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

2019), their efficacy urgently requires testing (Greenwood et al., 2016; Morecroft et al., 2019). A number of studies have documented the impact that individual components of conservation practice have on species' responses to climate change. For example, protected areas have been shown to facilitate bird and butterfly range expansion in response to climate change (Thomas et al., 2012; Gillingham et al., 2015a, 2015b), the maintenance of areas of woodland habitat have been shown to boost woodland bird population recovery from extreme weather events (Newson et al., 2014), and targeted management can reduce the negative impact of damaging weather conditions upon vulnerable black grouse (*Tetrao tetrix*) populations (Pearce-Higgins et al., 2019). However, it is unclear whether these are isolated examples or indicative of generally positive environmental responses to climate change adaptation interventions.

Clarifying the likely success of different adaptation interventions is important to guide future conservation strategies in a changing climate (e.g. Wintle et al., 2011; Pearce-Higgins et al., 2022). For example, if interventions can increase the resilience of vulnerable species and habitats to climate change, then conservation resources could be targeted towards the most vulnerable species and habitats to minimise climate-driven extinction. However, if effective adaptation is not possible, then ongoing efforts to conserve and manage systems and species under significant threat from climate change may be misdirected or wasted (Oliver et al., 2012).

Answering questions about the effectiveness of adaptation is challenging as the outcome of adaptation has no single definition of success (Dilling et al., 2019) and depends upon predetermined objectives (Pearce-Higgins et al., 2022). In the context of biodiversity conservation, adaptation may aim to reduce exposure or vulnerability to climate change, or to enhance the capacity of species and systems to adjust to climate change (Stein et al., 2013; Prober et al., 2019). Given this context, our approach was firstly to identify studies that were relevant to understanding the potential success of those interventions for climate change adaptation. Secondly, we quantified the likelihood of adaptation having a statistically significant impact on a species affected by variation in climatic variables, by assessing the effects of interventions on the demographic parameters (survival and productivity), abundance, population growth-rates or occurrence metrics reported. Thirdly, given that the impacts of climate change vary across the globe and between species and habitats (Pearce-Higgins et al., 2015; Thackeray et al., 2016; Warren et al., 2018), and that different conservation interventions also vary in their effectiveness (Rands et al., 2010; Franks et al., 2018; Sutherland et al., 2021), we tested how the impact of adaptation interventions may vary between the context of studies (habitat, taxon, location) and the interventions being tested.

Given that we aimed to assess the effectiveness of climate change adaptation, we focused in particular on the likelihood of interventions being beneficial for the populations and systems being studied. Beneficial interventions were defined as those that have a positive effect on the responses of populations or assemblages to changes in climatic variables, by either reducing climate vulnerability or enhancing adaptive capacity (Pearce-Higgins and Green, 2014). 'Climate change adaptation' can be defined as interventions intentionally implemented in response to specific climate impacts and risks (Mawdsley et al., 2009; Stein et al., 2013). However, the science of climate change adaptation is very much in its infancy and so very few formally defined adaptation responses to climate change have so far been tested (Parmesan et al., 2022; see below). Therefore, in order to draw upon a much wider evidence-base, we also included literature that considered the effects of conservation interventions during a period of changing climatic conditions, irrespective of such intentionality (i.e. the intervention may or may not have been implemented as a response to climate change). We do so because it is the intervention itself that will influence species' responses, rather than the intention behind that intervention. However, recognising that specific adaptation interventions may be implemented differently to other conservation interventions, we tested for any difference in the probability of benefit between intentional adaptation and other conservation interventions. We focused on studies that examined impacts on species' populations and distributions, and on ecological communities, as metrics most relevant for species' conservation in the context of concerns over climate-driven extinction.

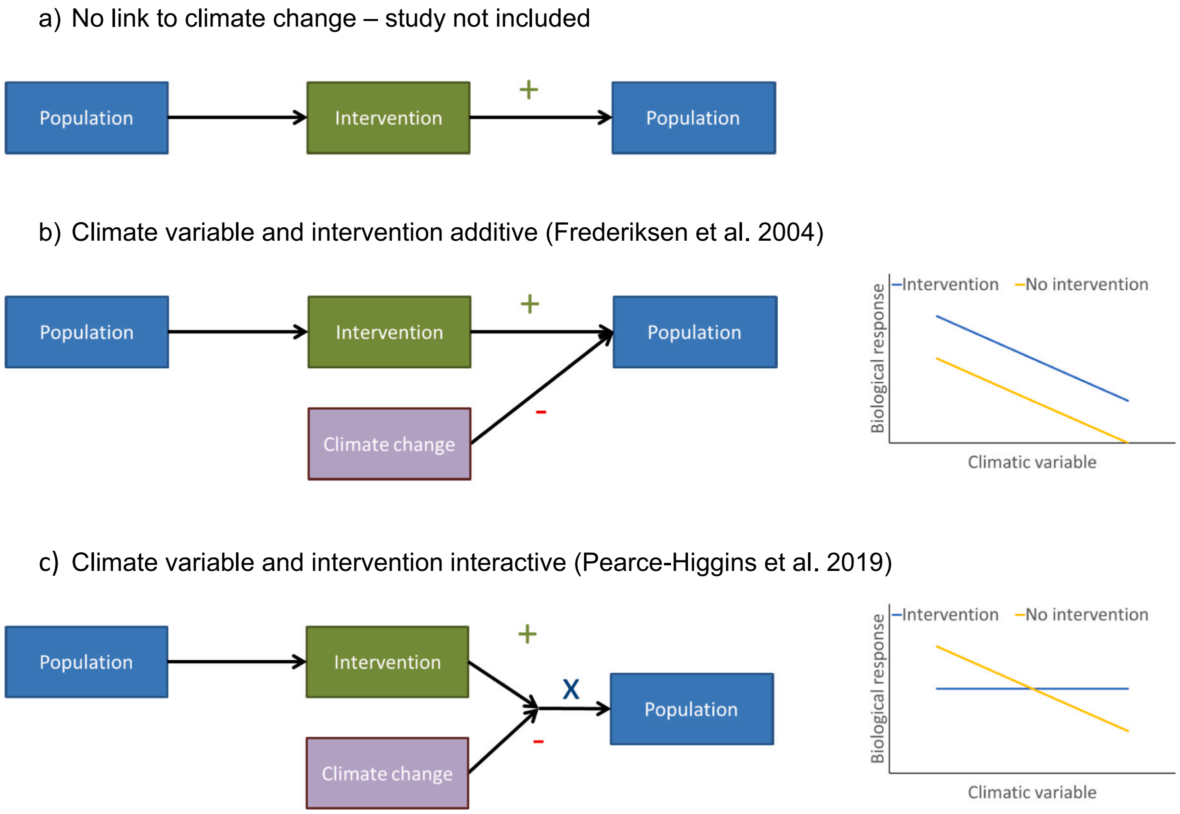
2. Materials and methods

We reviewed published studies of the effectiveness of conservation interventions that also consider the impacts of particular climatic variables, individual climatic events, or the longer-term impacts of climate change, to assess the extent to which those interventions are likely to be beneficial for more targeted climate change adaptation. We had three main aims:

1. To describe the existing published information about the likely effectiveness of conservation interventions in the context of climate change, and how that varies geographically, with habitat, climatic variable, taxa, and conservation intervention.
2. To quantify the extent to which conservation interventions are likely to have a beneficial impact upon species' populations, and to identify examples.
3. To assess which types of conservation interventions are more likely to be beneficial than others, and whether that benefit varies with context.

2.1. Source material and review process

As noted, there are currently insufficient studies that test the effectiveness of climate change adaptation for biodiversity conservation (i.e. conservation interventions specifically put in place in response to climate change) to justify the adoption of strict systematic review methodology. This restriction is exacerbated by the potentially contrasting outcomes that different adaptation interventions may seek to achieve. As a result, we consider all conservation interventions (whether they were initially undertaken for the purposes of climate change adaptation or not) as potentially relevant literature, but to be included, studies had to test the effect of an intervention on a species' population or assemblage whilst also considering responses to climatic variables, single climatic events, or longer-term impacts of climate change (Fig. 1). Because such studies were not easily identified using standard search-terms, we used a range of sources to gather literature using the following pre-agreed approaches. Firstly, we searched Conservation Evidence (www.conservationevidence.com), which provides an online resource of evidence for the effects of conservation interventions (Sutherland et al., 2019). We reviewed their online database of 5442 summaries of studies testing interventions, as well as the abstracts of a further 3386 studies from their literature database not yet summarised online (summaries downloaded 27/08/2018). Secondly, we used the database of 1192 references from two reviews on responses of species' populations to climatic variables that we have previously undertaken (Ockendon et al., 2014; Pearce-Higgins et al., 2015), to identify those that also contain information about variables that describe species' responses to particular conservation interventions. Thirdly, we searched previous reviews of climate change adaptation (Heller and Zavaleta, 2009; Greenwood et al., 2016; Prober et al., 2019) to identify another 545 potentially relevant studies. Fourthly, we undertook a bespoke literature search of studies of climatic impacts on ecological communities and species' distributions that would not have been picked up by the other sources, using the search terms: ((shift* OR change* OR colon* OR extinc*) AND (rang* OR communit* OR expansion* OR distribut*) AND "climate change" AND (conserv* OR adapt*) AND (specie* OR ecolog*)) in Web of Science on 14th December 2018. We included studies of community or distribution responses that were consistent with previously observed climate change impacts (e.g. poleward range-shifts)


a) No link to climate change – study not included

b) Climate variable and intervention additive (Frederiksen et al. 2004)

c) Climate variable and intervention interactive (Pearce-Higgins et al. 2019)

Fig. 1. Schematic diagram describing three different types of studies assessed: a) were not be included due to a lack of climatic variable being considered; b) describes additive studies and c) interactive studies; both of which were included in the review. The graphs illustrate idealised responses in each case.

even if they were not specifically modelled in relation to climate change (e.g. Thomas et al., 2012). These approaches identified 12450 studies.

These studies were firstly filtered by title and any irrelevant studies removed. Potentially relevant studies were then identified from the abstract to identify those that also tested variation in responses in relation to conservation interventions (Fig. A1). We excluded studies from the marine environment, where both the underlying responses to climate change, and potential for adaptation, differ fundamentally from those in terrestrial and freshwater environments (Burrows et al., 2011; Pinsky et al., 2019). However, coastal studies were retained. We also excluded modelling studies that did not document observed effects of an intervention or climatic response, as well as studies where the climatic response and the intervention were not tested together. In combination, the four complementary search techniques substantially improved our ability to identify relevant studies from both the conservation science and climate change impacts literature. The final database contained 77 studies where it was possible to examine both the effect of an adaptation intervention and the impact of a climatic variable. Some studies reported on multiple species and/or interventions and/or locations (median 2 cases per study, range 1–99), resulting in 443 specific cases (data rows).

Data were extracted from these studies in order to undertake both qualitative and quantitative syntheses. Given the wide range of biological responses measured, it was not possible to quantify effect sizes associated with different interventions. Instead, we assessed the probability of significant beneficial responses to interventions being reported. We regarded a statistically significant ($P < 0.05$) positive response to an intervention, or a positive response being identified in the best-supported model, as beneficial and a non-significant or significant negative response as not beneficial (Franks et al., 2018). Very few negative responses were reported (Fig. A3). By attempting to describe the existing evidence base, and quantify some initial patterns and quality of the data, this study is therefore closer to a systematic mapping study (e.g. James et al., 2016) than a true systematic review as described by Gurevitch et al. (2018), but in addition to describing and mapping the studies, we also include a subsequent meta-analysis of the results of those studies. A full description of our methodological approach to review is given in Appendix A using the PRISMA 2020 checklist (Page et al., 2021).

We extracted data on the following ecological variables against which to measure variation in adaptation responses (Table A2): ecological response, taxon, geographical location, habitat (using the IUCN Habitat Classification Scheme v3.1; IUCN, 2012a) and climate variable considered. Ecological responses were separated into abundance, distribution/colonisation, species diversity/richness, growth, population trends, productivity, and survival. Climate variables were split into rainfall, temperature, increasing snowpack, and wind/storm severity, and associated sub-categories, following the IUCN Threats Classification Scheme v.3.2 (Salafsky et al., 2008; IUCN, 2012b).

Conservation interventions were categorised using the IUCN Conservation Actions Classification Scheme (Table A1; Salafsky et al., 2008; IUCN, 2012c) to facilitate comparison with previous studies of the effectiveness of conservation action, adopting both broad intervention categories (e.g. land/water management, species management, law and policy) and sub-categories within these broad categories (e.g. species management, reintroduction, species recovery all within the broad category of species management). For example, providing elevated nesting ridges for birds threatened by flooding (Rounds et al., 2004) was categorised as Species Management (sub-category Species Recovery), while sowing native plant seeds to restore habitats vulnerable to drought (Piper, 2014) was categorised as Land and Water Management (sub-category Habitat and Natural Process Restoration).

A range of additional 'nuisance' (see explanation below) parameters were also recorded (Table A2), which describe characteristics of the study associated with potential bias or that may affect the statistical probability being reported. These included sample size, number of separate results reported in a study, the statistical test undertaken, the number of predictor variables in the model, study duration (years), study intentionality, and robustness. Study intentionality separated interventions applied specifically in response to climate change or a particular weather event (denoted by 1) from those originally implemented for conservation purposes without apparent consideration of climate change (denoted by 0). Robustness distinguished studies with a clear mechanistic understanding that linked the biological response underpinning the impacts of the intervention whose inference may be more robust (denoted by 1) from those that were simply correlative (denoted by 0).

Given inconsistent reporting of the results of different studies, following Ockendon et al. (2014), we maximised our ability to make use of the greatest number of studies by scoring whether there was a statistically significant effect ($P < 0.05$) of an intervention on the ecological responses. Although we also extracted information on the significance (P) and slope or effect sizes (± measures of error) of the impact of climatic variables and adaptation intervention variables, insufficient data on slope or effect size were reported in a comparable way to be useable. We classified each extracted result as being either 'interactive' (based on a model that included an interaction term between the climate variable and intervention) or 'additive' (based on a model conducted with the climatic variable included in the same model, but with no interaction tested; Fig. 1). In some cases, formal statistical tests were not clearly reported, but we also identified studies where the authors still reported apparent effects of interventions during a period of change in climatic variables or a specific climatic event (e.g. comparing the effect of a treatment upon population responses to a storm surge event) for our systematic mapping. To ensure consistency, extracted data for each study were reviewed and discussed by at least two of the authors (KB, EK, JPH), prior to finalisation.

2.2. *Statistical analysis*

The aim of our statistical analyses was to determine the effectiveness of different interventions for climate change (current and potential), as measured as a probability that the intervention will be beneficial for the studied populations or communities. Given the non-independence of multiple rows of data from the same studies, we used generalised linear mixed models (GLMMs) for the modelling, specifying reference identity as a random effect with a binomial error distribution and a logit link function. This was achieved with the lme4 package in R, with the significance of effects in the model estimated using ANOVA from the car package (Bates et al., 2015; Fox and Weisberg, 2019; R Development Core Team, 2020). Model estimates describe the probability of interventions being regarded as beneficial, derived from whether individual studies reported statistically significant positive responses. As a result, we regard estimates with 95% confidence intervals that exceed the null 5% probability for statistical significance, as being shown to have support for being effective for climate change adaptation (Franks et al., 2018).

Given our focus on statistical significance as the main common metric that applies across studies (see Ockendon et al., 2014; Franks et al., 2018), it was important to consider a range of potentially confounding variables that may affect the likelihood of significance, but that we were not interested in per se (Table A2). Literature source was included to check if our different search-types were associated with different probabilities of detecting significant impacts of interventions and separated into 1) Conservation Evidence database, 2) reviews of responses to climatic variables, 3) reviews of climate change adaptation or 4) range shift literature. The total number of rows extracted from a study was used to test for potential publication bias, given the risk of significant effects being more likely to be published. Modelling paradigm identified whether studies used statistical tests to identify significance or information theoretic approaches such as AIC to identify the best supported models; these two approaches may be associated with different likelihoods of detecting 'beneficial' responses. Given the debate about whether climate change adaptation interventions should be intentional, we used the framing of each study to identify whether the interventions were specifically for climate change adaptation or not, and tested whether that impacted the probability of a beneficial response being identified. How a study analysed an intervention was additionally assessed either as additive or interactive depending on the formula used (Fig. 1) in the event that this had an impact on likelihood effectiveness. Study reference was fitted as a random intercept term in all models to account for the variance attributable to literature source.

The response variable for an intervention was considered to be beneficial for the target species if there was a significant ($P < 0.05$) positive effect on the ecological response measured for each species/ group of species (denoted as 1) and unbeneficial if there was a non-significant or negative impact on the population or community (denoted as 0; Franks et al., 2018). The model structure is summarised below, with α the intercept, $\beta_{1\ldots n}$ the model coefficients, (1|Reference Number) the random effect, and ε_i the residual error.

In the full models we conducted separate analyses testing the effect of

a) interventions (using broad and specific categories separately; Table A2).

$$\text{logit}(\pi_i) = \alpha + \beta_1 \text{Intervention} + \beta_2 \text{ Sample Size} + \beta_3 \text{Rows} + (1|\text{Reference Number}) + \varepsilon_i$$

b) climatic threat (using broad and specific categories separately; Table A2).

$$\text{logit}(\pi_i) = \alpha + \beta_1 \text{Threat} + \beta_2 \text{ Sample Size} + \beta_3 \text{Rows} + (1|\text{Reference Number}) + \varepsilon_i$$

c) interventions plus one of the following additional variables (habitat, taxonomy, ecological response, additive / interactive, intentionality) in turn, to test the generality of results.

$$\text{logit}(\pi_i) = \alpha + \beta_1 \text{Intervention} + \beta_2 \text{ Sample Size} + \beta_3 \text{Rows} + \beta_4 \text{ Additional Variable} + (1|\text{Reference Number}) + \varepsilon_i$$

To avoid problems with convergence and estimates being derived from a small number of studies, all classes included in the tests contained data from a minimum of 10 rows of data from 5 studies per level. As a result, we removed bacteria, fungi (both ecological responses), snow (a climate threat), and law and policy (an intervention) from all models and additional specific low levels of combinations for certain interactions. This reduced the final dataset from the 443 rows of data from 77 peer-reviewed studies presented in the overview of relevant studies to 432 rows of data from 75 studies. Of these, 396 rows were suitable for statistical modelling – the remainder either did not report statistical significance (31) or the direction of effect was unclear (5).

3. Results

3.1. *Overview of relevant studies*

Most of the 77 studies were from Europe and North America (82%), and most were in forest, grassland, or wetland habitats (72%; Fig. 2); few were from the tropics. The most frequently encountered interventions were associated with land and water management (60% of studies), which included habitat and natural process restoration, site/ area management, and problematic or invasive species control (Fig. 3). Habitat and natural process restoration included sowing native plants (e.g. Piper, 2014) increasing tree cover (e.g. Nimmo et al., 2016), increasing habitat connectivity (e.g. Melles et al., 2011), and direct habitat creation (e.g. Pilliod and Scherer, 2015), whilst site/area management can improve plant and animal responses to damaging effects of weather extremes, such as drought (e.g. Benigno et al., 2013; Clermont-Dauphin et al., 2016; Han and Young, 2014; Pilliod and Scherer, 2015;

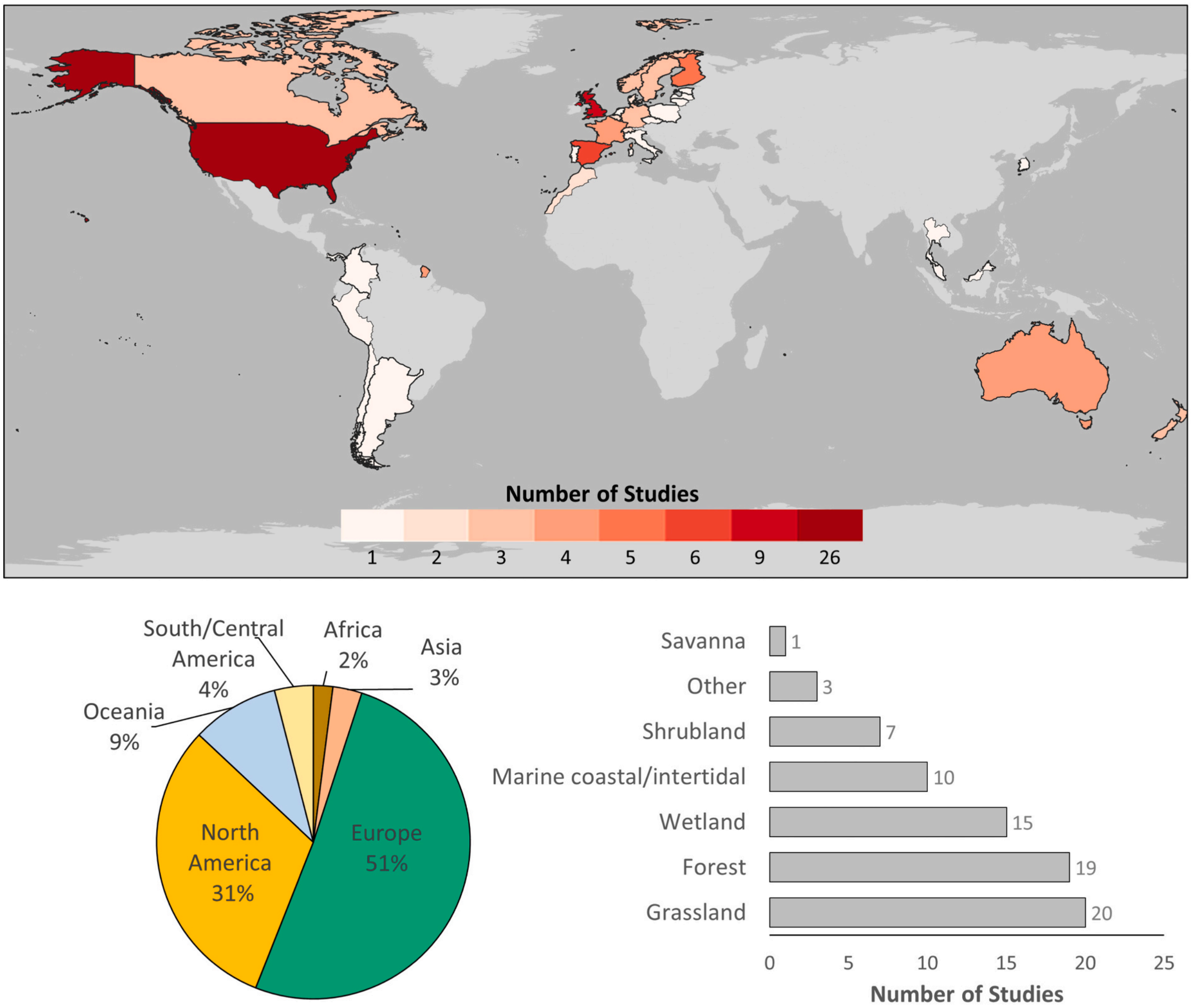


Fig. 2. Locations and number of studies looking at the effect of conservation interventions for species facing climate-related threats, the percentage of studies by continent, and the number of studies that tested interventions in different habitats.

Fig. A3a). Invasive or problematic species control was used to improve the survival, productivity, and abundance of target animal and plant species (Fig. A3a), for example, controlling red foxes *Vulpes vulpes* to counter negative impacts of warming on arctic foxes *Vulpes lagopus* (Angerbjörn et al., 2013).

Twelve percent of studies considered the impacts of land and water protection on animal populations (typically through the designation and management of formal protected areas); just under half of these found evidence of a significant benefit associated with protected areas for at least one species (e.g. Gaüzère et al., 2016; Gillingham et al., 2015a, 2015b; Lawson et al., 2014, Figs. 3 & 4). Over a quarter (27%) of studies looked at the impact of species' management interventions on plants and vertebrates, roughly three-quarters (72%) of which considered species-recovery, including protecting nest sites from storm surges (Rounds et al., 2004; Moore, 2005) or extreme high temperatures (Patino-Martinez et al., 2012).

The reviewed literature did not include any examples testing the impact of interventions relating to education and awareness, livelihood, capacity-building, and economic and other incentives on species. There was also an absence of studies on responses to changes in humidity, fire, water flow, or sea-level rise.

Only 11 of the 77 papers described interventions that were intentionally adaptive to climate change; the remainder were interventions that were not clearly linked to climate change adaptation but that were examined in the context of changes in climatic variables, single events, or long-term climate change responses.

3.2. *Variation in beneficial responses*

Across studies, 81% of papers reported at least one beneficial response (an average of 5.8 responses were reported per paper; Fig. 4). Five or more studies described successful conservation interventions in response to drought, flooding, changes in rainfall, and increases in mean temperature or reductions in cold extremes. There was the strongest evidence for positive responses to conservation interventions in birds, but also five or more studies reported positive responses in amphibians, insects and in each of eudicot, monocot, and piopsida plant groups. The conservation interventions with the greatest number of positive responses reported were habitat and natural process restoration, site/area management, site/area protection and species recovery, the latter particularly in birds (Fig. 4).

Taking a modelling approach to quantify the likelihood of benefit, 30% of individual statistical tests on those responses resulted in a statistically significant ($P < 0.05$) positive impact of interventions, while accounting for potentially confounding biases in the published literature. These were sample size, positively associated with the probability of a benefit being reported ($\chi^2 = 9.618$, $P = 0.002$), and the total number of rows reported from a study negatively correlated with the probability of benefit ($\chi^2 = 4.983$, $P = 0.026$ see Table A2 and Fig. A4). These two nuisance parameters were retained in all the subsequent models.

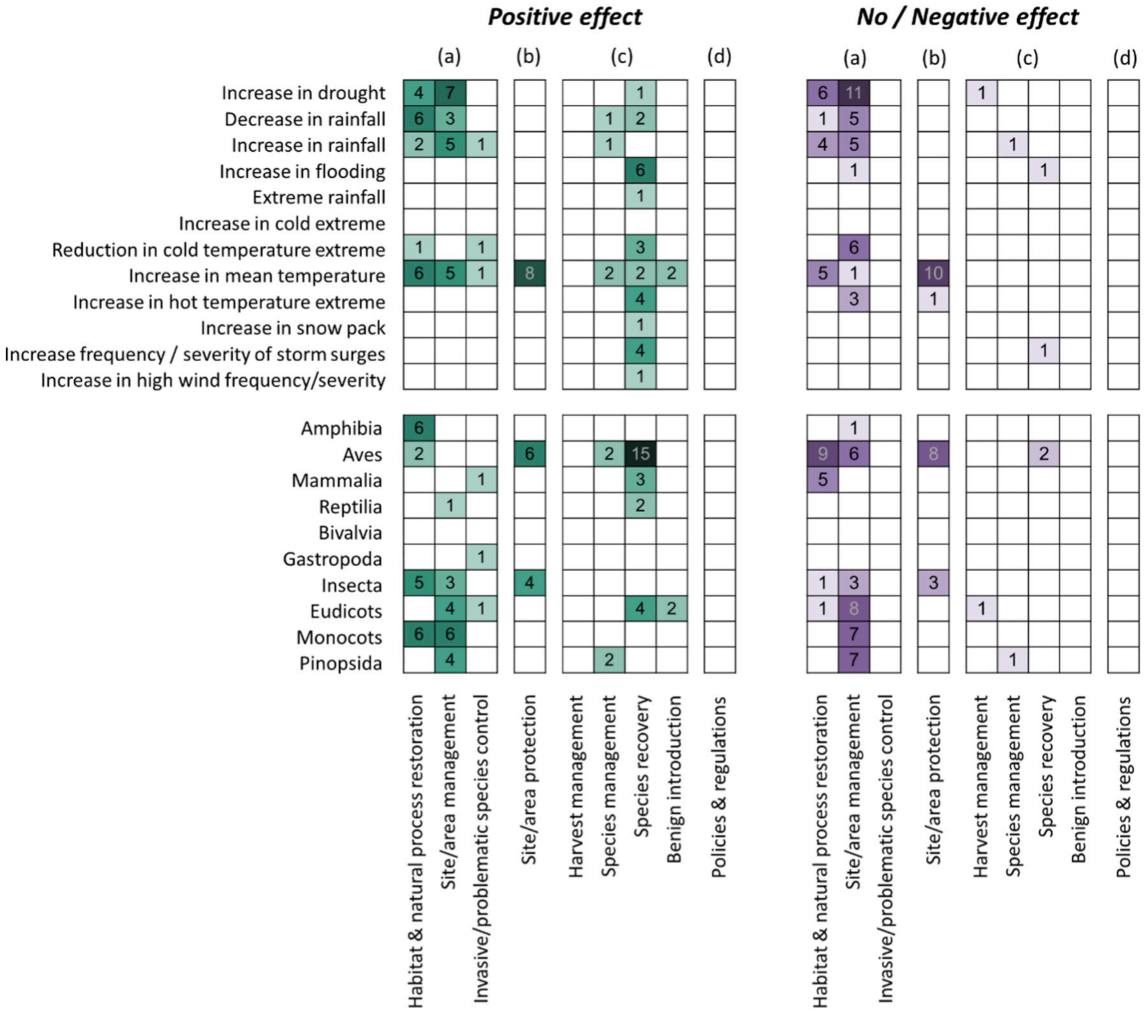
Fig. 3. The number of studies on invertebrates, vertebrates, and plants testing the effect of conservation interventions (x axis) under different climatic threats (y axis). Note that some publications included more than one study, such as testing different interventions or testing the response of different animal or plant groups.

The probability that an intervention would be beneficial varied significantly with intervention type ($\chi^2 = 6.996$, $P = 0.030$; Fig. 5a). Species management interventions were estimated by the model to be beneficial in 73% (23%–95%, 95% CI) of cases, while land and water management interventions were beneficial in 22% (6%–57%, 95% CI) of cases, and land and water protection interventions in 17% (4%–55%, 95% CI). The probability of benefit associated with the first two of these differed significantly from the 5% threshold of statistical significance, whilst the probability for land and water protection was close to this threshold. More specifically, species recovery interventions (which comprised 75% of the studies on species management and 20% of studies overall), were modelled to be beneficial in 78% (31%–97%, 95% CI) of cases tested (Fig. 5b,). These interventions appeared to improve the productivity and survival of birds, mammals, and flowering plants across climatic variables (Fig. 4).

Beyond these effects there was no impact of climatic variable type on the probability of benefit when considering either the broad ($\chi^2 = 0.109$, $P = 0.947$) or specific ($\chi^2 = 2.187$, $P = 0.823$) climatic categories, or ecological response ($\chi^2 = 3.839$, $P = 0.279$ for broad and $\chi^2 = 5.619$, $P = 0.132$ for specific interventions). There was also no significant variation in the probability of benefit between different habitats (broad interventions $\chi^2 = 2.451$, $P = 0.653$ and specific interventions $\chi^2 = 1.823$, $P = 0.768$) or taxonomic groups (neither animals/plants nor plants/invertebrates/vertebrates; $\chi^2 = 0.220$, $P = 0.639$ and $\chi^2 = 0.344$, $P = 0.842$ respectively for broad interventions, and $\chi^2 = 1.044$, $P = 0.307$ and $\chi^2 = 1.106$, $P = 0.575$ respectively for specific interventions). There was also no difference ($\chi^2 = 0.194$, $P = 0.659$) in outcome between studies that tested whether adaptation alters species' responses to climatic variables through an interaction (e.g. bird community responses to climate change vary between protected and unprotected sites; Santangeli et al., 2017), or had an additive effect (e.g. shading of leatherback turtle *Dermochelys coriacea* nests to alter sex-ratios of offspring; Patino-Martinez et al., 2012). Importantly, there was no difference ($\chi^2 = 0.117$, $P = 0.733$) in the probability of benefit between interventions that were intentionally adaptive (for example adding water to malleefowl *Leipoa ocellata* nest mounds during drought; Booth and Seymour, 1984) and those based on existing conservation responses (e.g. the effect of active conservation management in protected areas upon range expansion in response to climate change; Lawson et al., 2014), suggesting that our broad definition of studies to include in our analysis had not biased our results.

4. Discussion

Our results suggest that despite there being relatively few formal tests of interventions specifically for climate change adaptation available for inclusion in this review, a wide range of studies across taxa, interventions, and climatic variables provide evidence that conservation interventions can benefit species impacted by climate change. We describe how this evidence is distributed across taxa, habitats, climatic variables, and intervention types, achieving our first aim. Overall, four-fifths of studies reported at least one beneficial response to these



Positive effect

	(a)			(b)	(c)				(d)
	Habitat & natural process restoration	Site/area management	Invasive/problematic species control	Site/area protection	Harvest management	Species management	Species recovery	Benign introduction	Policies & regulations
Increase in drought	4	7					1		
Decrease in rainfall	6	3				1	2		
Increase in rainfall	2	5	1			1			
Increase in flooding							6		
Extreme rainfall							1		
Increase in cold extreme									
Reduction in cold temperature extreme	1		1				3		
Increase in mean temperature	6	5	1	8		2	2	2	
Increase in hot temperature extreme							4		
Increase in snow pack							1		
Increase frequency / severity of storm surges							4		
Increase in high wind frequency/severity							1		
Amphibia	6								
Aves	2			6		2	15		
Mammalia			1				3		
Reptilia		1					2		
Bivalvia									
Gastropoda			1						
Insecta	5	3		4					
Eudicots		4	1				4	2	
Monocots	6	6							
Pinopsida		4				2			

No / Negative effect

	(a)			(b)	(c)				(d)
	Habitat & natural process restoration	Site/area management	Invasive/problematic species control	Site/area protection	Harvest management	Species management	Species recovery	Benign introduction	Policies & regulations
Increase in drought	6	11			1				
Decrease in rainfall	1	5							
Increase in rainfall	4	5				1			
Increase in flooding		1					1		
Extreme rainfall									
Increase in cold extreme									
Reduction in cold temperature extreme		6							
Increase in mean temperature	5	1		10					
Increase in hot temperature extreme		3		1					
Increase in snow pack									
Increase frequency / severity of storm surges							1		
Increase in high wind frequency/severity									
Amphibia		1							
Aves	9	6		8			2		
Mammalia	5								
Reptilia									
Bivalvia									
Gastropoda									
Insecta	1	3		3					
Eudicots	1	8			1				
Monocots		7							
Pinopsida		7				1			

Fig. 4. The number of studies to find a positive or no/negative effect of conservation interventions on species under different climatic threats, and by animal/plant group. Note that some publications tested the same intervention, climate variable and animal/plant group, but found a positive effect of the intervention in one instance and a negative or no effect in another. Letters refer to high-level conservation actions: (a) land/water management; (b) land/water protection; (c) species management; (d) law & policy. Refer to Fig. A3 to see the negative responses separated out.

interventions, although when modelled as a probability per individual test the response rate was 30%, fulfilling our second aim. We then demonstrate how different types of conservation intervention were associated with different likelihoods of beneficial effect, whilst providing little evidence of variation in relation to other contexts (our third aim).

Whilst the modelled 30% likelihood of beneficial response may seem a relatively low figure, this probability is similar in magnitude to the success of other conservation interventions from similar analyses (e.g. Franks et al., 2018). Given the significant negative relationship between the number of tests undertaken in a study and the probability of individual tests being statistically significant, there may be a publication bias that studies reporting single tests are more likely to document significantly positive impacts of interventions than those that consider multiple species or multiple tests. This makes it difficult to accurately quantify the overall probability of interventions being successful, and indeed, given the heterogeneity that seems to exist between different intervention types and this probability, such a metric may not be meaningful. Given the range of examples described in the studies reviewed, our first conclusion is that there is a growing evidence-base in support for climate change adaptation interventions being beneficial for species' populations and assemblages in many circumstances, which our mapping highlighted and our modelling quantified.

Despite any potential biases in the literature that affect the overall estimation of probability of benefit across studies, a significant contrast between different intervention types is likely to be robust. The higher probability of benefit associated with species management interventions (particularly for birds) than land and water protection interventions suggests that interventions targeted at management for individual species were more likely to result in significant population-level benefits than other measures (Fig. 5); our second conclusion. This strongly suggests that targeted interventions can be used to reduce the climate vulnerability of particular populations and species. Potential interventions could range from habitat manipulations to protect specific species from extreme events (e.g. Moore, 2005; Patino-Martinez et al., 2012; Rounds et al., 2004; Stokes and Boersma, 1998) to supplementary feeding in response to climate-driven food shortages (e.g. Angerbjörn et al., 2013; Heath et al., 2008; Robel and Kemp, 1997; Smith et al., 2008). In order to maximise their effectiveness, interventions should be supported by a good understanding of the species and the system being managed, building on a well-evidenced model of effective conservation science, but adapted for a climate change context (Pearce-Higgins, 2011a).

Our third conclusion is that more generic approaches to site protection and habitat management were less effective at providing benefit for individual species than management targeted at those individual species. However, we might expect that by their very nature, these interventions are more likely to benefit a larger number of species overall,

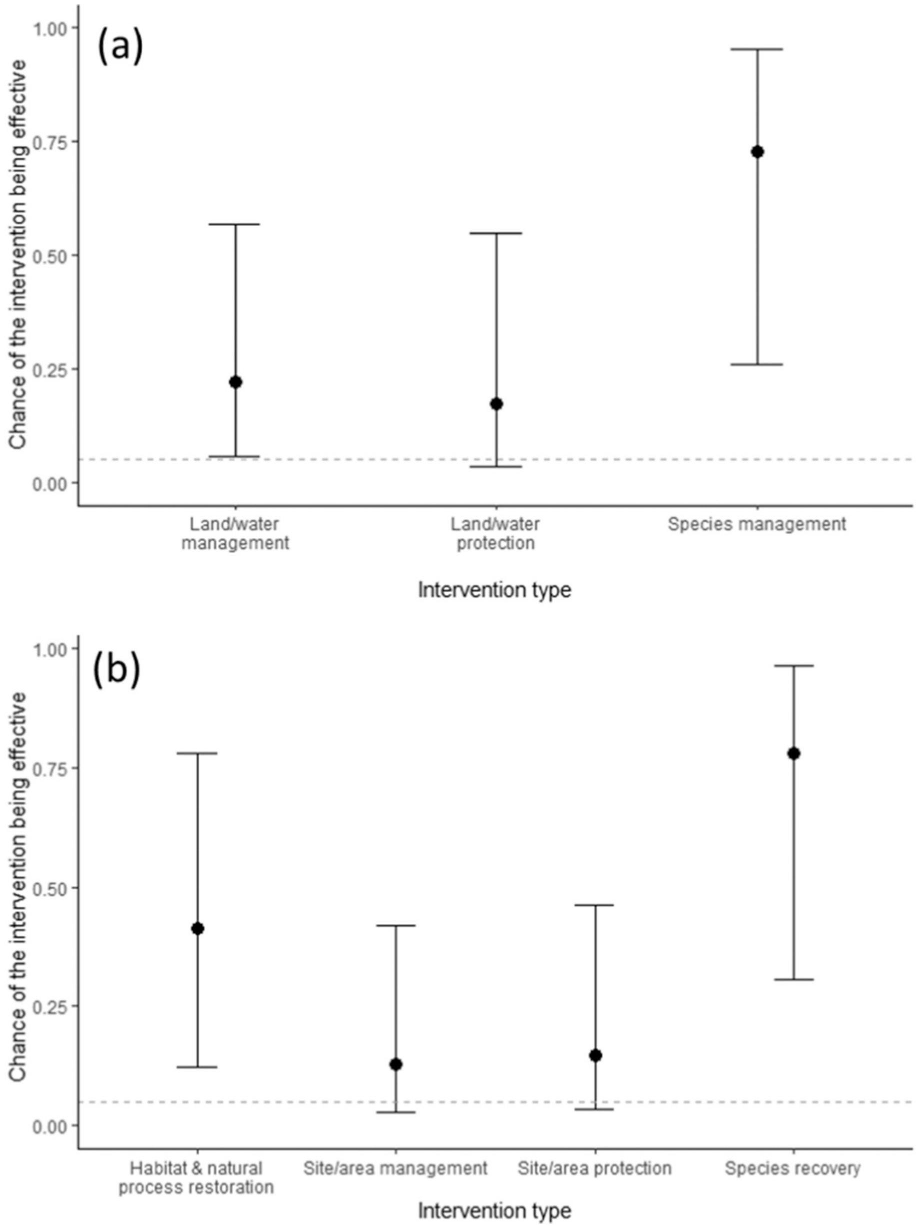


Fig. 5. Predicted probabilities (mean ± 95% confidence interval) that an intervention will result in a beneficial outcome (i.e. a positive impact on the population) for a) broad intervention type and b) specific intervention types as defined by the IUCN Conservation Actions Classification Scheme (IUCN, 2012c). The dotted line indicates 0.05, the 5% threshold above which interventions were successful more often than expected by chance.

although further research is required to test this assertion. For example, the provision of protected areas as a mechanism for maintaining natural and semi-natural habitat for habitat specialists of conservation concern has been shown to support the poleward climate-driven expansion of a range of taxa in response to climate change (Thomas et al., 2012; Virkkala et al., 2014; Gillingham et al., 2015b; Lindström et al., 2019), even if the proportion of individual species that demonstrate statistically significant positive responses across such multi-species studies was lower than reported compared with studies of interventions on single species.

The benefit associated with interventions did not appear to vary with climatic variables, habitat, or among taxa, although there are significant limitations of the literature available, and variation in the effectiveness of different interventions undoubtedly exists. Our fourth conclusion is therefore that much more monitoring of the success of adaptation interventions, and publication of the results in the peer-reviewed literature, is required, particularly given the relatively small proportion of studies that were specifically testing climate change adaptation interventions. Our mapping of the literature highlighted that few studies were from the tropics, where species' responses to climatic variables differ from those at higher latitudes (Deutsch et al., 2008; Pearce-Higgins et al., 2015), whilst there were also gaps in taxonomic coverage, in the types of interventions that were tested, and the climatic drivers considered. In particular, there was a lack of studies reporting on the effectiveness of interventions relating to education and awareness, livelihood, capacity building, and economics and other incentives on species; issues that apply more generally to biodiversity conservation (Hochkirch et al., 2020, Kusmanoff et al., 2020, Christie et al., 2021). Such gaps can be used to prioritise future evidence and monitoring needs.

Although there was no evidence for the effectiveness of adaptation varying with habitat, taxa, and climatic drivers, more data needs to be collected across a range of circumstances to improve our ability to quantify the effectiveness of adaptation in different circumstances. We therefore suggest repeating this review in a few years when more literature is available to quantify variation in adaptation effectiveness between taxa, habitats, locations, and in relation to different climatic drivers. We also recognise that only 11 of the studies considered were clearly testing responses to specific climate change adaptation interventions; the majority examined responses to more standard conservation interventions that could also help moderate species responses to climate change. Given these gaps and limitations in the published literature so far, ongoing monitoring and evaluation of adaptive conservation interventions is required to build this evidence base (Morecroft et al., 2019; Pearce-Higgins et al., 2022). Noting the potential for publication bias in the literature, we particularly urge the reporting of null results as well as significant effects, and a greater understanding of the potential for more generic approaches to habitat management and site protection to benefit a large number of species.

Our analysis was based on the premise that conservation measures that currently appear to be ineffective are also less likely to work in the future, particularly as the current magnitude of climate change experienced is less than that projected. Conversely, conservation interventions that our analysis suggests are beneficial for species under current conditions might have the greatest prospect of future benefit. However, it is worth noting that some interventions may have a long time-lag before they are effective (Watts et al., 2020), and their impact may therefore be underestimated by short-term studies. In this context, the monitoring of interventions will be particularly important not just to help prioritise different options, but also to identify the limits to different adaptation interventions, in order to help understand the impact that interventions may have on species' vulnerability to climate change (Pacifici et al., 2015; Foden et al., 2019). This evidence is starting to be collated. For example, targeted conservation action for a population of golden plover *Pluvialis apricaria* at the southern edge of the species' distribution, through habitat restoration and management to reduce predation risk, is expected to enable that population to resist 2 °C of warming (Pearce-Higgins, 2011b). Given the importance of monitoring for the evaluation of the success of adaptation interventions (Mäkinen et al., 2018; Pearce-Higgins et al., 2022), we urge conservationists and the funders of adaptation actions to support the ongoing monitoring and evaluation of their actions to improve the effectiveness of such interventions into the future, particularly as many cases appeared to provide little evidence of benefit.

Despite the uncertainties noted, our results suggest that species management interventions can help the species most vulnerable to climate change to adapt, while more generic habitat management and protection measures may benefit the widest range of species. There is debate about the implications of conservation triage (Bottrill et al., 2008) for climate change adaptation. Deprioritising vulnerable trailing-edge populations has been suggested to be an important element of future conservation triage in a changing climate, but decisions are currently hampered by uncertainty (Gilbert et al., 2020). Quantifying the effectiveness of interventions in specific circumstances will improve decision-making (e.g. Wintle et al., 2011). In this context, our results suggest there may be more that can be done for vulnerable trailing-edge populations than previously assumed, but as noted, more evidence is required to inform specific decisions. Further consideration of the ethical dimensions around the triage approach to biodiversity conservation (Wilson and Law, 2016) is also required. In the context of climate change adaptation, where synergies and trade-offs may exist between biodiversity conservation, climate change mitigation, and human adaptation, these issues are likely to be even more important (Morecroft et al., 2019).

5. Conclusions

This study provides an important evidence base to support investment in climate change adaptation, which appears beneficial in many contexts, in much the same way as current conservation action has significantly reduced extinction risk (Butchart et al., 2006; Monroe et al., 2019; Bolam et al., 2021). Gaps in the coverage of published studies, particularly in the tropics, and also across some habitats, taxa, and climatic drivers considered, highlight the need to prioritise the monitoring and evaluation of adaptation interventions to inform future optimisation of interventions for different species, habitats, and circumstances. Despite being at a relative early stage in the study of climate change adaptation effectiveness, sufficient studies were available to demonstrate that conservation interventions can have positive impacts on species being affected by variation in climatic variables or can alter the form of response to those variables. An appropriate response to growing concerns about impacts of climate change on species' extinction risk is therefore to catalyse targeted actions to reduce risks faced by the most climate-vulnerable species, which our analyses suggest can have a high likelihood of benefit. Although more generalised habitat management and site protection measures appeared less likely to be successful for individual species, this does not mean that they are unlikely to be effective, as by their very nature, they may well impact a greater number of species overall. We therefore interpret our results as also supporting the value of expanding habitat management and site protection measures to enhance the ability of a broad array of species and ecosystems to persist in the face of changing climatic conditions.

Glossary

Adaptive capacity: The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC, 2014 Annex II Glossary).

Climate change adaptation: The process of adjustment to actual or expected climate and its effects. In the context of this paper, climate change adaptation are conservation interventions that seek to moderate harm or exploit beneficial opportunities resulting from climate change.

Nuisance variables: Variables not of primary interest but that are included in the model to account for additional potential variation or reduce potential impacts of bias or other confounding effects.

CRediT authorship contribution statement

This paper was conceived by JPH with input from SHMB, JAC, WBF, GM, RKS, WJS & TCB. The literature review, data extraction and analyses were undertaken by KMB and EK, with input from JPH. The manuscript was written by KMB, EK and JPH with input from all authors. MDM and BAS also contributed to the external advisory group.

Data availability

The dataset underlying this study are deposited online with Figshare (https://figshare.com/articles/dataset/Bowgen_et_al_2022_BiolCons_DatabaseSubFinal_csv/19145435).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to Olly Watts for commenting on the manuscript and providing external advice through the project. This research was funded by the Cambridge Conservation Initiative (http://www.conservation.cam.ac.uk/), a strategic collaboration between the University of Cambridge, UK, and nine leading conservation organisations, thanks to the generosity of the Arcadia Fund. This work was carried out as an activity of the IUCN Species Survival Commission's Climate Change Specialist

Group. We thank three anonymous reviewers for helpful comments to an earlier draft of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109524.

References

Angerbjörn, A., Eide, N.E., Dalén, L., Elmhagen, B., Hellström, P., Ims, R.A., Killengreen, S., Landa, A., Meijer, T., Mela, M., Niemimaa, J., Norén, K., Tannerfeldt, M., Yoccoz, N.G., Henttonen, H., 2013. Carnivore conservation in practice: replicated management actions on a large spatial scale. J. Appl. Ecol. 50, 59–67.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.

Benigno, S.M., Dixon, K.W., Stevens, J.C., 2013. Increasing soil water retention with native-sourced mulch improves seedling establishment in postmine Mediterranean sandy soils. Restor. Ecol. 21, 617–626.

Bolam, F.C., Mair, L., Angelico, M., Brooks, T.M., Burgman, M., Hermes, C., Hoffmann, M., Martin, R.W., McGowan, P.J.K., Rodrigues, A.S.L., Rondinini, C., Westrip, J.R.S., Wheatley, H., Bedolla-Guzmán, Y., Calzada, J., Child, M.F., Cranswick, P.A., Dickman, C.R., Fessl, B., Fisher, D.O., Garnett, S.T., Groombridge, J. J., Johnson, C.N., Kennerley, R.J., King, S.R.B., Lamoreux, J.F., Lees, A.C., Lens, L., Mahood, S.P., Mallon, D.P., Meijaard, E., Méndez-Sánchez, F., Percequillo, A.R., Regan, T.J., Renjifo, L.M., Rivers, M.C., Roach, N.S., Roxburgh, L., Safford, R.J., Salaman, P., Squires, T., Vázquez-Domínguez, E., Visconti, P., Woinarski, J.C.Z., Young, R.P., Butchart, S.H.M., 2021. How many bird and mammal extinctions has recent conservation action prevented? Conserv. Lett. 14, e12762 https://doi.org/10.1111/conl.12762.

Booth, D.T., Seymour, R.S., 1984. Effect of adding water to malleefowl mounds during a drought. Emu 84, 116–118.

Bottrill, M.C., Joseph, L.N., Carwadine, J., Bode, M., Cook, C., Game, E.T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R.L., Walker, S., Wilson, K.A., Possingham, H.P., 2008. Is conservation triage just smart decision making? Trends Ecol. Evol. 23, 649–654.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K. M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., Richardson, A.J., 2011. The pace of shifting climate in marine and terrestrial ecosystems. Science (80-.) 334, 652–655.

Butchart, S.H.M., Stattersfield, A.J., Collar, N.J., 2006. How many bird extinctions have we prevented? Oryx 40, 266–278.

Chen, I.C., Hill, J.K., Ohlemüller, R., Roy, D.B., Thomas, C.D., 2011. Rapid range shifts of species associated with high levels of climate warming. Science (80-.) 333, 1024–1026.

Christie, A.P., Amano, T., Martin, P.A., Petrovan, S.O., Shackelford, G.E., Simmons, B.I., Smith, R.K., Williams, D.R., Wordley, C.F.R., Sutherland, W.J., 2021. The challenge of biased evidence in conservation. Conserv. Biol. 35, 249–262.

Clermont-Dauphin, C., Suvannang, N., Pongwichian, P., Cheylan, V., Hammecker, C., Harmand, J.M., 2016. Dinitrogen fixation by the legume cover crop Pueraria phaseoloides and transfer of fixed N to Hevea brasiliensis-impact on tree growth and vulnerability to drought. Agric. Ecosyst. Environ. 217, 79–88.

Dilling, L., Prakash, A., Zommers, Z., Ahmad, F., Singh, N., de Wit, S., Nalau, J., Daly, M., Bowman, K., 2019. Is adaptation success a flawed concept? Nat. Clim. Chang. 9, 572–574.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C., Martin, P.R., 2008. Impacts of climate warming on terrestrial ectotherms across latitude. Proc. Natl. Acad. Sci. 105, 6668–6672.

Foden, W.B., Young, B.E., Akçakaya, H.A., Garcia, R.A., Hoffmann, A.A., Stein, B.A., Thomas, C.D., Wheatley, C.J., Bickford, B., Carr, J.A., Hole, D.G., Martin, T.G., Pacifici, M., Pearce-Higgins, J.W., Platts, P.J., Visconti, P., Watson, J.E.M., Huntley, B., 2019. Climate change vulnerability assessment of species. WIREs Clim. Change 2018, e551.

Fox, J., Weisberg, S., 2019. An {R} Companion to Applied Regression, Third edition. Sage, Thousand Oaks CA.

Franks, S.E., Roodbergen, M., Teunissen, W., Carrington Cotton, A., Pearce-Higgins, J. W., 2018. Evaluating the effectiveness of conservation measures for european grassland-breeding waders. Ecol. Evol. 8, 10555–10568.

Gaüzère, P., Jiguet, F., Devictor, V., 2016. Can protected areas mitigate the impacts of climate change on bird's species and communities? Divers. Distrib. 22, 625–637.

Gilbert, S.L., Broadley, K., Doran-Myers, D., Droghini, A., Haines, J.A., Hamalainen, A., Lamb, C.T., Neilson, E.W., Boutin, S., 2020. Conservation triage at the trailing edge of climate envelopes. Conserv. Biol. 34, 289–292.

Gillingham, P.K., Alison, J., Roy, D.B., Fox, R., Thomas, C.D., 2015a. High abundances of species in protected areas in parts of their geographic distributions colonized during a recent period of climatic change. Conserv. Lett. 8, 97–106.

Gillingham, P.K., Bradbury, R.B., Roy, D.B., Anderson, B.J., Baxter, J.M., Bourn, N.A.D., Crick, H.Q.P., Findon, R.A., Fox, R., Franco, A., Hill, J.K., Hodgson, J.A., Holt, A.R., Morecroft, M.D., O'Hanlon, N.J., Oliver, T.H., Pearce-Higgins, J.W., Procter, D.A., Thomas, J.A., Walker, K.J., Walmsley, C.A., Wilson, R.J., Thomas, C.D., 2015b. The effectiveness of protected areas in the conservation of species with changing geographical ranges. Biol. J. Linn. Soc. 115, 707–717.

Gurevitch, J., Koricheva, J., Nakagawa, S., Stuart, G., 2018. Meta-analysis and the science of research synthesis. Nature 555, 175–182.

Greenwood, O., Mossman, H.L., Suggitt, A.J., Curtis, R.J., Maclean, I.M.D., 2016. Using in situ management to conserve biodiversity under climate change. J. Appl. Ecol. 53, 885–894.

Han, C., Young, S.L., 2014. Drought and grazing disturbances and resistance to invasion by warm- and cool-season perennial grassland communities. Ecol. Restor. 32, 28–36.

Heath, S.R., Kershner, E.L., Cooper, D.M., Lynn, S., Turner, J.M., Warnock, N., Farabaugh, S., Brock, K., Garcelon, D.K., 2008. Rodent control and food supplementation increase productivity of endangered San Clemente loggerhead shrikes (Lanius ludovicianus mearnsi). Biol. Conserv. 141, 2506–2515.

Heller, N.E., Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biol. Conserv. 142, 14–32.

Hochkirch, A., Samways, M.J., Gerlach, J., Böhm, M., Williams, P., Cardoso, P., Cumberlidge, N., Stephenson, P.J., Seddon, M.B., Clausnitzer, V., et al., 2020. A strategy for the next decade to address data deficiency in neglected biodiversity. Conserv. Biol. 35, 502–509.

IPCC, 2014. In: Field, C.B. (Ed.), Summary for policymakers In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32 (Cambridge).

IUCN, 2012a. Habitats classification scheme, version 3.1 [WWW document]. URL. https://www.iucnredlist.org/resources/habitat-classification-scheme (accessed 11.7.18).

IUCN, 2012b. Unified classification of direct threats, version 3.2) [WWW document]. URL. http://www.iucnredlist.org/technical-documents/classification-schemes/threats-classification-scheme.

IUCN, 2012c. Conservation actions classification scheme, version 2.0 [WWW document]. https://www.iucnredlist.org/resources/conservation-actions-classification-scheme.

James, K.L., Randall, N.P., Haddaway, N.R., 2016. A methodology for systematic mapping in environmental sciences. Environ. Evid. 5, 7.

Kusmanoff, A.M., Fidler, F., Gordon, A., Garrard, G.E., Bekessy, S.A., 2020. Five lessons to guide more effective biodiversity conservation message framing. Conserv. Biol. 35, 1131–1141.

Lawson, C.R., Bennie, J.J., Thomas, C.D., Hodgson, J.A., Wilson, R.J., 2014. Active management of protected areas enhances metapopulation expansion under climate change. Conserv. Lett. 7, 111–118.

Lindström, Å., Green, M., Husby, M., Kalas, J.A., Lehikoinen, A., Stjernman, M., 2019. Population trends of waders on their boreal and arctic breeding grounds in northern Europe. Wader Study 126, 200–216.

Mäkinen, K., Prutsch, A., Karali, E., Leitner, M., Völler, S., Lyytimäki, J., 2018. Indicators for adaptation to climate change at national level – lessons from emerging practice in Europe. In: European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA) Technical paper2018/3. https://doi.org/10.25424/CMCC/CLIMATE_CHANGE_ADAPTATION_INDICATORS_2018.

Mawdsley, J.R., O'Malley, R., Ojima, D.S., 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. Conserv. Biol. 23, 1080–1089.

Melles, S.J., Fortin, M.J., Lindsay, K., Badzinski, D., 2011. Expanding northward: influence of climate change, forest connectivity, and population processes on a threatened species' range shift. Glob. Chang. Biol. 17, 17–31.

Monroe, M.J., Butchart, S.H.M., Mooers, A.O., Bokma, F., 2019. The dynamics underlying avian extinction trajectories forecast a wave of extinctions. Biol. Lett. 15, 20190633.

Moore, P., 2005. Storm surge protection of Chatham Island oystercatcher Haematopus chathamensis nests using Tyre nest-platforms, Chatham Island, New Zealand. Conserv. Evid. 2, 78–79.

Morecroft, M.D., Duffield, S., Harley, M., Pearce-Higgins, J.W., Stevens, N., Watts, O., Whitaker, J., 2019. Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. Science 366, eaaw9259.

Newson, S.E., Oliver, T.H., Gillings, S., Crick, H.Q.P., Morecroft, M.D., Duffield, S.J., Macgregor, N.A., Pearce-Higgins, J.W., 2014. Can site and landscape-scale enironmental attributes buffer bird populations against weather events? Ecography 37, 872–882.

Nimmo, D.G., Haslem, A., Radford, J.Q., Hall, M., Bennett, A.F., 2016. Riparian tree cover enhances the resistance and stability of woodland bird communities during an extreme climatic event. J. Appl. Ecol. 53, 449–458.

Ockendon, N., Baker, D.J., Carr, J.A., White, E.C., Almond, R.E.A., Amano, T., Bertram, E., Bradbury, R.B., Bradley, C., Butchart, S.H.M., Doswald, N., Foden, W., Gill, D.J.C., Green, R.E., Sutherland, W.J., Tanner, E.V.J., Pearce-Higgins, J.W., 2014. Mechanisms underpinning climatic impacts on natural populations: altered species interactions are more important than direct effects. Glob. Chang. Biol. 20, 2221–2229.

Oliver, T.H., Smithers, R.J., Bailey, S., Walmsley, C.A., Watts, K., 2012. A decision framework for considering climate change adaptation in biodiversity conservation planning. J. Appl. Ecol. 49, 1247–1255.

Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M., Scheffers, B.R., Hole, D.G., Martin, T.G., Akcakaya, H.R., Corlett, R.T., Huntley, B., Bickford, D., Carr, J.A., Hoffmann, A.A., Midgley, G.F., Pearce-Kelly, P., Pearson, R. G., Williams, S.E., Willis, S.G., Young, B., Rondinini, C., 2015. Assessiing species vulnerabiilty to climate change. Nat. Clim. Chang. 5, 215–224. https://doi.org/10.1038/nclimate2448.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021 (372), n71. https://doi.org/10.1136/bmj.n71.

Parmesan, C., Morecroft, M.D., Trisurat, Y, Adrian, R., Anshari, G.Z., Arneth, A., Gao, Q., Gonzalez, P., Harris, R., Price, J., Stevens, N., Talukdarr, G.H., 2022. Terrestrial and Freshwater Ecosystems and their Services. In: Portner, H.-O., Roberts, D.C., Tignor, E.S., Poloczanska, E.S., Mintenbeck, K., Alegria, A., Craig, M., Langsdorf, S., Loschke, S., Moller, V., Okem, A., Rama, B. (Eds.), Climate Change 2022: Impacts, Adaptation, and Vulnerabiilty. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In press.

Patino-Martinez, J., Marco, A., Quiñones, L., Hawkes, L., 2012. A potential tool to mitigate the impacts of climate change to the caribbean leatherback sea turtle. Glob. Chang. Biol. 18, 401–411.

Pearce-Higgins, J.W., 2011. How ecological science can help manage the effects of climate change: a case study of upland birds. In: Marrs, S.J., Foster, S., Hendrie, C., Mackey, E.C., Thompson, D.B.A. (Eds.), The Changing Nature of Scotland. TSO Scotland, Edinburgh, pp. 397–414.

Pearce-Higgins, J.W., 2011. Modelling conservation management options for a southern range-margin population of Golden Plover Pluvialis apricaria vulnerable to climate change. Ibis (Lond. 1859) 153, 345–356.

Pearce-Higgins, J.W., Ockendon, N., Baker, D.J., Carr, J., White, E.C., Almond, R.E.A., Amano, T., Bertram, E., Bradbury, R.B., Bradley, C., Butchart, S.H.M., Doswald, N., Foden, W., Gill, D.J.C., Green, R.E., Sutherland, W.J., Tanner, E.V.J., 2015. Geographical variation in species' population responses to changes in temperature and precipitation. Proc. Roy. Soc. B. 282, 20151561.

Pearce-Higgins, J.W., Antao, L.H., Bates, R.E., Bowgen, K.M., Bradshaw, C.D., Duffield, S. J., Ffoulkes, C., Franco, A.M.A., Geschke, J., Gregory, R.D., Harley, M.J., Hodgson, J. A., Jenkins, R.I.M., Kapos, V., Maltby, K.M., Watts, O., Willis, S.G., Morecroft, M.D., 2022. A framework for climate change adaptation indicators for the natural environment. Ecol. Indic. 136, 108690 https://doi.org/10.1016/j.ecolind.2022.108690.

Pearce-Higgins, J.W., Green, R.E., 2014. Birds and climate change: impacts and conservation responses. In: Birds and Climate Change: Impacts and Conservation Responses. Cambridge University Press, Cambridge, UK.

Pearce-Higgins, J.W., Lindley, P.J., Johnstone, I.G., Thorpe, R.I., Douglas, D.J.T., Grant, M.C., 2019. Site-based adaptation reduces the negative effects of weather upon a southern range margin welsh black grouse Tetrao tetrix population that is vulnerable to climate change. Clim. Chang. 153, 253–265.

Pilliod, D.S., Scherer, R.D., 2015. Managing habitat to slow or reverse population declines of the Columbia spotted frog in the northern Great Basin. J. Wildl. Manag. 79, 579–590.

Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L., Sunday, J.M., 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature 569, 108–111.

Piper, J.K., 2014. Incrementally rich seeding treatments in tallgrass prairie restoration. Ecol. Restor. 32, 396–406.

Prober, S.M., Doerr, V.A.J., Broadhurst, L.M., Williams, K.J., Dickson, F., 2019. Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. Ecol. Monogr. 89, e01333.

R Development Core Team, 2020. R: A Language and Environment for Statistical Computing.

Rands, M.R.W., Adams, W.M., Bennun, L., Butchart, S.H.M., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P.W., Sutherland, W.J., Vira, B., 2010. Biodiversity conservation: challenges beyond 2010. Science 329, 1298–1303.

Robel, R.J., Kemp, K.E., 1997. Winter mortality of northern bobwhites: effects of food plots and weather. Southwest. Nat. 42, 59–67.

Rounds, R.A., Erwin, R.M., Porter, J.H., 2004. Nest-site selection and hatching success of waterbirds in coastal Virginia: some results of habitat manipulation. J. F. Ornithol. 75, 317–329.

Salafsky, N., Salzer, D., Stattersfield, A.J., Hilton-Taylor, C., Neugarten, R., Butchart, S.H. M., Collen, B., Cox, N., Master, L.L., O'Conner, S.O., Wilkie, D., 2008. A standard lexicon for biodiversity conservation: unified classifications of threats and actions. Conserv. Biol. 22, 897–911. https://doi.org/10.1111/j.1523-1739.2008.00937.x.

Santangeli, A., Rajasarkka, A.I., Lehikoinen, A., 2017. Effects of high latitude protected areas on bird communities under rapid climate change. Glob. Chang. Biol. 23, 2241–2249.

Scheffers, B.R., De Meester, L., Bridge, T.C.L., Hoffmann, A.A., Pandolfi, J.M., Corlett, R. T., Butchart, S.H.M., Pearce-Kelly, P., Kovacs, K.M., Dudgeon, D., Pacifici, M., Rondinini, C., Foden, W.B., Martin, T.G., Mora, C., Bickford, D., Watson, J.E.M., 2016. The broad footprint of climate change from genes to biomes to people. Science 354.

Smith, K.W., Aghnaj, A., El Bekkay, M., Oubrou, W., Ribi, M., Armesto, M.J., Bowden, C. G.R., 2008. The provision of supplementary fresh water improves the breeding success of the globally threatened Northern Bald Ibis Geronticus eremita. Ibis 150, 728–734.

Spooner, F.E.B., Pearson, R.G., Freeman, R., 2018. Rapid warming is associated with population decline among terrestrial birds and mammals globally. Glob. Chang. Biol. 24, 4521–4531.

Stein, B.A., Staudt, A., Cross, M.S., Dubois, N.S., Enquist, C., Griffis, R., Hansen, L.J., Hellmann, J.J., Lawler, J.J., Nelson, E.J., Pairis, A., 2013. Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Front. Ecol. Environ. 11, 502–510.

Stephens, P.A., Mason, L.R., Green, R.E., Gregory, R.D., Sauer, J.R., Alison, J., Aunins, A., Brotons, L., Butchart, S.H.M., Campedelli, T., Chodkiewicz, T., Chylarecki, P., Crowe, O., Elts, J., Escandell, V., Foppen, R.P.B., Heldbjerg, H., Herrando, S., Husby, M., Jiguet, F., Lehikoinen, A., Lindström, Å., Noble, D.G., Paquet, J.Y., Reif, J., Sattler, T., Szép, T., Teufelbauer, N., Trautmann, S., Van Strien, A.J., Van Turnhout, C.A.M., Vorisek, P., Willis, S.G., 2016. Consistent response of bird populations to climate change on two continents. Science 352, 84–87.

Stokes, D.L., Boersma, P.D., 1998. Nest-site characteristics and reproductive success in magellanic penguins (Spheniscus magellanicus). Auk 115, 34–49.

Sutherland, W.J., Taylor, N.G., MacFarlane, D., Amano, T., Christie, A.P., Dicks, L., Lemasson, A.J., Littlewood, N.A., Martin, P.A., Ockendon, N., Petrovan, S.O., Robertson, R.J., Rocha, R., Shackelford, G.E., Smith, R.K., Tyler, E.H.M., Wordley, C. F.R., 2019. Building a tool to overcome barriers in research-implementation spaces: the conservation evidence database. Biol. Conserv. 238, 108199.

Sutherland, W.J., Dicks, L.V., Petrovan, S.O., Smith, R.K., 2021. What Works in Conservation. Open Book Publishers, Cambridge, UK.

Thackeray, S.J., Henrys, P.A., Hemming, D., Bell, J.R., Botham, M.S., Burthe, S., Helaouet, P., Johns, D.G., Jones, I.D., Leech, D.I., MacKay, E.B., Massimino, D., Atkinson, S., Bacon, P.J., Brereton, T.M., Carvalho, L., Clutton-Brock, T.H., Duck, C., Edwards, M., Elliott, J.M., Hall, S.J.G., Harrington, R., Pearce-Higgins, J.W., Høye, T. T., Kruuk, L.E.B., Pemberton, J.M., Sparks, T.H., Thompson, P.M., White, I., Winfield, I.J., Wanless, S., 2016. Phenological sensitivity to climate across taxa and trophic levels. Nature 535, 241–245.

Thomas, C.D., Gillingham, P.K., Bradbury, R.B., Roy, D.B., Anderson, B.J., Baxter, J.M., Bourn, N.A.D., Crick, H.Q.P., Findon, R.A., Fox, R., Hodgson, J.A., Holt, A.R., Morecroft, M.D., O'Hanlon, N.J., Oliver, T.H., Pearce-Higgins, J.W., Procter, D.A., Thomas, J.A., Walker, K.J., Walmsley, C.A., Wilson, R.J., Hill, J.K., 2012. Protected areas facilitate species' range expansions. Proc. Natl. Acad. Sci. 109, 14063–14068.

Urban, M.C., 2015. Accelerating extinction risk from climate change. Science 348, 571–573.

Virkkala, R., Pöyry, J., Heikkinen, R.K., Lehikoinen, A., Valkama, J., 2014. Protected areas alleviate climate change effects on northern bird species of conservation concern. Ecol. Evol. 4, 2991–3003.

Warren, R., Price, J., Graham, E., Forstenhaeusler, N., VanDerWal, J., 2018. The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. Science 360, 791–795.

Watts, K., Whytock, R.C., Park, K.J., Funtes-Montemayor, E., Macgregor, N.A., Duffield, S., McGowan, P.J.K., 2020. Ecological time lags and the journey towards conservation success. Nat. Ecol. Evol. 4, 304–311.

Wilson, K.A., Law, E.A., 2016. Ethics of conservation triage. Front. Ecol. Evol. 4, 112.

Wintle, B.A., Bekessy, S.A., Keith, D.A., van Wilgen, B.W., Cabeza, M., Schröder, C., Carvalho, S.B., Falcucci, A., Maiorano, L., Regan, T.J., Rondinini, C., Boitani, L., Possingham, H.P., 2011. Ecological-economic optimization of biodiversity conservation under climate change. Nat. Clim. Chang. 1, 355–359.

Further reading

Frederiksen, M., Wanless, S., Harris, M.P., Rothery, P., Wilson, L.J., 2004. The role of industrial fisheries and oceanographic change in the decline of North Sea black-legged kittiwakes. J. Appl. Ecol. 41, 1129–1139.