


# Space-for-time substitutions in climate change ecology and evolution

Rebecca S. L. Lovell<sup>1,\*</sup> , Sinead Collins<sup>1</sup>, Simon H. Martin<sup>1</sup>, Alex L. Pigot<sup>2</sup> and Albert B. Phillimore<sup>1</sup>

<sup>1</sup>*Ashworth Laboratories, Institute of Ecology and Evolution, The University of Edinburgh, Charlotte Auerbach Road, Edinburgh, EH9 3FL, UK*

<sup>2</sup>*Centre for Biodiversity and Environment Research, Department of Genetics, Evolution and Environment, University College London, Gower Street, London, WC1E 6BT, UK*

## ABSTRACT

In an epoch of rapid environmental change, understanding and predicting how biodiversity will respond to a changing climate is an urgent challenge. Since we seldom have sufficient long-term biological data to use the past to anticipate the future, spatial climate–biotic relationships are often used as a proxy for predicting biotic responses to climate change over time. These ‘space-for-time substitutions’ (SFTS) have become near ubiquitous in global change biology, but with different subfields largely developing methods in isolation. We review how climate-focussed SFTS are used in four subfields of ecology and evolution, each focussed on a different type of biotic variable – population phenotypes, population genotypes, species’ distributions, and ecological communities. We then examine the similarities and differences between subfields in terms of methods, limitations and opportunities. While SFTS are used for a wide range of applications, two main approaches are applied across the four subfields: spatial *in situ* gradient methods and transplant experiments. We find that SFTS methods share common limitations relating to (i) the *causality* of identified spatial climate–biotic relationships and (ii) the *transferability* of these relationships, i.e. whether climate–biotic relationships observed over space are equivalent to those occurring over time. Moreover, despite widespread application of SFTS in climate change research, key assumptions remain largely untested. We highlight opportunities to enhance the robustness of SFTS by addressing key assumptions and limitations, with a particular emphasis on where approaches could be shared between the four subfields.

*Key words:* space-for-time substitutions, climate change, ecology, evolution, reciprocal transplants, common garden transplants, *in situ* gradients, ecological niche models, biotic lags, biotic offsets.

## CONTENTS

I. Introduction	2
II. Commonalities of SFTS approaches	2
III. Application of SFTS to climate–biotic relationships	13
(1) Population phenotypes	13
(2) Population genotypes	15
(3) Species’ distributions	16
(4) Ecological communities	17
IV. Validation of SFTS	18
(1) Population phenotypes	19
(2) Population genotypes	19
(3) Species’ distributions	19
(4) Ecological communities	20
(5) Feasibility and logistics of SFTS validation	20
V. Opportunities for SFTS	20

\* Author for correspondence (Tel.: +0131 650 5440; E-mail: [rebecca.lovell@ed.ac.uk](mailto:rebecca.lovell@ed.ac.uk)).

VI. Conclusions	22
VII. Acknowledgements	22
VIII. References	22

## I. INTRODUCTION

Environmental conditions that vary over space and time can drive changes in biotic variables through processes such as plasticity, adaptation, colonisation and extinction (Parmesan, 2006). For example, climate variables such as temperature and precipitation have impacts on biotic variables ranging from changes in population phenotypes (Bergmann, 1848; Darwin, 1859) and genotypes (Bradshaw & Holzapfel, 2001), to shifts in species' distributions (Merriam, 1894; Grinnell, 1914) and the composition and functioning of ecological communities (Moritz *et al.*, 2008). As we progress through the Anthropocene – an epoch defined by rapid human-induced global change (Lewis & Maslin, 2015) – the biotic impacts of climate change are becoming increasingly apparent (Walther *et al.*, 2002; Root *et al.*, 2003; Scheffers *et al.*, 2016; IPCC, 2022). Consequently, there is an urgent call for ecologists and evolutionary biologists to understand and predict how populations, species and ecological communities will respond to changes in climate variables.

Given that ecological and evolutionary processes operate over time, predicting biotic responses to future climate change would ideally use long-term monitoring data to observe temporal climate–biotic relationships directly and project these into the future (time-for-time approach; see glossary Table 1c,e; Fig. 1A; Roy *et al.*, 2001; Simmonds *et al.*, 2020). However, long-term ecological data are rare (Estes *et al.*, 2018; Lindenmayer, 2018), as highlighted by recent efforts to collate time-series data (e.g. Dornelas *et al.*, 2018; Comte *et al.*, 2021; Johnson *et al.*, 2022a). The urgent need to make predictions of biotic responses to future climate change has led global change biologists to consider an alternative approach, space-for-time-substitution (SFTS; Fig. 1B; Table 1p). SFTS uses spatial climate–biotic relationships to predict biotic responses to climate change over time, under the assumption of space–time equivalence (Tables 1r and 2; Pickett, 1989). This approach can generate predictions rapidly (e.g. Blüthgen *et al.*, 2022), often from existing data or relatively small data sets that can be collected during shorter projects and/or funding cycles. Given this relative feasibility of SFTS compared to time-for-time approaches, SFTS has become near ubiquitous for understanding and predicting biotic responses to climate change (Table 3).

Studies employing SFTS to predict biotic responses to future climate change have been conducted across a variety of spatial climate gradients including elevation/altitudinal (Zografou *et al.*, 2020), latitudinal (De Frenne *et al.*, 2013) and urbanisation [heat islands (Lahr, Dunn & Frank, 2018; Diamond & Martin, 2021)] gradients, with each gradient type providing different strengths and weaknesses (Verheyen, Tüzün & Stoks, 2019). While the comparative

straightforwardness of collecting data for SFTS is an attraction, the method has inherent limitations (Table 4) that need to be acknowledged, explored, and minimised to maximise the robustness of predictions. Namely, for all biotic variables, SFTS relies on the fundamental, often implicit, and rarely tested assumption that climate–biotic relationships observed in space are predictive of those that occur over time (e.g. Phillimore *et al.*, 2010; Isaac *et al.*, 2011; Blois *et al.*, 2013).

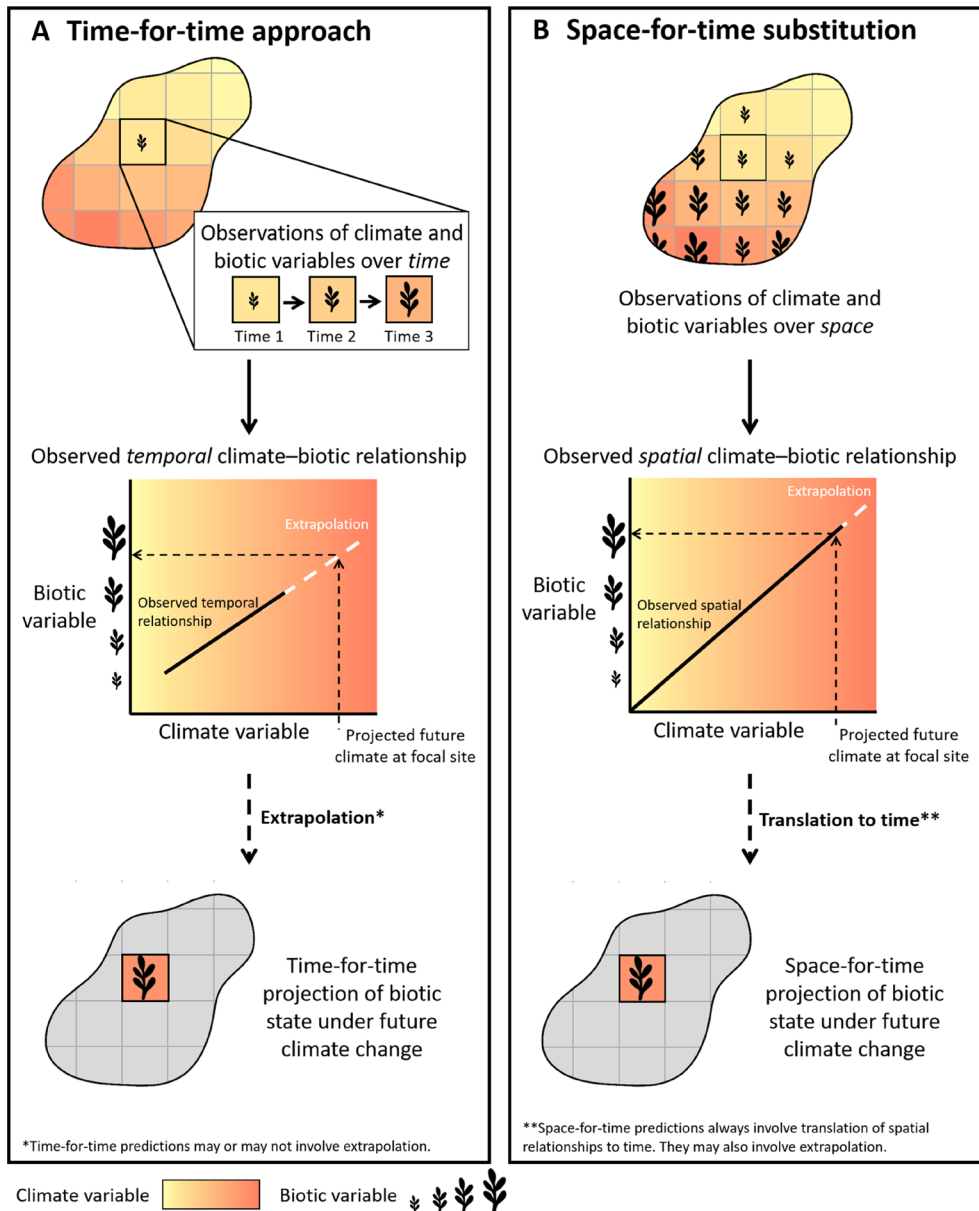
The use of SFTS in global change research has progressed somewhat independently across subfields focussing on different biotic variables. This review aims to synthesise the use of SFTS across four broad classes of biotic variables: population phenotypes, population genotypes, species' distributions and ecological communities (Table 3). We first describe the most widely used SFTS approaches that are applied across different biotic variables, and highlight limitations that are common to all of our focal subfields. Second, we consider each subfield in turn, focussing on the SFTS methods employed, their applications and the insights gained, and any subfield-specific limitations. For each subfield, we highlight an exemplar SFTS study in Table 3. Third, we discuss the broad challenges of SFTS validation. Finally, we identify opportunities for improving the robustness of SFTS, including cross-fertilisation of ideas between the different subfields. While the focus of this review is on the use of SFTS to understand and predict the effects of climate variables, many of the insights into methods, assumptions, limitations and validation apply to SFTS across other types of ecological and environmental gradients [e.g. land-use intensity (Purvis *et al.*, 2018); ecological succession (Johnson & Miyanishi, 2008)].

## II. COMMONALITIES OF SFTS APPROACHES

There are two main method types that are employed across the four subfields to investigate biotic responses to climate variation over space: *in situ* gradient approaches and transplant experiments (Table 1k,s). These are compared in Fig. 2 and Table 2. *In situ* gradient methods involve observing the value of a biotic variable, hereafter 'biotic state' (Table 1d), at multiple sites along a spatial climate gradient to allow estimation of the spatial climate–biotic relationship (Fig. 2A, Table 2a; Dunne *et al.*, 2004). A variant of the *in situ* gradient approach that was developed for studying species' distributions is ecological niche models (ENMs; Table 1h, Section III.3), which are variously termed environmental niche, species distribution, (bio)climatic envelope and habitat suitability models (see Peterson & Soberón, 2012; Araújo & Peterson, 2012). The *in situ* gradient method presents a

Table 1. Glossary.

(a) Biotic lag	The biotic distance (e.g. Euclidian distance between phenotypic trait values) between the observed (or predicted) biotic state (e.g. phenotype, genotype or probability of species presence) under specific climate conditions and the predicted equilibrium biotic state for those conditions (see Fig. 3B). Also termed maladaptation, mismatch, disequilibrium, and climate debt.
(b) Biotic offset	The biotic distance between the current biotic state (e.g. phenotype, genotype or probability of species presence) at a focal site and the predicted equilibrium biotic state at this site under future climatic conditions (see Fig. 3A; Fitzpatrick & Keller, 2015; Frank <i>et al.</i> , 2017). Where there is an immediate biotic response to climate change (e.g. <i>via</i> phenotypic plasticity), this results in a realised biotic offset. Our use of the term biotic offset is inspired by ‘genetic offset’ introduced by Fitzpatrick & Keller (2015), extended to generalise across biotic variables. Within the ecological genomics literature, this has been termed vulnerability, risk of non-adaptedness, and (relative) risk of maladaptation.
(c) Biotic response	A change in a biotic state, which can be driven by a change in climate. In this review the main biotic variables we discuss relate to population phenotypes, population genotypes, species’ distributions and ecological communities. We use the terms phenotypic response, genetic response, species response and community response to refer to the specific biotic responses discussed.
(d) Biotic state	A value of a biotic variable.
(e) Climate–biotic relationship	The correlation between climate variable(s) and a biotic variable in space or time. We use ‘climate–phenotype’, ‘climate–genotype’, ‘climate–species’ and ‘climate–community’ relationships to refer more specifically to the biotic responses discussed.
(f) Common garden transplants	Organisms (i.e. individuals or communities) are moved into a shared ‘common garden’ environment (see Fig. 2B, Table 2b.i). This includes when organisms are subjected to experimentally manipulated environments, with each treatment level being a common garden.
(g) Distance of biotic lag	A biotic lag quantified in terms of spatial distance (see Fig. 3C, Table 2a.iii). Where spatial and temporal data are both available, changes in climate and biotic responses over time can each be quantified in terms of a shift in spatial distance, and the difference between these shifts is the distance of biotic lag (Devictor <i>et al.</i> , 2008, 2012). Also referred to as a spatial lag.
(h) Ecological niche model (ENM)	A group of <i>in situ</i> gradient methods aiming to correlate the distribution of a biotic variable (usually a species’ presence/absence) with one or more environmental variables (usually including climate) in order to predict environmental suitability for the biotic states across a landscape and under altered conditions. There are various other terms for ENMs including environmental niche models, species distribution models, (bio)climate envelope models, and habitat suitability models (Peterson & Soberón, 2012; Araújo & Peterson, 2012).
(i) Equilibrium	A biotic state that is stationary in relation to its environment, where the effects of countervailing processes are in balance (Coulson, 2021). There may be multiple stable equilibria for a single biotic state (Chase, 2003).
(j) Exposure	The nature, magnitude and rate of climate change experienced by a biotic system (Foden <i>et al.</i> , 2019).
(k) <i>In situ</i> gradient approach	Spatial climate gradients are used to identify climate–biotic relationships (see Fig. 2A, Table 2a). This includes ecological niche models. Note that an <i>in situ</i> gradient could also refer to a gradient in time, but we use the term for spatial gradients alone.
(l) Local adaptation	Where spatially variable environments impose selection that maintains genotypic differences between locations, such that the fitness of local individuals tends to be greater than foreign individuals in their home conditions.
(m) Phenotypic plasticity	Where a genotype gives rise to different phenotypes under different environmental conditions.
(n) Putatively adaptive loci	Loci identified as potentially being involved in adaptation. These loci exhibit relationships with climate, but correlative methods do not prove that they are causally involved in adaptation.
(o) Reciprocal transplant	Organisms (i.e. individuals or communities) from different sites are moved into each other’s environments so that the performance and/or traits (e.g. phenotypes) of organisms experiencing local <i>versus</i> foreign and/or home <i>versus</i> away environments can be compared (see Fig. 2C, Table 2b.ii).
(p) Space-for-time substitution (SFTS)	Spatial climate–biotic relationships are used as a substitute for temporal relationships to make inferences about biotic responses to climate change over time (Pickett, 1989). Note that here our focus is on climate–biotic relationships but SFTS are also applied to other drivers and responses.
(q) Space–time comparison	Climate–biotic relationships are estimated separately over space and over time. Comparison of these relationships can provide insights into the processes generating these spatial and temporal patterns (Table 2a.ii). Note that this has an implicit SFTS since the spatial climate–biotic relationship is assumed to capture the equilibrium relationship.
(r) Space–time equivalence	An observation, inference or assumption that climate–biotic relationships in space and time are equivalent. This is a key assumption underlying SFTS and relates to the limitations inherent in transferring spatial climate–biotic relationships over time (Table 4b).
(s) Transplant experiments	Organisms (i.e. species or communities) are moved from a home site into different environments over space (away sites) (Table 2b). Transplants may be common garden transplants or reciprocal transplants.
(t) Vulnerability	The extent to which biotic systems are susceptible to the adverse effects of climate change (Foden <i>et al.</i> , 2019).



**Fig. 1.** Approaches for predicting biotic responses to future climate change at a focal site (black square). (A) Time-for-time approaches, where climate–biotic relationships are observed over time and extrapolated under projected future climates. (B) Space-for-time substitution (SFTS), where climate–biotic relationships observed in geographical space are translated to time under projected future climates. Note that time-for-time and space-for-time climate–biotic relationships are not necessarily equivalent.

comparatively low logistical hurdle to data collection, meaning that spatial replication (i.e. number of sampling locations) is often high (e.g. Morán-Ordóñez *et al.*, 2017). However, a correlative *in situ* gradient approach in isolation is typically uninformative about the processes that generate the spatial pattern of a biotic state, such as the relative contributions of short-term processes including phenotypic plasticity *versus* longer-term equilibrium processes such as local adaptation (Tables 1i,l,m and 2a; Adler, White & Cortez, 2020).

The second main SFTS approach involves transplant experiments, either as (i) a common garden transplant to a shared environment, including experimentally manipulated environments, or (ii) a reciprocal transplant between pairs of sites (Fig. 2B,C, Tables 1f,o and 2bi,ii). Transplant experiments can yield information on the processes (e.g. plasticity *versus* genetic divergence) that generate spatial climate–biotic relationships (Turesson, 1922; Nooten & Hughes, 2017; Stamp & Hadfield, 2020). However, the logistics of transplant experiments often leads to low levels of spatial

Table 2. Main space-for-time substitution (SFTS) approaches used in climate change ecology and evolution.

Method	Purpose and inference	Limits to inferences
<p><b>(a) <i>In situ</i> gradients approaches including ecological niche models (ENMs)</b></p> <p>Use of spatial climate gradients (e.g. latitudinal, altitudinal) to identify climate–biotic relationships (Fig. 2A). This can then be used in a SFTS to make predictions about biotic responses over time.</p>	<p>(1) Climate–biotic relationships are assumed to capture causal effects, under the assumption that there are no unmeasured causal variables. Estimates can then be used to predict biotic responses to a change in the focal climate variable(s) over time.</p> <p>(2) Where multiple climate variables are considered, it is possible to infer the relative importance of different variables as predictors of a biotic response.</p>	<p>(1) Does not prove a causal effect of climate variables in driving the biotic response and the relationship is sensitive to unmeasured variables.</p> <p>(2) Silent on the mechanisms of the biotic response to climate variables in space and whether the biotic response manifests over short or long timescales.</p> <p>(3) Assumes that current spatial patterns reflect the equilibrium relationship (or in special cases optimum relationship; Slatkin, 1978) between the focal climate variables and the biotic variable.</p>
<p><b>(ii) Space–time comparison</b></p> <p>Estimate the climate–biotic relationship separately over space and over time and compare the direction and magnitude of the slopes.</p>	<p>(1) Where the slope of the climate–biotic relationship is in the same direction over space and time and similar in magnitude, this is consistent with climate having a causal effect and implies that spatial estimates are transferable to a temporal context (i.e. it is a form of space–time equivalence validation – see Section IV).</p> <p>(2) Where the estimated slopes of the spatial and temporal climate–biotic relationships differ in direction or magnitude, this may suggest that different processes are operating over space and time. Where slopes differ in direction or one of the relationships is non-significant, this reduces confidence that the climate variable is causal.</p> <p>(3) Spatial climate–biotic relationships are often assumed to capture the equilibrium relationship (and in special cases the optimum relationship; Slatkin, 1978). Therefore, where spatial and temporal climate–biotic relationships have slopes that are in the same direction but steeper over space than over time, this can reveal the presence of a contemporary biotic lag or a biotic offset under a future climate.</p>	<p>(1) Particularly sensitive to unmeasured variables, as both the spatial and temporal climate–biotic responses may be affected (Tansey <i>et al.</i>, 2017), necessitating caution when drawing inferences.</p> <p>(2) Assumes that current spatial patterns reflect the equilibrium relationship (or in special cases optimum relationship; Slatkin, 1978) between the biotic variable and the focal climate variables.</p>
<p><b>(iii) Quantifying temporal change as distance</b></p> <p>Estimating the change in a climate or biotic variable over a spatial gradient and over</p>	<p>(1) When applied to climate data alone this approach can be used to quantify local climate velocity (Loarie <i>et al.</i>, 2009), which is a vector of the distance in space</p>	<p>As for (ii).</p>

(Continues on next page)



Table 2. (Cont.)

Method	Purpose and inference	Limits to inferences
<p>time allows a temporal change to be translated into the spatial distance over which the equivalent change in the variable state is observed.</p>	<p>that provides an equivalent shift in climate to the change observed over time.</p> <p>(2) A temporal biotic lag can be quantified in terms of spatial distance by finding the difference between the spatial shift in climate and the spatial shift in a biotic variable in a focal time period (Fig. 3C). This 'distance of biotic lag' metric has the benefit of units (e.g. km) being easily interpretable and allowing multiple biotic variables to be compared on the same axis.</p>	<p>(1) Where replication is insufficient (i.e. a limited number of sites are considered) and climatic conditions are not manipulated experimentally, common garden transplants do not inform on the effects of specific climate drivers on biotic variables.</p> <p>(2) Differences among organisms in a common garden environment are not sufficient on their own to evidence spatial differences in equilibrium biotic state (e.g. local adaptation).</p> <p>(3) For some taxa, transplant experiments are impractical or even impossible. Therefore, the use of transplants is largely limited to taxa such as plants (e.g. Alexander <i>et al.</i>, 2015).</p>
<p><b>(b) Transplants</b> Moving organisms into different environments over <i>space</i> to provide insights into biotic responses to climate. Can be used to make predictions of biotic responses that may occur over <i>time</i>.</p>	<p>(1) Comparing the biotic state at a home site to that at away (transplant) sites can reveal an immediate biotic response to environmental change (e.g. plasticity; Stamp &amp; Hadfield, 2020). The immediate biotic responses to a specific climate driver can be estimated where (i) the climate variable(s) is/are manipulated across experimental replicates or (ii) replication of source sites permits correlation-based analysis of causal effects of climate variables.</p> <p>(2) Comparing the biotic states of organisms from different sites of origin within a common environment can inform about persistent differences between sites (e.g. genetic differentiation).</p> <p>(3) Where a transplant climate is representative of historical conditions, this can inform regarding biotic lags: if performance (e.g. fitness) is higher in climates resembling those occupied in the past, it may suggest that the biotic state is lagging behind the changing environment.</p> <p>(4) When the conditions within a common garden (away) site are representative of the future conditions expected at the home site, predictions can be made about the expected biotic responses to future climate change, assuming that climate is</p>	<p>(1) Where replication is insufficient (i.e. a limited number of sites are considered) and climatic conditions are not manipulated experimentally, common garden transplants do not inform on the effects of specific climate drivers on biotic variables.</p> <p>(2) Differences among organisms in a common garden environment are not sufficient on their own to evidence spatial differences in equilibrium biotic state (e.g. local adaptation).</p> <p>(3) For some taxa, transplant experiments are impractical or even impossible. Therefore, the use of transplants is largely limited to taxa such as plants (e.g. Alexander <i>et al.</i>, 2015).</p>

(Continues on next page)

Table 2. (Cont.)

Method	Purpose and inference	Limits to inferences
<p><b>(ii) Reciprocal transplants (sometimes called reciprocal common garden transplants)</b> Organisms from different sites are moved into each other's environments allowing the performance (and biotic state) of local and foreign organisms at a site to be compared (Fig. 2C).</p>	<p>causal. This includes estimating biotic offsets (Fig. 3A).</p> <p>(1) Comparing biotic states in home sites to those in away (transplant) sites or under manipulated conditions can reveal an immediate biotic response to environmental change (e.g. plasticity; Stamp &amp; Hadfield, 2020).</p> <p>(2) Comparing the biotic states of organisms from different sites of origin within a common environment allows quantification of persistent differences between sites (e.g. genetic differentiation) with respect to the environment. Since reciprocal transplants involve maintaining organisms in both local and foreign sites – such that native and foreign performance can be compared – they allow these persistent differences in performance (but not other aspects, e.g. phenotypes) to be attributed to spatial differences in the equilibrium biotic state (e.g. local adaptation; Kawecki &amp; Ebert, 2004).</p> <p>(3) Where replication (i.e. the number of sites) is sufficient, reciprocal transplants allow (1) and (2) to be estimated with respect to a specific climate driver.</p> <p>(4) Where a transplant climate is representative of historical conditions, this can inform regarding biotic lags: if performance (e.g. fitness) is higher in climates resembling those occupied in the past, it may suggest that the biotic response is lagging behind the changing environment.</p> <p>(5) When the conditions within an away (transplant) site are representative of the future conditions expected for a focal home site, predictions can be made about the expected biotic responses to future climate change, assuming that climate is causal. This includes estimating biotic offsets (Fig. 3A).</p>	<p>(1) Where the focal environmental driver is not directly manipulated and replication is insufficient (i.e. a limited number of sites are considered), reciprocal transplants cannot reveal which environmental variables (including climate) drive biotic responses.</p> <p>(2) For some taxa, transplant experiments are impractical or even impossible. Therefore, the use of transplants is largely limited to taxa such as plants (e.g. Alexander <i>et al.</i>, 2015).</p>

Table 3. Examples of studies that employ space-for-time substitution (SFTS) for each of the four eco-evolutionary subfields included in this review (population phenotypes, population genotypes, species' distributions, ecological communities). Papers were selected to showcase the breadth of SFTS methods, inferences and limitations.

Subfield and example paper	Method	Inference	Key assumptions
(a) Population phenotypes Wilczek <i>et al.</i> (2014)	Wilczek <i>et al.</i> (2014) transplanted seed-banked accessions of <i>Arabidopsis thaliana</i> collected across Europe into each of four common garden sites across the species' European range (Spain, UK, Germany and Finland). They estimated the fitness (based on fecundity) of different genotypes at the four sites.	At three of the four common garden sites, genotypes with origins that were local had higher relative fitness than those from other regions (foreign), suggesting the presence of local adaptation. However, for the most northerly common garden site (Finland), accessions originating from a historically warmer location had higher fitness than the home accessions. The authors suggest that this is indicative of the historically collected accessions exhibiting a biotic lag to temperature.	The conclusion that adaptation is lagging behind climate warming relies on the assumption that temperature is driving the among-population variation in fitness (Table 4a.i). However, other environmental variables may also exhibit similar patterns of variation across sites and so the causal variable is not robustly established.
(b) Population genotypes Gougherty <i>et al.</i> (2021)	Gougherty <i>et al.</i> (2021) modelled spatial genotype–climate relationships for North American balsam poplar ( <i>Populus balsamifera</i> ) based on genetic differentiation ( $F_{ST}$ ) across 75 phenology-related candidate single nucleotide polymorphisms (SNPs) and 81 populations. These contemporary relationships were then used to predict future $F_{ST}$ (centred on 2070). From this, three different genetic offset metrics were derived to estimate potential maladaptation: (i) 'local offset' was the predicted genetic differentiation between a grid cell under current and future climates (i.e. a scenario where populations remain <i>in situ</i> with no migration or gene flow); (ii) 'forward offset' was the predicted genetic differentiation between a grid cell under the current climate and all other grid cells under the future climate (i.e. genetic offset under a scenario of unlimited dispersal); and (iii) 'reverse offset' which is similar to forward offset but with the predicted genetic differentiation calculated between a grid cell under the future climate and all other grid cells under the current climate.	The authors found that all three genetic offset metrics were generally lower in the centre of the species' range, suggesting that these populations may be the most pre-adapted to future climates. Conversely, the most eastern and northern populations had higher genetic offsets, suggesting that these populations lack pre-adaptation to future climates, and that these populations are likely to face the greatest challenge in adapting to future climates.	While this study addresses the assumption of causality (Table 4a) by using candidate SNPs, which are hypothesised to be sensitive to climate, the robustness of predictions relies on the key assumption that these spatial relationships are transferable over time (Table 4b).
(c) Species' distributions Thomas <i>et al.</i> (2004)	Thomas <i>et al.</i> (2004) fitted separate ecological niche models (ENMs) to 1103 terrestrial animal and plant species, based on the climate conditions they currently occupy. They used these contemporary associations to predict species' distributions under projected climate change for 2050.	Based on the predicted change in climatically suitable areas, the authors estimated the proportion of species expected to go extinct under different climate-warming scenarios. They estimated that between 9% and 52% of species would be 'committed to extinction', depending on climate and dispersal scenarios.	This study relies on a number of key assumptions, as demonstrated by the high variability in the number of species 'committed to extinction' (9–52%). In particular, there is a lack of validation of both causality and transferability of models (Table 4), with the authors instead citing generic validation of ENMs, despite considerable variability in the transferability of

(Continues on next page)



Table 3. (Cont.)

Subfield and example paper	Method	Inference	Key assumptions
(d) Ecological communities Alexander <i>et al.</i> (2015)	Alexander <i>et al.</i> (2015) transplanted both (i) four focal plant species and (ii) intact alpine plant communities to two sites on an elevational gradient in the Swiss Alps. Transplants simulated different migration scenarios that may occur under climate change, such that each focal species experienced different combinations of (i) current or warmer temperatures and (ii) current or novel communities.	Novel competitors were found to reduce the performance of focal plant species under increased temperatures (i.e. under the scenario where a species fails to migrate to track climate change) but had little effect under current temperatures (i.e. under the scenario where a species migrates to track the changing climate).	ENMs across space, time, taxa and modelling methods (Jarnveich <i>et al.</i> , 2015). This study relies on the key assumption of causality: with only three common garden sites, it is impossible to demonstrate a causal effect of temperature on community composition (Table 4a.i).

replication (Johnson *et al.*, 2022b), which makes it difficult to identify the causal driver(s) of biotic responses. There are also many taxa for which transplant experiments are challenging or unfeasible, and most transplant experiments have involved organisms that are more easily moved, such as plants (e.g. Alexander, Diez & Levine, 2015).

Two extensions of the SFTS approach have been developed to predict the challenge that climate change poses to aspects of biodiversity; we term these metrics ‘biotic offsets’ and ‘biotic lags’ (Table 1a,b,t; Fig. 3). The first, a biotic offset, is defined as the difference between the observed biotic state at a site and the predicted equilibrium biotic state at that site under a future climate (Fig. 3A; Fitzpatrick & Keller, 2015; Frank *et al.*, 2017). Within the ecological genomics literature, this type of metric has been termed vulnerability (Bay *et al.*, 2018), risk of non-adaptedness (Rellstab *et al.*, 2016), and (relative) risk of maladaptation (St Clair & Howe, 2007). Here we use the term biotic offset – inspired by the ‘genetic offset’ introduced by Fitzpatrick & Keller (2015) – to apply to any biotic variable. The second metric, a biotic lag, is the difference between the observed biotic state at a site and the predicted equilibrium biotic state at that site under the current climate conditions (Fig. 3B). This has been variously termed maladaptation (e.g. Hällfors *et al.*, 2020), disequilibrium (e.g. Sandel, 2019) and climatic debt (e.g. Devictor *et al.*, 2012). In some studies, the biotic lag is translated into a spatial distance (Devictor *et al.*, 2012). This involves quantifying the shifts in both a biotic state and climate variables over a given time period, and identifying the geographic distance over which a shift of the same magnitude can be observed (Balanyá *et al.*, 2006). The extent to which the geographic distance for climate exceeds that of the biotic state is the ‘distance of biotic lag’ (Table 1g; Fig. 3C; Table 2a.iii; Devictor *et al.*, 2008, 2012; Ash, Givnish & Waller, 2017). For example, Devictor *et al.* (2012) examined temporal and spatial trends in temperature and community temperature index (CTI; a measure of the thermal ranges of the species in a community) for birds and butterflies across Europe. They found that the increases in temperature that had been observed over 18 years corresponded to a northwards shift of 249 km, whilst the equivalent shifts in CTI for birds and butterflies were 37 and 114 km, respectively, corresponding to a biotic lag distance of 212 and 135 km.

Common to most ecological and evolutionary applications of SFTS is the often implicit expectation that spatial climate–biotic relationships will arise *via* a combination of comparatively rapid processes and slow processes, and may potentially be at equilibrium (Dunne *et al.*, 2004; Adler *et al.*, 2020). For instance, phenotypic plasticity is a rapid process, whereas genetic adaptation and shifts in species’ distributions are slower processes that generally take place over multiple generations. Conversely, in the short term, temporal climate–biotic relationships will often be dominated by rapid processes, and it may only be over longer timescales that slower acting processes will come to the fore (Dunne *et al.*, 2004; Adler *et al.*, 2020). Insights into the relative contributions of these fast and slow processes can be obtained *via* a

Table 4. General limitations of space-for-time substitution (SFTS) that apply across all four subfields (population phenotypes, population genotypes, species' distributions, ecological communities) and potential mitigations.

Type of limitation	Specific limitation	Improvements and recommendations
<b>(a) Causality</b> Issues identifying causal climate–biotic relationships (i.e. where climate is driving the biotic response).	<b>(i) Identification of causal climate predictors</b> Both the omission of causal variables and the inclusion of too many or non-causal predictor variables (i.e. overfitting) can bias SFTS estimates (Synes & Osborne, 2011; Beale & Lennon, 2012; Fourcade <i>et al.</i> , 2018). Unmeasured causal variables could be other abiotic or biotic variables and their non-inclusion reduces our ability to predict biotic responses in time accurately. It may also lead to correlated but non-causal variables being identified as important predictors, although with a weaker effect than the true causal variable would have (Dormann <i>et al.</i> , 2013). Omitted causal variables are especially problematic for SFTS where correlations between the causal and non-causal variable differ in space and time (Tansey <i>et al.</i> , 2017). Causal inference can also be problematic in transplant experiments, where 'excludability' (where the treatment has other unintended consequences) and 'non-compliance' (where the treatment climate that a transplant site experiences cannot be fully controlled) may be particular challenges (Kimmel <i>et al.</i> , 2021). Problems with inferring causality are likely to be most pronounced where replication is insufficient.	(1) Using biological knowledge to select climate variables that are likely to be causal (Elith & Leathwick, 2009), e.g. forcing temperature as a predictor of plant phenology. (2) Where the estimated slope of the climate–biotic relationship is similar across multiple gradients or types of gradients (e.g. altitudinal, latitudinal, urbanisation), this can increase confidence that relationships have a causal basis (Loewen <i>et al.</i> , 2023). (3) Estimating the relationships between multiple abiotic (including climate) and biotic variables in space <i>versus</i> time would provide us with an insight into how often and where differing correlations are likely to pose a challenge to predictions (Dormann <i>et al.</i> , 2013). (4) There are approaches for choosing drivers that could be shared between the four subfields. For example, phenotypic studies often focus on the seasonal timing over which a climate variable is important (Roberts, 2008; van de Pol <i>et al.</i> , 2016), whereas ecological niche models (ENMs) generally consider multiple climate variables and non-linear climate–biotic relationships.
	<b>(ii) Appropriate sampling</b> A spatial sample may not capture the true relationship between variables, such as due to sampling biases or incomplete sampling. Additionally, if there is variation in the frequency of different climate conditions over space, this may result in unequal climate representation in the sample. <b>(iii) Spatial autocorrelation</b> Spatial autocorrelation is ubiquitous in biotic and climatic data, with sites that are closer together being more similar. This means that spatial samples will often not be independent and this leads to inflated confidence in model estimates (Dormann, 2007). <b>(iv) Spatial scale</b> Generally, <i>in situ</i> climate–biotic relationships are modelled using relatively coarse grain predictors (e.g. estimates for 100, 10 or 1 km <sup>2</sup> ; Fick & Hijmans, 2017), which may not be representative of the local conditions that drive a biotic response (Potter <i>et al.</i> , 2013). This can introduce measurement error variance	(1) Selective sampling of environments, such as stratified sampling or matching methods (Andam <i>et al.</i> , 2008), could be used to generate a sample that is representative of the available climate conditions. (2) A greater emphasis should be placed on statistical power in study design, including selection of sampling locations that minimise the autocorrelation between predictor variables. (1) Modelling methods that address spatial autocorrelation in the residuals now exist and are getting faster and more able to deal with large and complex data sets, e.g. INLA (Rue <i>et al.</i> , 2009). (2) For genomic data, where spatial proximity may lead to greater genetic similarity <i>via</i> isolation by distance, methods have been developed to try to capture and control for relatedness between populations (reviewed by Rellstab <i>et al.</i> , 2015). (1) Where interpolated climate data are used we recommend using the finest scale available, depending on suitability to the biotic response (Suggitt <i>et al.</i> , 2017). (2) Where the biology of the system suggests that microclimates are likely to be important for predicting impacts on biotic states, we recommend that microclimatic modelling (Kearney <i>et al.</i> , 2020;

(Continues on next page)

Table 4. (Cont.)

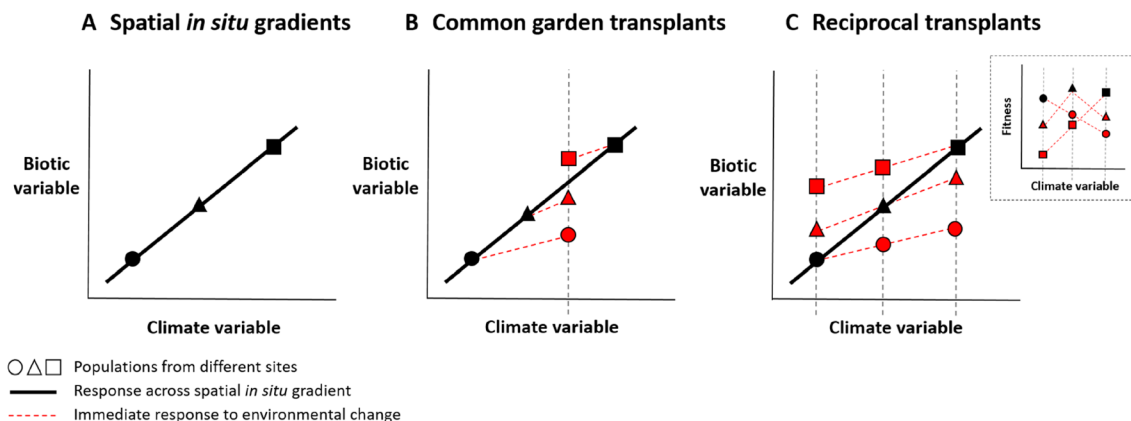
Type of limitation	Specific limitation	Improvements and recommendations
	<p>into our climate predictors, which will bias climate–biotic slope estimates towards zero.</p> <p>It is also possible for estimates of climate–biotic relationships to be biased away from zero when, as one moves towards more extreme climates, there is a greater tendency for organisms to use microclimates that are less extreme than coarser scale climate conditions. For example, microclimates can provide suitable climatic refugia for organisms, even when coarser scale climate conditions would render a site unsuitable (Lawson <i>et al.</i>, 2014; Suggitt <i>et al.</i>, 2018). For instance, such an effect might arise in butterfly phenology if individuals experiencing a colder environment seek out warmer microclimates, whilst those in a warmer environment seek out cooler microclimates (Roy <i>et al.</i>, 2015).</p>	<p>Maclean, 2020) is used to generate climate predictors (Stark &amp; Fridley, 2022).</p> <p>(3) If microclimates are changing in the same way as coarser climate variables over space and over time, this may not affect SFTS predictions. Therefore, we recommend examining relationships between microclimates and coarser climate variables in both space and time to determine when this will be an issue. See also recommendation a.i.3.</p>
	<p><b>(b) Transferability</b> Issues relating to the transferability of spatial climate–biotic relationships over time (Sequeira <i>et al.</i>, 2018; Yates <i>et al.</i>, 2018).</p> <p><b>(i) Lack of temporal validation</b> Models are often used to make predictions over time, under future (or past) climates, but their ability to predict biotic changes accurately over time is rarely assessed due to a lack of testing data.</p>	<p>(1) Where opportunities to test the accuracy and precision of equilibrium predictions on appropriate timescales can be identified, they should be prioritised.</p> <p>(2) In some instances, greater use could be made of existing historic data that have been underutilised for hindcasting, e.g. museum and herbarium specimens (Guerin <i>et al.</i>, 2012), dendrochronology (Klesse <i>et al.</i>, 2020), genomic data (Miller <i>et al.</i>, 2021), palaeodata (Blois <i>et al.</i>, 2013).</p> <p>(3) Where the time to reach equilibrium precludes quantitative analysis, there may be potential to make qualitative predictions over shorter timescales amenable to validation tests.</p> <p>(4) Where suitable testing data are not available, there is still great value in using simulations to detect limits to inference (e.g. Zurell <i>et al.</i>, 2010; Qiao <i>et al.</i>, 2019; Adler <i>et al.</i>, 2020).</p> <p>(5) Space–time comparison provides an opportunity to test whether climate–biotic relationships are of similar magnitude in space and time (Phillimore <i>et al.</i>, 2010; Table 2a.ii).</p>
	<p><b>(ii) Assumption of contemporary spatial equilibrium</b> A common assumption is that current spatial patterns reflect the equilibrium outcome of eco-evolutionary responses to spatial variation in the long-term average climate. However, there may be a biotic lag between the contemporary biotic state and the equilibrium biotic state for those climate conditions (Fig. 3B); whether current spatial patterns are at equilibrium with the climate is unclear, variable across systems (Gaüzère <i>et al.</i>, 2018), and largely untested.</p> <p>Recent anthropogenic shifts in climate may have perturbed many systems from their long-term equilibrium. There is potential for the climate–biotic relationship to be out of equilibrium in its</p>	<p>(1) Rather than using a single historical average for each climate variable at a site, we suggest analysis of a sliding window of historical climate to identify the time period over which climate best predicts the system (van de Pol <i>et al.</i>, 2016). The situation where current biotic states are better predicted by historic rather than current climate may indicate that the system exhibits biotic lag behind the equilibrium.</p> <p>(2) We are not aware of an approach to test whether <i>in situ</i> biotic systems are at equilibrium with climate in the absence of temporal data. Therefore, we suggest that theory represents the most promising avenue for exploring the problems that non-equilibrium in the intercept and/or slope of the climate–biotic relationship presents to SFTS methods.</p>

(Continues on next page)

Table 4. (Cont.)

Type of limitation	Specific limitation	Improvements and recommendations
	<p>intercept and/or slope. The consequences of either for SFTS predictions are unknown (Coulson, 2021). If a system is in a transient biotic state, and not at equilibrium, this need not invalidate future predictions, as these may also be interpreted as indicating the expected transient, rather than equilibrium, biotic response. Equilibrium also does not necessarily imply the system is at its optimum, e.g. phenotypes may be perturbed from their local optima by migration load (introduction of alleles from other populations), and instead be at selection–migration equilibrium (Hadfield, 2016).</p> <p><b>(iii) Timescale of projection</b> Relationships observed over space are likely to be the result of both long-term and short-term processes, but the immediate temporal biotic responses that are more relevant to climate change predictions (i.e. over decades) will be mostly driven by short-term processes (Dunne <i>et al.</i> 2004; Adler <i>et al.</i>, 2020; Münzbergová <i>et al.</i>, 2021). Therefore, there may be a biotic lag in the temporal biotic response, with equilibrium not reached in the short term or potentially not reached at all (Chevin <i>et al.</i>, 2010). This biotic lag may be exacerbated by future climate change occurring at a faster rate than that in the past, with biotic responses unable to occur rapidly enough to reach equilibrium. Consequently, the timescale over which SFTS predictions are valid is uncertain.</p> <p><b>(iv) No-analogue climates</b> In the future, organisms may be exposed to climatic conditions not experienced today, but models do not contain any information about biotic responses to these novel conditions and so rely on extrapolation (Williams &amp; Jackson, 2007; Fitzpatrick &amp; Hargrove, 2009). This includes both new values of individual variables but also novel combinations of variable values. This will be a particular issue where linear models are used for non-linear climate–biotic relationships. Tipping points may be reached.</p>	<p>(3) If current spatial patterns are not at equilibrium, future predictions will indicate transient rather than equilibrium biotic responses. Moving beyond static snapshot predictions to understand how the transient biotic response is expected to change dynamically over fine temporal resolutions (i.e. annual) would provide an indication of (i) the sensitivity of the predicted biotic responses to the choice of future time horizon (Petchev <i>et al.</i>, 2015) and (ii) the rate, timing and abruptness of the expected biotic response, not just the magnitude.</p> <p>A method for quantifying the predicted timescale for a biotic lag to be closed and equilibrium reached would be invaluable for predicting consequences. We are not aware of such tools, but suggest that simulation would provide a potential avenue.</p>
		<p>(1) Where possible, experiments can provide insights into biotic responses to novel conditions.</p> <p>(2) Similarity between current and future climates can be quantified to assess the level of uncertainty in extrapolation (Qiao <i>et al.</i>, 2019).</p> <p>(3) Whilst linear assumptions in modelling are convenient, we encourage wider testing of their adequacy (Iler <i>et al.</i>, 2013).</p>





**Fig. 2.** The main methods used to identify spatial climate–biotic relationships for space-for-time substitution (SFTS): (A) spatial *in situ* gradients, and (B, C) transplant experiments. Across all plots, shapes represent populations that have different sites of origin. (A) *In situ* gradient approaches, where biotic states observed at sites across a spatial climate gradient are used to model climate–biotic relationships (black line). (B, C) Transplant approaches where organisms are moved across space into different environments. Here, dashed red lines indicate an immediate biotic response to a new environment (e.g. phenotypic plasticity). Transplant approaches include (B) common garden transplants, where organisms from different sites are moved into a shared environment and (C) reciprocal transplants, where organisms from different sites are reciprocally moved into each other’s environments. The insert in C shows the case when the biotic variable is fitness and each population is the fittest at its site of origin (indicating local adaptation; Kawecki & Ebert, 2004). Note that while linear climate–biotic relationships are depicted, non-linear relationships are possible.

space–time comparison approach, which compares climate–biotic relationships estimated separately over space and time (Table 1q; Phillimore *et al.*, 2010). This generally relies on an implicit SFTS because the spatial biotic response to climate is assumed to capture the equilibrium climate–biotic relationship.

Whilst SFTS offers substantial promise as a tractable approach for generating much-needed biotic predictions (Fukami & Wardle, 2005), several general limitations exist that, in the absence of successful validation, may undermine the robustness of SFTS predictions. Limitations fall into two broad categories: causality and transferability. These are discussed in detail in Table 4 (note that this is a non-exhaustive list), and so here we give only a brief overview of the issues. The first type of limitation, causality, relates to the fact that correlative methods may fail to capture the true causal effect of a climate variable on a biotic variable (Table 4a). This can arise from suboptimal selection of focal climate predictors, inadequate sampling, spatial autocorrelation, and the spatial scale of variables used (see Table 4a for details). The second type of limitation, transferability, relates to the fact that robust prediction of future biotic changes relies on the assumption that climate–biotic relationships are equivalent in space and time, and that these relationships will hold under future climates (Table 4b; Blois *et al.*, 2013; Sequeira *et al.*, 2018; Yates *et al.*, 2018). Limitations relating to transferability include lack of validation over time (space–time equivalence validation, see Section IV), the largely untested assumption of contemporary spatial equilibrium, the time-scale of projection, and the occurrence of novel future climates (see Table 4b for details). Alongside a discussion of the limitations, Table 4 includes recommendations and

improvements to address these issues and thus improve the robustness of SFTS.

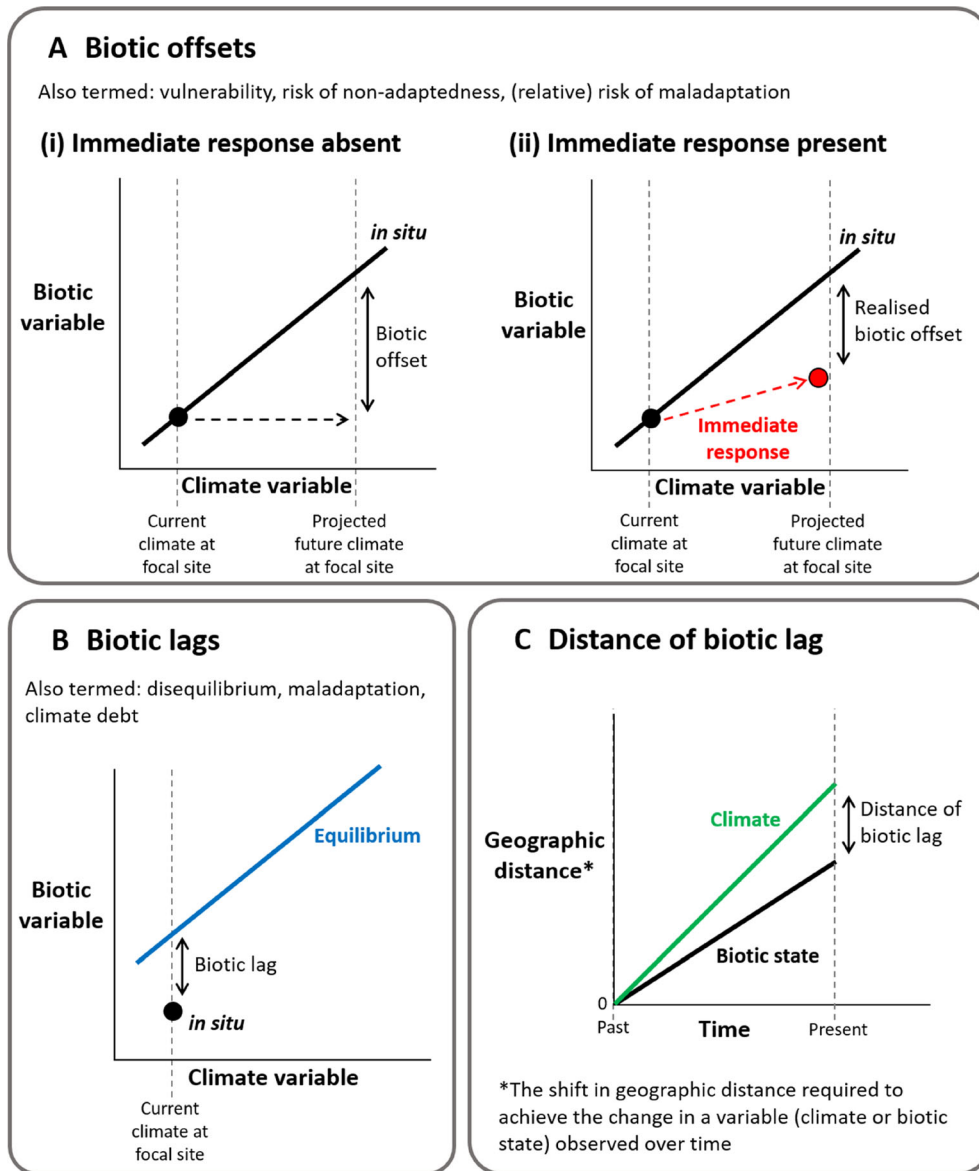
### III. APPLICATION OF SFTS TO CLIMATE–BIOTIC RELATIONSHIPS

#### (1) Population phenotypes

Correlations between spatial climate gradients and population phenotypes have long been observed, including a tendency for body mass to decrease with increasing temperatures (Bergmann, 1848) and spring phenology to advance with increasing temperatures (Hopkins, 1919). SFTS informed by *in situ* gradients and transplant experiments have been used to understand and predict the effects of climate change on a broad array of traits including morphology (Jaramillo *et al.*, 2017; Stelling-Wood, Poore & Gribben, 2021), phenology (Kramer, 1995; Ford *et al.*, 2016), life history (Etterson, 2004; McCabe, Aslan & Cobb, 2022), behaviour (Refsnider *et al.*, 2018), physiology (Pratt & Mooney, 2013; Logan, Cox & Calsbeck, 2014) and gene expression (Swaegers, Spanier & Stoks, 2020).

Where *in situ* gradients are used in isolation to generate a SFTS prediction for phenotypic data, the spatial phenotypic response is sometimes implicitly assumed to be entirely driven by phenotypic plasticity, such that the response will be immediate (Jaramillo *et al.*, 2017), or the underlying mechanism and timescale of predictions are vague. Where phenotypic and climate data are available in time as well as space, the spatial climate–phenotype relationship can be compared to that over time and this may provide insight into the





**Fig. 3.** Space-for-time substitution (SFTS) metrics predicting the challenge that climate change poses to aspects of biodiversity. Black circles represent a focal site. (A) Biotic offset, the distance between the current biotic state at a focal site and the predicted equilibrium biotic state at that site under future climate conditions. The current biotic state may either be (i) that observed *in situ* at the focal site or (ii) that accounting for an immediate biotic response to climate change (e.g. due to phenotypic plasticity; red circle) which can be observed *via* a transplant experiment representing the expected future conditions (realised biotic offset). (B) Biotic lag, the distance between the observed biotic state at a focal site and the predicted equilibrium biotic state at that site under current climatic conditions. (C) Where both spatial and temporal data are available, temporal shifts in both biotic states and climate variables can be quantified in terms of an equivalent shift in spatial distance, and this can be used to find the distance of biotic lag. Linear climate–biotic relationships are depicted here for simplicity but some relationships may be non-linear. Note that where the biotic response is a species’ distribution, the focus is generally on how the biotic state (presence or abundance) covaries with climate across many populations, rather than a single population as depicted here. Where the biotic response is species occurrence, the biotic state can be thought of as either the probability of presence or the climate suitability.

processes that contribute to the spatial climate–phenotype relationship. When making such space–time comparisons, the temporal slope of a climate–phenotype relationship estimated over years to decades is assumed to arise primarily due to plasticity, whereas the spatial slope is assumed to arise

from plasticity plus local adaptation (Phillimore *et al.*, 2010). Space–time comparisons using phenology and temperature data have been used to draw inferences about (i) the contributions that climate-mediated phenotypic plasticity and local adaptation make to the spatial climate–phenotype

relationship (Phillimore *et al.*, 2010; Hodgson *et al.*, 2011; Roy *et al.*, 2015; Delgado *et al.*, 2020) and (ii) biotic lags and offsets (Fig. 3) (Phillimore *et al.*, 2010). As far as we are aware, most space–time comparisons have used phenological data [but see Youngflesh *et al.* (2022) for an example using morphological data], reflecting the abundance of extensive spatiotemporal phenological data arising from citizen science schemes.

Where the goal is to separate the contributions that phenotypic plasticity and genetic divergence (including local adaptation) make to spatial variation in phenotypes, transplant experiments have a long history (Turesson, 1922). The contribution of phenotypic plasticity can be quantified as the difference in phenotypes between environments when holding the genotype constant, whereas the contribution of genetic differentiation can be quantified as the difference between population phenotypes when holding the environment constant in a shared common garden (Kawecki & Ebert, 2004; Merilä & Hendry, 2014; Stamp & Hadfield, 2020). The ‘gold-standard’ for identifying local adaptation involves comparing fitness (a special case of a phenotype) of populations following a reciprocal transplant (Savolainen, Lascoux & Merilä, 2013). Here, local adaptation is inferred where both (i) populations are fitter in home than away environments, and (ii) local populations are fitter than foreign populations (Kawecki & Ebert, 2004; Blanquart *et al.*, 2013). A challenge with all these approaches is to establish a causal role of climate variables, with replication across populations and/or sites often insufficient for this purpose (see Tables 2b and 4a).

Transplant experiments that succeed in identifying the processes underpinning spatial climate–phenotype relationships can then inform as to the nature and timescale of the phenotypic response to climate change. For instance, where a plastic response to a climate variable is identified, phenotypic responses to climate change are expected to be immediate, as found, for example, in the reproductive phenology of grassland plants (Frei *et al.*, 2014) and foliar traits in beech and spruce saplings (Sanginés de Cárcer *et al.*, 2017). Conversely, where local adaptation of a trait or population to climate is detected (Leimu & Fischer, 2008; Halbritter *et al.*, 2018; Lortie & Hierro, 2021), climate change is expected to shift the optimum phenotype and place populations under directional selection to adapt over multiple generations (Etterson, 2004). Transplant studies can also be used to infer whether phenotypic responses are lagging behind changing climate conditions (Fig. 3B). For example, Wilczek *et al.* (2014) found that when populations of *Arabidopsis thaliana* were transplanted to four regions of Europe, local populations were generally fitter than foreign populations. However, the most northerly population was less fit than a more southerly population, which the authors interpreted as evidence that adaptation of the northern population was lagging behind the optimum temperature as the climate warmed (see Table 3a for further discussion).

Transplant studies also provide an opportunity to calculate the phenotypic offset (Fig. 3A) of populations to future climates (often termed ‘relative risk of maladaptation’)

(St Clair & Howe, 2007; Frank *et al.*, 2017; Rellstab, Dauphin & Exposito-Alonso, 2021). The phenotypic offset approach was originally developed to identify the best seeds to plant in different spatial locations, based on the climatic differences between the planting site and the seeds’ site of origin (Campbell, 1986). This approach combines common garden estimates of phenotypic distributions within populations, phenotypic differences between populations, and *in situ* information on how mean phenotypes change with climate. However, to date the phenotypic offset approach has not been widely applied (Frank *et al.*, 2017).

The major limitations that are most pertinent to phenotypic SFTS are those that apply broadly across biotic responses (Table 4). For instance, the accuracy of phenotypic SFTS will be highly dependent on the contributions of rapid processes – in this case phenotypic plasticity – versus slower processes – in this case genetic adaptation – over space versus time (Table 4b.iii) (Merilä & Hendry, 2014; Stamp & Hadfield, 2020).

## (2) Population genotypes

At the genetic level, *in situ* gradient approaches have provided insights into the genomic basis of climate adaptation and selection over spatial gradients (Wogan & Wang, 2018). Yet in many instances, the space-for-time inference from genetic studies is implicit (Hancock *et al.*, 2011; Waldvogel *et al.*, 2018), with only a small proportion making explicit predictions regarding the impact of climate change on genotypes (e.g. Row *et al.*, 2014; Jordan *et al.*, 2017; Martins *et al.*, 2018; Exposito-Alonso *et al.*, 2018). Transplant studies are also used to study genetic markers, with the motivation usually to identify the genetic loci underlying climate–phenotype relationships, rather than direct correlations between genotypes and climate (Fournier-Level *et al.*, 2011; de Villemereuil *et al.*, 2018; Housset *et al.*, 2018). Nonetheless, where the focus of transplant studies is on fitness-associated genotypes, it is possible to estimate climate–genotype relationships (Fournier-Level *et al.*, 2011) and make predictions about how allele frequencies will respond to future climate change (Exposito-Alonso *et al.*, 2018, 2019).

Two methods are commonly applied across *in situ* gradients to identify climate–genotype relationships and putatively adaptive loci (Table 1n; Schoville *et al.*, 2012; Hoban *et al.*, 2016; Li *et al.*, 2017). The first is genotype–environment association analyses, which estimate climate–genotype relationships across a spatial climate gradient (Rellstab *et al.*, 2015). The second, differentiation outlier methods, involve identification of the loci that are most highly differentiated between different climates over space, and are therefore most likely to be involved in local adaptation (Hoban *et al.*, 2016). These approaches are often used in combination to increase confidence in the identification of putatively adaptive loci (Jordan *et al.*, 2017; Martins *et al.*, 2018). The focal genotypes can be specific candidate genes, known or suspected to be associated with a particular function that may be involved in a genetic response to climate

(Gougherty, Keller & Fitzpatrick, 2021), such as the relationship between latitude (as a proxy for climate) and alcohol dehydrogenase polymorphism in *Drosophila melanogaster* (Umina *et al.*, 2005). Alternatively, multiple regions of the genome can be screened to identify the molecular markers (often single nucleotide polymorphisms, SNPs) exhibiting the strongest relationships with climate variables (Hancock *et al.*, 2011; Bay *et al.*, 2018).

Climate–genotype relationships identified across *in situ* gradients can be used to make SFTS predictions of genomic changes and selection pressures under climate change (e.g. Row *et al.*, 2014; Rellstab *et al.*, 2016; Jordan *et al.*, 2017). Recently, ENM methods – first developed for studying species’ distributions (Pearson & Dawson, 2003; Guisan & Thuiller, 2005; Elith & Leathwick, 2009) – have been applied to identify climate–genotype relationships from *in situ* gradients (Jay *et al.*, 2012; Fitzpatrick & Keller, 2015) or common garden transplants (Exposito-Alonso *et al.*, 2018, 2019), and used to predict changes in the distribution of alleles or selection pressures under future climates. Analogues of ENMs (Section III.3) can account for the multi-dimensionality of spatial genomic variation by modelling alleles at multiple loci in an integrated way, as with methods that model multiple species in a community (Fitzpatrick & Keller, 2015; Section III.4). SFTS predictions are increasingly being used to find the biotic (genomic) offset (Fig. 3A.i) (Fitzpatrick & Keller, 2015), the difference between current genetic compositions and those predicted to be required under future climate change. This represents the expected level of maladaptation of a population to its future environment, and hence the amount of genetic change (i.e. adaptation) needed for the population to track the changing climate and maintain fitness (Fitzpatrick & Keller, 2015; Gougherty *et al.*, 2021; Table 3b). The genomic offset has been variously termed genetic offset, genomic vulnerability, and risk of non-adaptedness (reviewed by Capblancq *et al.*, 2020; Rellstab *et al.*, 2021; Hoffmann, Weeks & Sgrò, 2021).

There are two main types of limitations that are particular to genotypic SFTS. The first is in identifying the causal loci underlying adaptation to climate. Multi-marker screening methods for identifying adaptive loci are prone to false positives (Hoban *et al.*, 2016); neutral alleles may appear to exhibit variation with a climate variable for several reasons including demographic history, population structure, linkage disequilibrium, spatial autocorrelation, correlated environmental variables, incomplete selective sweeps, statistical bias, failure to account for multiple testing, or genotyping errors (Rellstab *et al.*, 2015, 2021; Hoban *et al.*, 2016; Li *et al.*, 2017; Booker, Yeaman & Whitlock, 2021; Hoffmann *et al.*, 2021). In addition to false positives, multi-marker screening methods are also prone to false negatives. This can arise because local adaptation often results from small changes at many loci (i.e. it is polygenic), and a single phenotype may be achieved through multiple different combinations of genotypes across loci [i.e. redundancy (Yeaman, 2015; Hoffmann *et al.*, 2021)]. This results in low

power to detect each locus’ effect (Hoban *et al.*, 2016; Rellstab *et al.*, 2017; De La Torre, Wilhite & Neale, 2019; Hoffmann *et al.*, 2021). However, although high redundancy hinders prediction of the genomic response to environmental change, it is usually associated with greater adaptive potential, resulting in better predictability of *phenotypic* responses for polygenic traits compared to those controlled by a small number of loci (Kardos & Luikart 2021). The second limitation of genotypic SFTS is that the critical assumptions required for this approach to work may often not be met because the loci involved in adaptation in space and time may differ. For example, adaptation in time may occur *via* the emergence of novel genotypes (Booker *et al.*, 2021), whereas the presence of maladaptive gene flow or a lack of adaptive gene flow can hinder adaptation in time (Lenormand, 2002). As a result, even with perfect knowledge of the complete set of loci involved in adaptation to climate in space, we may fail to predict genotypic change over time (Rellstab *et al.*, 2021).

### (3) Species’ distributions

The most prolific use of SFTS in climate change ecology and evolution is in using ENMs (Table 2a) to predict climate risks to populations or how species’ distributions will shift as the climate changes (Elith & Leathwick, 2009; Melo-Merino, Reyes-Bonilla & Lira-Noriega, 2020). In the SFTS context, ENMs estimate the spatial relationships between multiple climate variables and a species’ geographical distribution (occupancy or abundance) over *in situ* gradients (Pearson & Dawson, 2003; Guisan & Thuiller, 2005; Elith & Leathwick, 2009) and use this to predict species’ potential future distributions/risk (Thuiller, 2004; Thomas *et al.*, 2004; Huntley *et al.*, 2008) or past distributions (Nogués-Bravo, 2009; Varela, Lobo & Hortal, 2011; Maguire *et al.*, 2015). ENMs differ from other applications of SFTS in that they typically consider multiple climatic drivers and non-linear spatial relationships. Given the extensive literature on the applications of ENMs (e.g. Guisan & Zimmermann, 2000; Pearson, 2010; Santini *et al.*, 2021) and that our focus is on SFTS more generally, we only give a brief overview here of how ENMs are used to predict the impacts of future climate change on biodiversity.

ENMs can be used to predict whether the climatically suitable area for a species will change in size and/or shift in space under future climates, which allows predictions of species’ future distributions, population trends, and extinction risks (Berry *et al.*, 2002; Thomas *et al.*, 2004; Thuiller *et al.*, 2005; Huntley *et al.*, 2008). ENMs are also used to make inferences about biotic lags, although this concept differs slightly in the context of species’ distributions because the focus is on a biotic state (local presence/absence or abundance) summarised across many populations (e.g. using distribution margins or centroids; Lenoir *et al.*, 2020) rather than within a single population (as shown in Fig. 3B). Nonetheless, a biotic lag can be inferred by projecting ENMs calibrated on past data to the present day: where distribution shifts

are in the direction predicted but not of the magnitude predicted, it may suggest a contemporary biotic lag (Fig. 3B; Lewthwaite *et al.*, 2018; Soltan *et al.*, 2022). Biotic lags can also be quantified in terms of spatial distance (distance of biotic lag; Fig. 3C; Ash *et al.*, 2017). Similarly, comparing observed geographical shifts in climate variables and species' distributions can indicate the presence of a biotic lag, and can be used to reveal how much of the distributional shift is explained by the shift in climate (Lenoir *et al.*, 2020). A recent variation of this type of approach uses a series of hind-cast ENM predictions to estimate the distance of past shifts in the climatically suitable areas for a species, and hence the potential colonisation rate, which can then be compared to the rate required under future climate change (Brodie *et al.*, 2021).

In comparison with the *in situ* gradient approach, the application of transplant experiments to species-focussed SFTS is much less common. Transplants of individuals to sites either within or beyond a species' current geographical range have been used to provide insights into the factors limiting species' ranges (e.g. climate variables, dispersal limitation, biotic interactions), the presence of biotic lags, and species' responses to future climate change (e.g. Marsico & Hellmann, 2009; Willis *et al.*, 2009; Pelini *et al.*, 2009; Van der Veken *et al.*, 2012). For example, Willis *et al.* (2009) transplanted two UK butterfly species to a site beyond their range margins and used the successful establishment of these populations to infer the presence of a biotic lag.

The limitations, assumptions and uncertainties that accompany ENM predictions have been reviewed extensively (e.g. Pearson & Dawson, 2003; Sinclair, White & Newell, 2010; Peterson, Cobos & Jiménez-García, 2018), and so we focus herein on the assumptions made when ENMs are used for SFTS predictions of climate change impacts. In particular, there is an assumption that (i) either the realised climatic niche is conserved over time or climate is the sole determinant of species' distributions and (ii) the species is at equilibrium with climate (Pearson & Dawson, 2003; Araújo & Guisan, 2006; Veloz *et al.*, 2012; Beale & Lennon, 2012; Peterson *et al.*, 2018). However, the realised niche may change over time due to (i) a shift in climate not being accompanied by shifts in the other variables that limit a species' distribution or (ii) the emergence of new suitable climate conditions that are novel within the accessible geographic area (Pearson & Dawson, 2003; Veloz *et al.*, 2012; Beale & Lennon, 2012; Peterson *et al.*, 2018). Recent years have seen major efforts to address these issues by extending ENMs to incorporate eco-evolutionary processes (Thuiller *et al.*, 2013) such as intraspecific variation (i.e. local adaptation) (DeMarche, Doak & Morris, 2019; Garzón, Robson & Hampe, 2019; Aguirre-Liguori, Ramírez-Barahona & Gaut, 2021), demography (including dispersal and, by proxy, gene flow) (Fitzpatrick *et al.*, 2008; Fordham *et al.*, 2018), and other range-limiting factors such as biotic interactions (Araújo & Luoto, 2007; Staniczenko *et al.*, 2017; Abrego *et al.*, 2021).

#### (4) Ecological communities

At the community level – which we define as considering the effects of climate on more than one species simultaneously – both *in situ* gradient and transplant SFTS have been widely applied to predict community responses to future climate change. These have focussed on two facets of communities. The first is community composition, which includes species composition [e.g. identity, richness (Nooten, Andrew & Hughes, 2014; Niu *et al.*, 2019; Kinard, Patrick & Carvalho, 2021)] and trait (or functional type) composition (Dubuis *et al.*, 2013; de Oliveira *et al.*, 2020). This includes metrics such as the community temperature/precipitation index (CTI/CPI), which captures the climate conditions encountered within the geographic ranges of the species within a community (Devictor *et al.*, 2012). The second is species interactions, including consumer–resource (Rasmann *et al.*, 2014; Tran *et al.*, 2016), competitive (Alexander *et al.*, 2015), symbiotic (Steidinger *et al.*, 2019), and parasite (–vector)–host (Pickles *et al.*, 2013). Where the focus is on species composition and species interactions, community-focussed SFTS is effectively an extension of species-focussed approaches, and where the focus is on community traits it is an extension of phenotype-focussed SFTS. As a consequence, many of the same methods and limitations are relevant.

*In situ* gradient methods, often ENMs, are widely used to make community-level SFTS predictions (Meerhoff *et al.*, 2012; Dubuis *et al.*, 2013; Mokany *et al.*, 2015; Newsham *et al.*, 2016; Kwon *et al.*, 2019; de Oliveira *et al.*, 2022). Three main approaches are used (Ferrier & Guisan, 2006; Nieto-Lugilde *et al.*, 2018): (i) modelling the relationship between climate and a community-level attribute, such as species grouped into vegetation classes (Hilbert & Ostendorf, 2001; Pearson *et al.*, 2013); (ii) modelling individual species' responses to future climate change and overlaying their potential distributions to make community-level inferences [stacked models (Thuiller *et al.*, 2006; Gallagher, Hughes & Leishman, 2013; Davis, Champion & Coleman, 2022)]; or (iii) simultaneously modelling multiple species' distributions to allow for reciprocal interactions, often termed joint species distribution modelling [JSDM (Pollock *et al.*, 2014; Tikhonov *et al.*, 2017)], although the focus of this approach can be on either the community or a species. Where temporal and spatial data are available, inferences can also be made about the presence of a biotic lag in the temporal community response to climate change (Fig. 3B), using analogous approaches as described for phenotypes [space–time comparison (Sandel, 2019; Gauthier *et al.*, 2020); Section III.1] or species' distributions [comparing observations to predictions from a different time (Menéndez *et al.*, 2006; Bertrand *et al.*, 2011); Section III.3]. These biotic lags can also be quantified in terms of geographic distance (distance of biotic lag; Fig. 3C; Devictor *et al.*, 2008, 2012).

For community trait compositions, SFTS can provide insights into the processes that have generated spatial



patterns and thus may be involved in community responses to future climate change (Lajoie & Vellend, 2018). In particular, the relative contributions of interspecific processes (species turnover) and intraspecific processes (plasticity and genetic differentiation; Section III.1) can be separated. This involves comparing the slopes estimated between a climate variable and (i) community trait means calculated across all individuals of all species, which result from a combination of interspecific and intraspecific trait variation, and (ii) species-weighted community trait means, which represent interspecific variation alone (Lajoie & Vellend, 2018).

Community-focussed transplants present considerable logistical challenges, and so their application has been relatively limited. The most straightforward approach involves moving a single species into a new community, thus mimicking the novel species interactions that may occur as species' distributions and phenologies shift under climate change (Andrew & Hughes, 2007; Heimonen *et al.*, 2015). More challenging, is to move multiple species simultaneously into new environments to provide insights into how a community may respond to climate change, either by directly moving species (De Block *et al.*, 2013; Nooten *et al.*, 2014; Descombes *et al.*, 2020) or by transplanting soil cores containing microbial communities and/or seed banks (Budge *et al.*, 2011; Tomiolo, Bilton & Tielbörger, 2020). Alexander *et al.* (2015) combined these approaches by transplanting both individual species and a multi-species plant community to different elevations in the Alps to explore the potential impacts of novel biotic interactions and increased temperatures (see Table 3d for details).

Community-focussed SFTSs are subject to similar limitations as for species (Section III.3) and phenotypes (Section III.1), with additional complexities that arise when considering multiple species together. For example, different species may shift their distributions and phenologies in different ways in response to climate change, resulting in complex changes in community compositions and biotic interactions (Tylianakis *et al.*, 2008; Kharouba *et al.*, 2018; Beissinger & Riddell, 2021; Roslin *et al.*, 2021; Antão *et al.*, 2022) that are not captured by contemporary *in situ* gradients and transplant experiments. Alternatively, it is possible that community responses to climate change may be more predictable if the consideration of multiple species averages away some of the stochasticity in individual species' responses (Srivastava *et al.*, 2021). Additional limitations arise with multi-species transplants because they tend to involve (i) a sample of species from a community, which is often taxonomically biased due to the logistics of moving species, and (ii) a relatively small number of individuals of each species, despite the fact that population size can impact community outcomes such as species interactions (Morton & Rafferty, 2017). Furthermore, the issue of inadequate spatial replication is particularly pronounced for community-focussed transplant experiments due to the logistical challenges of moving multiple species. In fact, it is common to see climate variation represented by just two or three sites (e.g. Alexander *et al.*, 2015; see Table 3b), which precludes robust inference of a causal climatic variable (Table 4a).

#### IV. VALIDATION OF SFTS

Across all four subfields, the performance of climate change SFTS has been found to be mixed, with studies both supporting (e.g. Blois *et al.*, 2013; Banet & Trexler, 2013) and contesting (e.g. La Sorte *et al.*, 2009; Isaac *et al.*, 2011; Wu *et al.*, 2022) the use of SFTS. The predictive ability of SFTS appears to vary across different ecological contexts including biotic variables (e.g. Bjorkman *et al.*, 2018), taxa (e.g. Dobrowski *et al.*, 2011) and timescales (e.g. Roberts & Hamann, 2012). A quantitative analysis of the scenarios under which SFTS performs best is a priority for future work in this area. In the interim, we suggest that SFTS may perform better when the level of extrapolation is minimised (e.g. Fitzpatrick *et al.*, 2018a; Sequeira *et al.*, 2018; Qiao *et al.*, 2019) and should be approached with caution where successful validation is lacking for a study's specific system and context.

Two types of validation are needed when a SFTS prediction is made. First, we need to test whether the climate variable(s) is/are causal of the biotic variation observed through space, which we term 'spatial validation' (Table 4a). Opportunities for spatial validation include non-independent spatial data [e.g. data splitting (Berry *et al.*, 2002; Norberg *et al.*, 2019)], independent spatial data from a different location [i.e. replication (e.g. Randin *et al.*, 2006; Early & Sax, 2014)] or experiments (including transplants; Hancock *et al.*, 2011). Where there has been successful spatial validation, this increases our confidence that the identified drivers are causal, but it does not test transferability. The second validation type, which we term 'space–time equivalence validation', involves comparing spatial climate–biotic relationships with temporal relationships or SFTS predictions with temporal data. Assuming that causal relationships have been estimated in space, then the space–time equivalence validation tests the central assumption of space–time transferability (Sequeira *et al.*, 2018; Table 4b). Different types of data can be used for space–time equivalence validation (Rellstab *et al.*, 2021), including from historic long-term monitoring (La Sorte *et al.*, 2009; Rapacciuolo *et al.*, 2012), museum or herbarium collections (Guerin, Wen & Lowe, 2012), palaeodata such as pollen records or fossils (Blois *et al.*, 2013), dendrochronology (Klesse *et al.*, 2020), genomics-based inference (Miller *et al.*, 2021), and *in silico* simulations (Qiao *et al.*, 2019).

When conducting space–time equivalence validation, the timescale is an important, yet often overlooked, consideration since SFTS predictive accuracy will often be sensitive to whether predictions are for the long or short term (Table 4b.iii; Petchey *et al.*, 2015; Adler *et al.*, 2020). Note that testing for biotic lags (Fig. 3B) – which generally involves comparing temporal climate–biotic relationships with those expected based on the spatial relationship – is a type of space–time equivalence validation, where one can assess whether the biotic response is in the correct direction, with additional inferences made about whether the biotic state is lagging behind the equilibrium biotic state.



Ideally, both successful spatial validation and successful space–time equivalence validation should support any application of SFTS. However, a lack of long-term temporal data has meant that most validation has been conducted in space alone. Below, we consider how validation has been conducted in each subfield and highlight where further validation is needed.

### (1) Population phenotypes

Neither spatial nor space–time equivalence validation is common practice when analysing correlative climate–phenotype relationships across *in situ* gradients or transplant experiments. This may be attributable to the exploratory nature of many analyses, funding, time and logistical constraints, or perhaps simply oversight. An indication that spatial relationships are causal could be obtained using meta-analyses, replication across multiple gradients or gradient types, or experimental manipulation of climate variables. There are a handful of instances of space–time equivalence validation using historical data (Hodgson *et al.*, 2011; Guerin *et al.*, 2012; Jochner, Caffarra & Menzel, 2013) and repeated experiments (Bradshaw & Holzapfel, 2001). Additionally, space–time comparisons have been used to assess the extent to which spatial climate–biotic relationships are transferable over time (Table 2a.ii; Phillimore *et al.*, 2010, 2012; Kharouba *et al.*, 2014; Klesse *et al.*, 2020; Wu *et al.*, 2022).

### (2) Population genotypes

Where validation has been conducted at the genotypic level, it has typically focussed on spatial validation rather than space–time equivalence validation. Spatial validation is often assessed by using multiple approaches to identify putatively adaptive loci – such as both genome–environment association analyses and differentiation outlier methods – to increase confidence that identified loci are involved in local adaptation (Jordan *et al.*, 2017; Martins *et al.*, 2018; Exposito-Alonso *et al.*, 2019). Additionally, there are cases where a locus shows parallel adaptation to climate in different regions (Umina *et al.*, 2005; van Boheemen & Hodgins, 2020). Alternatively, direct validation of fitness effects can be obtained experimentally to provide a more direct link between alleles and fitness under particular conditions. This has been done using transplants (Barrett, Rogers & Schluter, 2008; Hancock *et al.*, 2011; Jaramillo-Correa *et al.*, 2015; Faske *et al.*, 2021) and there is also potential to utilise genetic modifications (e.g. knock-outs, gene transfers, or gene editing; Li *et al.*, 2017). Similarly, SNPs associated with high fitness in a common garden environment can be validated by observing whether they are more abundant in areas with climates that are more similar to the common garden's climate (Fournier-Level *et al.*, 2011; Exposito-Alonso *et al.*, 2019). As well as validation of the loci involved in adaptation, transplants have also been used to validate genomic offset predictions by looking for relationships between these predictions and performance in the

corresponding common garden environment (Fitzpatrick *et al.*, 2021).

There have been few tests of whether the same loci are correlated with climate variables over space and time (but see Umina *et al.*, 2005; Balanyá *et al.*, 2006), presumably due to a lack of suitable long-term genetic data. Indirect space–time equivalence validation of genomic offset predictions can be made by comparison with data on population trends from surveys (Bay *et al.*, 2018, but see Fitzpatrick *et al.*, 2018b), or by measuring proxies for fitness in the wild (Borrell *et al.*, 2020).

### (3) Species' distributions

Validation of species' distribution-focussed SFTS typically involves spatial validation only; this sometimes involves spatially independent data (Randin *et al.*, 2006; Early & Sax, 2014), transplants (Willis *et al.*, 2009; Dixon & Busch, 2017; Merlin, Duputié & Chuine, 2018; Greiser *et al.*, 2020) or simulations (Beale, Lennon & Gimona, 2008), but most often validation is conducted using spatial data that is not truly independent which can lead to severe underestimates of parameter uncertainty (Araújo *et al.*, 2005; Bahn & McGill, 2013; Santini *et al.*, 2021). Introductions of alien species provide an opportunity for spatial validation of the relationships estimated by an ENM. For instance, in a study of plant species native to Europe and invasive in North America, Early & Sax (2014) found that ENMs calibrated on the native range had mixed performance in terms of predicting occupancy in North America, with performance improving for species with larger native geographic extents.

Underlying an ENM prediction of a species' geographic distribution is a description of its niche in terms of a climate–species relationship for each climate variable, and rankings of the importance of each variable can be obtained; these estimates represent an additional, underutilised opportunity for spatial validation (Buermann *et al.*, 2008; Convertino *et al.*, 2012; Searcy & Shaffer, 2016; Mothes *et al.*, 2019). This involves either (i) comparing the observed and predicted occurrence probabilities for dominant climate variables (Buermann *et al.*, 2008; Convertino *et al.*, 2012) or (ii) comparing climate–species relationships and/or climate variable rankings with independent data on physiological tolerance (Searcy & Shaffer, 2016; Mothes *et al.*, 2019), population dynamics (Thuiller *et al.*, 2014) or simulations (Smith & Santos, 2020) to increase confidence that identified relationships are causal. However, as far as we are aware, very few studies have used these underlying metrics to assess ENM performance in the context of climate change predictions (Searcy & Shaffer, 2016).

Space–time equivalence validation of ENMs has used historic data including past species distribution records (e.g. Araújo *et al.*, 2005; Dobrowski *et al.*, 2011; Rapacciuolo *et al.*, 2012; Brun *et al.*, 2016; Morán-Ordóñez *et al.*, 2017), palaeodata (e.g. Pearman *et al.*, 2008; Veloz *et al.*, 2012), simulations (Qiao *et al.*, 2019; Santini *et al.*, 2021), comparisons of

predictions made using spatial data and time series data (Isaac *et al.*, 2011) and space–time comparisons (Oedekoven *et al.*, 2017; Bradter *et al.*, 2022).

#### (4) Ecological communities

Spatial validation of community-focussed SFTS often involves spatial data that is not truly independent, such as with data partitioning (Norberg *et al.*, 2019; Zurell *et al.*, 2020), and sometimes utilises spatially independent data (Loewen, Jackson & Gilbert, 2023). Community transplants can also be used to validate *in situ* gradient approaches by exploring whether species' relative abundances in a common garden environment correspond to those expected based on the climate–phenotype relationships observed across an *in situ* gradient (Guittar *et al.*, 2016). As far as we are aware, spatial validation for species interaction-focussed SFTS is lacking.

Space–time equivalence validation of community responses has been assessed using historical data including observations in the recent past (e.g. Lemoine, Schaefer & Böhning-Gaese, 2007; Algar *et al.*, 2009; Kharouba, Algar & Kerr, 2009; Bjorkman *et al.*, 2018) and palaeodata (Blois *et al.*, 2013; Maguire *et al.*, 2016). Another space–time equivalence validation approach has involved a comparison of the spatial and temporal relationships between climate and community traits (La Sorte *et al.*, 2009; Elmendorf *et al.*, 2015; Sandel, 2019; Gaüzère *et al.*, 2020) or community composition (Lemoine & Böhning-Gaese, 2003; White & Kerr, 2006; Adler & Levine, 2007; La Sorte *et al.*, 2009). Similarly, warming and water-addition experiments have been used to validate *in situ* gradient SFTS for species interactions (Kazeneil *et al.*, 2019) and trait compositions (Sandel *et al.*, 2010).

#### (5) Feasibility and logistics of SFTS validation

Both spatial and space–time equivalence validation are essential for ensuring the accuracy of SFTS predictions, yet validation is strikingly scarce. In some cases, such as space–time equivalence validation for species' distributions, validation is logistically challenging because of the long timescales involved. However, in many cases, the lack of validation is likely due to the constraints of resources and funding rather than a lack of feasibility, since validation requires the acquisition of additional spatial data (spatial validation) or temporal data (space–time equivalence validation). Given that successful validation is essential for generating robust predictions, greater value should be placed on this component of SFTS.

### V. OPPORTUNITIES FOR SFTS

The acute challenge of predicting the biotic impacts of rapid anthropogenic climate change (IPCC, 2022) means that

SFTS is likely to remain a convenient and vital tool. Here, we consider some of the major ways in which robustness of predictions could be improved, with an emphasis on how approaches could be transferred among the four subfields; see Table 4 for a more comprehensive overview of how the major limitations of SFTS may be addressed.

The challenge of identifying causal climate–biotic relationships is common to all SFTS (Table 4a), but is most acute for transplant studies. Many transplant studies consider just a single transplant site and few source populations (Johnson *et al.*, 2022b) and are thus lacking power to detect a causal climate–biotic relationship. One remedy is to encourage greater replication across sites, climate gradients and gradient types (e.g. altitudinal and latitudinal) to a level that provides adequate statistical power. We recognise that increasing replication will incur substantial logistical and financial costs, but this is essential to establish causality before making SFTS predictions.

A related issue is in giving appropriate attention to the selection of putatively causal climate variables (Table 4a.i), and there are approaches used in some of the assessed subfields that could be applied more widely. For example, ENMs, which are usually applied to species or communities, are unique among SFTS approaches in the fact that they commonly consider multiple climate variables simultaneously and non-linear climate–biotic relationships. On the other hand, some phenotype-focussed studies aim to narrow down the seasonal period over which a climate variable is important (Simmonds, Cole & Sheldon, 2019) using approaches such as sliding windows (see van de Pol *et al.*, 2016) and penalised signal regression (see Roberts, 2008). These methods could usefully be applied in other eco-evolutionary subfields to give more focus to the specific climate variables used, the timing over which they are important for driving biotic responses, and the type of relationship with the biotic variable (e.g. quadratic) (Table 4a.i).

The other major challenge across SFTS relates to the temporal transferability of spatial climate–biotic relationships (Table 4b). An underutilised avenue for space–time equivalence validation lies with historical data: SFTS can be validated against the past or calibrated on past data and validated against the present (Dobrowski *et al.*, 2011; Maguire *et al.*, 2015). Additionally, there is clear value in the greater use of simulations to examine the accuracy and precision of predictions under different hypothetical scenarios, and thus the limits to inference (Zurell *et al.*, 2010; Qiao *et al.*, 2019). Powerful methods for simulating realistic genome evolution now make this particularly feasible for testing inference at the genomic level (Haller & Messer, 2019; Láruson *et al.*, 2022). Furthermore, while many studies predict biotic responses to climate change at distant time horizons (e.g. the end of the century), near-term forecasts provide a means of validating metrics of change (Slingsby, Moncrieff & Wilson, 2020), although this will only capture short-term biotic responses and so may overestimate long-term predictability. Finally, as well as validating SFTS

predictions for a single point in time, comparison of the slopes (i.e. direction and magnitude) of spatial and temporal climate–biotic relationships (space–time comparison; Phillimore *et al.*, 2010; Table 2a.ii), as we describe for population and community phenotype data, could be applied more widely. This represents an opportunity for space–time equivalence validation and to provide further insights into (i) how SFTS predictive accuracy and biotic offsets vary with timescale of prediction and (ii) the processes that give rise to spatial climate–biotic relationships.

Many biodiversity predictions are based on a static ‘snapshot’ approach, where a SFTS model is predicted forwards in a single step using climatic conditions averaged over some future, often remote, time period (e.g. Thomas *et al.*, 2004; Table 3c). As a result, important aspects of the temporal transferability of SFTS (Table 4b) relate to whether current biotic states are at equilibrium with the environment (Gaüzère *et al.*, 2018) and to the timescale of prediction (Adler *et al.*, 2020). If current climate–biotic relationships are at equilibrium, then SFTS-based snapshot predictions will indicate the future biotic state(s) expected at equilibrium. By contrast, if current climate–biotic relationships are not at equilibrium and lag behind recent climate change, then future snapshot predictions will underestimate the magnitude of the biotic response. However, such underestimation does not necessarily invalidate SFTS predictions as they may still reliably indicate the direction and magnitude of the *transient* biotic response. Specifically, if the biotic lag is constant over time (i.e. the biotic state remains a consistent distance from the equilibrium biotic state), then predictions would still be expected to indicate reliably the magnitude of the transient biotic response (Blonder *et al.*, 2017). On the other hand, if the biotic lag is growing over time, due for instance to accelerating climate change, or shows more complex response dynamics (Blonder *et al.*, 2017), then predictions would underestimate the magnitude of the transient biotic response.

An important avenue for research is to quantify biotic lags and how these may be expected to change over time. For example, ENMs typically use historical averages of climate variables (e.g. 30-year averages from WorldClim; Fick & Hijmans, 2017), but a sliding-window approach (van de Pol *et al.*, 2016) could be applied to identify the decadal period over which historical climates best predict the current biotic state, which may provide an opportunity to identify biotic lags. Similarly, when making predictions of future biotic responses to climate change, fine-temporal-resolution climate data (e.g. daily to annual) from climate models can be used to predict how biotic offsets may accumulate dynamically over time, providing an indication of the rate, timing and abruptness of expected biotic responses that is not provided by static snapshot predictions (Trisos, Merow & Pigot, 2020).

Another priority for future work on SFTS is to establish the timescale over which future predictions are made and how they should be used and interpreted. Low SFTS predictive accuracy may be due to mismatches between the

timescale of predictions and the timescale of the processes driving biotic responses (Adler & Levine, 2007; Elmendorf *et al.*, 2015; Münzbergová, Vandvik & Hadincová, 2021). However, relatively few studies have explored directly how timescale affects SFTS performance using historical data (e.g. Roberts & Hamann, 2012; Blois *et al.*, 2013; Morán-Ordóñez *et al.*, 2017; Bradter *et al.*, 2022) or *in silico* simulations (Adler *et al.*, 2020). Additionally, dynamic process-based models (e.g. Buckley *et al.*, 2010; Bush *et al.*, 2016) offer considerable potential for predicting biotic responses to climate change over time. In such models, rather than making snapshot predictions for a single time point, biotic responses are iterated forwards through time, constrained by empirically estimated parameters describing rates of key ecological or evolutionary processes (Morin, Augspurger & Chuine, 2007).

Any assessment of SFTS predictive performance will be sensitive to what we are trying to predict. For example, ENMs may be able to identify reliably those populations that will be exposed to unsuitable climates under a given magnitude of warming, but predicting the biotic response to exposure is more challenging because this is likely to depend on when in the future exposure occurs and thus the capacity for processes such as adaptation to rescue populations (Table 1j; Trisos, Merow & Pigot, 2021). In some cases, predictions of exposure may be sufficient to provide a reliable indicator of the magnitude of climate risk across geographic space or species. If, however, the aim is to provide a reliable indication of the biotic response to exposure, then studies would benefit from considering the temporal aspect of climate change more explicitly by using process-based models (e.g. Buckley *et al.*, 2010; Bush *et al.*, 2016), or at least dynamic predictions of climate change, rather than static snapshots. Genomic studies would also benefit from greater clarity on what we are trying to predict. Unlike ENMs, genotype–environment association analyses are only informative about the *relative* fitness of different genotypes in a given environment. As they do not reveal *absolute* fitness, this means that they cannot tell us whether the population growth rate will become negative in a given environment (Brady *et al.*, 2019).

From examination of the tools used in the four subfields, it is evident that greater communication amongst these subfields could benefit the progression of SFTS methods. In some cases, different subfields have developed equivalent inferential tools independently and this is particularly evident in the case of what we have termed biotic lags and offsets (Fig. 3). However, the opportunities to identify these parallels may have been reduced by each subfield adopting its own terminology. We hope that that by emphasising the similarities of aims, tools, limitations and challenges across these different eco-evolutionary subfields that this review will foster greater communication and exchange of ideas.

One additional opportunity that applies across all subfields is to broaden spatial and taxonomic representation. Most SFTS studies to date have focussed on biotic systems in Europe, North America and Australia, with ENM being the only approach that is widely applied across all continents. Taxonomically, most studies employing transplant methods



have involved plants and invertebrates for logistical reasons. Any studies that find ways to broaden the taxonomic scope promise to be highly informative (e.g. Refsnider *et al.*, 2018; Lane *et al.*, 2019). Finally, most *in situ* gradient studies focus on well-studied taxa, particularly plants and vertebrates, and as global data sets improve there should be excellent opportunities to broaden the taxonomic scope.

## VI. CONCLUSIONS

(1) SFTS is currently used very widely across subfields of ecology and evolution as a practical tool for generating urgent predictions of biotic responses to future climate change. Across the four subfields that we assess (population phenotypes, population genotypes, species' distributions and ecological communities) there are many similarities in the approaches used, their strengths and their weaknesses.

(2) Across the assessed subfields, the shared limitations that can undermine the robustness of SFTS inference relate to (i) correctly detecting causal climate–biotic relationships, and (ii) the transferability of spatial climate–biotic relationships over time. We identify opportunities and best practice to address these limitations and improve the robustness of SFTS.

(3) We identify several instances where equivalent approaches go under different names in different subfields, highlighting the value of increased cross-talk between the four subfields and recognition of parallels in SFTS methods, limitations and innovations.

(4) We anticipate that SFTS will remain one of the major approaches for predicting future biotic responses to global change. Therefore, we strongly encourage engagement with development of new methods and protocols that can address the limitations we identify and increase the robustness of predictions.

## VII. ACKNOWLEDGEMENTS

R. S. L. L. is funded by a NERC Doctoral Training Partnership grant (NE/S007407/1). S. H. M. is funded by a Royal Society University Research Fellowship (URF\R1\180682). A. L. P. is funded by a Royal Society University Research Fellowship and NERC Standard Grant (NE/W006618/1). The authors thank the reviewers for critical and highly constructive comments. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

## VIII. REFERENCES

ABREGO, N., ROSLIN, T., HUOTARI, T., JI, Y., SCHMIDT, N. M., WANG, J., YU, D. W. & OVASKAINEN, O. (2021). Accounting for species interactions is

necessary for predicting how arctic arthropod communities respond to climate change. *Ecography* **44**, 885–896.

- ADLER, P. B. & LEVINE, J. M. (2007). Contrasting relationships between precipitation and species richness in space and time. *Oikos* **116**, 221–232.
- ADLER, P. B., WHITE, E. P. & CORTEZ, M. H. (2020). Matching the forecast horizon with the relevant spatial and temporal processes and data sources. *Ecography* **43**, 1729–1739.
- AGUIRRE-LIGUORI, J. A., RAMÍREZ-BARAHONA, S. & GAUT, B. S. (2021). The evolutionary genomics of species' responses to climate change. *Nature Ecology & Evolution* **5**, 1350–1360.
- ALEXANDER, J. M., DIEZ, J. M. & LEVINE, J. M. (2015). Novel competitors shape species' responses to climate change. *Nature* **525**, 515–518.
- ALGAR, A. C., KHAROUBA, H. M., YOUNG, E. R. & KERR, J. T. (2009). Predicting the future of species diversity: macroecological theory, climate change, and direct tests of alternative forecasting methods. *Ecography* **32**, 22–33.
- ANDAM, K. S., FERRARO, P. J., PFAFF, A., SANCHEZ-AZOFEIFA, G. A. & ROBALINO, J. A. (2008). Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of the National Academy of Sciences* **105**(42), 16089–16094.
- ANDREW, N. R. & HUGHES, L. (2007). Potential host colonization by insect herbivores in a warmer climate: a transplant experiment. *Global Change Biology* **13**, 1539–1549.
- ANTAO, L. H., WEIGEL, B., STRONA, G., HÄLLFORS, M., KAARLEJÄRVI, E., DALLAS, T., OPEDAL, Ø. H., HELIÖLÄ, J., HENTTONEN, H., HUITU, O., KORPIMÄKI, E., KUUSSAARI, M., LEHIKONEN, A., LEINONEN, R., LINDÉN, A., *ET AL.* (2022). Climate change reshuffles northern species within their niches. *Nature Climate Change* **12**, 587–592.
- ARAÚJO, M. B. & GUISAN, A. (2006). Five (or so) challenges for species distribution modelling. *Journal of Biogeography* **33**, 1677–1688.
- ARAÚJO, M. B. & LUOTO, M. (2007). The importance of biotic interactions for modelling species distributions under climate change. *Global Ecology and Biogeography* **16**, 743–753.
- ARAÚJO, M. B., PEARSON, R. G., THULLER, W. & ERHARD, M. (2005). Validation of species–climate impact models under climate change. *Global Change Biology* **11**, 1504–1513.
- ARAÚJO, M. B. & PETERSON, A. T. (2012). Uses and misuses of bioclimatic envelope modeling. *Ecology* **93**(7), 1527–1539.
- ASH, J. D., GYVNIŠH, T. J. & WALLER, D. M. (2017). Tracking lags in historical plant species' shifts in relation to regional climate change. *Global Change Biology* **23**, 1305–1315.
- BAHN, V. & MCGILL, B. J. (2013). Testing the predictive performance of distribution models. *Oikos* **122**, 321–331.
- BALANYÁ, J., OLLER, J. M., HUEY, R. B., GILCHRIST, G. W. & SERRA, L. (2006). Global genetic change tracks global climate warming in *Drosophila subobscura*. *Science* **313**, 1773–1775.
- BANET, A. I. & TREXLER, J. C. (2013). Space-for-time substitution works in everglades ecological forecasting models. *PLoS One* **8**(11), e81025.
- BARRETT, R. D. H., ROGERS, S. M. & SCHLUTER, D. (2008). Natural selection on a major armor gene in threespine stickleback. *Science* **322**, 255–257.
- BAY, R. A., HARRIGAN, R. J., UNDERWOOD, V. L., GIBBS, H. L., SMITH, T. B. & RUEGG, K. (2018). Genomic signals of selection predict climate-driven population declines in a migratory bird. *Science* **359**, 83–86.
- BEALE, C. M. & LENNON, J. J. (2012). Incorporating uncertainty in predictive species distribution modelling. *Philosophical Transactions of the Royal Society B: Biological Sciences* **367**, 247–258.
- BEALE, C. M., LENNON, J. J. & GIMONA, A. (2008). Opening the climate envelope reveals no macroscale associations with climate in European birds. *Proceedings of the National Academy of Sciences* **105**(39), 14908–14912.
- BEISSINGER, S. R. & RIDDELL, E. A. (2021). Why are species' traits weak predictors of range shifts? *Annual Review of Ecology, Evolution, and Systematics* **52**, 47–66.
- BERGMANN, C. (1848). *Über die Verhältnisse der Wärmeökonomie der Thiere zu ihrer Grösse*. Vandenhoeck und Ruprecht, Göttingen.
- BERRY, P. M., DAWSON, T. P., HARRISON, P. A. & PEARSON, R. G. (2002). Modelling potential impacts of climate change on the bioclimatic envelope of species in Britain and Ireland. *Global Ecology and Biogeography* **11**, 453–462.
- BERTRAND, R., LENOIR, J., PIEDALLU, C., RIOFRÍO-DILLON, G., DE RUFFRAY, P., VIDAL, C., PIERRAT, J.-C. & GÉGOUT, J.-C. (2011). Changes in plant community composition lag behind climate warming in lowland forests. *Nature* **479**, 517–520.
- BJORKMAN, A. D., MYERS-SMITH, I. H., ELMENDORF, S. C., NORMAND, S., RÜGER, N., BECK, P. S. A., BLACH-OVERGAARD, A., BLOK, D., CORNELISSEN, J. H. C., FORBES, B. C., GEORGES, D., GOETZ, S. J., GUAY, K. C., HENRY, G. H. R., HILLERISLAMBERS, J., *ET AL.* (2018). Plant functional trait change across a warming tundra biome. *Nature* **562**, 57–62.
- BLANQUART, F., KALTZ, O., NUISMER, S. L. & GANDON, S. (2013). A practical guide to measuring local adaptation. *Ecology Letters* **16**, 1195–1205.
- BLOIS, J. L., WILLIAMS, J. W., FITZPATRICK, M. C., JACKSON, S. T. & FERRIER, S. (2013). Space can substitute for time in predicting climate-change effects on biodiversity. *Proceedings of the National Academy of Sciences* **110**(23), 9374–9379.

- BLONDER, B., MOULTON, D. E., BLOIS, J., ENQUIST, B. J., GRAAE, B. J., MACIAS-FAURIA, M., MCGILL, B., NOGUÉ, S., ORDONEZ, A., SANDEL, B. & SVENNING, J.-C. (2017). Predictability in community dynamics. *Ecology Letters* **20**, 293–306.
- BLÜTHGEN, N., STAAB, M., ACHURY, R. & WEISSER, W. W. (2022). Unravelling insect declines: can space replace time? *Biology Letters* **18**, 20210666.
- BOOKER, T. R., YEAMAN, S. & WHITLOCK, M. C. (2021). Global adaptation complicates the interpretation of genome scans for local adaptation. *Evolution Letters* **5**, 4–15.
- BORRELL, J. S., ZOHREN, J., NICHOLS, R. A. & BUGGS, R. J. A. (2020). Genomic assessment of local adaptation in dwarf birch to inform assisted gene flow. *Evolutionary Applications* **13**, 161–175.
- BRADSHAW, W. E. & HOLZAPFEL, C. M. (2001). Genetic shift in photoperiodic response correlated with global warming. *Proceedings of the National Academy of Sciences* **98**(25), 14509–14511.
- BRADTER, U., JOHNSTON, A., HOCHACHKA, W. M., SOULTAN, A., BROMMER, J. E., GAGET, E., KÁLÁS, J. A., LEHIKONEN, A., LINDSTRÖM, Å., PIIRAINEN, S., PAVÓN-JORDÁN, D., PÄRT, T., ØIEN, I. J. & SANDERCOCK, B. K. (2022). Decomposing the spatial and temporal effects of climate on bird populations in northern European mountains. *Global Change Biology* **28**, 6209–6227.
- BRADY, S. P., BOLNICK, D. I., BARRETT, R. D. H., CHAPMAN, L., CRISPO, E., DERRY, A. M., ECKERT, C. G., FRASER, D. J., FUSSMANN, G. F., GONZALEZ, A., GUICHARD, F., LAMY, T., LANE, J., McADAM, A. G., NEWMAN, A. E. M., *ET AL.* (2019). Understanding maladaptation by uniting ecological and evolutionary perspectives. *The American Naturalist* **194**(4), 495–515.
- BRODIE, L. P., GREY, K.-A., BISHOP, J. M. & MIDGLEY, G. F. (2021). Broadening predictive understanding of species' range responses to climate change: the case of *Alويدendron dichotomum*. *Frontiers in Ecology and Evolution* **9**, 715702.
- BRUN, P., KIÖRBOE, T., LICANDRO, P. & PAYNE, M. R. (2016). The predictive skill of species distribution models for plankton in a changing climate. *Global Change Biology* **22**(9), 3170–3181.
- BUCKLEY, L. B., URBAN, M. C., ANGILLETTA, M. J., CROZIER, L. G., RISSLER, L. J. & SEARS, M. W. (2010). Can mechanism inform species' distribution models? *Ecology Letters* **13**, 1041–1054.
- BUDGE, K., LEIFELD, J., EGLI, M. & FUHRER, J. (2011). Soil microbial communities in (sub)alpine grasslands indicate a moderate shift towards new environmental conditions 11 years after soil translocation. *Soil Biology and Biochemistry* **43**, 1148–1154.
- BUERMANN, W., SAATCHI, S., SMITH, T. B., ZUTTA, B. R., CHAVES, J. A., MILÁ, B. & GRAHAM, C. H. (2008). Predicting species distributions across the Amazonian and Andean regions using remote sensing data. *Journal of Biogeography* **35**, 1160–1176.
- BUSH, A., MOKANY, K., CATULLO, R., HOFFMANN, A., KELLERMANN, V., SGRÒ, C., McEVEY, S. & FERRIER, S. (2016). Incorporating evolutionary adaptation in species distribution modelling reduces projected vulnerability to climate change. *Ecology Letters* **19**, 1468–1478.
- CAMPBELL, R. K. (1986). Mapped genetic variation of Douglas-fir to guide seed transfer in Southwest Oregon. *Silvae Genetica* **35**, 85–96.
- CAPBLANCO, T., FITZPATRICK, M. C., BAY, R. A., EXPOSITO-ALONSO, M. & KELLER, S. R. (2020). Genomic prediction of (mal)adaptation across current and future climatic landscapes. *Annual Review of Ecology, Evolution, and Systematics* **51**, 245–269.
- CHASE, J. M. (2003). Community assembly: when should history matter? *Oecologia* **136**, 489–498.
- CHEVIN, L.-M., LANDE, R. & MACE, G. M. (2010). Adaptation, plasticity, and extinction in a changing environment: towards a predictive theory. *PLoS Biology* **8**(4), e1000357.
- COMTE, L., CARVAJAL-QUINTERO, J., TEDESCO, P. A., GIAM, X., BROSE, U., ERŐS, T., FILIPE, A. F., FORTIN, M.-J., IRVING, K., JACQUET, C., LARSEN, S., SHARMA, S., RUHI, A., BECKER, F. G., CASATTI, L., *ET AL.* (2021). RivFishTIME: A global database of fish time-series to study global change ecology in riverine systems. *Global Ecology and Biogeography* **30**, 38–50.
- CONVERTINO, M., WELLE, P., MUÑOZ-CARPENA, R., KIKER, G. A., CHU-AGOR, M. L., FISCHER, R. A. & LINKOV, I. (2012). Epistemic uncertainty in predicting shorebird biogeography affected by sea-level rise. *Ecological Modelling* **240**, 1–15.
- COULSON, T. (2021). We live in a changing world, but that shouldn't mean we abandon the concept of equilibrium. *Ecology Letters* **24**, 3–5.
- DARWIN, C. (1859). *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*. John Murray, London.
- DAVIS, T. R., CHAMPION, C. & COLEMAN, M. A. (2022). Ecological interactions mediate projected loss of kelp biomass under climate change. *Diversity and Distributions* **28**, 306–317.
- DE BLOCK, M., PAUWELS, K., VAN DEN BROECK, M., DE MEESTER, L. & STOKS, R. (2013). Local genetic adaptation generates latitude-specific effects of warming on predator–prey interactions. *Global Change Biology* **19**, 689–696.
- DE FRENNE, P., GRAAE, B. J., RODRÍGUEZ-SÁNCHEZ, F., KOLB, A., CHABRIERIE, O., DECOQ, G., DE KORT, H., DE SCHRIJVER, A., DIEKMANN, M., ERIKSSON, O., GRUWEZ, R., HERMY, M., LENOIR, J., PLUE, J., COOMES, D. A., *ET AL.* (2013). Latitudinal gradients as natural laboratories to infer species' responses to temperature. *Journal of Ecology* **101**, 784–795.
- DE LA TORRE, A. R., WILHITE, B. & NEALE, D. B. (2019). Environmental genome-wide association reveals climate adaptation is shaped by subtle to moderate allele frequency shifts in loblolly pine. *Genome Biology and Evolution* **11**(10), 2976–2989.
- DE OLIVEIRA, A. C. P., NUNES, A., OLIVEIRA, M. A., RODRIGUES, R. G. & BRANQUINHO, C. (2022). How do taxonomic and functional diversity metrics change along an aridity gradient in a tropical dry forest? *Frontiers in Plant Science* **13**, 923219.
- DE OLIVEIRA, A. C. P., NUNES, A., RODRIGUES, R. G. & BRANQUINHO, C. (2020). The response of plant functional traits to aridity in a tropical dry forest. *Science of the Total Environment* **747**, 141177.
- DE VILLEMEREUIL, P., MOUTERDE, M., GAGGIOTTI, O. E. & TILL-BOTTRAUD, I. (2018). Patterns of phenotypic plasticity and local adaptation in the wide elevation range of the alpine plant *Arabis alpina*. *Journal of Ecology* **106**, 1952–1971.
- DELGADO, M. M., ROSLIN, T., TIKHONOV, G., MEYKE, E., LO, C., GURARIE, E., ABADONOVA, M., ABDURAIMOV, O., ADRIANOVA, O., AKIMOVA, T., ARKIEV, M., ANANIN, A., ANDREEVA, E., ANDRIYCHUK, N., ANTIPIN, M., *ET AL.* (2020). Differences in spatial versus temporal reaction norms for spring and autumn phenological events. *Proceedings of the National Academy of Sciences* **117**(49), 31249–31258.
- DEMARCHÉ, M. L., DOAK, D. F. & MORRIS, W. F. (2019). Incorporating local adaptation into forecasts of species' distribution and abundance under climate change. *Global Change Biology* **25**, 775–793.
- DESCOMBES, P., PITTELOU, C., GLAUSER, G., DEFOSSEZ, E., KERGUENTEUIL, A., ALLARD, P.-M., RASMANN, S. & PELLISSIER, L. (2020). Novel trophic interactions under climate change promote alpine plant coexistence. *Science* **370**, 1469–1473.
- DEVICTOR, V., JULLIARD, R., COUVET, D. & JIGUET, F. (2008). Birds are tracking climate warming, but not fast enough. *Proceedings of the Royal Society B: Biological Sciences* **275**, 2743–2748.
- DEVICTOR, V., VAN SWAAY, C., BRERETON, T., BROTONS, L., CHAMBERLAIN, D., HELIÖLÄ, J., HERRAND, S., JULLIARD, R., KUUSSAARI, M., LINDSTRÖM, A., REIF, J., ROY, D. B., SCHWEIGER, O., SETTELE, J., STEFANESCU, C., *ET AL.* (2012). Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change* **2**, 121–124.
- DIAMOND, S. E. & MARTIN, R. A. (2021). Physiological adaptation to cities as a proxy to forecast global-scale responses to climate change. *Journal of Experimental Biology* **224**, jeb229336.
- DIXON, A. L. & BUSCH, J. W. (2017). Common garden test of range limits as predicted by a species distribution model in the annual plant *Mimulus bicolor*. *American Journal of Botany* **104**(6), 817–827.
- DOBROWSKI, S. Z., THORNE, J. H., GREENBERG, J. A., SAFFORD, H. D., MYNSBERGE, A. R., CRIMMINS, S. M. & SWANSON, A. K. (2011). Modeling plant ranges over 75 years of climate change in California, USA: temporal transferability and species traits. *Ecological Monographs* **81**(2), 241–257.
- DORMANN, C. F. (2007). Effects of incorporating spatial autocorrelation into the analysis of species distribution data. *Global Ecology and Biogeography* **16**, 129–138.
- DORMANN, C. F., ELITH, J., BACHER, S., BUCHMANN, C., CARL, G., CARRÉ, G., MARQUÉZ, J. R. G., GRUBER, B., LAFOURCADE, B., LEITAO, P. J., MÜNKEMÜLLER, T., McCLEAN, C., OSBORNE, P. E., REINEKING, B., SCHRÖDER, B., *ET AL.* (2013). Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography* **36**, 27–46.
- DORNELAS, M., ANTAO, L. H., MOYES, F., BATES, A. E., MAGURRAN, A. E., ADAM, D., AKHMETZHANOVA, A. A., APPELTANS, W., ARCOS, J. M., ARNOLD, H., AYYAPPAN, N., BADIHI, G., BAIRD, A. H., BARBOSA, M., BARRETO, T. E., *ET AL.* (2018). BioTIME: a database of biodiversity time series for the Anthropocene. *Global Ecology and Biogeography* **27**, 760–786.
- DUBUIS, A., ROSSIER, L., POTTIER, J., PELLISSIER, L., VITTOZ, P. & GUISAN, A. (2013). Predicting current and future spatial community patterns of plant functional traits. *Ecography* **36**, 1158–1168.
- DUNNE, J. A., SALESKA, S. R., FISCHER, M. L. & HARTE, J. (2004). Integrating experimental and gradient methods in ecological climate change research. *Ecology* **85**(4), 904–916.
- EARLY, R. & SAX, D. F. (2014). Climatic niche shifts between species' native and naturalized ranges raise concern for ecological forecasts during invasions and climate change. *Global Ecology and Biogeography* **23**, 1356–1365.
- ELITH, J. & LEATHWICK, J. R. (2009). Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics* **40**, 677–697.
- ELMENDORF, S. C., HENRY, G. H. R., HOLLISTER, R. D., FOSAA, A. M., GOULD, W. A., HERMANNUTZ, L., HOFGAARD, A., JÓNSDÓTTIR, I. S., JØRGENSEN, J. C., LÉVESQUE, E., MAGNUSSON, B., MOLAU, U.,



- MYERS-SMITH, I. H., OBERBAUER, S. F., RIXEN, C., *ET AL.* (2015). Experiment, monitoring, and gradient methods used to infer climate change effects on plant communities yield consistent patterns. *Proceedings of the National Academy of Sciences* **112**(2), 448–452.
- ESTES, L., ELSÉN, P. R., TREUER, T., AHMED, L., CAYLOR, K., CHANG, J., CHOI, J. J. & ELLIS, E. C. (2018). The spatial and temporal domains of modern ecology. *Nature Ecology & Evolution* **2**, 819–826.
- ETTERSON, J. R. (2004). Evolutionary potential of *Chamaecrista fasciculata* in relation to climate change. I. Clinal patterns of selection along an environmental gradient in the Great Plains. *Evolution* **58**(7), 1446–1456.
- EXPOSITO-ALONSO, M., BURBANO, H. A., BOSSDORF, O., NIELSEN, R., WEIGEL, D. & 500 GENOMES FIELD EXPERIMENT TEAM (2019). Natural selection on the *Arabidopsis thaliana* genome in present and future climates. *Nature* **573**, 126–129.
- EXPOSITO-ALONSO, M., VASSEUR, F., DING, W., WANG, G., BURBANO, H. A. & WEIGEL, D. (2018). Genomic basis and evolutionary potential for extreme drought adaptation in *Arabidopsis thaliana*. *Nature Ecology & Evolution* **2**, 352–358.
- FASKE, T. M., AGNERAY, A. C., JAHNER, J. P., SHETA, L. M., LEGER, E. A. & PARCHMAN, T. L. (2021). Genomic and common garden approaches yield complementary results for quantifying environmental drivers of local adaptation in rubber rabbitbrush, a foundational Great Basin shrub. *Evolutionary Applications* **14**, 2881–2900.
- FERRIER, S. & GUISAN, A. (2006). Spatial modelling of biodiversity at the community level. *Journal of Applied Ecology* **43**, 393–404.
- FICK, S. E. & HIJMANS, R. J. (2017). WorldClim 2: new 1 km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* **37**, 4302–4315.
- FITZPATRICK, M. C., BLOIS, J. L., WILLIAMS, J. W., NIETO-LUGILDE, D., MAGUIRE, K. C. & LORENZ, D. J. (2018a). How will climate novelty influence ecological forecasts? Using the quaternary to assess future reliability. *Global Change Biology* **24**, 3575–3586.
- FITZPATRICK, M. C., CHHATRE, V. E., SOOLANAYAKANAHALLY, R. Y. & KELLER, S. R. (2021). Experimental support for genomic prediction of climate maladaptation using the machine learning approach gradient forests. *Molecular Ecology Resources* **21**, 2749–2765.
- FITZPATRICK, M. C., GOVE, A. D., SANDERS, N. J. & DUNN, R. R. (2008). Climate change, plant migration, and range collapse in a global biodiversity hotspot: the *Banksia* (Proteaceae) of Western Australia. *Global Change Biology* **14**, 1337–1352.
- FITZPATRICK, M. C. & HARGROVE, W. W. (2009). The projection of species distribution models and the problem of non-analog climate. *Biodiversity and Conservation* **18**, 2255–2261.
- FITZPATRICK, M. C. & KELLER, S. R. (2015). Ecological genomics meets community-level modelling of biodiversity: mapping the genomic landscape of current and future environmental adaptation. *Ecology Letters* **18**, 1–16.
- FITZPATRICK, M. C., KELLER, S. R. & LOTTERHOS, K. E. (2018b). Comment on ‘genomic signals of selection predict climate-driven population declines in a migratory bird’. *Science* **361**(6401), eaat7279.
- FODEN, W. B., YOUNG, B. E., AKÇAKAYA, H. R., GARCIA, R. A., HOFFMANN, A. A., STEIN, B. A., THOMAS, C. D., WHEATLEY, C. J., BICKFORD, D., CARR, J. A., HOLE, D. G., MARTIN, T. G., PACIFICI, M., PEARCE-HIGGINS, J. W., PLATTS, P. J., *ET AL.* (2019). Climate change vulnerability assessment of species. *WIREs Climate Change* **10**, e551.
- FORD, K. R., HARRINGTON, C. A., BANSAL, S., GOULD, P. J. & ST. CLAIR, J. B. (2016). Will changes in phenology track climate change? A study of growth initiation timing in coast Douglas-fir. *Global Change Biology* **22**, 3712–3723.
- FORDHAM, D. A., BERTELSMEIER, C., BROOK, B. W., EARLY, R., NETO, D., BROWN, S. C., OLLIER, S. & ARAÚJO, M. B. (2018). How complex should models be? Comparing correlative and mechanistic range dynamics models. *Global Change Biology* **24**, 1357–1370.
- FOURCADE, Y., BESNARD, A. G. & SECONDI, J. (2018). Paintings predict the distribution of species, or the challenge of selecting environmental predictors and evaluation statistics. *Global Ecology and Biogeography* **27**, 245–256.
- FOURNIER-LEVEL, A., KORTE, A., COOPER, M. D., NORDBOG, M., SCHMITT, J. & WILCZEK, A. M. (2011). A map of local adaptation in *Arabidopsis thaliana*. *Science* **334**, 86–89.
- FRANK, A., HOWE, G. T., SPERISEN, C., BRANG, P., ST. CLAIR, J. B., SCHMATZ, D. R. & HEIRI, C. (2017). Risk of genetic maladaptation due to climate change in three major European tree species. *Global Change Biology* **23**, 5358–5371.
- FREI, E. R., GHAZOU, J., MATTER, P., HEGGLI, M. & PLUESS, A. R. (2014). Plant population differentiation and climate change: responses of grassland species along an elevational gradient. *Global Change Biology* **20**, 441–455.
- FUKAMI, T. & WARDLE, D. A. (2005). Long-term ecological dynamics: reciprocal insights from natural and anthropogenic gradients. *Proceedings of the Royal Society B: Biological Sciences* **272**, 2105–2115.
- GALLAGHER, R. V., HUGHES, L. & LEISHMAN, M. R. (2013). Species loss and gain in communities under future climate change: consequences for functional diversity. *Ecography* **36**, 531–540.
- GARZÓN, M. B., ROBSON, T. M. & HAMPE, A. (2019).  $\Delta$ TraitSDMs: species distribution models that account for local adaptation and phenotypic plasticity. *New Phytologist* **222**, 1757–1765.
- GAÜZÈRE, P., IVERSEN, L. L., BARNAGAUD, J.-Y., SVENNING, J.-C. & BLONDER, B. (2018). Empirical predictability of community responses to climate change. *Frontiers in Ecology and Evolution* **6**, 186.
- GAÜZÈRE, P., IVERSEN, L. L., SEDDON, A. W. R., VIOLLE, C. & BLONDER, B. (2020). Equilibrium in plant functional trait responses is stronger under higher climate variability during the Holocene. *Global Ecology and Biogeography* **29**, 2052–2066.
- GOUGHERTY, A. V., KELLER, S. R. & FITZPATRICK, M. C. (2021). Maladaptation, migration and extirpation fuel climate change risk in a forest tree species. *Nature Climate Change* **11**, 166–171.
- GREISER, C., HYLANDER, K., MEINER, E., LUOTO, M. & EHRLEN, J. (2020). Climate limitation at the cold edge: contrasting perspectives from species distribution modelling and a transplant experiment. *Ecography* **43**, 637–647.
- GRINNELL, J. (1914). Barriers to distribution as regards birds and mammals. *The American Naturalist* **48**, 248–254.
- GUERIN, G. R., WEN, H. & LOWE, A. J. (2012). Leaf morphology shift linked to climate change. *Biology Letters* **8**, 882–886.
- GUISAN, A. & THUILLER, W. (2005). Predicting species distribution: offering more than simple habitat models. *Ecology Letters* **8**, 993–1009.
- GUISAN, A. & ZIMMERMANN, N. E. (2000). Predictive habitat distribution models in ecology. *Ecological Modelling* **135**, 147–186.
- GUITTA, J., GOLDBERG, D., KLANDERUD, K., TELFORD, R. J. & VANDVIK, V. (2016). Can trait patterns along gradients predict plant community responses to climate change? *Ecology* **97**(10), 2791–2801.
- HADFIELD, J. D. (2016). The spatial scale of local adaptation in a stochastic environment. *Ecology Letters* **19**, 780–788.
- HALBRITTER, A. H., FIOR, S., KELLER, I., BILLETER, R., EDWARDS, P. J., HOLDEREGGER, R., KARRENBERG, S., PLUESS, A. R., WIDMER, A. & ALEXANDER, J. M. (2018). Trait differentiation and adaptation of plants along elevation gradients. *Journal of Evolutionary Biology* **31**, 784–800.
- HALLER, B. C. & MESSER, P. W. (2019). SLiM 3: forward genetic simulations beyond the Wright–Fisher model. *Molecular Biology and Evolution* **36**(3), 632–637.
- HÄLLFORS, M., LEHVÄVIRTA, S., AANDAH, T., LEHTIMÄKI, I.-M., NILSSON, L. O., RUOTSALAINEN, A., SCHULMAN, L. E. & HYVÄRINEN, M. T. (2020). Translocation of an arctic seashore plant reveals signs of maladaptation to altered climatic conditions. *PeerJ* **8**, e10357.
- HANCOCK, A. M., BRACHI, B., FAURE, N., HORTON, M. W., JARYMOWYCZ, L. B., SPERONE, F. G., TOOMAJIAN, C., ROUX, F. & BERGELSON, J. (2011). Adaptation to climate across the *Arabidopsis thaliana* genome. *Science* **334**, 83–86.
- HEIMONEN, K., VALTONEN, A., KONTUNEN-SOPPELA, S., KESKI-SAARI, S., ROUSI, M., OKSANEN, E. & ROININEN, H. (2015). Insect herbivore damage on latitudinally translocated silver birch (*Betula pendula*) – predicting the effects of climate change. *Climatic Change* **131**, 245–257.
- HILBERT, D. W. & OSTENDORF, B. (2001). The utility of artificial neural networks for modelling the distribution of vegetation in past, present and future climates. *Ecological Modelling* **146**, 311–327.
- HOBAN, S., KELLEY, J. L., LOTTERHOS, K. E., ANTOLIN, M. F., BRADBURY, G., LOWRY, D. B., POSS, M. L., REED, L. K., STORFER, A. & WHITLOCK, M. C. (2016). Finding the genomic basis of local adaptation: pitfalls, practical solutions, and future directions. *The American Naturalist* **188**(4), 379–397.
- HODGSON, J. A., THOMAS, C. D., OLIVER, T. H., ANDERSON, B. J., BRERETON, T. M. & CRONE, E. E. (2011). Predicting insect phenology across space and time. *Global Change Biology* **17**, 1289–1300.
- HOFFMANN, A. A., WEEKS, A. R. & SGRÖ, C. M. (2021). Opportunities and challenges in assessing climate change vulnerability through genomics. *Cell* **184**, 1420–1425.
- HOPKINS, A. D. (1919). The bioclimatic law as applied to entomological research and farm practice. *The Scientific Monthly* **8**(6), 496–513.
- HOUSSET, J. M., NADEAU, S., ISABEL, N., DEPARDIEU, C., DUCHESNE, I., LENZ, P. & GIRARDIN, M. P. (2018). Tree rings provide a new class of phenotypes for genetic associations that foster insights into adaptation of conifers to climate change. *New Phytologist* **218**, 630–645.
- HUNTLEY, B., COLLINGHAM, Y. C., WILLIS, S. G. & GREEN, R. E. (2008). Potential impacts of climatic change on European breeding birds. *PLoS One* **3**(1), e1439.
- IILER, A. M., HØYE, T. T., INOUE, D. W. & SCHMIDT, N. M. (2013). Nonlinear flowering responses to climate: are species approaching their limits of phenological change? *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**, 20120489.
- IPCC (2022). Climate change 2022: impacts, adaptation and vulnerability. In *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds H.-O. PORTNER, D. C. ROBERTS, M. TIGNOR, E. S. POLOCZANSKA, K. MINTENBECK, A. ALEGRIA, M. CRAIG, S. LANGSDORF, S. LOSCHKE, V. MOLLER, A. OKEM and B. RAMA), p. 3056. Cambridge University Press. Cambridge University Press, Cambridge, and New York. <https://doi.org/10.1017/9781009325844>.

- ISAAC, N. J. B., GIRARDELLO, M., BRERETON, T. M. & ROY, D. B. (2011). Butterfly abundance in a warming climate: patterns in space and time are not congruent. *Journal of Insect Conservation* **15**, 233–240.
- JARAMILLO, E., DUGAN, J. E., HUBBARD, D. M., CONTRERAS, H., DUARTE, C., ACUÑA, E. & SCHOEMAN, D. S. (2017). Macroscale patterns in body size of intertidal crustaceans provide insights on climate change effects. *PLoS One* **12**(5), e0177116.
- JARAMILLO-CORREA, J.-P., RODRÍGUEZ-QUILÓN, I., GRIVET, D., LEPOITTEVIN, C., SEBASTIANI, F., HEUERTZ, M., GARNIER-GÉRÉ, P. H., ALÍA, R., PLOMION, C., VENDRAMIN, G. G. & GONZÁLEZ-MARTÍNEZ, S. C. (2015). Molecular proxies for climate maladaptation in a long-lived tree (*Pinus pinaster* Aiton, Pinaceae). *Genetics* **199**, 793–807.
- JARNEVICH, C. S., STOHLGREN, T. J., KUMAR, S., MORISETTE, J. T. & HOLCOMBE, T. R. (2015). Caveats for correlative species distribution modeling. *Ecological Informatics* **29**, 6–15.
- JAY, F., MANEL, S., ALVAREZ, N., DURAND, E. Y., THUILLER, W., HOLDEREGGER, R., TABERLET, P. & FRANÇOIS, O. (2012). Forecasting changes in population genetic structure of alpine plants in response to global warming. *Molecular Ecology* **21**, 2354–2368.
- JOCHNER, S., CAFFARRA, A. & MENZEL, A. (2013). Can spatial data substitute temporal data in phenological modelling? A survey using birch flowering. *Tree Physiology* **33**, 1256–1268.
- JOHNSON, E. A. & MIYANISHI, K. (2008). Testing the assumptions of chronosequences in succession. *Ecology Letters* **11**, 419–431.
- JOHNSON, L. C., GALLIART, M. B., ALSDURF, J. D., MARICLE, B. R., BAER, S. G., BELLO, N. M., GIBSON, D. J. & SMITH, A. B. (2022b). Reciprocal transplant gardens as gold standard to detect local adaptation in grassland species: new opportunities moving into the 21st century. *Journal of Ecology* **110**, 1054–1071.
- JOHNSON, T. F., CRUZ, P., ISAAC, N. J. B., PAVIOLO, A. & GONZÁLEZ-SUÁREZ, M. (2022a). CaPTrends: a database of large carnivore population trends from around the world. *Global Ecology and Biogeography* **31**, 2475–2482.
- JORDAN, R., HOFFMANN, A. A., DILLON, S. K. & PROBER, S. M. (2017). Evidence of genomic adaptation to climate in *Eucalyptus microcarpa*: implications for adaptive potential to projected climate change. *Molecular Ecology* **26**, 6002–6020.
- KARDOS, M. & LUIKART, G. (2021). The genetic architecture of fitness drives population viability during rapid environmental change. *The American Naturalist* **197**(5), 511–525.
- KAWECKI, T. J. & EBERT, D. (2004). Conceptual issues in local adaptation. *Ecology Letters* **7**, 1225–1241.
- KAZENEL, M. R., KIVLIN, S. N., TAYLOR, D. L., LYNN, J. S. & RUDGERS, J. A. (2019). Altitudinal gradients fail to predict fungal symbiont responses to warming. *Ecology* **100**(8), e02740.
- KEARNEY, M. R., GILLINGHAM, P. K., BRAMER, I., DUFFY, J. P. & MACLEAN, I. M. D. (2020). A method for computing hourly, historical, terrain-corrected microclimate anywhere on earth. *Methods in Ecology and Evolution* **11**, 38–43.
- KHAROUBA, H. M., ALGAR, A. C. & KERR, J. T. (2009). Historically calibrated predictions of butterfly species' range shift using global change as a pseudo-experiment. *Ecology* **90**(8), 2213–2222.
- KHAROUBA, H. M., EHRLEIN, J., GELMAN, A., BOLMGREN, K., ALLEN, J. M., TRAVERS, S. E. & WOLKOVICH, E. M. (2018). Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of the National Academy of Sciences* **115**(20), 5211–5216.
- KHAROUBA, H. M., PAQUETTE, S. R., KERR, J. T. & VELLEND, M. (2014). Predicting the sensitivity of butterfly phenology to temperature over the past century. *Global Change Biology* **20**, 504–514.
- KIMMEL, K., DEE, L. E., AVOLIO, M. L. & FERRARO, P. J. (2021). Causal assumptions and causal inference in ecological experiments. *Trends in Ecology & Evolution* **36**(12), 1141–1152.
- KINARD, S., PATRICK, C. J. & CARVALLO, F. (2021). Effects of a natural precipitation gradient on fish and macroinvertebrate assemblages in coastal streams. *PeerJ* **9**, e12137.
- KLESSE, S., DE ROSE, R. J., BABST, F., BLACK, B. A., ANDEREGG, L. D. L., AXELSON, J., ETTINGER, A., GRIESBAUER, H., GUITERMAN, C. H., HARLEY, G., HARVEY, J. E., LO, Y. H., LYNCH, A. M., O'CONNOR, C., RESTAINO, C., ET AL. (2020). Continental-scale tree-ring-based projection of Douglas-fir growth: testing the limits of space-for-time substitution. *Global Change Biology* **26**, 5146–5163.
- KRAMER, K. (1995). Phenotypic plasticity of the phenology of seven European tree species in relation to climatic warming. *Plant, Cell & Environment* **18**, 93–104.
- KWON, E., WEISER, E. L., LANCTOT, R. B., BROWN, S. C., GATES, H. R., GILCHRIST, G., KENDALL, S. J., LANK, D. B., LIEBEZEIT, J. R., MCKINNON, L., NOL, E., PAYER, D. C., RAUSCH, J., RINELLA, D. J., SAALFELD, S. T., ET AL. (2019). Geographic variation in the intensity of warming and phenological mismatch between Arctic shorebirds and invertebrates. *Ecological Monographs* **89**(4), e01383.
- LA SORTE, F. A., LEE, T. M., WILMAN, H. & JETZ, W. (2009). Disparities between observed and predicted impacts of climate change on winter bird assemblages. *Proceedings of the Royal Society B: Biological Sciences* **276**, 3167–3174.
- LAHR, E. C., DUNN, R. R. & FRANK, S. D. (2018). Getting ahead of the curve: cities as surrogates for global change. *Proceedings of the Royal Society B: Biological Sciences* **285**, 20180643.
- LAJOIE, G. & VELLEND, M. (2018). Characterizing the contribution of plasticity and genetic differentiation to community-level trait responses to environmental change. *Ecology and Evolution* **8**, 3895–3907.
- LANE, J. E., CZENZE, Z. J., FINDLAY-ROBINSON, R. & BAYNE, E. (2019). Phenotypic plasticity and local adaptation in a wild hibernator evaluated through reciprocal translocation. *The American Naturalist* **194**(4), 516–528.
- LÁRUSON, Á. J., FITZPATRICK, M. C., KELLER, S. R., HALLER, B. C. & LOTTERHOS, K. E. (2022). Seeing the forest for the trees: assessing genetic offset predictions from gradient forest. *Evolutionary Applications* **15**, 4033–416.
- LAWSON, C. R., BENNIE, J., HODGSON, J. A., THOMAS, C. D. & WILSON, R. J. (2014). Topographic microclimates drive microhabitat associations at the range margin of a butterfly. *Ecography* **37**(8), 732–740.
- LEIMU, R. & FISCHER, M. (2008). A meta-analysis of local adaptation in plants. *PLoS One* **3**(12), e4010.
- LEMOINE, N. & BÖHNING-GAESE, K. (2003). Potential impact of global climate change on species richness of long-distance migrants. *Conservation Biology* **17**(2), 577–586.
- LEMOINE, N., SCHAEFER, H.-C. & BÖHNING-GAESE, K. (2007). Species richness of migratory birds is influenced by global climate change. *Global Ecology and Biogeography* **16**, 55–64.
- LENOIR, J., BERTRAND, R., COMTE, L., BOURGEOUD, L., HATTAB, T., MURIENNE, J. & GRENOUILLET, G. (2020). Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution* **4**, 1044–1059.
- LENORMAND, T. (2002). Gene flow and the limits to natural selection. *Trends in Ecology & Evolution* **17**(4), 183–189.
- LEWIS, S. L. & MASLIN, M. A. (2015). Defining the Anthropocene. *Nature* **519**, 171–180.
- LEWTHWAITE, J. M. M., ANGERT, A. L., KEMBEL, S. W., GORING, S. J., DAVIES, T. J., MOOERS, A. Ø., SPERLING, F. A. H., VAMOSI, S. M., VAMOSI, J. C. & KERR, J. T. (2018). Canadian butterfly climate debt is significant and correlated with range size. *Ecography* **41**, 2005–2015.
- LI, Y., ZHANG, X.-X., MAO, R.-L., YANG, J., MIAO, C.-Y., LI, Z. & QIU, Y.-X. (2017). Ten years of landscape genomics: challenges and opportunities. *Frontiers in Plant Science* **8**, 2136.
- LINDENMAYER, D. (2018). Why is long-term ecological research and monitoring so hard to do? (and what can be done about it). *Australian Zoologist* **39**(4), 576–580.
- LOARIE, S. R., DUFFY, P. B., HAMILTON, H., ASNER, G. P., FIELD, C. B. & ACKERLY, D. D. (2009). The velocity of climate change. *Nature* **462**, 1052–1055.
- LOEWEN, C. J. G., JACKSON, D. A. & GILBERT, B. (2023). Biodiversity patterns diverge along geographic temperature gradients. *Global Change Biology* **29**, 603–617.
- LOGAN, M. L., COX, R. M. & CALSBEEK, R. (2014). Natural selection on thermal performance in a novel thermal environment. *Proceedings of the National Academy of Sciences* **111**(39), 14165–14169.
- LORTIE, C. J. & HIERRO, J. L. (2021). A synthesis of local adaptation to climate through reciprocal common gardens. *Journal of Ecology* **110**, 1015–1021.
- MACLEAN, I. M. D. (2020). Predicting future climate at high spatial and temporal resolution. *Global Change Biology* **26**, 1003–1011.
- MAGUIRE, K. C., NIETO-LUGILDE, D., BLOIS, J. L., FITZPATRICK, M. C., WILLIAMS, J. W., FERRIER, S. & LORENZ, D. J. (2016). Controlled comparison of species- and community-level models across novel climates and communities. *Proceedings of the Royal Society B: Biological Sciences* **283**, 20152817.
- MAGUIRE, K. C., NIETO-LUGILDE, D., FITZPATRICK, M. C., WILLIAMS, J. W. & BLOIS, J. L. (2015). Modeling species and community responses to past, present, and future episodes of climatic and ecological change. *Annual Review of Ecology, Evolution, and Systematics* **46**, 343–368.
- MARSICO, T. D. & HELLMANN, J. J. (2009). Dispersal limitation inferred from an experimental translocation of *Lomatium* (Apiaceae) species outside their geographic ranges. *Oikos* **118**, 1783–1792.
- MARTINS, K., GUGGER, P. F., LLANDERAL-MENDOZA, J., GONZÁLEZ-RODRÍGUEZ, A., FITZ-GIBBON, S. T., ZHAO, J.-L., RODRÍGUEZ-CORREA, H., OYAMA, K. & SORK, V. L. (2018). Landscape genomics provides evidence of climate-associated genetic variation in Mexican populations of *Quercus rugosa*. *Evolutionary Applications* **11**, 1842–1858.
- MCCABE, L. M., ASLAN, C. E. & COBB, N. S. (2022). Decreased bee emergence along an elevation gradient: implications for climate change revealed by a transplant experiment. *Ecology* **103**(2), e03598.
- MEERHOFF, M., TEIXEIRA-DE MELLO, F., KRUK, C., ALONSO, C., GONZÁLEZ-BERGONZONI, I., PACHECO, J. P., LACEROT, G., ARIM, M., BEKLIOĞLU, M., BRUCET, S., GOYENOLA, G., IGLESIAS, C., MAZZEO, N., KOSTEN, S. & JEPPESEN, E. (2012). Environmental warming in Shallow Lakes. A review of potential changes in community structure as evidenced from space-for-time substitution approaches. *Advances in Ecological Research* **46**, 259–349.

- MELO-MERINO, S. M., REYES-BONILLA, H. & LIRA-NORIEGA, A. (2020). Ecological niche models and species distribution models in marine environments: a literature review and spatial analysis of evidence. *Ecological Modelling* **415**, 108837.
- MENÉNDEZ, R., MEGÍAS, A. G., HILL, J. K., BRASCHLER, B., WILLIS, S. G., COLLINGHAM, Y., FOX, R., ROY, D. B. & THOMAS, C. D. (2006). Species richness changes lag behind climate change. *Proceedings of the Royal Society B: Biological Sciences* **273**, 1465–1470.
- MERILÄ, J. & HENDRY, A. P. (2014). Climate change, adaptation, and phenotypic plasticity: the problem and the evidence. *Evolutionary Applications* **7**, 1–14.
- MERLIN, M., DUPUTÉ, A. & CHUINE, I. (2018). Limited validation of forecasted northward range shift in ten European tree species from a common garden experiment. *Forest Ecology and Management* **410**, 144–156.
- MERRIAM, C. H. (1894). *Laws of temperature control of the geographic distribution of terrestrial animals and plants*. National Geographic Magazine **6**, 229–238.
- MILLER, E. F., GREEN, R. E., BALMFOORD, A., MAISANO DELSER, P., BEYER, R., SOMVEILLE, M., LEONARDI, M., AMOS, W. & MANICA, A. (2021). Bayesian skyline plots disagree with range size changes based on species distribution models for Holarctic birds. *Molecular Ecology* **30**, 3993–4004.
- MOKANY, K., THOMSON, J. J., LYNCH, A. J. J., JORDAN, G. J. & FERRIER, S. (2015). Linking changes in community composition and function under climate change. *Ecological Applications* **25**(8), 2132–2141.
- MORÁN-ORDÓÑEZ, A., LAHOZ-MONFORT, J. J., ELITH, J. & WINTLE, B. A. (2017). Evaluating 318 continental-scale species distribution models over a 60-year prediction horizon: what factors influence the reliability of predictions? *Global Ecology and Biogeography* **26**, 371–384.
- MORIN, X., AUGSPURGER, C. & CHUINE, I. (2007). Process-based modeling of species' distributions: what limits temperate tree species' range boundaries? *Ecology* **88**(9), 2280–2291.
- MORITZ, C., PATTON, J. L., CONROY, C. J., PARRA, J. L., WHITE, G. C. & BEISSINGER, S. R. (2008). Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. *Science* **322**, 261–264.
- MORTON, E. M. & RAFFERTY, N. E. (2017). Plant–pollinator interactions under climate change: the use of spatial and temporal transplants. *Applications in Plant Sciences* **5**(6), 1600133.
- MOTHES, C. C., STROUD, J. T., CLEMENTS, S. L. & SEARCY, C. A. (2019). Evaluating ecological niche model accuracy in predicting biotic invasions using South Florida's exotic lizard community. *Journal of Biogeography* **46**, 432–441.
- MŮNZBERGOVÁ, Z., VANDVIK, V. & HADINCOVÁ, V. (2021). Evolutionary rescue as a mechanism allowing a clonal grass to adapt to novel climates. *Frontiers in Plant Science* **12**, 659479.
- NEWSHAM, K. K., HOPKINS, D. W., CARVALHAIS, L. C., FRETWELL, P. T., RUSHTON, S. P., O'DONNELL, A. G. & DENNIS, P. G. (2016). Relationship between soil fungal diversity and temperature in the maritime Antarctic. *Nature Climate Change* **6**, 182–186.
- NIETO-LUGILDE, D., MAGUIRE, K. C., BLOIS, J. L., WILLIAMS, J. W. & FITZPATRICK, M. C. (2018). Multiresponse algorithms for community-level modelling: review of theory, applications, and comparison to species distribution models. *Methods in Ecology and Evolution* **9**, 834–848.
- NIU, Y., YANG, S., ZHOU, J., CHU, B., MA, S., ZHU, H. & HUA, L. (2019). Vegetation distribution along mountain environmental gradient predicts shifts in plant community response to climate change in alpine meadow on the Tibetan Plateau. *Science of the Total Environment* **650**, 505–514.
- NOGUÉS-BRAVO, D. (2009). Predicting the past distribution of species climatic niches. *Global Ecology and Biogeography* **18**, 521–531.
- NOOTEN, S. S., ANDREW, N. R. & HUGHES, L. (2014). Potential impacts of climate change on insect communities: a transplant experiment. *PLoS One* **9**(1), e85987.
- NOOTEN, S. S. & HUGHES, L. (2017). The power of the transplant: direct assessment of climate change impacts. *Climatic Change* **144**, 237–255.
- NORBERG, A., ABREGO, N., BLANCHET, F. G., ADLER, F. R., ANDERSON, B. J., ANTILLA, J., ARAÚJO, M. B., DALLAS, T., DUNSON, D., ELITH, J., FOSTER, S. D., FOX, R., FRANKLIN, J., GODSOE, W., GUISAN, A., ET AL. (2019). A comprehensive evaluation of predictive performance of 33 species distribution models at species and community levels. *Ecological Monographs* **89**(3), e01370.
- OEDEKOVEN, C. S., ELSTON, D. A., HARRISON, P. J., BREWER, M. J., BUCKLAND, S. T., JOHNSTON, A., FOSTER, S. & PEARCE-HIGGINS, J. W. (2017). Attributing changes in the distribution of species abundance to weather variables using the example of British breeding birds. *Methods in Ecology and Evolution* **8**, 1690–1702.
- PARMESAN, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* **37**, 637–669.
- PEARMAN, P. B., RANDIN, C. F., BROENNIMANN, O., VITTOZ, P., VAN DER KNAAP, W. O., ENGLER, R., LAY, G. L., ZIMMERMANN, N. E. & GUISAN, A. (2008). Prediction of plant species distributions across six millennia. *Ecology Letters* **11**, 357–369.
- PEARSON, R. G. (2010). Species' distribution modeling for conservation educators and practitioners. *Lessons in Conservation* **3**, 54–89.
- PEARSON, R. G. & DAWSON, T. P. (2003). Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography* **12**, 361–371.
- PEARSON, R. G., PHILLIPS, S. J., LORANTY, M. M., BECK, P. S. A., DAMOULAS, T., KNIGHT, S. J. & GOETZ, S. J. (2013). Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Climate Change* **3**, 673–677.
- PELINI, S. L., DZURISIN, J. D. K., PRIOR, K. M., WILLIAMS, C. M., MARSICO, T. D., SINCLAIR, B. J. & HELLMANN, J. J. (2009). Translocation experiments with butterflies reveal limits to enhancement of poleward populations under climate change. *Proceedings of the National Academy of Sciences* **106**(27), 11160–11165.
- PETCHEY, O. L., PONTARP, M., MASSIE, T. M., KÉFI, S., OZGUL, A., WEILENMANN, M., PALAMARA, G. M., ALTERMATT, F., MATTHEWS, B., LEVINE, J. M., CHILDS, D. Z., MCGILL, B. J., SCHAEPMAN, M. E., SCHMID, B., SPAAK, P., ET AL. (2015). The ecological forecast horizon, and examples of its uses and determinants. *Ecology Letters* **18**, 597–611.
- PETERSON, A. T., COBOS, M. E. & JIMÉNEZ-GARCÍA, D. (2018). Major challenges for correlational ecological niche model projections to future climate conditions. *Annals of the New York Academy of Sciences* **1429**, 66–77.
- PETERSON, A. T. & SOBERÓN, J. (2012). Species distribution modeling and ecological niche modeling: getting the concepts right. *Natureza & Conservação* **10**(2), 102–107.
- PHILLIMORE, A. B., HADFIELD, J. D., JONES, O. R. & SMITHERS, R. J. (2010). Differences in spawning date between populations of common frog reveal local adaptation. *Proceedings of the National Academy of Sciences* **107**(18), 8292–8297.
- PHILLIMORE, A. B., STÄLHANDSKE, S., SMITHERS, R. J. & BERNARD, R. (2012). Dissecting the contributions of plasticity and local adaptation to the phenology of a butterfly and its host plants. *The American Naturalist* **180**(5), 655–670.
- PICKETT, S. T. A. (1989). Space-for-time substitution as an alternative to long-term studies. In *Long-Term Studies in Ecology* (ed. G. E. LIKENS), pp. 110–135. Springer, New York.
- PICKLES, R. S. A., THORNTON, D., FELDMAN, R., MARQUES, A. & MURRAY, D. L. (2013). Predicting shifts in parasite distribution with climate change: a multitrophic level approach. *Global Change Biology* **19**, 2645–2654.
- POLLOCK, L. J., TINGLEY, R., MORRIS, W. K., GOLDING, N., O'HARA, R. B., PARRIS, K. M., VESK, P. A. & MCCARTHY, M. A. (2014). Understanding co-occurrence by modelling species simultaneously with a joint species distribution model (JSDM). *Methods in Ecology and Evolution* **5**, 397–406.
- POTTER, K. A., ARTHUR WOODS, H. & PINCEBOURDE, S. (2013). Microclimatic challenges in global change biology. *Global Change Biology* **19**, 2932–2939.
- PRAATT, J. D. & MOONEY, K. A. (2013). Clinal adaptation and adaptive plasticity in *Artemisia californica*: implications for the response of a foundation species to predicted climate change. *Global Change Biology* **19**, 2454–2466.
- PURVIS, A., NEWBOLD, T., DE PALMA, A., CONTU, S., HILL, S. L. L., SANCHEZ-ORTIZ, K., PHILLIPS, H. R. P., HUDSON, L. N., LYSENKO, I., BÖRGER, L. & SCHARLEMANN, J. P. W. (2018). Modelling and projecting the response of local terrestrial biodiversity worldwide to land use and related pressures: the PREDICTS project. *Advances in Ecological Research* **58**, 201–241.
- QIAO, H., FENG, X., ESCOBAR, L. E., PETERSON, A. T., SOBERÓN, J., ZHU, G. & PAGES, M. (2019). An evaluation of transferability of ecological niche models. *Ecography* **42**, 521–534.
- RANDIN, C. F., DIRNBÖCK, T., DULLINGER, S., ZIMMERMANN, N. E., ZAPPA, M. & GUISAN, A. (2006). Are niche-based species distribution models transferable in space? *Journal of Biogeography* **33**, 1689–1703.
- RAPACCIUOLO, G., ROY, D. B., GILLINGS, S., FOX, R., WALKER, K. & PURVIS, A. (2012). Climatic associations of British species distributions show good transferability in time but low predictive accuracy for range change. *PLoS One* **7**(7), e40212.
- RASMANN, S., PELLISSIER, L., DEFOSSÉ, E., JACTEL, H. & KUNSTLER, G. (2014). Climate-driven change in plant–insect interactions along elevation gradients. *Functional Ecology* **28**, 46–54.
- REFSNIDER, J. M., QIAN, S. S., STREBY, H. M., CARTER, S. E., CLIFTON, I. T., SIEFKER, A. D. & VAZQUEZ, T. K. (2018). Reciprocally transplanted lizards along an elevational gradient match light environment use of local lizards via phenotypic plasticity. *Functional Ecology* **32**, 1227–1236.
- RELLSTAB, C., DAUPHIN, B. & EXPOSITO-ALONSO, M. (2021). Prospects and limitations of genomic offset in conservation management. *Evolutionary Applications* **14**, 1202–1212.
- RELLSTAB, C., FISCHER, M. C., ZOLLER, S., GRAF, R., TEDDER, A., SHIMIZU, K. K., WIDMER, A., HOLDEREGGER, R. & GUGERLI, F. (2017). Local adaptation (mostly) remains local: reassessing environmental associations of climate-related candidate SNPs in *Arabidopsis halleri*. *Heredity* **118**, 193–201.
- RELLSTAB, C., GUGERLI, F., ECKERT, A. J., HANCOCK, A. M. & HOLDEREGGER, R. (2015). A practical guide to environmental association analysis in landscape genomics. *Molecular Ecology* **24**, 4348–4370.
- RELLSTAB, C., ZOLLER, S., WALTHERT, L., LESUR, I., PLUESS, A. R., GRAF, R., BODÉNÈS, C., SPERISEN, C., KREMER, A. & GUGERLI, F. (2016). Signatures of local adaptation in candidate genes of oaks (*Quercus* spp.) with respect to present and future climatic conditions. *Molecular Ecology* **25**, 5907–5924.

- ROBERTS, A. M. I. (2008). Exploring relationships between phenological and weather data using smoothing. *International Journal of Biometeorology* **52**, 463–470.
- ROBERTS, D. R. & HAMANN, A. (2012). Predicting potential climate change impacts with bioclimate envelope models: a palaeoecological perspective. *Global Ecology and Biogeography* **21**, 121–133.
- ROOT, T. L., PRICE, J. T., HALL, K. R., SCHNEIDER, S. H., ROSENZWEIG, C. & POUNDS, J. A. (2003). Fingerprints of global warming on wild animals and plants. *Nature* **421**, 57–60.
- ROSLIN, T., ANTAO, L., HÄLLFORS, M., MEYKE, E., LO, C., TIKHONOV, G., DELGADO, M. D. M., GURARIE, E., ABADONOVA, M., ABDURAIMOV, O., ADRIANOVA, O., AKIMOVA, T., AKKIEV, M., ANANIN, A., ANDREEVA, E., ET AL. (2021). Phenological shifts of abiotic events, producers and consumers across a continent. *Nature Climate Change* **11**, 241–248.
- ROW, J. R., WILSON, P. J., GOMEZ, C., KOEN, E. L., BOWMAN, J., THORNTON, D. & MURRAY, D. L. (2014). The subtle role of climate change on population genetic structure in Canada lynx. *Global Change Biology* **20**, 2076–2086.
- ROY, D. B., OLIVER, T. H., BOTHAM, M. S., BECKMANN, B., BRERETON, T., DENNIS, R. L. H., HARROWER, C., PHILLIMORE, A. B. & THOMAS, J. A. (2015). Similarities in butterfly emergence dates among populations suggest local adaptation to climate. *Global Change Biology* **21**, 3313–3322.
- ROY, D. B., ROTHERY, P., MOSS, D., POLLARD, E. & THOMAS, J. A. (2001). Butterfly numbers and weather: predicting historical trends in abundance and the future effects of climate change. *Journal of Animal Ecology* **70**, 201–217.
- RUE, H., MARTINO, S. & CHOPIN, N. (2009). Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* **71**, 319–392.
- SANDEL, B. (2019). Disequilibrium in trait-climate relationships of trees and birds. *Frontiers in Ecology and Evolution* **7**, 138.
- SANDEL, B., GOLDSTEIN, L. J., KRAFT, N. J. B., OKIE, J. G., SHULDMAN, M. I., ACKERLY, D. D., CLELAND, E. E. & SUDING, K. N. (2010). Contrasting trait responses in plant communities to experimental and geographic variation in precipitation. *New Phytologist* **188**, 565–575.
- SANGINÉS DE CÁRCER, P., SIGNARBIEX, C., SCHLAEPFER, R., BUTTLER, A. & VOLLENWEIDER, P. (2017). Responses of antinomic foliar traits to experimental climate forcing in beech and spruce saplings. *Environmental and Experimental Botany* **140**, 128–140.
- SANTINI, L., BENÍTEZ-LÓPEZ, A., MAIORANO, L., CENGIĆ, M. & HUIJBREGTS, M. A. J. (2021). Assessing the reliability of species distribution projections in climate change research. *Diversity and Distributions* **27**, 1035–1050.
- SAVOLAINEN, O., LASCoux, M. & MERILÄ, J. (2013). Ecological genomics of local adaptation. *Nature Reviews Genetics* **14**, 807–820.
- SCHIEFFERS, B. R., DE MEESTER, L., BRIDGE, T. C. L., HOFFMANN, A. A., PANDOLFI, J. M., CORLETT, R. T., BUTCHART, S. H. M., PEARCE-KELLY, P., KOVACS, K. M., DUDGEON, D., PACIFICI, M., RONDININI, C., FODEN, W. B., MARTIN, T. G., MORA, C., ET AL. (2016). The broad footprint of climate change from genes to biomes to people. *Science* **354**(6313), aaf7671.
- SCHOVILLE, S. D., BONIN, A., FRANÇOIS, O., LOBREAUX, S., MELODELIMA, C. & MANEL, S. (2012). Adaptive genetic variation on the landscape: methods and cases. *Annual Review of Ecology, Evolution, and Systematics* **43**, 23–43.
- SEARCY, C. A. & SHAFFER, H. B. (2016). Do ecological niche models accurately identify climatic determinants of species ranges? *The American Naturalist* **187**(4), 423–435.
- SEQUEIRA, A. M. M., BOUCHET, P. J., YATES, K. L., MENGERSEN, K. & CALEY, M. J. (2018). Transferring biodiversity models for conservation: opportunities and challenges. *Methods in Ecology and Evolution* **9**, 1250–1264.
- SIMMONDS, E. G., COLE, E. F. & SHELDON, B. C. (2019). Cue identification in phenology: a case study of the predictive performance of current statistical tools. *Journal of Animal Ecology* **88**, 1428–1440.
- SIMMONDS, E. G., COLE, E. F., SHELDON, B. C. & COULSON, T. (2020). Phenological asynchrony: a ticking time-bomb for seemingly stable populations? *Ecology Letters* **23**, 1766–1775.
- SINCLAIR, S. J., WHITE, M. D. & NEWELL, G. R. (2010). How useful are species distribution models for managing biodiversity under future climates? *Ecology and Society* **15**(1), 8.
- SLATKIN, M. (1978). Spatial patterns in the distributions of polygenic characters. *Journal of Theoretical Biology* **70**, 213–228.
- SLINGSBY, J. A., MONCRIEFF, G. R. & WILSON, A. M. (2020). Near-real time forecasting and change detection for an open ecosystem with complex natural dynamics. *ISPRS Journal of Photogrammetry and Remote Sensing* **166**, 15–25.
- SMITH, A. B. & SANTOS, M. J. (2020). Testing the ability of species distribution models to infer variable importance. *Ecography* **43**, 1801–1813.
- SOULTAN, A., PAVÓN-JORDÁN, D., BRADTER, U., SANDERCOCK, B. K., HOCHACHKA, W. M., JOHNSTON, A., BROMMER, J., GAGET, E., KELLER, V., KNAUS, P., AGHABABYAN, K., MAXHUNI, Q., VINTCHEVSKI, A., NAGY, K., RAUDONIKIS, L., ET AL. (2022). The future distribution of wetland birds breeding in Europe validated against observed changes in distribution. *Environmental Research Letters* **17**, 024025.
- SRIVASTAVA, D. S., CRISTINE, L., ANGERT, A. L., BONTRAGER, M., AMUNDRUD, S. L., WILLIAMS, J. L., YEUNG, A. C. Y., DE ZWAAN, D. R., THOMPSON, P. L., AITKEN, S. N., SUNDAY, J. M., O'CONNOR, M. I., WHITTON, J., BROWN, N. E. M., MACLEOD, C. D., ET AL. (2021). Wildcards in climate change biology. *Ecological Monographs* **91**(4), e01471.
- ST CLAIR, J. B. & HOWE, G. T. (2007). Genetic maladaptation of coastal Douglas-fir seedlings to future climates. *Global Change Biology* **13**, 1441–1454.
- STAMP, M. A. & HADFIELD, J. D. (2020). The relative importance of plasticity versus genetic differentiation in explaining between population differences; a meta-analysis. *Ecology Letters* **23**, 1432–1441.
- STANICZENKO, P. P. A., SIVASUBRAMANIAM, P., SUTTLE, K. B. & PEARSON, R. G. (2017). Linking macroecology and community ecology: refining predictions of species distributions using biotic interaction networks. *Ecology Letters* **20**, 693–707.
- STARK, J. R. & FRIDLEY, J. D. (2022). Microclimate-based species distribution models in complex forested terrain indicate widespread cryptic refugia under climate change. *Global Ecology and Biogeography* **31**, 562–575.
- STEIDINGER, B. S., CROWTHER, T. W., LIANG, J., VAN NULAND, M. E., WERNER, G. D. A., REICH, P. B., NABUURS, G. J., DE-MIGUEL, S., ZHOU, M., PICARD, N., HERAULT, B., ZHAO, X., ZHANG, C., ROUTH, D., PEAY, K. G. & GFB CONSORTIUM (2019). Climatic controls of decomposition drive the global biogeography of forest-tree symbioses. *Nature* **569**, 404–408.
- STELLINGWOOD, T. P., POORE, A. G. B. & GRIBBEN, P. E. (2021). Shifts in biomass and structure of habitat-formers across a latitudinal gradient. *Ecology and Evolution* **11**, 8831–8842.
- SUGGITT, A. J., PLATTS, P. J., BARATA, I. M., BENNIE, J. J., BURGESS, M. D., BYSTRIKOVA, N., DUFFIELD, S., EWING, S. R., GILLINGHAM, P. K., HARPER, A. B., HARTLEY, A. J., HEMMING, D. L., MACLEAN, I. M. D., MALTBY, K., MARSHALL, H. H., ET AL. (2017). Conducting robust ecological analyses with climate data. *Oikos* **126**, 1533–1541.
- SUGGITT, A. J., WILSON, R. J., ISAAC, N. J. B., BEALE, C. M., AUFFRET, A. G., AUGUST, T., BENNIE, J. J., CRICK, H. Q. P., DUFFIELD, S., FOX, R., HOPKINS, J. J., MACGREGOR, N. A., MORECROFT, M. D., WALKER, K. J. & MACLEAN, I. M. D. (2018). Extinction risk from climate change is reduced by microclimatic buffering. *Nature Climate Change* **8**, 713–717.
- SWAEGERS, J., SPANIER, K. I. & STOKS, R. (2020). Genetic compensation rather than genetic assimilation drives the evolution of plasticity in response to mild warming across latitudes in a damselfly. *Molecular Ecology* **29**, 4823–4834.
- SYNES, N. W. & OSBORNE, P. E. (2011). Choice of predictor variables as a source of uncertainty in continental-scale species distribution modelling under climate change. *Global Ecology and Biogeography* **20**, 904–914.
- TANSEY, C. J., HADFIELD, J. D. & PHILLIMORE, A. B. (2017). Estimating the ability of plants to plastically track temperature-mediated shifts in the spring phenological optimum. *Global Change Biology* **23**, 3321–3334.
- THOMAS, C. D., CAMERON, A., GREEN, R. E., BAKKENES, M., BEAUMONT, L. J., COLLINGHAM, Y. C., ERASMUS, B. F. N., DE SIQUEIRA, M. F., GRAINGER, A., HANNAH, L., HUGHES, L., HUNTLEY, B., VAN JAARSVELD, A. S., MIDGLEY, G. F., MILES, L., ET AL. (2004). Extinction risk from climate change. *Nature* **427**, 145–148.
- THULLER, W. (2004). Patterns and uncertainties of species' range shifts under climate change. *Global Change Biology* **10**, 2020–2027.
- THULLER, W., LAVOREL, S., ARAÚJO, M. B., SYKES, M. T. & PRENTICE, I. C. (2005). Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences* **102**(23), 8245–8250.
- THULLER, W., LAVOREL, S., SYKES, M. T. & ARAÚJO, M. B. (2006). Using niche-based modelling to assess the impact of climate change on tree functional diversity in Europe. *Diversity and Distributions* **12**, 49–60.
- THULLER, W., MÜNDEMÜLLER, T., LAVERGNE, S., MOUILLOT, D., MOUQUET, N., SCHIFFERS, K. & GRAVEL, D. (2013). A road map for integrating eco-evolutionary processes into biodiversity models. *Ecology Letters* **16**, 94–105.
- THULLER, W., MÜNDEMÜLLER, T., SCHIFFERS, K. H., GEORGES, D., DULLINGER, S., ECKHART, V. M., EDWARDS, T. C. JR., GRAVEL, D., KUNSTLER, G., MEROW, C., MOORE, K., PIEDALLU, C., VISSAULT, S., ZIMMERMANN, N. E., ZURELL, D., ET AL. (2014). Does probability of occurrence relate to population dynamics? *Ecography* **37**, 1155–1166.
- TIKHOV, G., ABRIGO, N., DUNSON, D. & OVASKAINEN, O. (2017). Using joint species distribution models for evaluating how species-to-species associations depend on the environmental context. *Methods in Ecology and Evolution* **8**, 443–452.
- TOMIOLLO, S., BILTON, M. C. & TIELBÖRGER, K. (2020). Plant community stability results from shifts in species assemblages following whole community transplants across climates. *Oikos* **129**, 70–80.
- TRAN, T. T., JANSSENS, L., DINH, K. V., OP DE BEECK, L. & STOKS, R. (2016). Evolution determines how global warming and pesticide exposure will shape predator-prey interactions with vector mosquitoes. *Evolutionary Applications* **9**, 818–830.
- TRISOS, C. H., MEROW, C. & PIGOT, A. L. (2020). The projected timing of abrupt ecological disruption from climate change. *Nature* **580**, 496–501.

- TRISOS, C. H., MEROW, C. & PIGOT, A. L. (2021). Reply to: spatial scale and the synchrony of ecological disruption. *Nature* **599**, E11–E13.
- TURESSON, G. (1922). The genotypical response of the plant species to the habitat. *Hereditas* **3**, 211–230.
- TYLIANAKIS, J. M., DIDHAM, R. K., BASCOMPTE, J. & WARDLE, D. A. (2008). Global change and species interactions in terrestrial ecosystems. *Ecology Letters* **11**, 1351–1363.
- UMINA, P. A., WEEKS, A. R., KEARNEY, M. R., MCKECHNIE, S. W. & HOFFMANN, A. A. (2005). A rapid shift in a classic clinal pattern in *Drosophila* reflecting climate change. *Science* **308**, 691–693.
- VAN BOHEEMEN, L. A. & HODGINS, K. A. (2020). Rapid repeatable phenotypic and genomic adaptation following multiple introductions. *Molecular Ecology* **29**, 4102–4117.
- VAN DE POL, M., BAILEY, L. D., MCLEAN, N., RIJSDIJK, L., LAWSON, C. R. & BROUWER, L. (2016). Identifying the best climatic predictors in ecology and evolution. *Methods in Ecology and Evolution* **7**, 1246–1257.
- VAN DER VEKEN, S., DE FRENNE, P., BAETEN, L., VAN BEEK, E., VERHEYEN, K. & HERMY, M. (2012). Experimental assessment of the survival and performance of forest herbs transplanted beyond their range limit. *Basic and Applied Ecology* **13**, 10–19.
- VARELA, S., LOBO, J. M. & HORTAL, J. (2011). Using species distribution models in paleobiogeography: A matter of data, predictors and concepts. *Palaogeography, Palaeoclimatology, Palaeoecology* **310**, 451–463.
- VELOZ, S. D., WILLIAMS, J. W., BLOIS, J. L., HE, F., OTTO-BLIESNER, B. & LIU, Z. (2012). No-analog climates and shifting realized niches during the late quaternary: implications for 21st-century predictions by species distribution models. *Global Change Biology* **18**, 1698–1713.
- VERHEYEN, J., TÜZÜN, N. & STOKS, R. (2019). Using natural laboratories to study evolution to global warming: contrasting altitudinal, latitudinal, and urbanization gradients. *Current Opinion in Insect Science* **35**, 10–19.
- WALDVOGEL, A.-M., WIESER, A., SCHELL, T., PATEL, S., SCHMIDT, H., HANKELN, T., FELDMAYER, B. & PFENNINGER, M. (2018). The genomic footprint of climate adaptation in *Chironomus riparius*. *Molecular Ecology* **27**, 1439–1456.
- WALTHER, G.-R., POST, E., CONVEY, P., MENZEL, A., PARMESAN, C., BEEBEE, T. J. C., FROMENTIN, J.-M., HOEGH-GULDBERG, O. & BAIRLEIN, F. (2002). Ecological responses to recent climate change. *Nature* **416**, 389–395.
- WHITE, P. & KERR, J. T. (2006). Contrasting spatial and temporal global change impacts on butterfly species richness during the 20th century. *Ecography* **29**, 908–918.
- WILCZEK, A. M., COOPER, M. D., KORVES, T. M. & SCHMITT, J. (2014). Lagging adaptation to warming climate in *Arabidopsis thaliana*. *Proceedings of the National Academy of Sciences* **111**(22), 7906–7913.
- WILLIAMS, J. W. & JACKSON, S. T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* **5**(9), 475–482.
- WILLIS, S. G., HILL, J. K., THOMAS, C. D., ROY, D. B., FOX, R., BLAKELEY, D. S. & HUNTLEY, B. (2009). Assisted colonization in a changing climate: a test-study using two U.K. butterflies. *Conservation Letters* **2**, 45–51.
- WOGAN, G. O. U. & WANG, I. J. (2018). The value of space-for-time substitution for studying fine-scale microevolutionary processes. *Ecography* **41**, 1456–1468.
- WU, F., JIANG, Y., ZHAO, S., WEN, Y., LI, W. & KANG, M. (2022). Applying space-for-time substitution to infer the growth response to climate may lead to overestimation of tree maladaptation: evidence from the North American White Spruce Network. *Global Change Biology* **28**, 5172–5184.
- YATES, K. L., BOUCHET, P. J., CALEY, M. J., MENGERSEN, K., RANDIN, C. F., PARNELL, S., FIELDING, A. H., BAMFORD, A. J., BAN, S., BARBOSA, A. M., DORMANN, C. F., ELITH, J., EMBLING, C. B., ERVIN, G. N., FISHER, R., *ET AL.* (2018). Outstanding challenges in the transferability of ecological models. *Trends in Ecology & Evolution* **33**(10), 790–802.
- YEAMAN, S. (2015). Local adaptation by alleles of small effect. *The American Naturalist* **186**, S74–S89.
- YOUNGFLESH, C., SARACCO, J. F., SIEGEL, R. B. & TINGLEY, M. W. (2022). Abiotic conditions shape spatial and temporal morphological variation in North American birds. *Nature Ecology & Evolution* **6**, 1860–1870.
- ZOGRAFOU, K., GRILL, A., WILSON, R. J., HALLEY, J. M., ADAMIDIS, G. C. & KATI, V. (2020). Butterfly phenology in Mediterranean mountains using space-for-time substitution. *Ecology and Evolution* **10**, 928–939.
- ZURELL, D., BERGER, U., CABRAL, J. S., JELTSCH, F., MEYNARD, C. N., MÜNKEMÜLLER, T., NEHRBASS, N., PAGEL, J., REINEKING, B., SCHRÖDER, B. & GRIMM, V. (2010). The virtual ecologist approach: simulating data and observers. *Oikos* **119**, 622–635.
- ZURELL, D., ZIMMERMANN, N. E., GROSS, H., BALTENSWEILER, A., SATTLER, T. & WÜEST, R. O. (2020). Testing species assemblage predictions from stacked and joint species distribution models. *Journal of Biogeography* **47**, 101–113.

(Received 6 September 2022; revised 20 July 2023; accepted 24 July 2023)