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Climate change adaptation for biodiversity in protected areas: An overview of actions

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ABSTRACT

Protected Areas (PAs) have been a cornerstone of conservation policy in the past but are generally static and thus might be less useful under climate change as species move away from reserves designated for them. In addition, shifting phenology and habitat alteration due to extreme events could make conditions unviable within PAs for species unable to move. However, several recent papers documented their utility in retaining contracting species, acting as stepping-stones for expanding species of conservation concern and resisting invasion by vagrants. Theoretical studies have suggested a role for both protected area design and management to enable biodiversity to adapt to climate change and implementation of these actions has begun. Here we synthesise case studies of climate change adaptation actions in protected areas from the globally available literature. We found 91 case studies of 114 different actions from 30 countries, mostly within Europe, specifically the UK. Half reported an outcome of actions, however, these were generally either the area restored or protected, or incidental reports of colonisation by desired species, without a description of monitoring before and after action. In addition, 72 % of actions would have been beneficial to biodiversity without the presence of climate change, so transformative action is lacking. Better monitoring and reporting of outcomes are urgently needed to develop the evidence base on which actions are most effective, to enable more reserve managers to take action. Managers also need encouragement to identify transformative actions, perhaps by the use of scenario planning to aid understanding of future uncertainties.

1. Introduction

Despite mitigation efforts, the planet has already warmed by over 1 °C since 1850–1900 with the last four decades being successively warmer, and this warming is projected to continue until at least 2050 under all emissions scenarios (IPCC, 2021). To have a reasonable chance of limiting global warming to 1.5 °C, greenhouse gas emissions must be reduced by 45 % by 2030 compared to those expected under current policies and must continue to decline rapidly after this (United Nations Environment Programme, 2022). This seems unlikely given that global policy changes have only achieved projected reductions of 0.5 $GtCO_2e$ compared to the situation at COP 26 (United Nations Environment Programme, 2022). Therefore, biodiversity has had to cope with extensive climate change in recent decades and will have to cope with further change into the future.

Species, communities and ecosystems have responded to recent climate change, showing increased abundance of warm-adapted species and decreased abundance of cold-adapted species at revisited sites (Pauli et al., 2007; Hastings et al., 2020), leading to reorganisation of communities. A large number of species have shown range expansions at polewards range margins in terrestrial, freshwater (Hickling et al., 2006; VanDerWal et al., 2013) and marine (Poloczanska et al., 2013) environments, whilst range retractions of cold-adapted species have also been demonstrated (Franco et al., 2006; Stafford et al., 2013). Species have also changed their phenology, with spring events tending to occur earlier in the year and autumn events shifting later (Menzel et al., 2006), with both changes in distribution and phenology potentially leading to mismatches between dependent species. Extreme events such as wildfire and coastal flooding also directly destroy habitats and result in losses of ecosystem services (Parmesan et al., 2022).

Historically, conservation efforts have often centred around protecting areas for particular species and habitats, such as Ramsar wetland

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sites (https://rsis.ramsar.org/), and across Europe, Special Protection Areas, protected under the Birds Directive, and Special Conservation Areas, protected under the Habitats Directive (CEC, 2000). The Convention on Biological Diversity's Aichi target 11 called for 17 % of terrestrial and inland waters and 10 % of coastal and marine areas to be protected by 2020. These targets were missed, but the protected area estate did expand between 2000 and 2020 from about 10 % to at least 15 % terrestrially, and from about 3 % to at least 7 % in marine areas (Secretariat of the Convention on Biological Diversity, 2020), although there has been limited success in increasing coverage for threatened species (Maxwell et al., 2020). More recently, the targets have been updated to protect 30 % of the planet by 2030, with a specific emphasis on areas of importance for biodiversity, ecological integrity and connectivity (https://www.cbd.int/gbf/targets/).

In light of climate change, some authors have questioned whether protected areas can remain useful, as many species are predicted to move away from areas designated for them in response to both temperature and hydrological changes (e.g. Araújo et al., 2011, Xi et al., 2021), with this issue first being highlighted decades ago (Peters and Darling, 1985). In some cases, driven by climate change, species are even using new locations for critical habitat such as nursery areas (e.g. Bangley et al., 2018). However, PAs could remain important under a changing climate, since many contain systems and landscape features that are likely to continue to support high biodiversity even if species compositions change, and the landscapes and management in many PAs might help species currently present to persist (Gillingham et al., 2015, Thomas and Gillingham, 2015), especially if they are managed as networks across broad scales such as ecoregions (Balantic et al., 2021). In some places, the proportion of distributions of species of conservation concern protected may actually increase in future (Critchlow et al., 2022).

Empirical studies have shown that protected areas (PAs) have retained cold-adapted species more effectively than unprotected sites, particularly at lower latitudes (Gillingham et al., 2015) and resisted invasion by warm-associated vagrants compared to non-reserve sites (Bates et al., 2014; Hiley et al., 2014). Corals in PAs have shown more resilience to climate change (Mellin et al., 2016, but see Bates et al., 2019) and faster recovery following climate change–related disturbances (Olds et al., 2014). In addition, PAs have enabled species of conservation concern to expand their distributions polewards (e.g. Hiley et al., 2014; Thomas et al., 2012), particularly when they are managed for biodiversity (Lawson et al., 2014), which suggests that removing interacting threats improves responses to climate change. Some authors have therefore suggested incorporating climate change impacts into the prioritisation of new sites for protection (e.g. Stralberg et al., 2020) and/or the creation of dynamic protected areas (D'Aloia et al., 2019). Protection from human impacts may not be enough to protect species in all PAs and other interventions may be necessary (Kleypas et al., 2021). For example, predator control has been shown to reduce negative effects of climate, so reserve management has the potential to improve resilience to climate change in vulnerable populations (Pearce-Higgins et al., 2019).

There is therefore a growing interest in enabling biodiversity to cope with climate change using protected areas. Climate change adaptation (CCA) has been defined as "human activities intended to minimize the adverse effects of climate change on human infrastructure and sensitive aspects of the natural environment" (Mawdsley et al., 2009), whilst the IPCC (2014) explicitly mention adjustment to expected as well as actual climates. Here, as in Pearce-Higgins et al. (2022), we focus on adaptation interventions for biodiversity and ecosystem function. In a protected area context, PA networks could be designed with climate change in mind (e.g. Wilson et al., 2020). Within individual PAs and PA networks, resistance to a limited amount of warming could be achieved by providing resources or reducing other pressures (Pearce-Higgins, 2011). PAs could also be managed to increase adaptive capacity (for example planting climate-adapted genotypes, allowing immigration of new species), or enable transformation (for example via assisted migration or by planting non-native but naturalised climate adapted species, Dudney et al., 2018).

Several efforts have been made to review climate change adaptation literature in the past. Heller and Zavaleta (2009) found 524 recommended actions from 113 papers across 22 years. Many of these called for further research on species responses (15 recommendations, joint fourth most popular) or integrating climate change into planning exercises (19 recommendations, second most popular) rather than action on the ground. Glick et al. (2011) updated this review, finding 600 papers with recommended climate change adaptation actions published between 2007 and 2011, showing a proliferation of this literature. Over three times as many papers in that review were about adaptation of human systems (the most common category) compared to biodiversity or ecosystem conservation (the least common category), despite their search terms being skewed to the latter, with North America and Europe being the best represented regions. These reviews concentrated on the recommendations made by authors in the reviewed papers, rather than actions taken to aid biodiversity in adapting to climate change and indeed most scientific literature on adaptation to reduce risk to biodiversity from climate change has been based on ecological theory rather than observations or practical experience (Parmesan et al., 2022), although Gross et al. (2016) released guidance on CCA for PA managers and planners.

More recently, Jenkins et al. (2022) developed an Adaptation Inventory for the UK, based on national reporting to government by public and private sector organisations and a systematic review of peer-reviewed literature. They identified 360 examples of climate change adaptation across all sectors, over 80 % of which had already been implemented. Of these, 48 (13 %) were ecosystem-based, including nine examples of habitat restoration and five of land management. However, only 15 were in the national parks/land/environment category, indicating biodiversity conservation may have been the driver. Berrang-Ford et al. (2021) screened over 48,000 articles using machine learning methods and a global network of 126 researchers, then synthesised the resulting 1682 articles. Terrestrial and freshwater ecosystems had 208 actions (12 % of those recorded) whilst ocean and coastal ecosystems had 166 (10 %) but these authors concentrated on climate change adaptation to protect people, their livelihoods and infrastructure and thus they removed any papers only about natural systems from their searches. Tittensor et al. (2019) reviewed literature on climate change adaptation in the design and operation of marine protected areas (MPAs) and MPA networks. They found 98 papers but only six with concrete implementations. Of these, only one (the Greater Farallones National Marine Sanctuary in California) included climate change in the management plan. Wilson et al. (2020) reviewed climate change adaptation actions in marine systems, but this was based on existing reviews and databases rather than systematically searching the literature. Conversely, Prober et al. (2019) systematically reviewed both recommendations and actions in terrestrial and freshwater systems in the peer-reviewed literature to 2016, finding that only 16 % of the 473 included studies offered new empirical evidence, with the remainder inferring recommendations from ecological reasoning. Of the 473 papers, only 25 reported implemented actions. In this issue, Hansen et al. (2023) found only 13 examples of studies testing the efficacy of climate adaptation actions.

Agencies responsible for PA management are often aware of the potential issues that climate change might cause, but do not feel empowered to respond to them. For example, Lemieux et al. (2011) surveyed 35 agencies responsible for 99 % of Canadian PAs. All respondents believed climate change is an issue for PA planning and its importance was perceived likely to increase. However, 91 % said that they currently do not have the capacity to respond effectively to climate change, including having knowledge of potential actions to take. Indeed, Handler et al. (2022) identified a need for best management practices and examples of successful adaptation to be shared with PA managers.

There is therefore a need to synthesise the effectiveness of CCA actions for biodiversity on protected areas globally to enable PA managers to act with confidence. Here we complete an evidence-based review on effective climate change adaptation management for biodiversity in Protected Areas, asking a) what are the drivers of reported actions (biodiversity only or also for people); b) are there spatial, or ecosystem-based patterns in the reported actions; c) are actions 'more of the same' or transformational and d) are there any early reports of the effectiveness of different actions?

2. Methods

We completed a rapid evidence review searching for instances of climate change adaptation actions for biodiversity conservation within protected areas, focussing on the most relevant literature rather than using machine-learning methods to search all returned sources. We used Google Scholar for all searches as previous reviews (e.g. Jenkins et al., 2022) have shown that many reports are found within grey literature and we did not want to exclude these. We completed searches using terms similar to Tittensor et al. (2019), which were broad so as not to miss potential examples. Our first search (completed 11/05/2022) used the string "climate change adaptation" AND "protected area" AND "example". Our second search (completed 22/06/2022) used the terms "climate change adaptation" AND "protected area" AND management. Results were ordered by relevance with citations and patents removed.

For both searches, we scanned the titles and abstracts of the first 200 results and, in some cases, skim read the paper where it was not clear from the abstract whether our inclusion criteria might be met. We firstly removed replicated papers and those that were obviously not about climate change adaptation. Where it was not clear whether our criteria were met, we retained the paper to read the full text. Criteria for inclusion were that the paper or report included concrete examples of climate change adaptation for biodiversity in one or several protected areas. We echoed Jenkins et al. (2022) that to be included in our final database, case studies had to reflect a tangible and physical change in response that delivers adaptation action, as opposed to building adaptive capacity, for example by training PA staff in the impacts of climate change. Even within PAs, many papers discussed Ecosystem-based Adaptation (EbA), where the driver was to protect people rather than biodiversity. We included these case studies where biodiversity conservation was also mentioned as a target. Some papers discussing climate change adaptation options or barriers to adaptation were also downloaded for use in our introduction and discussion but are not reported on within our results section. We then read the full text of retained papers and mined for any references (including databases) that appeared relevant from the text.

Two databases were discovered during our mined reference search. Within the United Nations Framework Convention on Climate Change (UNFCC) adaptation knowledge portal (https://www4.unfccc.int/sites/nwpstaging/pages/Search.aspx) we searched for Information Type "case study" with Adaptation Sector/Theme "Biodiversity" and Adaptation Element "Adaptation Planning and Practices" which returned 79 case studies. We checked each for CCA within protected areas and cross-checked with our existing case studies so as not to duplicate information. Within the European Environment Agency (EEA) Climate-ADAPT database (https://climate-adapt.eea.europa.eu/#t-database) we searched for Type of Item "Case studies" for Adaptation Sectors "biodiversity" which returned 30 case studies, which we treated as above.

From each paper or database report, we extracted: 1) the country and continent where the action took place; 2) whether the reserve was terrestrial, freshwater, coastal/marine, or any combination of these; 3) the site size (where reported); 4) the driver for action (whether for biodiversity only or also for people); 5) whether the action was implemented (Y, N or unclear); 6) details of the action; 7) whether the action involved reserve or reserve network design (including zoning plans), management within a particular reserve, education, translocation of species, monitoring, or a combination of any of these. We then separated the actions from case studies where multiple actions had been completed and for each action recorded: 8) whether the action involved protecting more sites (designated as 'protect'), reversing past harms (e.g. restoration, reduction of pollution or fishing pressure, designated as 'restore') or proactively changing management (e.g. managing microclimates, translocation, designated as 'proactive'); 9) any outcomes reported and 10) whether the outcomes reported area protected/restored, survival of target/planted species, positive effect on physical processes such as flooding, or recolonisation by desired species.

Because coastal and marine protected area coverage has increased more compared to freshwater/terrestrial sites since 2010 (Maxwell et al., 2020), we might expect MPAs to be more likely to incorporate climate change during the design phase. We therefore tested for an association between site type (Coastal/Marine or Terrestrial/Freshwater) and whether the CCA action included design of a PA or PA network. We also tested for an association between site type and action type (protection, restoration or proactive), as management plans for newer sites may have incorporated climate change when first written, so marine sites might be expected to include more proactive actions. Finally, we tested for an association between the driver of action (biodiversity only, or including people) and the action type, as CCA for people often incorporated EbA, which tends to restore ecosystems following damage by human actions. All associations were tested using Chi-Squared tests in IBM SPSS Statistics version 28. We additionally performed a Chi-squared goodness of fit test to determine whether types of action were equally spread between the three categories of protection, restoration and proactive.

3. Results

The string "climate change adaptation" AND "protected area" AND "example" returned ~9500 results, whilst "climate change adaptation" AND "protected area" AND management returned ~9910, many of which were already present in the first search (see Table 1). We read the titles and abstracts of 340 unique papers and searched two databases, of which 75 papers and the two databases met our criteria for inclusion. Of these papers, two were not available, meaning we read the full text of 75 papers, reports and databases, 42 of which included examples of climate change adaptation where biodiversity was at least one of the drivers, although individual case studies were not always reported (for example Jenkins et al., 2022 report on CCA actions from case studies, but do not include details of these case studies). We were able to extract case study information from 28 sources, some of which described the same case studies. Of the 79 case studies on the (UNFCC) adaptation knowledge portal, only three met our criteria for inclusion, two of which were also detailed in literature sources. Of the 30 case studies in the (EEA) Climate-ADAPT database, twelve met our criteria, of which three were also detailed in the literature. Full details on the literature searched are provided in Appendices 1 and 2.

From these 28 sources, alongside details provided of case studies in Parmesan et al., 2022, we compiled reports of 110 separate case studies of actions to aid either habitats or species to cope with climate change (see Appendix 3). In 13 cases it was unclear whether planned action had been implemented from the report, five were not implemented at the time of reporting, one was an observation of potential opportunities resulting from climate change, and one was an observation that historical management had made a site more resilient to climate change, leaving 91 cases where it was clear that CCA action had been taken. Details of all case studies, including a short description of the actions and whether we allocated these as restore, protect or proactive are available in Appendix 3.

From these 91 case studies, we found actions within 30 countries, dominated by reports from the UK (44 cases) followed by the USA (eight cases), with 40 of the UK actions coming from just two sources (Ausden, 2014; The Wildlife Trusts, 2022). As a result, most case studies were located in Europe (Fig. 1). Coastal/marine habitat was the most represented (39 case studies) followed by terrestrial (33 case studies) then freshwater (16 case studies), with three examples that spanned both terrestrial and freshwater habitats. Only 22 case studies reported site size (see Appendix 3), with the ten smallest all being in the UK (largest UK site 3700 Ha, all others <500 Ha) and the largest being in Australia (2.8 million Ha) and Indonesia (7.56 million Ha).

In terms of the types of action carried out, the majority of case studies included site management (see Table 2). Most were on single reserves, some were carried out at a number of reserves managed by the same organisation (e.g. Ausden, 2014) and a small number were landscape-scale connectivity initiatives such as the Australian Alps to Atherton initiative (Pulsford et al., 2010), which designated new reserves in 1996 to improve connectivity to 150 north–south kilometres of interconnected protected areas along the Great Escarpment. Although our searches were limited to Protected Areas, 24 of the case studies included benefits to people via ecosystem services such as flood prevention, coastal protection and freshwater provision.

There were only ten case studies where climate change impacts had been considered when designing the PA or PA network and this was not associated with coastal/marine sites (Chi-squared test, N = 91, $p > 0.05$).

We recorded 114 different types of action (some sites carried out several actions), of which 72 % were actions that would be desirable without climate change, either protecting more area or restoring ecosystems following past harms (Fig. 2), with more restore actions than expected by chance and fewer proactive and protect actions (Chi-squared goodness of fit test, N = 114, $p = 0.003$). There was no association between the type of action (protect, restore or proactive) with site type (coastal/marine or terrestrial/freshwater) (Chi-squared test, N = 114, $p > 0.05$) nor was there an association between the type of action and the driver for action (biodiversity only, or including people) (Chi-squared test, N = 114, $p > 0.05$).

Half of the actions (57) reported some outcomes, with 27 of these being the area restored or protected, 14 including reports of recolonisation by desired species, sometimes in addition to the area restored or protected, 12 quantifying survival of the target or planted species, three noting better outcomes of physical processes (fire, flooding and sedimentation) and one non-specific positive outcome. None reported neutral or negative outcomes.

4. The importance of making case studies discoverable

It is probable that many climate change adaptation actions go unreported in literature, even when including grey literature available via Google Scholar. Here, we report on three sources which were not returned in our literature search (so are not included in our results above) but that we are aware of. Firstly, the Climate Adaptation Knowledge Exchange (https://www.cakex.org) has a digital library of climate change adaptation case studies, tools, and resources. Case studies cover the Americas from Canada to the Caribbean, as well as Hawaii and the Pacific Islands, across a range of sectors and phases along the process (from assessment to monitoring). Selecting resource Type: Case Study, Sector Addressed: Biodiversity or Wildlife, and Adaptation Phase: Implementation on 04/10/2023 returned seven case studies, five of which relate to sea level rise and two to wetland restoration. Mason et al. (2023) created a calendar with eleven short descriptions of CCA interventions across Australia, of which one was discovered during our rapid review. Most of these interventions would have been classed as proactive in our system (e.g. sprinkler systems to deal with wildfires, planting climate resilient seeds, providing cooler locations within sites). Finally, the Joint Nature Conservation Committee has twelve Nature-based Solutions case studies from across the UK and a range of habitats, many of which mix CC mitigation and adaptation, on their website (https://jncc.gov.uk/our-work/nature-based-solutions-iaccg-case-studies/). Many of these involve significant effort to carry out. For example, the Keeping Rivers Cool project (https://jncc.gov.uk/our-work/keeping-rivers-cool/) aimed to reduce river temperatures by increasing riparian shading to enable persistence of species requiring cool waters, with the added bonus of providing coarse particulate organic matter, which may further enhance the resilience of invertebrate populations (Thomas et al., 2016). Between 2012 and 2016, 55,000 trees were planted and 37 km of fencing was erected at four demonstration catchments. In addition, best practice guidance and shade opportunity maps for England were created and made freely available so land managers can target areas which are exposed most to sunlight and potential warming, leading to planting of over 300,000 riparian trees. These case studies represent a huge amount of effort and cost many millions of US dollars, yet the details and outcomes of the projects are hard to find without prior knowledge of their existence.

Table 1
Details of the systematic literature review. Search 1 used the string “climate change adaptation” AND “protected area” AND “example”, search 2 used the string “climate change adaptation” AND “protected area” AND management. MR stands for “mined references”. Sources passed the filter if they appeared relevant from reading the title and abstract. * One source was not available as full text.

Search	Number of results	Unique results	Passed filter	Include CCA actions
One	~9500	200	28	16
Two	~9910	55	11*	6
MR one	NA	65	33	19
MR two	NA	22	5	1

5. Discussion

We found a large number of different actions reported, across different site types but largely within Europe and with the majority falling under site/reserve management rather than design of PA networks. Restorative action was significantly more prevalent than proactive or protective across case studies but only half of all case studies reported associated outcomes. We did not find any associations between marine/coastal sites and the likelihood of incorporating climate change impacts into the design of networks, or the use of more proactive actions, which was surprising given many of these sites are more recently designated. This is likely due to the small number of case studies which incorporated consideration of climate change into the design of the PA or network as well as the existence of three fairly recent corridor projects to improve connectivity in terrestrial environments, which supports our initial assumption that newer projects would be more likely to incorporate CCA action but shows that these new projects are also taking place in terrestrial environments (for an additional example, see Beazley and Hum, 2023, this issue). The small number of case studies where climate change considerations have been incorporated into the design of PAs or PA networks is likely due to the perceived difficulty of adopting this approach. A large amount of data is needed to create a climate-informed design and whilst hundreds of species distribution projections have been published (e.g. see Peterson and Soberón, 2012), when tested against independent assessments of occurrence, abundance, population performance, and genetic diversity they were rarely found to reflect biological reality (Lee-Yaw et al., 2022). PA designers may therefore hesitate to use this information and of course there are also socio-economic constraints which must be considered to ensure buy-in from local stakeholders (see Mangubhai et al., 2015 for an example implementation of this).

Most reported actions were conventional (i.e. would be priorities without considering climate change as a driver), despite having been identified as CCA actions. This is in alignment with Prober et al. (2019), who found that around three quarters of potential actions identified from the literature were low regrets options as opposed to climate-targeted. This is perhaps unsurprising since Barr (2020) found that

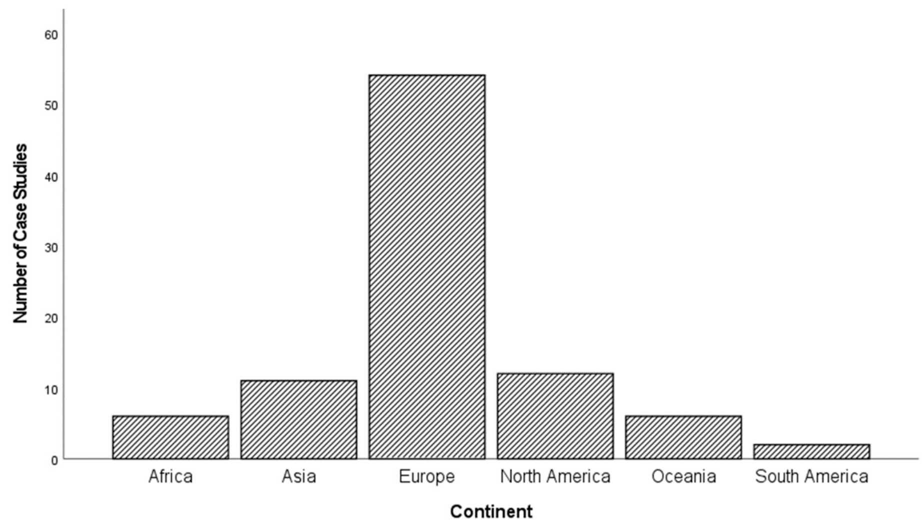

Fig. 1. Location of the 91 case studies by continent.

Table 2
The management actions carried out for 91 case studies of climate change adaptation within Protected Areas.

Action type	Number of case studies
Site Management	67
Site Management and Education	6
Site Management and Translocation	2
Site Management and Protected Area Design	8
Protected Area Design	1
Protected Area Design, Site Management and Translocation	1
Translocation	4
Monitoring	1
Education	1

when Canadian stakeholders were asked to generate adaptation options then rank them, the most commonly mentioned and highest ranked options for feasibility and effectiveness were conventional, perhaps because they are most familiar to practitioners and thus best understood. Early attempts to include CCA in management plans for National Wildlife Refuges in the USA also overwhelmingly resulted in actions to enable resistance to climate change being chosen (Fischman et al., 2014). Of the first 61 National Nature Reserves to complete vulnerability assessments in England, 41 identified a total of 608 adaptation actions, of which 56 % could be classified as interventions aiming to build the resilience of the reserves' target features and <10 % related to the management of change (Duffield et al., 2021). In Scotland, proposed options for adaptively managing Marine Protected Areas (MPAs), such as flexible boundaries, buffer zones of management, and temporary MPAs that track ecosystem processes or features were deemed impractical to implement (Hopkins et al., 2018). Similarly, Tan and Fischer (2022) reviewed management plans for 58 MPAs within six Australia Marine Parks networks and found they were lacking in transformative strategies such as dynamic MPAs, translocations and replication, all of which are suggested by IUCN guidance. Since 2008, Marine Conservation Zones have been designed and implemented within English waters using 'feature' based conservation, with features relating to habitats, biological assemblages or specific species. Many of these features may become degraded with climate change and species movements, yet there is considerable legal uncertainty as to whether climate change effects

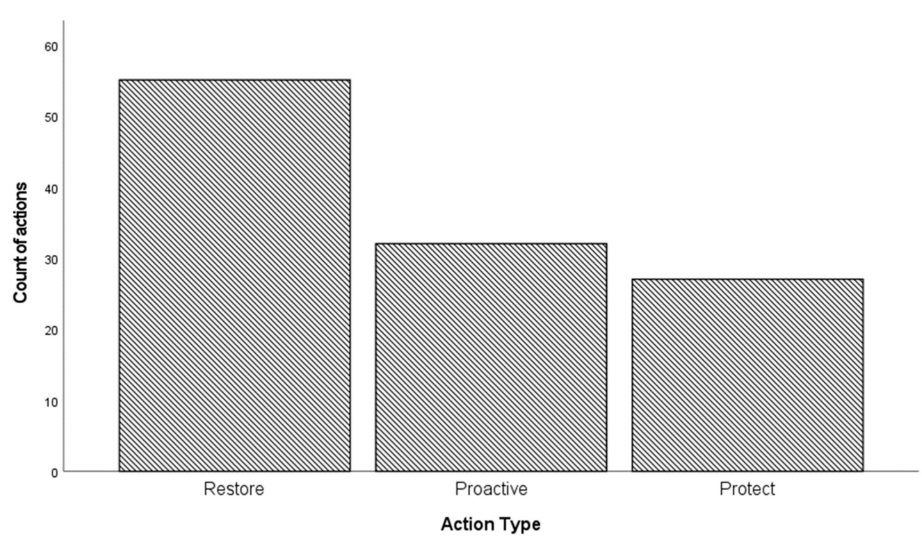

Fig. 2. Distribution of the 114 climate change adaptation actions carried out on protected areas across three categories: "Restore" includes actions such as planting native species, restoration of hydrological function and removal of invasive species, "Proactive" includes actions taken in anticipation of climate change impacts, such as translocations, management of microclimates and creation of new fire breaks, "Protect" includes designation of new reserves and removal of harms such as fishing closures.

would be considered in the degradation of protected features (Cliquet et al., 2009). We therefore concur with Prober et al. (2019) that more transformative approaches are likely to be needed in future as the climate changes further.

Parmesan et al. (2022) noted that a common pattern amongst studies investigating the extent of integration of climate change adaptation into conservation action is that vulnerability has been assessed and potential adaptation actions identified, but implementation has been limited beyond actions which may improve resilience via improving ecological condition. In one case study we found, an implemented strategy was indicated as a dynamic response to climate change (North Atlantic right whale *Eubalaena glacialis* mentioned in Tittensor et al., 2019), however the supporting literature is uncertain as to whether recorded changes in *E. glacialis* distribution are due to climate change or a prior lack of monitoring (Davies and Brillant, 2019). More transformative approaches within individual site management that have been implemented include providing cooler nesting sites via shading or insulated artificial nests, providing refuges from extreme events and creating artificial watering holes to improve water availability (Parmesan et al., 2022, Advani, 2023 this issue). In our review, seven of the 32 (22 %) identified proactive actions involved managed realignment to accept ecosystem change, with a range of other actions implemented (see Appendix 3).

Greenwood et al. (2016) reviewed site management options under climate change and found that replicated local management of habitat that monitored to determine the efficacy of management actions was scarce. Additionally, some options such as adding fertiliser to promote vegetation growth (providing cooler locations) or raising substrate for nesting birds (as a defence against sea level rise) had no evidence for success and some transformative options showed significant risk.

One constraint to adopting transformative approaches is therefore the lack of evidence to encourage reserve managers to select these more radical management actions. Whilst there are plenty of frameworks and guidance available to assess vulnerability then identify and rank potential climate change adaptation actions (e.g. Halofsky et al., 2018; Nelson et al., 2020), resources may be needed to support decision-making. For example, Bachelet et al. (2017) describe climate (CMIP5), landscape intactness and soil sensitivity datasets that have been made available for parts of the US in a user-friendly format for use by natural resources managers (e.g. for use in vulnerability assessments). Schuurman et al. (2019) and Miller et al. (2023) found that the use of scenarios during workshops to identify adaptation options resulted in recognition of the need to both change goals and change management, so use of this tool in future may inspire PA managers to look beyond the 'more of the same' approach. In addition, direct testing of CCA action effectiveness, whether on PAs or not, should provide evidence to aid PA managers in selecting options (e.g. see Chiquoine et al., 2023 and Hansen et al., 2023, both this issue). This is especially useful if CCA actions can be implemented using an experimental approach (see Nadeau et al., 2023, this issue), providing evidence of effectiveness that could be shared across the conservation community.

Despite searching for CCA within PAs, many of the reports were on Ecosystem-based Adaptation for people, with biodiversity benefitting as an additional benefit. This is perhaps not surprising as EbA can be extremely cost-effective. In Barbados, reef and mangrove revival were the most cost-effective actions for reducing hurricane risk and every dollar invested in the Folkestone Marine Park on the west coast of Barbados is expected to reduce loss and damage from hurricanes by 20 dollars (Caribbean Catastrophe Risk Insurance Facility (CCRIF), 2010). Although focussed on people as a driver for CCA management, this does provide an incentive for the restoration and protection of biodiversity. Jacobs et al. (2019) found considerable overlap in management options and in the actions along adaptation pathways between biodiversity and heritage assets, suggesting synergies in management interventions should be possible. However, it can be rare to find studies or data which evaluate management options of protected areas aiming to benefit people alongside necessary biological indices to assess their effectiveness in protecting biodiversity (Gill et al., 2017; Stafford, 2018) even without climate change being incorporated in the biodiversity indices.

It appears that biodiversity conservation may be falling behind other sectors in carrying out CCA actions, or at least in reporting them. Tompkins et al. (2010) documented over 300 examples of early adopters of adaptation practice (to 2005) in the UK, of which only 11 % were from the biodiversity and conservation sector. Similarly, Lesnikowski et al. (2015) found 4104 adaptation initiatives globally, of which 27 % contained some tangible adaptation actions. Most of the reported adaptations fell into the category of infrastructure, technology, and innovation. The EEA European Climate Adaptation Platform (http://climate-adapt.eea.europa.eu/) contains 115 case studies, 30 of which are linked to biodiversity, but only 14 had biodiversity conservation outside urban areas as a primary objective and of 79 case studies on the UNFCC Adaptation Knowledge Portal linked to biodiversity, only three had biodiversity conservation as a major objective. However, Berrang-Ford et al. (2021) found that "ecosystem-based" responses were 50 % of the 1682 they recorded, and were particularly common in Africa and South and Central America, despite rejecting papers concerned only with natural systems within their methods. Many actions designed to help people cope with climate change will also have a benefit to biodiversity (Parmesan et al., 2022), although the question remains whether they will also act as climate change adaptation options for biodiversity.

In contrast to Berrang-Ford et al. (2021) and Jenkins et al. (2022), we found that half of the actions reported some sort of outcome. However, these tended to be quite superficial, such as the extent of protected or restored habitat (e.g. Ausden, 2014), the survival rate of planted seedlings (Wibisono and Sualia, 2008) or the presence or recolonisation of desired species (Department of Environment, 2015; The Wildlife Trusts, 2022). None of these measures the success of actions in attaining desired outcomes (i.e. resistance or resilience of populations to climate change) and of course access to control (unmanaged) sites could be problematic even where monitoring is present, which means that the evidence base for the effectiveness of CCA actions is lacking. Protected Area managers therefore urgently need to use a wider set of indicators of success of climate change adaptation, such as those proposed by Pearce-Higgins et al. (2022). The implementation of many of these requires further development and international co-operation between PA managers and academics. Furthermore, comparison of outcomes with those predicted by modelling studies both including and without management actions (such as Pearce-Higgins, 2011) could help attribute the success or otherwise of management actions in achieving climate change adaptation of managed populations. The resources available for monitoring the outcomes of CCA actions are currently small compared to those spent carrying them out – for example the four projects reported in Keenleyside et al. (2014) which were carried out in Kenya, Colombia, Chile and Mexico amounted to CAN$3.3 million, but no outcomes were reported. There is an urgent need to allocate resources to developing the evidence base for CCA actions.

Whilst it is possible that implementation of actions is more common in smaller PAs (many of our reported actions were from small PAs in the UK), we also found many examples of implementation in larger reserves, usually as a part of the reserve rather than the whole (see Appendix 3). We therefore consider that implementation is likely to be driven by factors such as resources available, confidence of PA managers and external drivers such as targets for management set by governments.

Of the 342 sources we checked, 42 included concrete examples of CCA and 28 included case studies of CCA actions. This is slightly higher than the 5 % of broader adaptation literature reporting on implemented adaptation response within searches by Berrang-Ford et al. (2021), perhaps influenced by our inclusion of the search terms 'example' and 'management'. Our review undoubtedly under-represents the number of cases where climate change adaptation has been carried out, at least partly because there were thousands more papers which could have been scanned for a full systematic review, presumably with a diminishing return rate of case studies since we ordered results by relevance. In addition, the inclusion of 'adaptation' in our search terms may have excluded some sources where generic resilience was promoted and thus the CCA actions may be even more skewed towards low regret options than we found here, whilst the inclusion of 'protected area' may have excluded case studies relevant to protected areas but not actually carried out within them. Finally, not all actions go reported in sources accessible to literature search (see above section on the importance of making case studies discoverable). We also found sources which reviewed reports not available via literature search, where the resulting case study information was not available within supplementary materials. For example, Duffield et al. (2021) reviewed 61 vulnerability assessments of National Nature Reserves in England and identified 608 actions suggested by PA managers, but details of these identified actions are not available nor is it clear whether they have been or are planned to be implemented. Similarly, Rannow and Wilke (2013) developed a framework for the adaptation of protected area management and state it was tested in six investigation areas, but the details of these management plans, whether they were implemented, and any outcomes, are not reported. We suggest that a global review of climate change adaptation actions for protected areas, perhaps using methods such as those pioneered by Berrang-Ford et al. (2021), could produce a useful database of case studies open to PA managers, which could then be supplemented by additional reporting of CCA actions and outcomes if enough resources were made available. It would be particularly important to report on actions taken outside North America and Europe, since most of the case studies we found were from Europe, in line with the known and growing disparity in conservation research capacity across countries (Zhang et al., 2023). Our study is a first step in reviewing CCA actions reported as undertaken in protected areas across the world, and the database of case studies is provided (See Appendices 1–3). However, since we concentrated on easily discoverable literature much more work is required to represent CCA effectiveness for global biodiversity.

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Declaration of competing interest

Please note that two authors on this submission are editors of this special issue. The authors report no other conflict of interest.

Data availability

I have shared the data as appendices

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Appendices. Supplementary data

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