Journal of Applied Ecology

British Ecological Society

*Journal of Applied Ecology* 2012, **49,** 1247–1255 doi: 10.1111/1365-2664.12003

FORUM

# A decision framework for considering climate change adaptation in biodiversity conservation planning

**Tom H. Oliver[1]*, Richard J. Smithers[2], Sallie Bailey[3], Clive A.Walmsley[4] and Kevin Watts[5]**

[1]*Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford Wallingford, Oxfordshire, OX10 8BB, UK;* [2]*AEA Technology plc, The Gemini Building, Fermi Avenue, Harwell, Didcot, OX11 0QR, UK;* [3]*Forestry Commission, Silvan House, 231 Corstorphine Road, Edinburgh, EH12 7AT, UK;* [4]*Countryside Council for Wales, Maes-Y-Ffynnon, Penrhos Garnedd, Bangor, LL57 2LQ, UK; and* [5]*Forest Research, Alice Holt, Farnham, Surrey, GU10 4LH, UK*

## Summary

**1.** General principles of climate change adaptation for biodiversity have been formulated, but do not help prioritize actions. This is inhibiting their integration into conservation planning.

**2.** We address this need with a decision framework that identifies and prioritizes actions to increase the adaptive capacity of species. The framework classifies species according to their current distribution and projected future climate space, as a basis for selecting appropriate decision trees.

**3.** Decisions rely primarily on expert opinion, with additional information from quantitative models, where data are available. The framework considers in-situ management, followed by interventions at the landscape scale and finally translocation or ex-situ conservation.

**4.** *Synthesis and applications:* From eight case studies, the key interventions identified for integrating climate change adaptation into conservation planning were local management and expansion of sites. We anticipate that, in combination with consideration of socio-economic and local factors, the decision framework will be a useful tool for conservation and natural resource managers to integrate adaptation measures into conservation plans.

**Key-words:** adaptive capacity, connectivity, habitat management, habitat restoration, sensitivity, threatened species, translocation, vulnerability

## Introduction

Climate change is expected to have impacts on many species and alter ecosystem functions. Hence, there is a need to adapt landscapes to climate change, for biodiversity and people. Immediate adaptation actions are required owing to the time it will take to implement them and for biodiversity to respond (IPCC 2007).

Adaptation principles for biodiversity are based upon existing ecological theory and are aimed at conservation managers (Hopkins *et al.* 2007; Huntley 2007; Mitchell *et al.* 2007; Heller & Zavaleta 2009; Mawdsley, O'Malley & Ojima 2009) and land-users across all sectors (Smithers *et al.* 2008). The principles encourage landscape-scale actions, taking into account climatic impacts, landscape composition and configuration, and species' attributes. However, there is debate on the relative merits of these actions (e.g. Doerr, Barrett & Doerr 2011; Hodgson *et al.* 2011), and anecdotal evidence suggests a lack of understanding of how to prioritize and target them may be inhibiting translation of the principles into practice (Perkins, Ojima & Corell 2007; Heller & Zavaleta 2009). However, implementation is crucial; the Strategic Plan for Biodiversity 2011–2020 adopted by the Parties to the Convention on Biological Diversity at Nagoya in 2010 sets out strategic goals and 20 targets (the 'Aichi targets') to inspire urgent action by all countries and stakeholders (http://www.cbd.int). Target 10 is to minimize the multiple anthropogenic pressures on vulnerable ecosystems impacted by climate change, so as to maintain their integrity and functioning. In the UK, workshops with local biodiversity conservation coordinators, and informal discussions by the authors with government conservation agency staff, have confirmed a need for prioritization tools. For example, in England, the framework supports the need to

*Correspondence author. E-mail: toliver@ceh.ac.uk

integrate climate change adaptation in biodiversity conservation planning highlighted by the Government's recent Natural Environment White Paper, Biodiversity 2020 strategy and National Planning Policy Framework.

## A decision framework for climate change adaptation

In 2009–2010, a group of people from across science, policy and practice came together under the auspices of the UK Population Biology Network (UKPopNet, http://www.nerc.ac.uk/research/programmes/ukpopnet/) to discuss this need and subsequently develop the decision framework presented here. The framework provides a rapid, repeatable and transparent method to facilitate adaptive management (Mitchell *et al.* 2007). It can be applied at local, regional, national or international scales. It could help policymakers and planners to prioritize adaptation measures, tailored to the needs of species or habitats, for integration into the development or delivery of nature conservation legislation, regulation, incentives (e.g. agri-environment schemes), strategies and plans (e.g. State Wildlife Action Plans in the US or Local Biodiversity Action Plans in the UK). It could be employed as a screening tool to determine species of conservation concern in relation to climate change for IUCN Red List-type exercises or to identify species that might be used as indicators of the success of adaptation actions. The framework could also help nature conservation practitioners from statutory agencies and NGOs to provide advice on land management and to make site management decisions in the best interests of species and habitats.

The framework can be used for populations of individual species of conservation concern that are perceived as most threatened by climate change (Thomas *et al.* 2011). However, there is limited empirical data on how a majority of species may respond to climate change or interact with the surrounding landscape (Eycott *et al.* 2010). Even where data exists, its efficacy is often in doubt, especially when extrapolated to other locations. There may also be concerns about focusing on individual species, and a desire to address conservation at a habitat-level. Some may, therefore, wish to use the framework more broadly through the use of keystone species, umbrella species or generic focal species (Simberloff 1998; Watts *et al.* 2010). For example, generic focal species can be used to represent a guild of species believed to have similar habitat requirements and dispersal abilities (Watts *et al.* 2010). Alternatively, a number of individual species may be considered and synergies and conflicts critically evaluated to identify common management recommendations.

The decision framework identifies and prioritizes adaptation actions to increase species' adaptive capacity based on their exposure, sensitivity and current adaptive capacity to climate change. The 'sensitivity' of species to climate change, 'the degree to which they are affected, either adversely or beneficially' (IPCC 2007), will be unique to each species. The same is true of their 'adaptive capacity', 'the ability to adjust to climate change to moderate potential damage, to take advantage of opportunities or to cope with the consequences'. Their 'vulnerability', is then 'a function of the character, magnitude and rate of climate change and variation to which they are exposed, their sensitivity and adaptive capacity' (IPCC 2007). Adaptation actions seek to reduce vulnerability by increasing 'adaptive capacity' (Dawson *et al.* 2011).

Various conceptual models have been devised to assess species' vulnerability to climate change (Williams *et al.* 2008; Sajwaj *et al.* 2009; Thomas *et al.* 2011). However, empirical evidence on species' sensitivities is often lacking. Species distribution/bioclimate envelope models are commonly used to model associations between climate variables and species' distributions (Segurado & Araujo 2004). Although these models are subject to numerous assumptions and caveats (Pearson & Dawson 2004; Beale, Lennon & Gimona 2008), their outputs (i.e. projections of future climate space) capture exposure to climate change (Dawson *et al.* 2011) and species' sensitivity from physiological tolerances to different climatic variables (Williams *et al.* 2008).

Distribution data and bioclimate envelope model outputs are increasingly available for a wide range of taxa, for example, from the UK's National Biodiversity Network (NBN) gateway, or the Global Biodiversity Information Facility (GBIF). By comparing a species' current distribution with its future projected climate space, species' exposure and projected sensitivities can be approximately delimited spatially (Fig. 1). Therefore, the framework is comprised of three decision 'trees' for: (a) *Adversely Sensitive* areas within a species' current range, projected to become climatically unsuitable in the future (e.g. at low elevation/latitude range boundaries; Wilson *et al.* 2005; Fig 2), (b) *Climate Overlap* areas within a species' current range, projected to remain climatically suitable (Fig. 3) and (c) *New Climate Space* areas beyond a species' current range, projected to become climatically suitable and provide potential for range expansion (e.g. at high elevation/latitude range boundaries; Parmesan *et al.* 1999; Fig. 4).

## Using the decision framework

All three decision trees should be used where a species' current range includes *Adversely Sensitive* areas and *Climate Overlap* areas, and *New Climate Space* areas are projected (Fig. 1a). Only two decision trees may be needed where a species' current range is disjunct from *New Climate Space* areas (i.e. there are no *Climate Overlap* areas; Fig. 1b), and only one decision tree may be required where current range and *New Climate Space* areas completely coincide (Fig. 1c). Finally, where national or regional assessments of adaptation actions address a subset of a species' geographic range, only decision trees relevant to the study area need be used

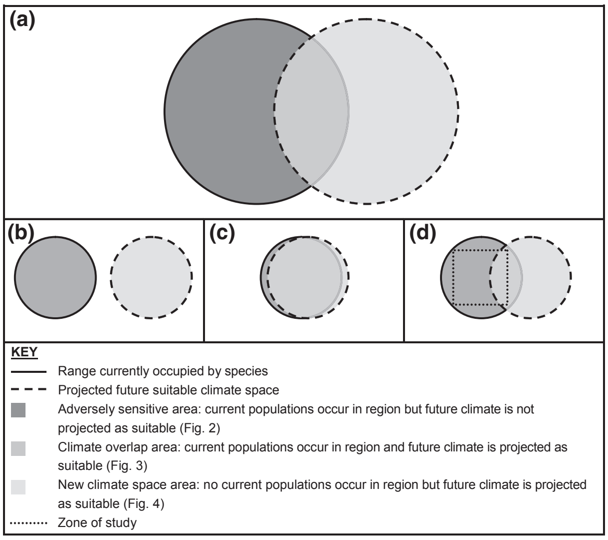


**Fig. 1.** Spatial relations between a species' current distribution and projected future suitable climate space. In (a) configuration of current distribution and projected climate space leads to three distinct areas. A separate decision tree is used for each area. In (b) current distribution and projected climate space are disjunct, with no *Climate Overlap* area. In contrast, in (c) most of the current distribution is projected to be suitable, leading to a large *Climate Overlap* area. (d) illustrates how it is also possible to use the decision framework for a subset of the species' current distribution and projected climate space (e.g. within national boundaries).

(Fig. 1d). However, uncertainty in model projections may mean all of the decision trees should be considered.

Adaptation actions determined from all three decision trees might be prioritized by the proportion of the species' total population that each addresses within its current range, and consideration of uncertainty in climate space projections. For example, if most of a species' total population is located in *Climate Overlap* areas rather than *Adversely Sensitive* areas and there is large uncertainty in climate space projections, then adaptation actions should be prioritized in *Climate Overlap* areas. Similarly, national or regional assessments (Fig. 1d) should consider the importance of national populations in a global context and the study area's location relative to potential future climate space when prioritizing adaptation actions between species.

Each decision tree involves a series of questions, designed to assess a species' adaptive capacity. Lack of empirical data means answering most questions requires expert opinion, although quantitative models (e.g. metapopulation models) can inform answers, where available. The questions lead to actions associated with published adaptation principles relevant to habitat and/or landscape management (Hopkins *et al.* 2007; Huntley 2007; Smithers *et al.* 2008; Mawdsley, O'Malley & Ojima 2009; Table S1, Supporting information). Table 1 gives a detailed descrip-

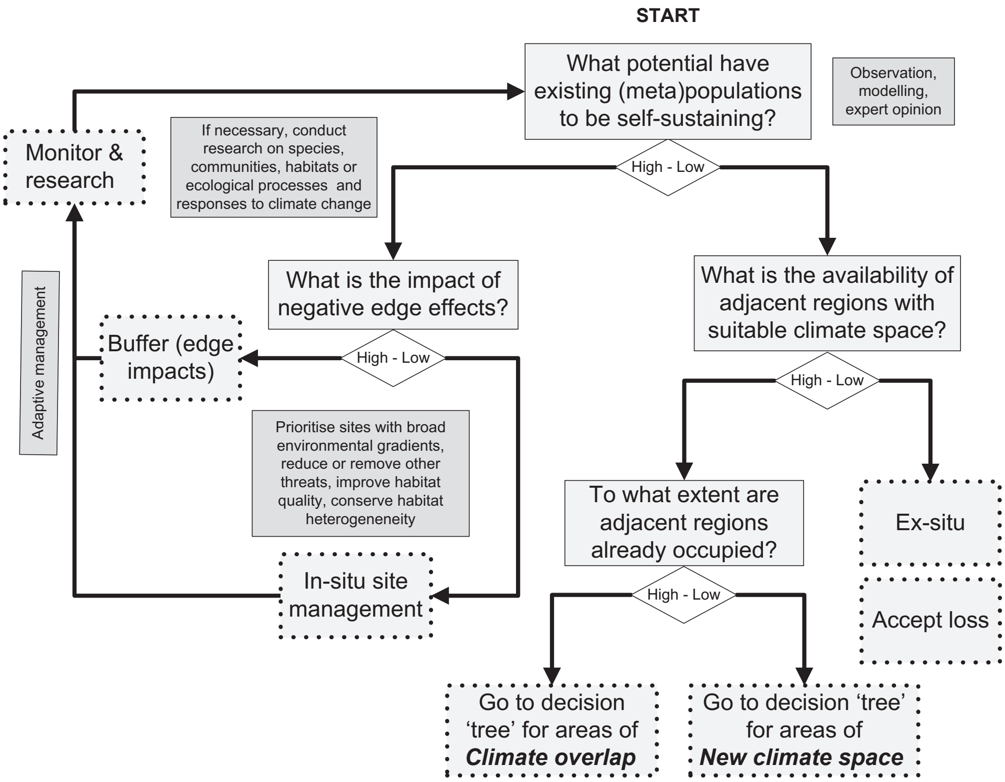


**Fig. 2.** Decision tree for *Adversely Sensitive* areas. Light grey boxes with solid borders indicate questions whose answers lead to different routes through the tree. If the answer to a question is uncertain, then multiple routes should be taken through the tree simultaneously. Light grey boxes with dashed borders indicate suggested adaptation actions, with relevant additional information in dark grey boxes.

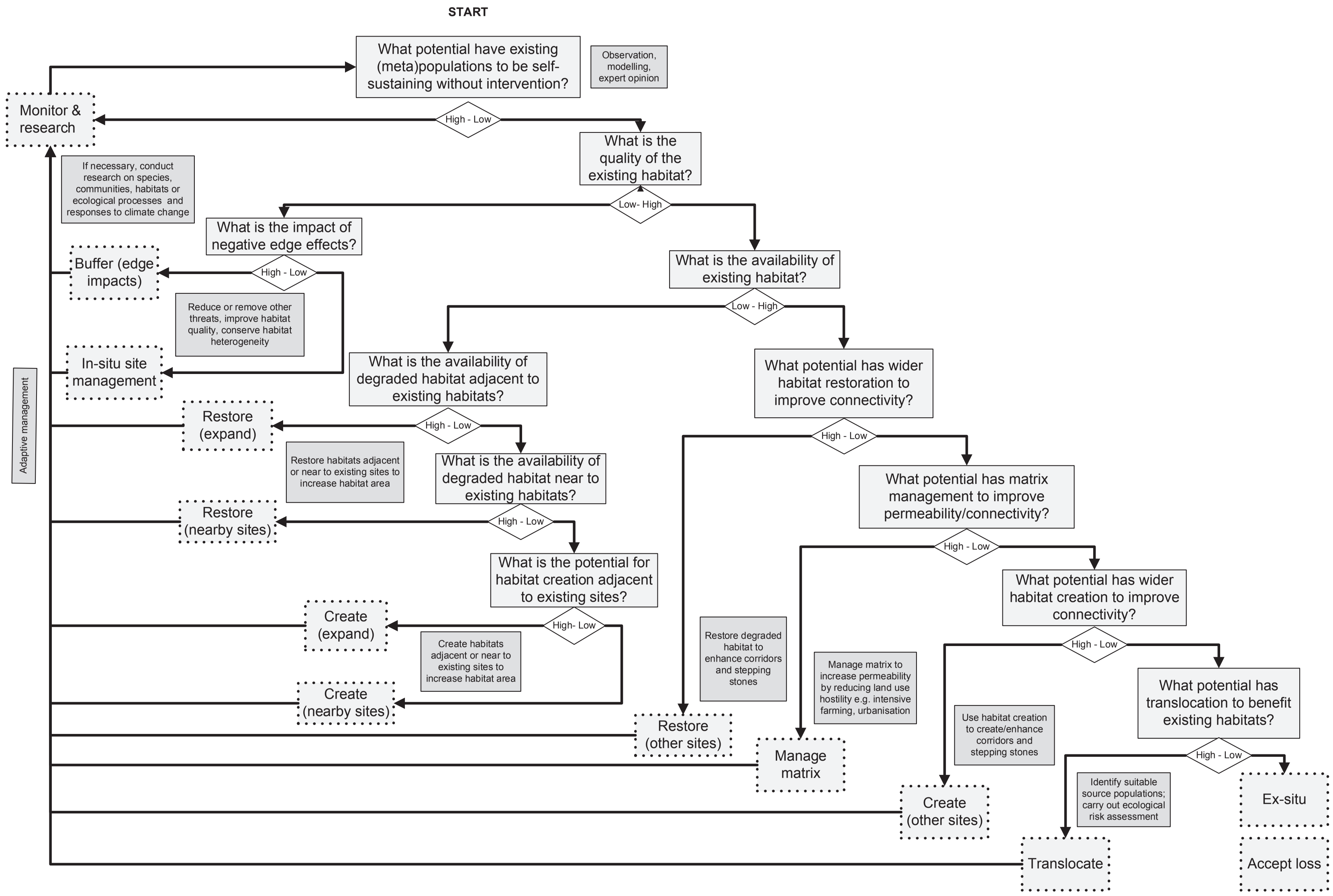


**Fig. 3.** Decision tree for *Climate Overlap* areas. Light grey boxes with solid borders indicate questions whose answers lead to different routes through the tree. If the answer to a question is uncertain, then multiple routes should be taken through the tree simultaneously. Light grey boxes with dashed borders indicate suggested adaptation actions, with relevant additional information in dark grey boxes.

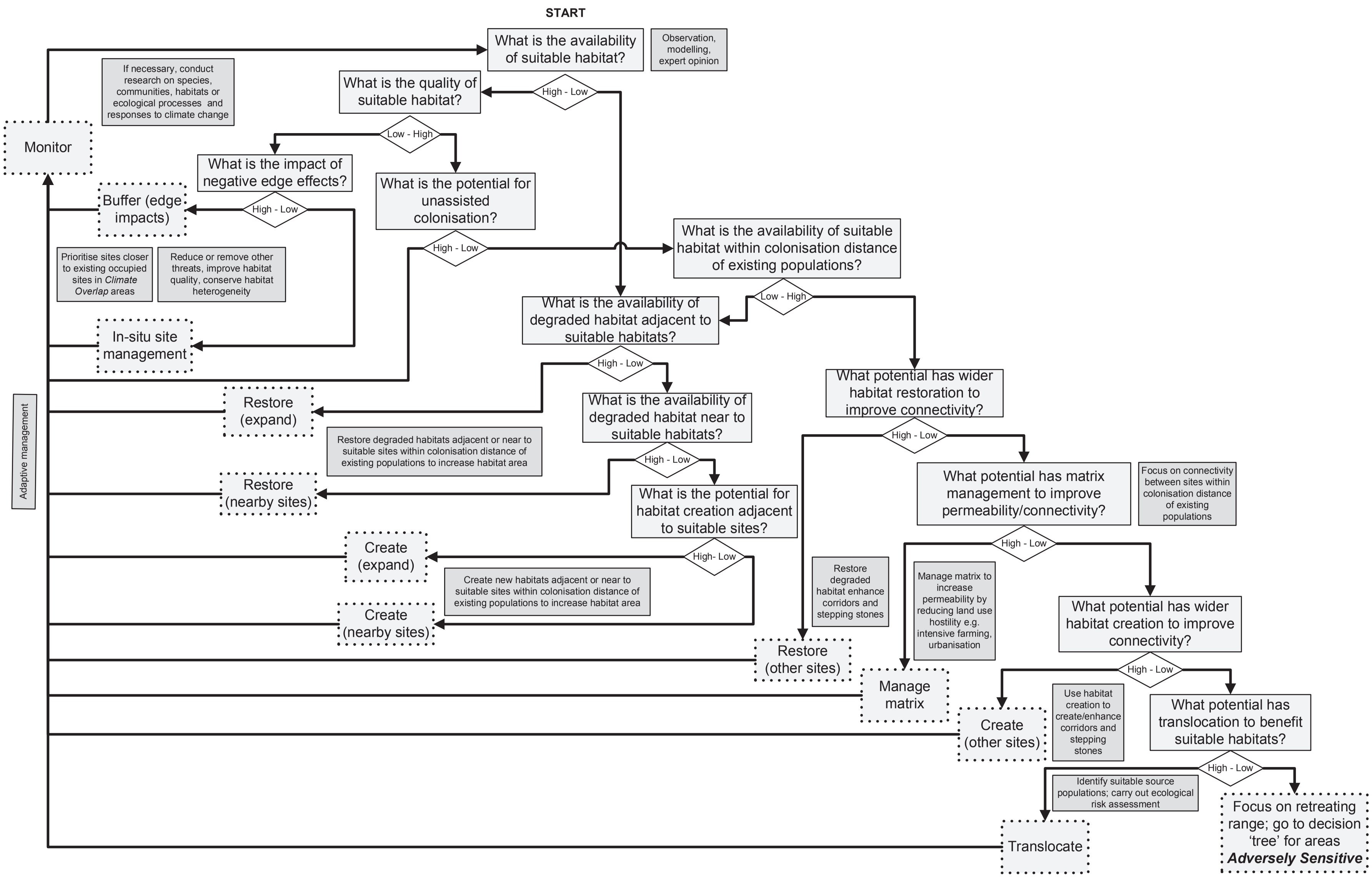


**Fig. 4.** Decision tree for *New Climate Space* areas. Light grey boxes with solid borders indicate questions whose answers lead to different routes through the tree. If the answer to a question is uncertain, then multiple routes should be taken through the tree simultaneously. Light grey boxes with dashed borders indicate suggested adaptation actions, with relevant additional information in dark grey boxes.

**Table 1.** Description and purpose of climate change adaptation actions

| Adaptation action | Description | Purpose |
|---|---|---|
| Buffer (edge impacts) | Manage buffer zone around existing habitat patches to reduce negative impacts from their surroundings (e.g. chemical drift from intensive farming, hunting). | Increase population size, propagule pressure and popn. resilience. |
| In-situ management | Manage and protect existing habitat to improve habitat quality; conserve heterogeneity; and reduce or remove other non-climate related threats (e.g. over-grazing). | Increase popn. size, propagule pressure and popn. Resilience. |
| Restore (expand/nearby/other sites)<br>Create (expand/nearby/other sites) | Restore degraded, or create new, habitat adjacent to existing suitable sites (expand), nearby occupied sites or at other sites. Restore or create habitat across environmental/elevational/geographical gradients to increase habitat area; increase ecological variability; improve connectivity; and improve representation and replication of habitats and ecosystems. | Increase popn. size, propagule pressure and local and regional-scale popn. resilience. Improve opportunities for species to adjust distributions in response to climate change. |
| Manage matrix | Protect, manage, restore, create features in the landscape that promote species movement, for example, less intensive farming, urban green space. | Improve opportunities for species to adjust distributions in response to climate change. Increase regional-scale popn. resilience. |
| Translocate | Augment current species' popns. with individuals from other areas, or aid colonization of species into new areas through transfer of individuals from existing source popns. | Increase popn. resilience and create colonization of new patches. |
| Ex-situ | Establish captive popns. of species that would otherwise become extinct due to climate change. | Conserve species. |
| Accept loss | Take no action to conserve a species where there appears to be no reasonable course of action that will ensure its continued existence in the locality. | Conserve resources where they would be better directed elsewhere. |
| Monitor & research | Monitor the success of conservation actions and improve understanding of the impact of climate change on viability and resilience of species, communities, habitats and ecological processes through research. | Inform adaptive management and choice of future actions. |

tion of each adaptation action. Wherever answers to questions are uncertain, multiple routes should be taken through trees, leading to a combination of recommended adaptation actions. Monitoring, research and subsequent re-assessment to inform adaptive management is essential (Mitchell *et al.* 2007).

The user may wish to undertake a number of iterations of a tree to prioritize a full list of adaptation actions based on their benefit to the focal species vs. non-focal species and practical considerations. We emphasize that the onus is on users to additionally consider the social, economic and political context, upon which successful implementation will ultimately depend.

## Applying the framework to selected UK species

The decision framework is appropriate for use in any country. In the Supporting Information (Appendix S1, Supporting information), we demonstrate its use in a UK-context for seven species selected from Thomas *et al.* (2011), which classified species into broad 'risk categories' in relation to climate change. Two are threatened (Annex II European Habitat Directive) species: Greater Stag Beetle *Lucanus cervus* L. ('High Benefit' from climate change; Test case 1) and Black grouse *Tetrao tetrix* L. ('High Risk'; Test case 2). The other five are butterfly species selected to span all risk categories in Thomas *et al.* (2011; Test cases 3–7). Additionally, we consider a generic focal species to represent a range of species associated with broad-leaved ancient semi-natural woodland, ASNW (Test case 8).

We strongly encourage consideration of these examples to understand how the decision framework questions are answered with varying levels of information available. A summary table of suggested adaptation actions from test cases can be found in Table 2 and Table S2, Supporting information.

## Adaptation actions depend on species risk and regional context

For species identified as 'High Benefit' by Thomas *et al.* (2011), and where large *Climate Overlap* zones are projected, the framework indicates limited need for actions beyond those recommended in the absence of climate change. For example, in Test Case 1, *L. cervus*, the primary recommendation is restoration of degraded habitat adjacent to currently occupied sites. This should

**Table 2.** Summary of adaptation actions prioritized by the decision framework for species in five broad risk categories related to climate change

| Species | Species risk from climate change (*from Thomas et al. 2011*) | *Adversely Sensitive* areas | | *Climate Overlap* areas | | *New Climate Space* areas | |
|---|---|---|---|---|---|---|---|
| | | Area | Adaptation actions | Area | Adaptation actions | Area | Adaptation actions |
| *Tetrao tetrix* | High risk | N. Eng., S. Scot. and Wales | Accept loss | N. Scot. | Restore adj. degraded habitat | None projected in UK | – |
| *Erebia epiphron* | High risk | All current UK populations | ISMMR | None projected in UK | – | Scandinavia | Translocate |
| *Boloria euphrosyne* | Medium risk | S. Eng. | Focus on Climate Overlap region | W. Eng. and Wales | ISMMR | Ire. | Focus on climate overlap region |
| *Hamearis lucina* | Limited impact | None projected in UK | – | S & NW Eng. | ISMMR | NW Eng. and SW Scot. | ISMMR, Restore habitat |
| *Argynnis paphia* | Medium benefit | None projected in UK | – | SW Eng. and Ire. | ISMMR | N Eng., S & E Scot. | ISMMR |
| *Melanargia galathea* | High benefit | None projected in UK | – | Central & S Eng. | Monitor | N Eng., Scot. and Irel. | Monitor |
| *Lucanus cervus* | High benefit | SE Eng. and East Anglia | ISMMR | Central & S Eng. | Restore adj. and nearby degraded habitat | N. Eng., Wales, Scot., N. Ire. | ISMMR |

In-situ management, monitor and research are abbreviated to 'ISMMR'. See main text and Supporting Information for further details.

help the species to recover its large historical range extent, originally lost due to habitat loss and degradation. For *Melanargia galathea* L. (Test Case 7), current populations are thriving and are already successfully colonizing sites in *New Climate Space*; suggesting continued monitoring is the primary action.

For species at greater risk from climate change, a broader suite of actions are recommended, depending on the species and regional context. As robust existing populations are vital for maintaining propagule pressure and refugia at climatic margins, the framework gives highest priority to reducing negative edge effects and improving in-situ management of existing habitat patches. This is demonstrated for *Erebia epiphron* Knoch (Test Case 3), a 'Very High Risk' species (Thomas *et al.* 2011), with no suitable future climate space projected for the UK by 2080 (Settele *et al.* 2008). Its restricted national range means that once habitat quality is improved, populations should be monitored and modelled to assess requirements for further measures.

The framework next prioritizes restoration or creation of habitats that are adjacent or functionally near to existing sites. This is demonstrated in Test Case 2, *T. tetrix*, for which reversing habitat loss is critical (Pierce-Higgins *et al.* 2007) and Test Case 8, the generic focal species, where habitat expansion is a high priority. Evidence suggests that increasing the area of existing sites where suitable habitat patches are very small (e.g. as is often the case in the UK) yields greater biodiversity benefits than improving connectivity (Hodgson *et al.* 2011). For the generic focal species, restoring Plantations on Ancient Woodland Sites (PAWS) is prioritized ahead of woodland creation because PAWS often support remnant populations, seed banks, broadleaved dead wood and relatively undisturbed soils. In contrast, it may take many decades for new native woodland to acquire attributes required by species characteristic of ancient woodland and for them to colonize (Brunet 2007).

Once populations of existing sites are robust, the framework favours management of the matrix between sites and creation of new habitats to improve functional connectivity, as in Test Case 8. Importantly, this test case demonstrates how the decision trees should be used to identify multiple conservation actions rather than focusing on the first action keyed out (e.g. Table S2). This allows different combinations of actions to be prioritized in different locations. For example, take an intensively managed landscape with lots of small ASNWs as compared to one with a small number of large ASNWs and scattered PAWS. In the first case, priorities may be to combat edge effects and create new native woodland adjacent to ASNWs, whereas in the second, they may be to enhance habitat quality, conserve habitat heterogeneity and restore PAWS to increase habitat area and improve connectivity.

Translocation, except that required for habitat creation, is only identified as a priority where probability of colonization is so low that translocation is the only viable option (Hoegh-Guldberg *et al.* 2008). It should be a 'last resort' due to the possible adverse impacts on non-target species, high economic costs, low success rates and potentially limited wider biodiversity benefits. In Test Case 3, *Erebia epiphron* was identified as a possible candidate for translocation, as unassisted colonization to suitable future climate space in Scandinavia was very unlikely. We note that full cost-benefit and ecological risk assessments must be considered prior to any such translocation action.

The final option is ex-situ conservation or accepting loss, when other actions have been exhausted or are unsuitable. In many cases, such as for *T. tetrix*, loss may be accepted in *Adversely Sensitive* areas, whilst undertaking adaptation actions in *Climate Overlap* areas. In practice, ex-situ conservation actions may only be chosen where no other adaptation actions are possible, or as an additional option if costs are very low (e.g. seed storage).

## Conclusion

The decision framework builds on current conservation practice by helping users to prioritize and geographically target different actions, depending on variation in the threats and opportunities from climate change across species' ranges. It follows the consensus for prioritizing actions outlined in a review of landscape-scale conservation by Lawton *et al.* (2010), but with a slight change of emphasis for 'better, bigger, more, improve connectivity, translocate and ex-situ', rather than 'more, bigger, better, joined' (cf. Lawton *et al.* 2010). Hence, it prioritizes removal of existing threats to species (i.e. addressing habitat degradation and loss through in-situ management and habitat expansion) before improving functional connectivity across landscapes (Lawton *et al.* 2010; Doerr, Barrett & Doerr 2011; Hodgson *et al.* 2011). We hope that the framework will provide a valuable decision-making tool for incorporating climate change adaptation into biodiversity conservation planning.

## Acknowledgements

The approach reported here was developed following workshops supported by UKPopNet (funded by NERC and Natural England). We thank the many colleagues who contributed ideas, particularly R. Bradbury, K. Kirby and R. Street.

## References

Beale, C.M., Lennon, J.J. & Gimona, A. (2008) Opening the climate envelope reveals no macroscale associations with climate in European birds. *PNAS*, **105**, 14908–14912.

Brunet, J. (2007) Plant colonization in heterogeneous landscapes: an 80 -year perspective on restoration of broadleaved forest vegetation. *Journal of Applied Ecology*, **44**, 563–572.

Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C. & Mace, G.M. (2011) Beyond predictions: biodiversity conservation in a changing climate. *Science*, **332**, 53–58.

Doerr, V.A.J., Barrett, T. & Doerr, E.D. (2011) Connectivity, dispersal behaviour and conservation under climate change: a response to Hodgson et al.. *Journal of Applied Ecology*, **48**, 143–147.

Eycott, A.E., Watts, K., Brandt, G., Buyung-Ali, L.M., Bowler, D., Stewart, G.B. & Pullin, A.S. (2010) *Which Matrix Features Affect Species Movement? Systematic Review CEE 08-006 (ex SR No. 43).* Collaboration for Environmental Evidence, Bangor, Wales, UK. Available at http://www.environmentalevidence.org/Documents/Completed%20Reviews/SR43.pdf Accessed 01.11.10.

Heller, N.E. & Zavaleta, E.S. (2009) Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, **142**, 14–32.

Hodgson, J.A., Moilanen, A., Wintle, B.A. & Thomas, C.D. (2011) Habitat area, quality and connectivity: striking the balance for efficient conservation. *Journal of Applied Ecology*, **48**, 148–152.

Hoegh-Guldberg, O., Hughes, L., McIntyre, S., Lindenmayer, D.B., Parmesan, C., Possingham, H.P. & Thomas, C.D. (2008) Assisted colonization and rapid climate change. *Science*, **321**, 345–346.

Hopkins, J.J., Allison, H.M., Walmsley, C.A., Gaywood, M. & Thurgate, G. (2007) *Conserving Biodiversity in a Changing Climate: Guidance on Building Capacity to Adapt*. Defra, UK.

Huntley, B. (2007) *Climatic Change and the Conservation of European Biodiversity: Towards the Development of Adaptation Strategies*. Convention on the Conservation of European Wildlife and Natural Habitats, Standing Committee 27th meeting, Strasbourg, 26–29 November 2007. Council of Europe, Strasbourg.

IPCC(2007) *Climate Change 2007 – Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,UK.

Lawton, J.H., Brotherton, P.N.M., Brown, V.K., Elphick, C., Fitter, A. H., Forshaw, J., Haddow, R.W., Hilbourne, S., Leafe, R.N., Mace, G. M., Southgate, M.P., Sutherland, W.A., Tew, T.E., Varley, J. & Wynne, G.R. (2010)*Making Space for Nature: A Review of England's Wildlife Sites and Ecological Network*. Report to Defra,UK.

Mawdsley, J.R., O'Malley, R. & Ojima, D. (2009) A review of climate-change adaptation strategies for wildlife management and conservation. *Conservation Biology*, **23**, 1080–1089.

Mitchell, R.J., Morecroft, M.D., Acreman, M., Crick, H.P.Q., Frost, M., Harley, M., Maclean, I.M.D., Mountford, O., Piper, J., Pontier, H., Rehfisch, M.M., Ross, L.C., Smithers, R.J., Stott, A., Walmsley, C.A., Watts, K. & Wilson, E. (2007) *England Biodiversity Strategy – Towards Adaptation to Climate Change*. Defra,UK.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W.J., Thomas, J.A. & Warren, M. (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, **399**, 579–583.

Pearson, R.G. & Dawson, T.P. (2004) Bioclimatic envelope models: what they detect and what they hide- response to Hampe. *Global Ecology and Biogeography*, **13**, 469–476.

Perkins, B., Ojima, D. & Corell, R. (2007) *A Survey of Climate Change Adaptation Planning*. The H. John Heinz III Center for Science, Economics and the Environment, Washington DC.

Pierce-Higgins, J.W., Grant, M.C., Robinson, M.C. & Haysom, S. (2007) The role of forest maturation in causing the decline of Black Grouse Tetrao tetrix. *Ibis*, **149**, 143–155.

Sajwaj, T., Tucker, G., Harley, M. & Soye, Yd. (2009) *Impacts of climate change and selected renewable energy infrastructures on EU biodiversity and the Natura 2000 network: Task 2a – An assessment framework for climate change vulnerability: methodology and results*. European Commission and International Union for Conservation of Nature, Brussels.

Segurado, P. & Araujo, M.B. (2004) An evaluation of methods for modelling species distributions. *Journal of Biogeography*, **31**, 1555–1568.

Settele, J., Kudma, O., Harpke, A., Kühn, I., Van Sway, C., Verovnik, R., Warren, M., Wiemers, M., Hanspach, J., Hickler, T., Kühn, E., Van Halder, I., Veling, K., Vliegenthart, A., Wynhoff, I. & Schweiger, O. (2008) *Climatic Risk Atlas of European Butterflies*. Pensoft Publishers,Sofia.

Simberloff, D. (1998) Flagships, umbrellas, and keystones: is single-species management passé in the landscape era? *Biological Conservation*, **83**, 247–257.

Smithers, R.J., Cowan, C., Harley, M., Hopkins, J.J., Pontier, H. & Watts, O. (2008)*England Biodiversity Strategy climate change principles: conserving biodiversity in a changing climate*. Defra, UK

Thomas, C.D., Hill, J.K., Anderson, B.J., Bailey, S., Beale, C.M., Bradbury, R.B., Bulman, C.R., Crick, H.P.Q., Eigenbrod, F., Griffiths, H., Kunin, W.E., Oliver, T.H., Walmsley, C.A., Watts, K., Worsfold, N.T. & Yardley, T. (2011) A framework for assessing threats and benefits to species responding to climate change. *Methods in Ecology and Evolution*, **2**, 125–142.

Watts, K., Eycott, A., Handley, P., Ray, C., Humphrey, J.W. & Quine, C. P. (2010) Targeting and evaluating biodiversity conservation action within fragmented landscapes: an approach based on generic focal species and least-cost networks. *Landscape Ecology*, **25**, 1305–1318.

Williams, S.E., Shoo, L.P., Isaac, J.L., Hoffman, A.A. & Langham, G. (2008) Towards an integrated framework for assessing the vulnerability of species to climate change. *PLOS Biology*, **6**, 2621–2626.

Wilson, R.J., Gutiérrez, D., Gutiérrez, J., Martinez, D., Agudo, R. & Monserrat, V.J. (2005) Changes to the elevational limits and extent of species ranges associated with climate change. *Ecology Letters*, **8**, 1138–1146.

*Received 9 July 2012; accepted 25 September 2012*
*Handling Editor: Paul Armsworth*

## Supporting Information

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

**Table S1.** Adaptation actions sourced from published adaptation principles.

**Table S2.** Summary of suggested adaptation actions for a generic focal species associated with broadleaved ancient semi-natural woodland.

**Appendix S1.** Introduction to test cases for the decision framework.

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials may be re-organized for online delivery, but are not copy-edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.