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Perspective Article

A framework for climate change adaptation indicators for the natural environment

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ABSTRACT

Impacts of climate change on natural and human systems will become increasingly severe as the magnitude of climate change increases. Climate change adaptation interventions to address current and projected impacts are thus paramount. Yet, evidence on their effectiveness remains limited, highlighting the need for appropriate ecological indicators to measure progress of climate change adaptation for the natural environment. We outline conceptual, analytical, and practical challenges in developing such indicators, before proposing a framework with three process-based and two results-based indicator types to track progress in adapting to climate change. We emphasize the importance of dynamic assessment and modification over time, as new adaptation targets are set and/or as intervention actions are monitored and evaluated. Our framework and proposed indicators are flexible and widely applicable across species, habitats, and monitoring programmes, and could be accommodated within existing national or international frameworks to enable the evaluation of both large-scale policy instruments and local management interventions. We conclude by suggesting further work required to develop these indicators fully, and hope this will stimulate the use of ecological indicators to evaluate the effectiveness of policy interventions for the adaptation of the natural environment across the globe.

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1. Introduction

The impacts of climate change on biodiversity and natural ecosystems are ubiquitous and well documented (Scheffers et al. 2016; IPCC 2019). The severity of future impacts will increase with the magnitude of climate change, potentially exacerbated by large carbon emissions from some ecosystems (Jia et al. 2019). These concerns underpin the importance of the Paris Agreement goal (IPCC 2018), reinforced by the Glasgow Climate Pact (UNFCCC 2021) to limit global climate change to below 2 °C above pre-industrial temperatures and pursuing efforts to limit it to 1.5 °C. Evidence is urgently required to inform the appropriate management of natural ecosystems in response to climate change, both to reduce greenhouse gas emissions for climate change mitigation and to adapt to climate change (Morecroft et al. 2019).

Climate change adaptation can be defined as interventions that intentionally address the impacts and risks of climate change on natural and human systems (Mawdsley et al., 2009, Stein et al. 2013). We focus here on adaptation interventions for biodiversity and ecosystem function. Adaptation interventions include those that aim to reduce the exposure or vulnerability of species and habitats to climate impacts, and those that may improve environmental capacity to adjust to climate change (Stein et al. 2013, Prober et al. 2019). The evidence that biodiversity can be helped to adapt is growing: protected areas have facilitated range expansion and reduced local extinctions of habitat specialists (Thomas et al. 2012, Bates et al. 2014, Gillingham et al. 2015), the extent of semi-natural habitat in the landscape may moderate species' responses to temperature increases (Newson et al. 2014, Oliver et al. 2017), and active management may help increase the resilience of vulnerable populations (Le Bris et al. 2018, Pearce-Higgins et al. 2019). However, the number of tests of the efficacy of adaptation interventions is insufficient to quantify the magnitude of benefits or identify when they may or may not work (Greenwood et al. 2016, Morecroft et al. 2019, Wilson et al. 2020).

There is an urgent need to adapt conservation practices to a changing climate, in order to protect vulnerable species and habitats whilst maintaining ecosystem functioning (Heller & Zavaleta 2009) and to develop nature-based solutions to climate change for people (Chausson et al. 2020). It is also important to consider the potential impacts of management on climate change mitigation by altering greenhouse gas emissions (Harmon 2001). Given the potential risks and synergies from these different land-management requirements, evidence about the impacts of different approaches to land, freshwater and marine policy and management in the face of climate change is required to optimise decision-making (Heino et al. 2009; Gattuso et al. 2018; Morecroft et al. 2019).

To provide that evidence, it is important that the success or failures of interventions are monitored. This will ensure that the associated policy instruments and interventions result in the desired action on the ground and track whether such actions drive the expected ecological responses. Although the success of mitigation can be relatively easily measured through greenhouse gas emissions, tracking the success of adaptation is more difficult (Morecroft et al. 2019). The development of a framework to guide the monitoring and evaluation of adaptation policies and plans, including indicators to track progress, is thus key to support the implementation of effective adaptation actions.

2. Challenges in the monitoring and evaluation of climate change adaptation

Monitoring and evaluation (M&E) allows the performance of policies, strategies, plans and actions to be assessed, providing important data and insights that can then be used to inform and improve current and future management (Mäkinen et al., 2018). Effective M&E will improve future adaptation interventions, whilst providing a mechanism for reporting results for national and international commitments (e.g. the Paris Agreement and the UN Sustainable Development Goals) through the development of associated indicators. For example, the Adaptation Committee of the UK's Climate Change Committee monitors and evaluates progress in preparing for climate change through their biennial assessment of the UK's National Adaptation Plan (NAP; Climate Change Committee 2021).

Effective M&E is challenging (GIZ, 2013), given the diverse range of interacting social, economic, and environmental contexts. This is particularly the case for climate change adaptation. In this paper, we outline: 1) conceptual challenges of identifying successful adaptation interventions; 2) analytical challenges of attributing observed ecological changes to climate change; and 3) practical challenges of measuring the success of adaptation interventions over time-frames appropriate for informing policy and management decisions. We then propose an example M&E framework within which we suggest a range of indicators for different stages of adaptation, based upon the UK's National Adaptation Plan.

2.1. Conceptual challenges

There is a conceptual question about when particular policies or management actions may be regarded as adaptation, since some argue that to be defined as adaptation, actions must intentionally be implemented in response to climate change impacts (Mawsley et al. 2009). In practice, many interventions that might be relevant to climate change may not have been intentionally established for that purpose, such as protected area networks (Elsen et al. 2020). Identifying intentionality may not be easy and therefore focussing on pre-defined adaptation interventions only could risk excluding potentially important management actions and techniques.

Even if climate change adaptation can be clearly defined, the desired outcome of that adaptation may differ between stakeholders (Moser and Ekstrom, 2010) or there may be different framings and understandings of what constitutes effectiveness (Singh et al. 2021). In some situations, adaptation may seek to reduce the negative impacts of climate change on species and ecosystems, whilst in others it may be used to facilitate desirable climate-driven change (Prober et al., 2019). In the former, successful adaptation may be defined as the persistence of a particular climate-threatened species (Pearce-Higgins 2011) or ecosystem properties. In the latter, success might promote ecological change, which include changes to species compositions with losses as well as gains as a result of changes in management priorities (Paterson et al. 2008). Furthermore, some stakeholders may seek to prioritise outcomes in a changing climate that are not specifically related to biodiversity conservation, notably the provision of ecosystem services. Such outcomes are likely to be particularly important in heavily modified farmed and forested landscapes (Morecroft et al. 2020) and fisheries (Lam et al. 2020).

Defined adaptation objectives may vary across biological levels, from the conservation of individual species to the persistence and functioning of whole ecosystems. Moreover, the importance of multiple objectives may change with increasing severity of climate change (Morecroft et al., 2012), making it difficult to clearly identify the desired biological responses at any specific time. For instance, reducing the negative impacts on a climate vulnerable species may be an initial priority until longer-term adaptation measures are in place to secure the future for that species elsewhere, resulting in a shift in priority from ameliorating climate change to enhancing adaptive capacity (Prober et al. 2019). Adaptation is therefore best regarded as a continuous process rather than an end point (Stein et al. 2013).

2.2. Analytical challenges

The attribution of responses to climate change has received considerable attention from the Intergovernmental Panel on Climate Change (IPCC) (Hegerl et al. 2010) and is particularly challenging in ecological contexts (Parmesan et al. 2013). There are two elements to this challenge for climate change adaptation. Firstly, can observed ecological changes in the absence of adaptation interventions be attributed to climate change? Secondly, how well can responses be attributed to adaptation interventions?

Detecting climate change impacts as a reference for comparison to responses to interventions can be difficult due to the variability and uncertainty surrounding climate trends and projections. This is particularly the case when applied regionally and locally, and over short timescales often used for M&E (Mullan et al. 2013). Where responses to climate change may be complex and nonlinear, for example involving thresholds or tipping points, this challenge is increased. Although such tipping points are generally poorly understood, they are starting to be identified (Jones et al., 2020), and more generally, there is growing confidence in the robust detection of ecological responses to climate change (Chen et al. 2011, Thackeray et al. 2016, Lenoir et al. 2020), and in the attribution of biological responses to single climatic events (Smale and Wernberg, 2013, Davis et al., 2019). Several ecological climate change impact indicators have been proposed, such as tracking variation in species population trends according to the anticipated impacts of climate change (Gregory et al. 2009, Stephens et al. 2016), or tracking community-level responses using traits that link species to climate (Devictor et al. 2012, Martay et al. 2016). Although these indicators produce strong signals in line with expectations, there is a risk that in some circumstances they may be confounded by other ecological processes and anthropogenic pressures correlated with species' sensitivity to climate change (Clavero et al. 2011, Barnagaud et al. 2012). They are also divorced from actions and interventions which limit their usefulness to inform decision-making.

Attribution to adaptation interventions may be equally difficult. Where large-scale processes strongly impact local ecological dynamics, population trends or community responses cannot simply be linked to interventions at particular sites. Confidence in the attribution of change to interventions can be improved using counterfactuals, for example comparing sites with and without adaptation (Gillingham et al. 2015) or across gradients of adaptation intervention (Pearce-Higgins et al. 2019). However, as interventions are usually non-randomly located in space, this can be challenging, and as vulnerability to climate change can vary between locations, adaptation actions may similarly vary, making it difficult to generalise responses for indicators (Rinnan and Lawler, 2019). Potential source-sink dynamics between sites also mean that increases in the abundance of one population may result as much from larger-scale processes as local management (Sullivan et al. 2015). In such instances, demographic information may help more precisely attribute change to the interventions adopted, but such information is rarely available. In relation to larger-scale interventions, counterfactual or gradient approaches are unlikely to apply and alternative theory-based measures of success may be required (HM Treasury 2020).

More generally, multiple drivers act on ecological systems that may either mask or exaggerate true climatic responses (Halpern et al. 2019, Bowler et al. 2020) and further complicate the attribution of responses to adaptation interventions. In systems where non-climatic drivers have dominated, such as farmland (Eglington & Pearce-Higgins 2012), detecting the long-term impacts of climate change, let alone responses to adaptation interventions, is particularly difficult. Although it may be argued that in such instances climate change adaptation is not the primary driver for conservation action, ignoring it could exclude the potential benefits of the resulting conservation action for climate change adaptation (Donald & Evans 2006).

2.3. Practical challenges

Climate change is a long-term and large-scale process with both global and local consequences. Monitoring across large temporal and spatial scales may be needed to disentangle the relative importance of different processes driving observed changes. However, monitoring is often not a funding priority, including the monitoring of ecological responses to management, making it difficult for conservation organisations to devote sufficient resources to M&E. Citizen science data, which are gathered through biodiversity surveillance schemes for a wide range of monitoring and research purposes, provide an important source of large-scale and long-term data, particularly on the status of species (e.g. Pocock et al. 2015), and have the potential to make valuable contributions to studies of climate change adaptation (e.g. Thomas et al. 2012, Oliver et al. 2017). Although cheaper than funding the collection of professional data, citizen science is not free, requiring support and feedback to volunteers from organisations that oversee such schemes (Pearce-Higgins et al., 2018).

Additionally, both the ecological responses to climate change and the interventions undertaken may be slow or stochastic. Following anthropogenic degradation it may take decades or centuries for ecological processes to be fully restored in late-successional habitats such as mature woodland (Watts et al. 2020). Alternatively, some climate change adaptation may be targeted at reducing the impacts of rare extreme events, which may not occur for many years (IPCC 2012). In such instances, there may be a need to separate indicators regarding the implementation of action on the ground (process-based indicators), from the ecological impact of that action through time (results-based indicators).

3. Towards an indicator framework for adaptation

Building on Harley & van Minnen (2009), we suggest a M&E framework to track the adaptation of the natural environment to climate change (Fig. 1) and populate this with a range of suggested potential indicators (Tables 1-3). This process was initiated at a two-day workshop in October 2018, when 44 participants came together to: 1)

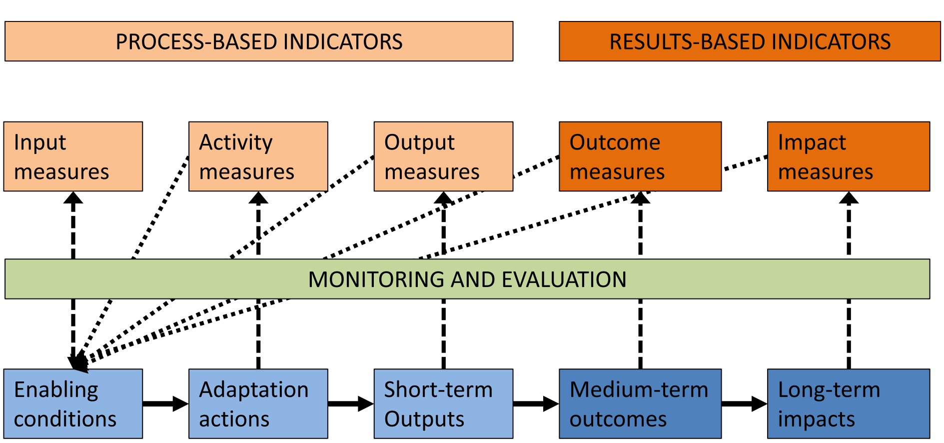

Fig. 1. Framework to track adaptation of the natural environment to climate change. The steps required for adaptation actions are outlined in light blue, with the different scales of responses in dark blue. These are monitored and evaluated (dashed arrows) to give a series of process-based indicator types (light orange) and results-based indicator types (dark orange). Depending upon progress with different indicators, various feedback loops (dotted arrows) may initiate additional adaptation actions, starting the process again. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Suggested indicators to track progress in the protection and improvement of protected sites and other areas of important wildlife habitat in the face of climate change. The likelihood of indicators being available is indicated by the symbols as follows: ☺- available, at least for some situations, 😐- possible with limited development, ☹- uncertain or requires significant development. PA: Protected Area; CCVA: climate change vulnerability assessments.

Input measures	Activity measures	Output measures	Outcome measures	Impact measures
Resources (funding/staff) available for PA designation and protection ☺	Extent and changes in PA extent (by habitat, area) ☺ Extent of protection of heterogeneous landscapes, climatic refugia, areas of projected future climate suitability 😐	Distribution and abundance of species in PAs ☺ (relative to non-PA counter-factual 😐) Extent, quality and condition of habitats in PAs ☺ (relative to non-PA counter-factual 😐) Spatial configuration of PA network 😐	Species colonisation/ persistence/trends in PAs relative to non-PAs 😐 (relative to changes in climatic variables ☹) Habitat condition/extent trends in PAs relative to non-PAs 😐 (relative to changes in climatic variables ☹) Observed trends on PAs relative to modelled projections and non-PAs ☹	Species' extinction risk (e.g. red-list assessment) ☺ Species' abundance ☺ Ecosystem service provision 😐 Ecological integrity/ ecosystem function 😐
Percentage of PAs integrating CCVA and climate change adaptation into planning 😐	Percentage of PAs/extent of habitat subject to management interventions for adaptation 😐			

identify the need for indicators to track the adaptation of the natural environment to climate change; 2) suggest data sources and analysis that could be used to inform indicators; and 3) outline potential indicators. All workshop participants were subsequently invited to contribute to this paper to develop and refine these ideas further. In our framework, three process-based indicator types measure (1) changes in the enabling conditions (input measures) required to (2) implement adaptation actions (activity measures), which then (3) alter ecological conditions on the ground (output measures; note these do not consider how those altered conditions deliver climate change adaptation). The success of adaptation is tracked by two results-based indicator types. Altered species and ecosystem responses to climate change as a result of the changed ecological conditions are tracked by outcome measures, whilst the long-term evaluation of adaptation over decades and centuries (impact measures) is measured by population viability, species' persistence, ecosystem function and service provision in a changing climate.

The focus of this paper is on the first four indicator types of our framework that measure inputs, activities, outputs and outcomes. The feasibility of individual indicators is rated using three categories depending upon the likely availability of existing data and the amount of development required. Given that the maintenance of species, habitats and ecosystems in a changing climate will *de facto* reflect successful climate change adaptation, population viability, species' persistence, ecosystem function and ecosystem service provision will consistently measure the proposed impact indicator across a suite of different adaptation indicators (Tables 1-3). Measures of these features already contribute to other indicators suites (e.g. Secretariat of the Convention on Biological Diversity 2020) and therefore are discussed in less detail than the other indicators. To provide most benefit indicators should be

Table 2
Suggested indicators to track the restoration of degraded ecosystems, and the expansion and connection of wildlife-rich habitat under climate change. The likelihood of indicators being available is indicated by the symbols as follows: ☺- available, at least for some situations, 😐- possible with limited development, ☹- uncertain or requires significant development. PA: Protected Area; CCVA: climate change vulnerability assessments.

Input measures	Activity measures	Output measures	Outcome measures	Impact measures
Resources available to support habitat creation/ restoration (funding, staff) ☺	Area of grant approval or undertaking habitat creation/ restoration ☺	Extent, quality and condition of habitats in grant areas ☺ (relative to non-grant counter-factual 😐) Occurrence/abundance of species in grant areas ☺ (relative to non-grant counter-factual 😐) Spatial configuration of grant areas 😐 (relative to non-grant counter-factual 😐)	Species colonisation/ persistence/trends in restored habitats relative to controls 😐 (relative to changes in climatic variables ☹) Changes in condition/extent of vulnerable habitats relative to controls 😐 (relative to changes in climatic variables ☹) Multi-species indicators linking climate change impact and adaptation responses ☹	Species' extinction risk (e.g. red-list assessment) ☺ Species' abundance ☺ Ecosystem service provision 😐 Ecological integrity/ ecosystem function 😐
Percentage/extent of schemes specifically for climate change adaptation 😐	Percentage/extent of species' population/land managed specifically for climate change adaptation 😐			
Mainstreaming of climate change adaptation for the natural environment across Government (e.g. planning, forestry, energy, transport) ☹				

Table 3
Suggested indicators to the success of action for species and habitats at particular risk from climate change. The likelihood of indicators being available is indicated by the symbols as follows: ☺- available, at least for some situations, 😐- possible with limited development, ☹- uncertain or requires significant development. PA: Protected Area; CCVA: climate change vulnerability assessments.

Input measures	Activity measures	Output measures	Outcome measures	Impact measures
Percentage of species/populations/habitats considering climate change adaptation in action plans ☺	Percentage of species/populations/habitats with specific climate change adaptation interventions in place 😐	Status of vulnerable species/habitats ☺	Multi-species indicators that demonstrate improved status for species targeted by adaptation 😐	Species' extinction risk (e.g. red-list assessment) ☺
The existence of appropriate species/habitat monitoring schemes ☺		Maintenance of genetic diversity ☹	Status of species/habitats vs expected from climate change impact ☹	Species' abundance ☺
Percentage of species/habitats assessed for vulnerability to climate change ☺	Protection of refugia for species 😐			Ecosystem service provision 😐
				Ecological integrity/ecosystem function 😐

regularly measured through time to monitor and evaluate the success of any interventions implemented (whether at the level of policy or management), as well as to enable progress towards any targets to be tracked. Progress is unlikely to be linear and interventions may require modification in response to progress reported by the indicators, resulting in the inclusion of feedback loops typical of an adaptive management M&E framework (Fig. 1). Some indicators may require development to ensure they can be devised, tracked, and reported on.

As a case-study, we apply the proposed indicators to the UK's 2018–2023 NAP (Defra, 2018) which outlines the Government's proposed actions for addressing risks and opportunities of climate change across sectors. Specifically, we focus on the three central goals for land and rivers of the Natural Environment section: 1) Protect and improve protected sites and other areas of important wildlife habitat; 2) Restore degraded ecosystems and expand and connect wildlife rich habitat; and 3) Take action for species and habitats at particular risk from climate change, recognising that there are inter-relationships between them. Given the broad nature of these goals around protected sites, land and vulnerable species and habitats, and their relevance to wider international programmes (e.g. the post-2020 Global Biodiversity Framework), the proposed framework and associated indicators may be adapted for use in other countries and contexts, and would likely remain applicable to future iterations of the UK NAP.

3.1. Indicators to assess the protection and improvement of protected sites and other areas of important wildlife habitat in the face of climate change

Protected areas are a key tenet of nature conservation that often deliver against species and habitat objectives (Donald et al. 2007, Cunningham et al. 2021) and that are supported by national laws and international agreements. Most protected areas were designated before climate change became a consideration, leading to concerns that their effectiveness in protecting the species or habitats they were designated for may decrease as a result of anticipated range shifts in species' distributions (Araújo et al., 2011). However, more recent evidence suggests that protected areas are likely to become even more important in a changing climate (Thomas et al. 2012, Gillingham et al. 2015, Tittensor et al. 2019). This does not mean, however, that protected areas are immune to the negative impacts of climate change, as habitats and ecosystems adjust to changing conditions (Bruno et al. 2018, Duffield et al. 2021). They are also places where adaptation management might be trialled and implemented.

Several adaptation indicators are suggested to track progress towards the goal to protect and improve protected areas from inputs to impacts (Table 1). Data on the resources (funding or staff) available to support protected area implementation, management and protection should be readily available to track enabling conditions. More sophisticated input measures specific to climate change adaptation could be developed to measure the extent to which climate change is factored into the designation, management and condition assessment of protected areas, or the extent that climate change vulnerability assessments (CCVA; Foden et al. 2019) are integrated into management planning. Positive progress in these indicators should increase the extent of habitats and protected areas being subject to climate change adaptation interventions.

Changes in the extent (already tracked by indicator C1 of the UK biodiversity indicators; Defra 2020) and management of protected areas, potentially subdivided by different features (e.g., habitat type or priority species groups) and ideally linked to national and international targets, provide potential activity measures. These could be more adaptation-specific by relating protected area and management extent to the likely future suitability of different sites, for example using information about topographical and microclimate heterogeneity and refugia (Suggitt et al. 2018) or using projections from species and habitat distribution models (Breiner et al., 2022).

Output measures track the ecological consequences of adaptation activities to demonstrate whether activities are resulting in the intended change on the ground. These could use species distribution and abundance data or information about the extent, quality and condition of habitats to demonstrate whether protected areas are successfully providing suitable habitats or protection for particular species (Donald et al. 2007, Cunningham et al. 2021). Supporting analysis with respect to change across non-protected counterfactuals may strengthen the attribution of observed changes to implemented activities. These measures demonstrate the ecological efficacy of the activities undertaken rather than being specific to climate change adaptation and are regarded as process- rather than results-based indicators. Where the goal of expanding protected areas is to achieve climate-appropriate protected area networks, then the spatial configuration of the network or resulting habitat patches could also be tracked against relatively simple targets of representativeness by region or habitat, or using more complex approaches e.g. accounting for current and future species' distributions (e.g. Hole et al. 2009) or the likely direction of species' range shifts (Travers et al. 2021).

The success of protected areas in the context of climate change adaptation could be measured by changes in species' colonisation, persistence, or abundance through time, on the expectation that protected areas will enhance the capacity for change by facilitating the colonisation of new sites or preventing local extinction (Thomas et al. 2012, Gillingham et al. 2015). Similar measures could assess changes in the extent and condition of climate-vulnerable habitats. The attribution of observed changes in outcome measures to successful climate change adaptation may be improved by using the results of repeated analyses of biological responses on protected areas, relative to non-protected sites, to track change (e.g. Jellesmark et al. 2021). Alternatively, for interventions that lack appropriate counterfactuals (because they apply across large spatial (e.g. national) scales), models of projected climate change impacts may be used to compare against observed biological responses. The divergence between projected and observed climate change responses could help quantify adaptation outcomes, although given the high uncertainty that can be associated with such projections (Wheatley et al. 2017), results would require careful interpretation to disentangle from the alternative hypothesis that they result from inaccurate model projections.

3.2. Indicators to track the restoration of degraded ecosystems, and the expansion and connection of wildlife-rich habitat under climate change

Beyond protected areas, enhancing the extent and quality of non-protected habitats across terrestrial, freshwater and marine environments is an important component of conservation action and climate change adaptation for nature (Ingerman et al., 2019, Duarte et al. 2020). In the context of producing larger, better, and more connected sites (Lawton et al. 2010), the quality and extent of non-protected habitats can play an important role in the resilience and adaptation of populations and ecological communities to climate change (Newson et al. 2014, Oliver et al. 2017).

In western Europe, agri-environment schemes are a key mechanism for delivering improvements in the extent, quality and connectedness of wildlife-rich habitat to support climate change adaptation (Donald & Evans 2006) within the farmed environment. More broadly, other policy mechanisms may support grants to restore degraded ecosystems and create wildlife-rich habitat. Input measures for this objective should track the size of grants available (Table 2), including new financial instruments, such as biodiversity offsets and carbon markets. The extent to which climate change adaptation for biodiversity is considered when making decisions across other sectors (mainstreaming) could provide an additional input measure, although current attempts to track the integration of biodiversity into business activities use proxies that do not consider adaptation (Defra 2020).

Trends in the resulting activities could be tracked through variation in the extent and uptake of schemes and grants (see indicator B1 of the UK biodiversity indicators; Defra 2020), potentially subdivided by region or habitat as required. More specific indicators of climate change adaptation interventions could report on the percent or extent of species' populations or habitats managed by interventions targeted at adaptation.

Output measures resulting from these schemes should include changes in the extent, quality, and condition of specific habitats. These could be related to background changes using appropriate counterfactuals as discussed for protected areas above. Similarly, variation in the occurrence or abundance of species in these locations, again relative to non-scheme or grant-funded control sites, would provide a mechanism for tracking species' response to interventions, building on approaches already used successfully to monitor agri-environment scheme effectiveness (e.g. Baker et al. 2012). When the aim of restoration is to connect wildlife-rich habitat, changes in the spatial configuration of habitats could be evaluated through time. Indicators could be made more specific to climate change adaptation by considering the spatial overlap between grant provision and the future suitability of different sites, either using models or by prioritising areas of environmental or microclimate heterogeneity.

Potential outcome measures resulting from these interventions should include improved distribution and/or abundance species trends, enhanced extent or quality of restored habitats, and improved provision of ecosystem services and function in restored areas, relative to controls (Table 2). Multi-species indicators may track changes in the occurrence of groups of species which are associated with the extent, quality or connectivity of particular habitats. For example, if a target for adaptation is to increase the extent of woodland, hedges and trees in the farmed landscape to improve connectivity for woodland habitat specialists, changes in the occurrence and abundance of woodland species may be a more informative indicator of the likelihood of successful adaptation for those species than changes in habitat extent and connectivity (e.g. Siriwardena et al. 2019).

The outcome indicators of successful adaptation will vary between objectives. If the restoration of degraded systems and habitats is to enhance metapopulation dynamics of a particular species of conservation concern, then trends in the occurrence and abundance of that species could be an appropriate outcome indicator, particularly if compared no non-intervention areas. Alternatively, if aiming to improve the capacity for change, then increases in the occurrence or abundance of newly colonising habitat specialists may be an alternative measure of success. Assessments may be more powerful if adopting multi-species indicators of change, for example using species' traits related to habitat specificity, temperature and dispersal (e.g. Oliver et al. 2017, Siriwardena et al. 2019).

3.3. Indicators to track the success of action for species and habitats at particular risk from climate change

Assessing the vulnerability of species to climate change is often regarded as an important precursor to determine appropriate conservation action and to inform adaptation responses (Hole et al. 2009, Oliver et al. 2012, Foden et al. 2019). Tracking the proportion of species assessed for climate change vulnerability, and the extent to which climate change is considered when developing management plans for species and habitats provide two relatively simple input measures (Table 3). Tracking the status of species and habitats relies on adequate monitoring data, the availability of which could be indicated by the coverage of appropriate species and habitat monitoring programmes.

The extent to which targeted, species or habitats are being managed with adaptation interventions would measure activity, but this would require the collation of data across large areas and multiple land ownerships. Projected distributions in response to future climate change are available for many species (e.g. Pearce-Higgins et al. 2017 for the UK and Warren et al. 2018 globally), which can be used to inform adaptation for the most vulnerable species (Hole et al. 2009; Breiner et al., 2022). Using these projections to identify climate change refugia or new sites for colonisation for species of interest, and tracking their protection, would also measure activity.

Output measures on the status of species and habitats may be tracked through existing monitoring schemes and reports, such as the State of Nature report in the UK (Hayhow et al. 2019) and UK biodiversity indicators (Defra 2020). This would indicate whether populations are responding positively to conservation action on the basis that one of the key principles of climate change adaptation is to minimise human activities that damage biodiversity (Hodgson et al. 2009). In the longer-term, such measures would also track impact. Given the role of genetic evolution in altering ecological responses to climate change (Nadeau and Urban, 2019), indicators could potentially be developed to additionally track genetic diversity or the occurrence of a particular allele (one of two or more forms of a gene variant) likely to confer adaptive advantage. Such measures are only just starting to be developed (Bay et al. 2018, Hollingsworth et al. 2020) and are unlikely to be available for routine use soon.

There has already been extensive work to quantify the impacts of climate change on individual species, communities, and habitats. Outcome measures can be derived by combining analyses of ecological responses to climate change with information about the extent or occurrence of climate change adaptation interventions. Projected climate change impacts on species may be used to identify potential changes that should be monitored or the timeframes over which impacts may be detected (e.g. Pearce-Higgins 2011), whilst indicators could track the divergence between projected and observed changes (while accounting for modelling caveats).

4. Discussion

We developed a framework to track the adaptation of the natural environment to climate change, and illustrated how a suite of indicators may be developed to track progress using the broad objectives of the UK NAP as an example. We suggest three types of process-based indicator (input, activity, and output) that aim to measure progress in the enabling conditions, activities and short-term results of climate change adaptation activities measured by the ecological responses to those interventions over timeframes of years. Two types of results-based indicators (outcome and impact) track longer-term responses over decades and centuries; the timescale over which action is required to be effective. Importantly, the indicator categories assess progress at key stages of the adaptation pathway: identifying and prioritising the need; action implementation; assessing change in condition from those actions; measuring the effectiveness of the interventions and whether the changed conditions achieve the desired impacts. Although developed around the UK's NAP, our proposed categories of indicators could be widely applicable across species, habitats and monitoring programmes, making our approach highly flexible and adaptable to other national and international frameworks.

The easiest indicators to develop will be some of the input measures that track the level of resourcing to support protected areas and habitat creation/restoration, as well as the existence of appropriate monitoring schemes to track trends in species and habitats. Although potentially distant from adaptation outcomes and conservative in their nature, these will track progress in important enabling conditions and can be refined to increase their specificity to climate change adaptation. It is these indicators which will perhaps most rapidly capture responses to adaptation policy interventions. Activity measures indicating changes in the extent of protected areas and habitat creation/restoration should be readily available (Defra 2020), although these could be made more specific to climate change adaptation by considering overlap with likely climatic refugia (already mapped for England – Suggitt et al. 2018) or areas of projected future suitability to climate change (e.g. Breiner et al., 2022 for waterbirds). Tracking changes in the extent of different climate change adaptation interventions will provide activity measures equivalent to the theory-based impact evaluation methods advocated by HM Treasury (2020). These are developed for the evaluation of complex interventions or simple interventions in complex environments, definitions which surely apply to climate change adaptation. Work will be required to capture such data from different stakeholders. The efficacy of these indicators will depend upon the strength of the theory of change linking adaptation actions to outcomes and impacts. However, as adaptation objectives may change in response to a changing climate (Stein et al. 2013, Prober et al. 2019), these indicators may likely require amendment through time, which our framework provides the flexibility to do.

The development of ecological output and outcome measures will provide important evidence of the impact of adaptation on the ground. These measures are similar in concept to experimental and semi-experimental methods best suited to instances when the attribution of outcomes to interventions is uncertain (HM Treasury 2020), which also applies to climate change adaptation. Their development will also improve the quantification of responses to interventions. Impact measures are non-specific to the outcomes of specific climate change adaptation policies and interventions but track the ultimate status of the environment as measured by abundance, extinction risk, ecosystem service provision, ecosystem function and ecological integrity. If these indicators remain healthy in a changing climate, then the adaptation of the natural environment will be successful. Whilst these impact measures will be resilient to any changes in adaptation objectives, their generality means that they are less useful to monitor the performance of individual policies or interventions. Outcome indicators to track the extent to which activities alter species' responses to climate change are therefore arguably the most important to demonstrate that adaptation effort has had a meaningful and expected impact on the ground. However, given complex ecological responses to both climate change and interventions, as Tables 1-3 indicate, we must consider the following issues for outcome indicator development.

First, the development of appropriate counterfactuals is key. As noted above, this could be through the collection of monitoring data from intervention and non-intervention sites, requiring careful consideration of monitoring design when setting-up interventions, or ensuring sufficient coverage of background monitoring data exists (Jellesmark et al. 2021). Alternatively, if robust projections of climate change impacts on ecological systems can be made, this would open the possibility of using such projections to compare against observed outcomes, which is potentially more appropriate for large-scale interventions where counterfactuals are lacking. For this latter option, further work is needed to compare among different approaches to vulnerability assessment (e.g. trait-based, envelope modelling and other methods) to improve our understanding of expected responses to climate change (Wheatley et al. 2017).

Second, indicators should be based on robust relationships between climatic variables, ecological responses, management, and adaptation objectives. However, there are inherent issues of transferability and predictability which make this particularly challenging in the context of long-term climate change, including: 1) modelling and ecological transferability, as the attributes of indicator species may vary either geographically or through time (Lindenmayer and Likens, 2011, Yates et al. 2018); 2) low co-association of indicator species with other taxa (Carignan & Villard 2002, Eglington et al., 2012); and 3) the past may not be a good predictor of the future, as previously unimportant or unknown factors may impact species' or ecosystem responses (Landres et al. 1988, Carignan & Villard 2002). Ecological processes may alter the efficacy of measures through time, via for instance density-dependence effects (Landres et al. 1988), changing interspecific interactions (Kharouba et al. 2018), or both (Layton-Matthews et al. 2020). The impacts of non-climatic pressures may also complicate the interpretation of indicators (Barnaguad et al. 2012, Clavero et al. 2012).

Despite these issues, further work to develop multi-species indicators of climate change adaptation outcomes on ecological systems should be explored, as they will be important in tracking ecological responses to adaptation. Understanding which dimensions of the environment should be measured to track changes in ecosystem structure and functioning, including changes in species composition (Hillebrand et al. 2017, Blowes et al. 2019) potentially leading to functional and phylogenetic homogenisation (Clavel et al., 2011; Saladin et al. 2020), will also be required.

Finally, two linked but overarching issues should be emphasised. First, the availability of sufficient good-quality data to estimate any of such proposed indicators is essential (Conde et al. 2019). This may be particularly challenging for outcome and impact measures, but citizen science schemes provide an effective long-term and large-scale approach to tracking some ecological changes (Hayhow et al. 2019), whose outputs underpin existing indicators of climate change impact (Gregory et al. 2009, Stephens et al. 2016). However, even in countries with a long tradition of collecting ecological data such as the UK, most monitoring data focuses on a few taxonomic groups (notably birds and Lepidoptera). Citizen science coverage should be reviewed (recently achieved for the UK; Border et al. 2019) to identify what may be possible and to prioritise further scheme development. Nevertheless increased professional data collection is likely to be necessary for some species groups and non-biological measurements requiring specialist knowledge. Second, establishing appropriate baselines is a critical, yet problematic, step, particularly as any newly established monitoring scheme risks missing previous climate change impacts ("shifting baseline syndrome"; Pauly 1995, Papworth et al. 2009). Progress in the enabling measure of appropriate monitoring schemes will help address these issues, but any new indicators resulting from new schemes will require presentation in the context of likely past trajectories that will have been missed.

To conclude, establishing appropriate indicators of climate change adaptation for the natural environment is difficult but urgent. Despite significant uncertainty about the future impacts of climate change and about the effectiveness of adaptive measures and actions, there is significant pressure to act, particularly to avoid conflicts between competing demands and priorities for land management (Morecroft et al. 2019, Pörtner et al., 2021). In response to these challenges, we propose an indicator framework aimed at tracking different stages towards successful climate change adaptation, which we broadly defined as species' persistence, ecosystem functioning and ecosystem service provision in a changing climate. Several input and activity measures could be already reportable with relatively little development, whilst more data should be gathered to produce measures more specific to climate change adaptation. Improving the evidence linking specific interventions to desired adaptation outcomes will improve confidence in activity and output indicators. A range of more ecological indicators are also proposed to track outputs and outcomes resulting from climate change adaptation. Although these will be perhaps the most challenging indicators to develop, requiring in some instances further ecological understanding of the impacts of climate change and responses to adaptation interventions, doing so will greatly improve the attribution of interventions to outcomes. Further analysis of multi-species monitoring data may provide particular opportunities for their development. Given current debates about the precise nature of future indicators of progress towards sustainable development, we hope that this framework and open discussion about the challenges of its implementation will help the development of the urgently needed indicators to identify whether our climate change adaptation interventions are effective.

CRediT authorship contribution statement

J.W. Pearce-Higgins: Methodology, Investigation, Writing – original draft, Supervision. **L.H. Antão:** Investigation, Writing – review & editing. **R.E. Bates:** Investigation, Writing – review & editing. **K.M. Bowgen:** Investigation, Writing – review & editing. **C.D. Bradshaw:** Investigation, Writing – review & editing. **S.J. Duffield:** Investigation, Writing – review & editing. **C. Ffoulkes:** Investigation, Writing – review & editing. **A.M.A. Franco:** Investigation, Writing – review & editing. **J. Geschke:** Investigation, Writing – review & editing. **R.D. Gregory:** Investigation, Writing – review & editing. **M.J. Harley:** Methodology, Investigation, Writing – review & editing. **J.A. Hodgson:** Investigation, Writing – review & editing. **R.L.M. Jenkins:** Investigation, Writing – review & editing. **V. Kapos:** Investigation, Writing – review & editing. **K.M. Maltby:** Methodology, Investigation, Writing – review & editing. **O. Watts:** Methodology, Investigation, Writing – review & editing. **S.G. Willis:** Investigation, Writing – review & editing. **M.D. Morecroft:** Methodology, Investigation, Writing – review & editing.

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.

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