A Novel Climatic Threat Framework Linking Biodiversity's Vulnerability to Administrative Responsibility.

Agustín Camacho Guerrero*[12], Alejandro E. Camacho[3], Jose Guerrero-Casado[4], Leonardo Vignoli[5], Juan de la Cruz Merino[6], & Francesco Cerini[7].

Email: agustin.camacho@uam.es

1 Departamento de Biología. Universidad Autónoma de Madrid, Fuencarral, España.

2 Centro de Investigación en Biodiversidad y Cambio Global, Universidad Autónoma de Madrid, Fuencarral, España.

3 School of Law, University of California, Los Angeles, USA.

4 Departamento de Zoología, Universidad de Córdoba, Córdoba, España.

5 Dipartimento di Scienze Ecologiche e Biologiche, Università degli Studi de Roma Tre, Italia.

6 Delegación Territorial de Sostenibilidad y Medio Ambiente. Córdoba, España.

7 Dipartimento di Scienze Ecologiche e Biologiche, Università degli Studi della Tuscia, Viterbo, Italia.

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Abstract

Biodiversity is now cornered by human habitat alteration and being dangerously eroded by climate change. Protecting it urgently requires the efficient allocation of conservation resources to protect vulnerable species and ecosystems. However, conservation decisions are often hindered by fragmented governance and a disconnect between policymakers, funders, managers and scientists. To address this, we propose the Climatic Threat and Responsibility approach to help allocate responsibilities and guide the use of adaptation funds. We rely on three key concepts: (1) Climatic Threat, defined as environmental conditions exceeding a species' realized historical niche at a given site; (2) Climatic Vulnerability, which encompasses a populations' sensitivity, exposure, adaptability, and resilience to climatic impacts; and (3) Administrative Climatic Responsibility, which proposes linking governance entities to conservation obligations based on the current and projected climate threats for species. Our framework ranks geographical locations more in need of climatic actions and administrative entities responsible for doing them based on: the amount of biodiversity value under climatic threat, the urgency to act, and the certainty of climatic threat. Based on these components, we present an R-based algorithm that maps species-specific exposure to climatic threats and, accordingly, ranks sites' climatic threat toward its inhabiting species. Additionally, it summarizes these threats across geopolitical regions to provide vital information relevant to each administration's climatic responsibility to preserve biodiversity. This system leverages species' realized climatic niches and multiple climatic scenarios within a present/near term time frame (2011–2040). Finally, we propose a trait-based ranking system to classify climatic vulnerability for local populations and guide adaptation actions, according to such ranks. This framework is intended to guide traditional climatic vulnerability assessments by flagging sites and populations for which such assessments should be prioritized, and offer managers an overview of assessments and measures needed. By uniting conservation practitioners, policymakers, and scientists, this framework aims to streamline adaptation funding and policies in a rapidly changing climate.

Keywords: Climate change, Climatic vulnerability, Climatic responsibility, Climate adaption, Climate threat.

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Introduction

Defending biodiversity against climatic impacts (Box 1) urges funders to swiftly allocate conservation funds among research and nature conservation actors (e.g., the European Climate-adapt partnership)(Ferraz *et al.* 2021; Habibullah *et al.* 2022). With the limited resources received, land administrators need to prioritize locations, species, and appropriate adaptation measures (e.g., regulating land use, minimizing harm to species, enhancing habitat quality, or directly supporting, moving, or replacing populations). For the defense of biodiversity to be effective, multiple actors (administrators, relevant managers, and scientists) need to speak a common language (e.g., Li *et al.* 2023) that facilitates shared understanding and effective collaboration to identify and prioritize conservation targets and ensuing adaptation measures.

Instead, the literature often focuses on the specific problems of each of these respective sectors. On one hand, scientists tend to focus on the technicalities of evaluating species climatic vulnerability (e.g., Clusella-Trullas et al. 2021; Ferraz et al. 2021; Pacifici et al. 2015; Tulloch et al. 2016). Meanwhile, on the other hand, funders and policymakers are often more interested in identifying the appropriate entities for allocating climatic adaptation funds and in implementing adaptation strategies (Boitan & Marchewka-Bartkowiak 2023; Brans 2022; Callahan & Mankin 2022; Rayer *et al.* 2023). This has led to key terms, such as climatic vulnerability, climatic risk, or threat, being conflated while representing different concepts (see section 2). This gap between conservation scientists and practitioners is an example of the "knowing-doing gap", which questions the utility of conservation biology as a practical science to provide useful solutions to conservation concerns (Knight *et al.* 2008). As a response, studies are starting to look for ways to integrate conservation within multiobjective frameworks that account for local social and economic aspects and include managers and stakeholders in the conservation planning process (e.g. (Deléglise *et al.* 2024; Nel *et al.* 2016).

Determining where to direct adaptation funds is complicated by multiple possible goals and priorities for land use and conservation actions, some of which are in tension with each other. First and foremost, there is a variety of funds available with different goals. To name some: the protection of endangered species (Bin Zayed conservation trust), the increase in the amount of protected land and its quality for native species (Kumming-Montreal Convention on Biological Diversity) the adaptation of biodiversity conservation to climate change (European LIFE program). Even when the goal is protecting biodiversity from climatic erosion there are multiple possible priorities. For example, some advocate for the conservation of phylogenetic diversity (Tietje *et al.* 2023) or geographical areas where significant concentrations of endemic species are experiencing substantial habitat loss (Myers *et al.* 2000); others push for the preservation of ecosystem services (Guerra *et al.* 2022), the ecological functions of local assemblages (Auber *et al.* 2022), cost effective conservation of the maximum amount of species (Ando *et al.* 1998), or a combination of conservation of threatened species, carbon retention and water quality regulation (Jung *et al.* 2021). Within the 2050 Goals of the Kummings-Montreal Global Biodiversity Framework, all such facets of biodiversity are mentioned. Furthermore, even if there were agreement on which of these forms of biodiversity protection to prioritize, the relative prioritization of each potential species, service, or function may remain unresolved.

Nonetheless, it may be reasonably agreed that populations are essential units in which eco-evolutionary processes take place (e.g., Fraser & Bernatchez 2001), and that ecological functions and ecosystem services depend on population dynamics of species involved in them (e.g., (Kremen & Ostfeld 2005). In addition, there is the global aim of keeping the abundance of populations to healthy levels in view of lowering their extinction risk (Conference of the Parties to the Convention on Biological Diversity 2022). Thus, whenever funders allocate specific resources to protect biodiversity against climatic erosion, focusing on actually climatically threatened populations of relevant species should contribute to a multi-objective approach for preserving biodiversity against climatic erosion.

Still, evaluating the climatic vulnerability of populations is a highly technical, multifaceted process (e.g., Foden et al., 2016). Measuring its different components (traditionally, Exposure, Sensitivity, Adaptability, see Box 2) requires implementing such costly approaches that often only one or some components are measured, making the outcomes hard to compare (Kling *et al.* 2020; Pacifici *et al.* 2015; Wheatley *et al.* 2017). A major limitation is the focus on entire species rather than on populations, despite the fact that climatic vulnerability varies among populations within a species' range (E.g., Gunderson and Leal, 2012; Camacho et al., 2023). While endemic species with narrow distributions are generally the more vulnerable ((Pearson *et al.* 2014), assessments that tag species as climatically vulnerable or not may obscure regional differences, particularly in species with large distribution areas. Climate shifts might promote a species in one geopolitical region and make it vulnerable in another. Besides, vulnerability assessments demand extensive data, often collected through field studies, which makes them rarely feasible across an entire species' range (Wheatley et al., 2017).

The technicalities of climatic vulnerability assessments also clash with the practicalities of funding allocation and on-the-ground conservation efforts (Clusella-Trullas *et al.* 2021; Gardali *et al.* 2012; Tulloch *et al.* 2016). Firstly, the components of climatic vulnerability are undergoing an intense process of redefinition and refinement (e.g., Beever *et al.* 2016; Seaborn *et al.* 2021, Hespanhol; 2022; see Box 2). Second, climatic vulnerability maps created through species distribution models are often questioned because uncertainties in their parameterization alter the geographic extension of regions where climate induces vulnerability (Camacho *et al.* 2023b; Soley-Guardia *et al.* 2024). Such uncertainties weaken the utility of such models in guiding conservation planning (Ferraz *et al.* 2021). Additionally, uncertainties in climate projections further complicate vulnerability maps, raising concerns about their reliability (Carvalho et al. 2022). Without objective and clearly communicable measures of actual climatic threats over biodiversity, the credibility and effectiveness of climatic adaptation measures may be questioned, potentially eroding public trust (Treen *et al.* 2020).

Nonetheless, funding and implementing climatic vulnerability assessments remain critical for ensuring the persistence of relevant species' populations at sites where they are threatened by climate change. A wide array of techniques to assess and address climatic vulnerability has been developed (e.g., Foden & Young 2016). While these methods are valuable for experts in field techniques of wildlife management (i.e., researchers, biologists, veterinarians), they often lack the practicality needed by conservation practitioners and policymakers. This is because preserving biodiversity typically depends on factors that go beyond the scope of biological expertise but rather implicate socioeconomic factors that shape governance's legal adaptive capacity to climate change (Camacho & Glicksman 2016). In this context, land administrators need to mediate between scientists and technical experts, higher-rank or politically elected managers, and other affected interests. Only through such interactions throughout plan funding, development, monitoring, and revision is it possible to implement effective conservation actions in light of the overlapping thicket of regulations, shared and non-shared competences, fragmented land ownership, and social willingness to support specific conservation actions. Fortunately, methods have been developed to document and leverage the socioeconomic climatic adaptive capacity (E.g. (Rosengren *et al.* 2020; Wade *et al.* 2017)).

Given the multidisciplinary nature of the climatic problem, we contend that less technical frameworks are needed. Such a framework should include at least two vital traits. it should provide means for scientists and policymakers to discuss upon how to geographically allocate climatic adaptation funds for biodiversity conservation ((Watts *et al.* 2017). Second, it should offer brief guidelines for scientists and policymakers to agree upon what to do at climatically threatening sites, based on objective criteria and measurable evidence. Our framework presents both, including an R script to map climatically threatening sites and administrative responsibility and an objective framework to address climate threats to species' populations *in situ*. Yet in order to make them useful, it becomes necessary to clarify some key concepts.

2. Disentangling key concepts for effective adaptation of biodiversity conservation to climate change.

Effective communication among managers is essential to clarify who is responsible for receiving and administering conservation funds. Such decisions can be challenging because they are taken within a conservation governance framework that is largely decentralized, uncoordinated, and overlapping (Fischman & Hyman 2010). Regulatory fragmentation often occurs when multiple agencies—such as national and provincial authorities—share responsibility for endangered species protection (Camacho & McLachlan 2021). Addressing these challenges requires improving inter-jurisdictional coordination (Camacho & Glicksman 2019).

In this context, if a vulnerable species is endemic and confined to a single geopolitical jurisdiction, determining responsibility for its conservation—and the corresponding funding allocation—is straightforward. However, often species have current or projected distributions that span multiple geopolitical jurisdictions (e.g., national or sub-national divisions) (Mason *et al.* 2020). Protecting those species involves determining relative responsibilities and derived action burdens across administrations (e.g.,(Keller & Bollmann 2004), and thus funding allocation becomes more complex.

To help navigate these complexities, we introduce the concept of **administrative climatic responsibility**. This is defined as the legal obligation of a land management or conservation agency to adapt its management practices to climate change. Traditionally, environmental responsibilities have been shaped by existing land management laws, which often emphasize either (1) historical preservation, i.e., maintaining or restoring ecosystems to a pre-existing baseline; (2) natural preservation, i.e., minimizing human intervention, or (3) ecosystem service maximization, i.e., optimizing benefits such as timber production and carbon sequestration through forest plantation (Reside et al., 2018; Camacho, 2020). However, national and international regulations have started to describe specific administrative obligations regarding climate change (E.g., National Forest Management Act/2012; the EU Regulation 2024/1991). Of course, traditional strategies may already support some forms of biodiversity conservation. For example, populations of forest dependent species and social actors (E.g., wood farmers) may benefit from carbon sequestration forests and, in parallel, be detrimental to populations of species that require open fields and other social actors (E.g., cattle farmers). While climate change increasingly places historical preservation, natural preservation, and ecosystem service maximization in tension with promoting biodiversity conservation, administrators nonetheless may be able to interpret existing laws in ways that still advance Biodiversity conservation (Camacho 2020).

In our view, administrative climatic responsibility should be directly linked to sites and “relevant” species’ populations affected by climate change, commensurate with three key factors: (1) the number of “relevant species” with populations under climatic threat (see “relevant” definition below); (2) the number of climatically threatening sites for populations of these species that the administration manages; and (3) the certainty that these populations are under climatic threat at such sites. Based on that premise, a tool that maps the geopolitical distribution of these factors and their spatial overlap should help conservation funders and/or administrators determine administrative climatic responsibility more efficiently and effectively.

Building effective administrative climatic responsibility is key to support a Climate-Smart Conservation framework, (Bagne *et al.* 2011; Stein *et al.* 2014). This framework seeks to promote proactive conservation based on three key criteria addressed in this manuscript: (1) linking conservation actions with climate impacts; (2) integrating evolutionary and ecological adaptation into existing conservation goals; and (3) using forward-looking, flexible strategies. To achieve these aims, it seems essential to sharply identify sites inhabited by **relevant species**' populations affected by climate change and relate them to the responsible land administration. Here, "relevant species" include organisms (i.e., animals, plants, fungi, etc.) identified under applicable laws as requiring public management and/or regulation of private activity for their conservation. Under most legal regimes, relevant species will include those deemed threatened (e.g., listed in the IUCN's or regional red list species), keystone species, and/or otherwise of ecological and/or socioeconomic interest.

In most legal contexts, unfortunately there still remains insufficient legal guidance and potential conflict over the particular way to effectuate biodiversity conservation in the context of climate change (e.g., which populations to preserve, which ones to move, or where to move them). As such, it will often be essential that managerial determinations of "relevant" species are subject to (1) democratically informed standards clearly defining and operationalizing "biodiversity conservation" in light of climate change, and (2) clear and open decision-making processes for reconciling any conflict over such standards between jurisdictions (Camacho 2020).

To operationalize the use of climatic administrative responsibility in order to manage populations of relevant species under climatic threat, it is essential to disentangle the concepts of **climatic threat**, **climatic unsuitability, climatic vulnerability, and climatic risk.** These terms have been used with varying meanings by different authors (e.g.,(Chowdhury *et al.* 2021; Gomides *et al.* 2021; Tulloch *et al.* 2016). Climatic threat simply refers to climatic conditions at a location that could, potentially, put one or more species' populations at a serious disadvantage (e.g., Murali et al., 2023). Thus, populations of relevant species inhabiting a site which is climatically threatening for them require proper assessment at such site and, if deemed necessary, prompt conservation measures. In this way, we argue that climatically threatening sites for relevant species should induce administrative climatic responsibility on the entities managing them.

Climatically threatening conditions can be objectively characterized for any species using a well-established concept in ecology: the realized niche range. Namely, the range of conditions that occur across a species' geographic range (Holt 2009). The geographic range, and thus the realized niche, of any species is constrained by an interaction of climatic tolerance, dispersal barriers, ecological interactions, and/or resource availability (Araújo & Peterson 2012; Rödder *et al.* 2017). Therefore, conditions can be reasonably defined as climatically threatening for a species when predicted present and/or near future climatic variables exceed the current known climatic niche limits within which the species is observed. Even more extreme conditions might not in fact pose problems for that species. Some species may tolerate even more extreme conditions than those represented in its realized niche (Soberón & Arroyo-Peña 2017). Yet, if a species suffers from any climatic disadvantage (see examples below), it will most likely happen at sites outside of its known climatic niche range.

Climatic threat should not be confounded with climatic unsuitability, climatic vulnerability, or climatic risk. For example, species distribution models often label sites outside the realized niche as climatically unsuitable sites, sites of climatic vulnerability, or sites at climatic risk for the studied species. However, such labelling is misleading for many reasons. First, climatic threat differs from climatic unsuitability or vulnerability because many species can inhabit conditions beyond their realized niche (e.g., invasive species;(Broennimann *et al.* 2007). Second, populations located at climatically threatening sites may still not be climatically vulnerable because climatic threat only addresses one of the three components of climatic vulnerability (Exposure, see Box 2). Third, climatic threat is not climatic risk because the latter represents the probability of a deleterious climatic event happening multiplied by the magnitude of its harm . In this case, again, the harm is not known for climatically threatening sites without further site-specific investigations. As recognized by (Juárez *et al.* 2013), even in the case of extreme events (droughts or floodings), they might be a 'catastrophe' for some species but create a bonanza for others. Finally, geographic models often label sites as suitable while many of which may not even be occupied by populations of a given species. In this context, climatic threat serves as an objective tag, indicating that assessments are needed at sites where species are factually present, which may be under climatic vulnerability or risk, and thus require local assessment.

Another essential clarification to connect administrative managers and technical experts is to separate the meanings of **species and population climatic vulnerability**. In the field of biodiversity conservation, a widely accepted definition of climatic vulnerability is: "the extent to which a species or population is threatened with decline, reduced fitness, genetic loss, or extinction owing to climate change" (Dawson *et al.* 2011). This definition includes important and correlated processes and assumes different levels of vulnerability. However, a similar definition for both species and populations may hamper resource allocation and urgent conservation actions. This problem arises from the fact that populations' tolerance and exposure to hazardous climatic conditions will often vary across a species' geographic range

(Gunderson & Leal 2012). This has the consequence that inferring the climatic vulnerability of an entire species using estimates made for a single or a few populations likely introduces artefactual under or over-estimations of the whole species' climatic vulnerabilities. Also, when multiple administrations compete for resources to protect a species against climatic erosion, this geographic variation in vulnerability should be taken into account when applying the available resources. To avoid this problem and guide more feasible climatic adaptation actions at the population level, we propose focusing on **climatically vulnerable populations**: populations that show a factually demonstrated disadvantage to persist, without human help, due to ongoing climatic trends (e.g., lower reproduction/survival/occupancy rates compared to other sites of their habitat).

In contrast, defining a **climatically vulnerable species** poses several difficulties (see Box 2). It could be defined as one species that is declared as climatically vulnerable for over 50% of its geographic range, based on IUCN's A criterion for population decline. Still, applying this criterion is complicated by the fact that species may experience reductions in one part of their range and expansions in the other, which are hard to estimate (e.g., (Mancini *et al.* 2024). Besides, for small ranged species, a 50% loss in total available range might be too much to guarantee its persistence in the wild. Thus, managers and technical experts from all relevant jurisdictions, subject to robust public input, should be required to coordinate on what to do to best promote biodiversity conservation in each case.

In the following section, we outline how to identify climatically threatening sites and compare climatic responsibility to allocate climatic adaptation funds for species' conservation. In general, any time a national or regional funding institution wants to fund actions to alleviate or reverse harm to biodiversity due to climate change, such institution could apply our algorithm to promote biodiversity conservation, or obtain it at www.vulneraweb.com. Project proponents could use it too to inform choices on potential conservation measures for a site.

To be clear, we do not assert that administrative climatic responsibility should only be calculated by estimating the climatically threatened populations of relevant species and sites upon which to act under each geopolitical jurisdiction. Instead, we argue that this estimate should be an essential component to calculate the administrative responsibility, and the related burden, of protecting biodiversity against climate shifts. The relevant administration in each case can gauge this component in the context of other important components worth of climate adaptation. Examples of those include: ecosystem services provided by species in the area, cultural values associated with wild populations, legal aspects and implementation costs, or the economic consequences of climate change and/or inaction in buffering strategies.

3. Ranking Climatic Threat and Administrative Responsibility across species, sites, and geopolitical limits.

Geopolitical boundaries do not typically exist in nature, yet climatic adaptation funds must be allocated across geopolitical space. This requires linking administrative entities to their responsibilities for biodiversity conservation against climate change. To ease this task, we propose a Climatic Threat and Responsibility Ranking (CTRR) system. This system calculates both the climatic threat a portion of land poses to species populations and the administrative responsibility of the entity that manages these sites to address climatic threats. For practicality, we define a ‘site’ as a geographical unit delimited by a reference climatic database. Climate data are typically stored as raster images, where each pixel represents a geographic area of 1-5 km^2 (Karger *et al.* 2017). This spatial subdivision enables highly precise, geographically targeted actions. Species recorded within each pixel’s boundaries are considered as inhabitants of that site under current climatic conditions. The actual extents of natural populations are hard to delimit accurately (Elsen *et al.* 2023). Thus, focusing on sites allows the application of objective criteria to rank these areas across administrative subdivisions to send funds to support later on-ground assessments that can identify these limits and other relevant information.

The CTRR system is based on three criteria to rank climatic responsibility: 1) the biological "value" of the attribute of concern (following Tonmoy *et al.* 2014), 2) the relative "urgency" for undertaking climatic adaptation measures, and 3) the "certainty" of such urgency. To rank sites according to these criteria we created an algorithm using the open-source coding language R (rproject.com). Specifically, the algorithm proceeds as follows:

A. Determining species exposure to Climatic Threat (CT_{exp})

Our algorithm first estimates the limits of the realized historical climatic niche range of each species of a species pool (e.g., the IUCN's red list of any given taxon) and later compares it with expected climates across all known sites of each species.

Step 1: Collecting Geographic and Climatic Data.

We need to feed the algorithm with a csv or excel file containing all the known geographic locations for each species of the pool of interest (Figure 1, Panels 1 and 2). This information can be obtained from available occurrence data from any database of choice (e.g., the Global Biodiversity Information Facility -GBIF, the Oceanic Biodiversity Information System-OBIS (Halpin *et al.* 2009; Telenius 2011), or any other, after proper data cleaning). Then, the user imports a set of climatic raster layers deemed relevant for the species' ecology. They can be obtained at a climatic database of preference (e.g., ecoclimate, Worldclim, Chelsa, Marspec, Biooracle (Hijmans *et al.* 2005; Karger *et al.* 2017; Sbrocco & Barber 2013; Tyberghein *et al.* 2012), Figure 1 Panel 3). Our supporting online file includes the algorithm with an example using annual maximum and minimum temperatures, and precipitation, but any can be imported. It is though important to import the same baseline layers for the recent past and the present-near-term future (e.g., maximum and minimum temperatures and precipitation for 1981-2010 versus 2011-2040, in our supported online file). The algorithm extracts climatic values for the selected variables at each species' registered location.

Step 2: Calculation of Climatic threat exposure.

In sequence, when the R algorithm runs, it extracts, for each species, the most extreme value for each of the selected climatic variables among the values obtained across all the geographic locations (e.g., the hottest of the maximum temperatures, the coldest of the annual minimum temperatures, Figure 1, Panel 4). Those values represent the limits of the realized historical niche of that species for those variables and are obtained from a baseline climatic database (1979-2013)(Karger *et al.* 2017). Using the 98th or 95th percentile to estimate niche limits leaves out outliers for characterizing the niche limits, making it more probable to find more populations under threat but which are actually in good conditions. Also, these outliers could very well be vicariant and highly endangered populations and thus have different tolerances or ways to withstand climatic vulnerability. Using the extremes, as we did, limits the number of sites considered under threat to the ones that can be most threatened due to climate change. Finally, the niche limits of species with very few locations would remain very narrowly characterized. These populations could be sometimes unsalvable, but that would be addressed with the climatic vulnerability assessments (see section 3).

After estimating historical niche limits, species' geographic locations are aggregated to the climatic database spatial resolution. This means that, for each species, all presence points falling within the climatic database' pixel count as one site for that species and obtain the same value for any of the variables used; Figure 1, Panel 6). Then, for each of the sites that each species is known to occupy, our algorithm compares the species' niche limits with the expected values of the same climatic variables for the present-near future time interval 2020-2040 (Brun *et al.* 2022). In each of those sites, the expected values are extracted from six different climatic scenarios. In our algorithm, the scenarios combine two carbon emission levels (low: 126ppm and high: 585ppm) and three global circulation models obtained at CHELSA database (gfdl-esm4, ipsl-cm6a-lr, ukesm1-0-ll, Karger *et al.* 2017))(Figure 1 Panel 7). These scenarios also can be customized by the user, but at least six are recommended to estimate uncertainty in predictions (Karger et al., 2017). In this way, a site is flagged as climatically threatening if any of the climatic conditions for 2011-2040 exceed the realized historical niche limits of the species it hosts, in any of the scenarios (Figure 1 Panel 8).

After identifying all threatening sites for all desired species, the exposure to climatic threats ($SpCT_{exp}$) is calculated for each species across the selected geographic boundaries. Here, $SpCT_{exp}$ is the proportion of climatically threatening sites relative to the total species' known sites, across the whole region of interest. This allows to proceed to step 2, where climatically threatening sites are ranked according to the above mentioned three criteria.

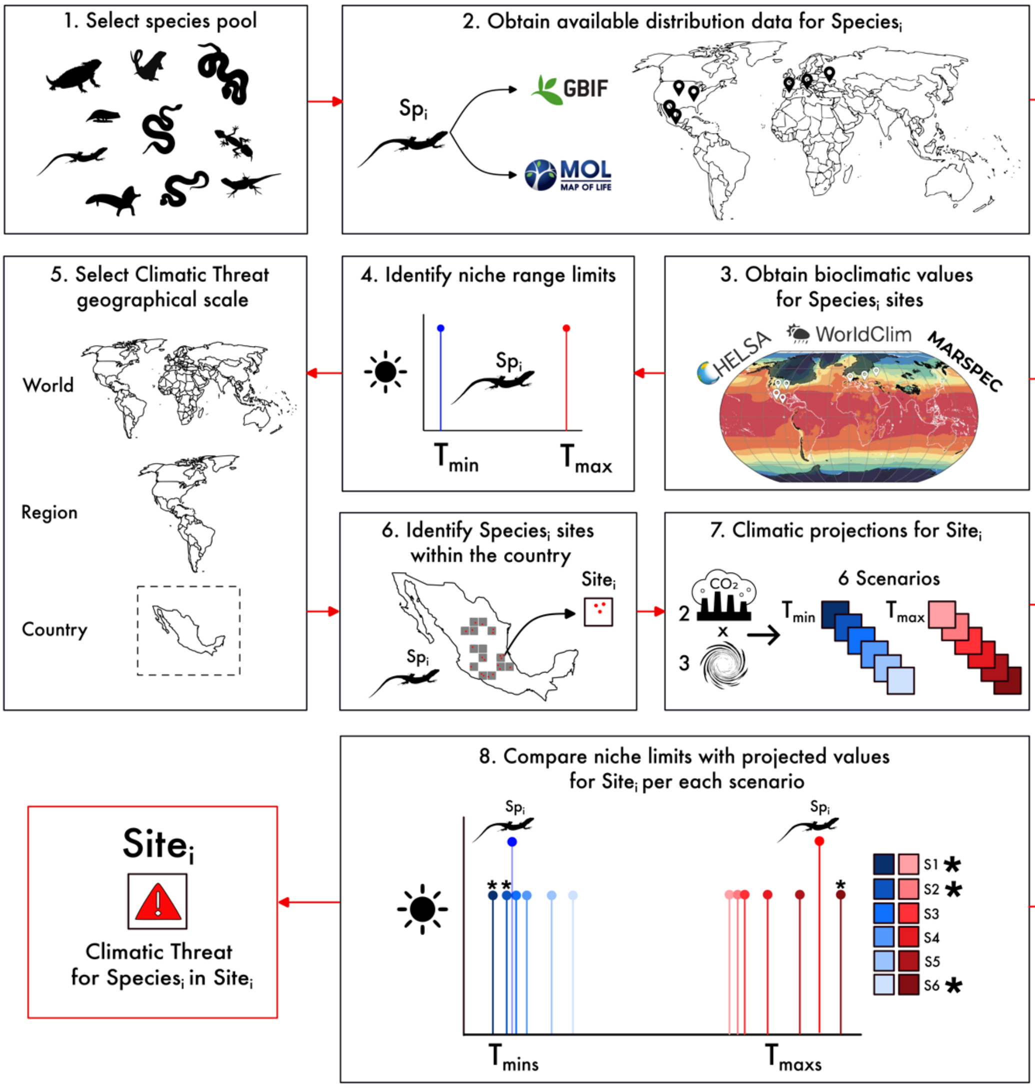

Figure 1. Steps to identify Climatic Threats. *Select a relevant species pool (Panel 1), obtain as many and as much verified distribution data as possible for these species (Panel 2), obtain each species (Sp$_i$) historical climatic data for each known location, located as a (Site$_i$) of a climatic database (Panel 3), and then determine limits for historical climate data (e.g., maximum and minimum annual temperatures across each species' range) (Panel 4). Next, select the geographical scale to rank climatic threats across such scale and species' locations (Panel 5). In this example we do it at the country scale selecting a random country (Mexico) where species of the exemplary*

species pool occur. The species locations are aggregated to sites, following the climatic database geographic resolution (e.g.,10 km^2) (Panel 6). The sites depicted in the figure map are much bigger for visual clarity. For each site, near future temperature projections (2021–2040) are obtained under six scenarios combining two carbon emission levels and three circulation models (Panel 7); the different shades of red and blue of the squares represent respectively higher and lower values of both the maximum and the minimum temperature estimated values for the future in each scenario. Finally, these future temperature values are compared to the limits of the species thermal niche (Panel 8). If maximum or minimum projected values exceed the historical species' niche limits under one or more scenarios, the site is flagged as climatically threatening. Threatening scenarios are marked with an asterisk, indicating a climatic threat for Sp_i *at* $Site_i$*. Our algorithm (see online complementary file) calculates steps 3 to 8.*

B. Ranking climatic threats across sites.

This step involves calculating a site's Climatic Threat Rank (CTR) by combining three objectively measured components (Figure 2, Panel 2):

- *Value (site):* the site's value for the conservation of the species pool, determined by the proportion of the species' pool that is climatically threatened at that location (e.g., six out of ten species).
- *Urgency (site):* the urgency to act in that site, calculated as the average CT_{exp} of the species inhabiting the site.
- *Certainty (site):* at each site, the certainty of climatic threat is calculated for each species and then averaged across the species inhabiting that site. First, we calculate the proportion of climatic scenarios that predict threatening

condition across all the considered bioclimatic variables. For instance, if we use temperature and precipitation as descriptors of the niche range of the species, each species will have estimates of the maximum and minimum values of those climatic variables (Figure 1). In a given site, if three out of the six scenarios predict that the maximum temperature will exceed the species' "tolerance", the probability of threat for the species for that variables will be 0.5. Then, certainty for each species is represented by the highest proportion estimated across the different bioclimatic variables evaluated. We do this to focus on sites with the highest certainty of threat (i.e., even under low emissions scenarios), independently of the variable that induces it. These ranks could be calculated across regions occupied by a single relevant species, too, by simply entering a list of one species and a territory of interest. In some cases, particularly when addressing large species pools, sites with lower certainty ranks could still be deemed very important for the conservation of particular species, or simply due to practical considerations given the existing resources and limitations.

Others have proposed reliance on a few understandable criteria when addressing populations' vulnerability (Gauthier *et al.* 2010). Our method, however, is specifically designed for climatic threats, does not depend on field studies of abundance, separates their measure of "responsibility" into value and urgency, and also includes measures of certainty, providing more facets to negotiate and plan for conservation against climate change.

Traditional methods based on species distribution models (SDMs) map potentially suitable habitats by correlating species' occurrences with climate and other layers under multiple models and assumptions (Araújo & Peterson 2012; Booth *et al.* 2014; Mancini *et al.* 2024; Patiño *et al.* 2016). Instead, our algorithm focuses only on reportedly occupied sites where climatic conditions are expected to reach beyond a species' realized historical niche. Thus, it does not make use of species' models and related assumptions and parameterization that strongly affect the mapped areas.

Our method also differs from recent models focused solely on heat extremes (e.g., Murali et al., 2023) by allowing researchers to incorporate any climatic niche descriptors deemed relevant, such as annual precipitation or sea level changes. Additionally, by incorporating methodologies from Karger et al. (2017), our algorithm makes predictions for the present or near-term (2011-2040) rather than distant projections (e.g., 2050-2100), which are typically more uncertain but very often used. This shorter time horizon helps identify immediate conservation funding priorities and address urgent biodiversity threats.

C. Calculating the Administrative Climatic Responsibility Rank (CTRR).

This step evaluates the administrative climatic responsibility for conserving the species pool by aggregating the same three components across a set of politically or administratively divided geographic regions (Figure 2, Panel 3):

- *Administrative Value:* the proportion of species pool found across the land under the responsibility of an administration (e.g., a province, a country).
- *Administrative Urgency:* the average CT_{exp} for species within the administration.

- *Administrative Certainty:* the average of the proportion of climatic scenarios indicating existing threatening conditions across all sites and species in the administration.

Sites or administrative regions with higher ranks, calculated through this method, represent regions of greater biological value under more urgent and certain need of climatic adaptation measures.

The CTRR can be applied to any species pool in any biological taxa. Yet reliable occurrence data are critical. It is worth noting that, for taxa with high dispersal abilities (e.g., birds), distinguishing transient sighting from established population is essential for accurate niche estimation and definition of sites requiring measures. Besides, in some cases the advance of taxonomic knowledge causes readjustments of the geographic distribution of attributed names to species. In other instances, human translocation of species, or keeping them at zoos or botanic gardens may render locations that do not reliably represent the species' realized historical niche. Thus, following expert advice may be done by using distribution polygons from IUCN or a specialized taxonomic Atlas' to crop locations obtained at the GBIF. There are also protocols to clean other nuisances typical of geographic records (E.g., (Hijmans & Elith 2014; Johnston *et al.* 2020)).

The CTRR framework fully depends on the comprehensiveness of the representation of sites holding populations of each evaluated species. When the records dataset of a species has less sites than actually occupied by a species, the CTRR gives this species a higher importance than it should when ranking urgency for action and also will not indicate sites where the species could be losing populations. Because of that, incorporating quality-checked records from citizen science platforms and taxonomical societies (e.g., Observation, Fishbase, etc) may be paramount for a better ranking of sites where to save populations from climatic extirpation.

The CTRR calculation is simple but highly customizable. The provided script (See Supplementary Material) allows users to adjust the weighting of urgency and/or value, if desired. This allows including variables such as IUCN threat categories (Mancini *et al.* 2024) to amplify the rank of sites with higher number of more threatened species, if desired. Furthermore, administrative climatic responsibility can be evaluated at any geographic or administrative scale of interest, limited only by the spatial resolution of the necessary datasets (i.e., climatic and species occurrence data). For example, conducting the CTRR calculation at the regional scale (e.g., South America) using a species pool shared by multiple countries would allow for identifying the country with the highest administrative responsibility. This country could then be prioritized to receive international funding to conduct detailed on-site assessments of vulnerable populations. Such flexibility makes the CTRR a valuable tool for decision-makers, facilitating effective fund allocation—whether within an ecoregion, a large protected area, among provinces, or across international boundaries (as demonstrated in our example; see Figures 1 and 2). Thus, there are no limits to data scalability of our approach as long as one has enough occurrence data within defined geographic boundaries (regions, countries, provinces, protected areas boundaries etc.).

The results of our algorithm can be also used in cases when there is a need to design the generation of reserves for Biodiversity conservation, for example within programs such as Marxan or Zonation, which combine estimates of biological value and costs into reserve design. Our algorithm provides estimates on the conservation value of sites with respect to climatic threats, and also if there is a high level of climatic threat and thus of costs to achieve the desired goal of preserving particular species, given the costs of the assessments and potentially needed measures (see (Watts *et al.* 2017)).

Finally, because species distribution models are not used, the algorithm calculating CTRR is not too computationally demanding. As an example, one notebook calculated CTRR for all species in the Habitats Directive annex II across whole Europe in a few seconds, after thousands of occurrence data were downloaded (AC, pers. Obs).

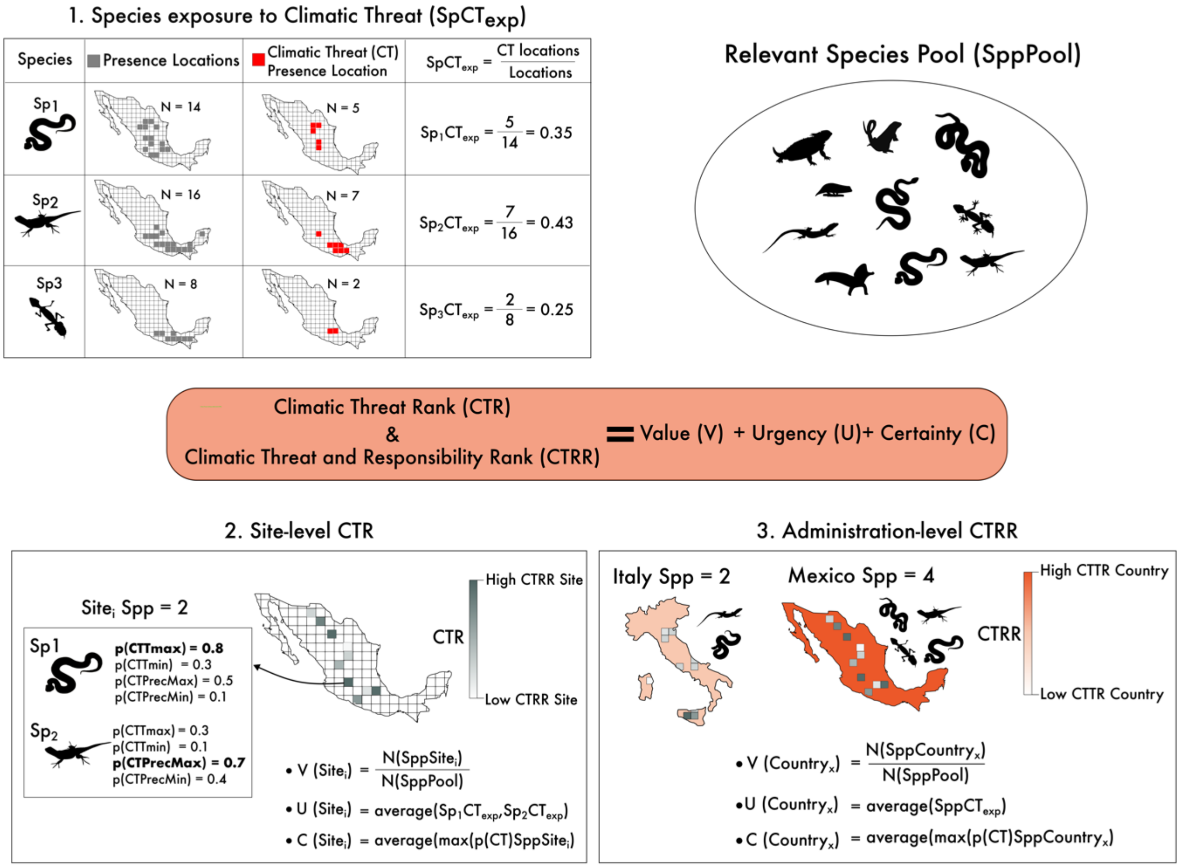

Figure 2. Ranking Climatic Threat Exposure for species and Climatic Threat and responsibility for sites and geopolitical administrations. *Panel 1 depicts how to calculate species exposure to climatic threat ($SpCT_{exp}$), that is the proportion of climatically threatening sites out of all known presence sites for each species, in our example, within a country. The squared grid represents a virtual division of geographic space made according to the climatic layers used by our algorithm (e.g., 5-10 km^2, see section 2); the sites depicted in the figure map are much bigger (i.e., approximately 100x100 km^2) for visual clarity. Panel 2 shows how to rank sites according to the site value (V) for conserving the relevant species pool, the urgency (U) with which species inhabiting that site require actions, and the certainty (C) that these*

species are under climatic threat. The terms "p(CTTmax)", "p(CTTmin)", "p(CTPrecMax)" and "p(CTPrecmin)" represent the proportion of climatic scenarios under which the values of minimum and maximum temperatures, and of annual precipitations, respectively, are expected to fall outside of the species' realised climatic niche range, in that site (Site$_i$*). Then the certainty (C) of climatic threat for Site*$_i$* is calculated as the average of the maximum values of such proportions (highlighted in bold) among the inhabiting species. Panel 3 illustrates how to calculate administrative climatic responsibility rank for a geopolitical region (a country) using the same concepts and procedure. At the country scale, the value (V) represents the proportion of the species pool harbored by the geopolitical region. Urgency (U) is represented by the mean climatic threat exposure measured across all species harbored by a geopolitical region. Certainty (C) is calculated by averaging the certainties measured across all the climatically threatening sites found within the geopolitical region considered. "Sp" refers to single species measures, "Spp" refers to multiple species, such as when doing the averages across multiple species. The terms "Site*$_i$*" and "Country*$_x$*" generalize the site and country applicability.*

This system makes explicit the biological attribute of concern (number of species exposed to Climatic Threat), the hazard (climate-dependent population crash), and the timeframe (present to immediate future). By doing that, the CTRR aligns well with existing conceptual frameworks for climate change assessments (Füssel 2007). Its intuitive structure—value, urgency, certainty—ensures understandability for researchers, policymakers, and funders, hopefully facilitating agreement and coordinated action. Besides, the algorithm could also be used without the rest of the framework, for example, to render comparative studies of climatic threats (AC, under preparation).

Critically, the CTRR approach does not replace other conservation prioritization methods, such as evaluating species' climatic vulnerability, or maximizing phylogenetic and functional diversity or ecosystem services (Auber *et al.* 2022; Foden *et al.* 2019; Guerra *et al.* 2022; Advani 2023). Instead, it complements them by ranking sites by the number of relevant species experiencing more certain climatic threats. Our approach and algorithm serve as a mapping system with two primary purposes: I) to identify responsible entities for climatic adaptation actions aimed at biodiversity conservation (Figure 2) and II) to promote focused multidisciplinary assessments at flagged sites to determine the necessity of conservation actions.

4. What to do at climatically threatening sites to preserve species' populations.

On-site assessments to determine the stage of climatic vulnerability

If an administration identifies climatically threatening sites for species within its jurisdiction, it should start multidimensional assessments of the climatic vulnerability of the corresponding relevant species populations. Climate Change Vulnerability Assessments (CCVA, see (Foden *et al.* 2019)) leverage field research, online data bases, theoretical frameworks to guide reliable predictions of species' responses to climate in that area (e.g., GLOBTHERM or Essential Biodiversity Variables, (Bennett *et al.* 2018; Camacho *et al.* 2024; Fernández *et al.* 2020, see introduction for reviews on types of procedures). To facilitate communication with the technical experts that should execute these evaluations, and help them navigate the plethora of approaches and concepts (Foden et al., 2019), we outline below a set of essential assessments that can guide tailored conservation actions:

- ***Thermo-hydroregulation assessment.*** This evaluation aims to determine whether the population is able to avoid deleterious abiotic conditions and obtain the necessary levels of water or humidity to reproduce and maintain its population (Paquette & Hargreaves 2021). Multiple stressors (.eg., land use, fire) can cause habitat alterations that negatively interact with climate change (e.g., by removing or degrading thermal refuges or water/humidity sources). Physiological tolerance to climatic conditions interacts with different types of pollutants in complex ways (e.g. sublethal doses of pesticides (Gonzalez *et al.* 2022; Op de Beeck *et al.* 2017)). Thus, these aspects need to be considered during thermohydroregulation and the other assessments in the field.

- Interaction assessment. This assessment identifies whether current or climate-induced future conditions in intra- and/or inter-specific interactions (symbiosis, predation, competition, parasitism (Paquette & Hargreaves 2021);(Gomides *et al.* 2021) could result in negative population trends (e.g., Paniw *et al.* 2019; Wheatley *et al.* 2017). Conservation technicians performing interaction assessments for animal species could leverage the biotic interaction focused vulnerability scores used within the SAVs (from System for Assessing Vulnerability of Species, (Bagne *et al.* 2011)).

- Genetic assessment. This is necessary to identify, if possible, more tolerant individuals, or neighboring populations, that could support the persistence or genetic rescue of the population living in the climatically threatening site. To achieve this, managers can examine local (Drury *et al.* 2022) or geographic variation in tolerance (Hertz *et al.* 1979), or perform genetic diversity assessments (Hoffmann *et al.* 2015). Genetic diversity provides the essential material for local adaptation to environmental changes but this metric still needs to be used with care: it may be increased by cross breeding with exotic lineages ((Chan *et al.* 2019; Wade *et al.* 2017)), but that could bring in other problems for processes of local adaptation to current environmental trends (e.g., diseases, new susceptibilities).

- Resilience assessment. Managers should understand the ecological requirements, recovery options, and expected timeframes for the natural or assisted restoration of population size, growth rates, or function levels following potential crashes (Capdevila et al. 2020; Medeiros et al. 2021; Nattrass & Lusseau 2016; Oliver et al. 2015). These factors should be assessed in the context of current and near future local climate conditions. Additionally, the feasibility of assisted immigration of suitable individuals should be carefully evaluated (Fritts *et al.* 1997; Whiteley *et al.* 2015), alongside the need for and viability of population migration to other locations or administrative jurisdictions (Camacho 2010). Population resilience is intrinsically related to habitat connectivity because, once extirpated, one population can only recover naturally if it is connected to a source population.

Climatic Vulnerability Stages

Once performed and evaluated, the assessments identify stages of climatic vulnerability that progressively escalate toward the climatic extirpation of a population. Each stage is characterized by factually demonstrable elements derivable from the previous described assessments and justify particular types of adaptation interventions. We propose four stages of climatic vulnerability for a population:

1. **Weakening.** This stage represents when climatic conditions expose the individuals to either thermal or hydric stress (Rozen-Rechels *et al.* 2019) to a level that impairs their performance during essential activities (e.g., food-gathering, settlement of youngers (Sinervo *et al.* 2010). These conditions, sometimes named *pejus* conditions (Pörtner *et al.* 2023), increase a population's susceptibility to negative biotic interactions (Paquette & Hargreaves 2021) or constrain population growth (e.g., due to lack of food or suitable shelter, (Gomides *et al.* 2021). To identify this stage, tolerance data and models of the hydrothermal environment should demonstrate available microclimatic refuges are not enough to ensure population's persistence.
2. **Intolerance.** A population's climatic vulnerability reaches the 'Intolerance' stage when exposure to physical conditions in a site overcomes the species' susceptibility (Box 2), even when the individuals are sheltering. This situation can potentially kill (Cowles &

Bogert 1944), decrease breeding success or even sterilize individuals (van Heerwaarden & Sgrò 2021). It occurs whenever minimum available temperatures in local shelters reach the upper tolerance limits of those individuals (Camacho *et al.* 2023) or of their gametes (Wang & Gunderson 2022). At this stage, the existence of intrapopulation variability in tolerance and/or habitat heterogeneity might still allow for some individuals to survive and reproduce locally. Even if all individuals of a certain population are intolerant, populations of other areas might still be better adapted to withstand local conditions (Herrando-Pérez *et al.* 2019). Early documentation of this stage should include study of intra and inter population variability in thermal tolerance and of reproductive performance (e.g., (Jordan 2003; Lupton *et al.* 2022)) under the site's conditions.

3. Non-resilience. A population's climatic vulnerability reaches the 'Non-resilience' stage when the population and/or the site lacks the respective physiological and eco-geographical traits necessary for natural recover of demographic or functional parameters following a crash (e.g., opportunities for immigration, settlement and population growth). At this stage, the population has not only reached the intolerance stage, but also faces barriers to natural recovery from nearby sites. Key questions to identify this stage include: is the site connected to source areas through a habitat matrix that facilitates natural movement (or dispersion) of the organism out and back into the area once conditions improve? Are the resources required for resettlement and population growth sufficient to sustain recovery after a crash? Answering 'no' to one or both of these questions is sufficient to classify the population as "non-resilient".

4. Inadaptability. A population's climatic vulnerability reaches the ultimate 'Inadaptability' stage when it is not only intolerant and non-resilient, but also lacks the genetic or phenotypic variants necessary to restore it to a state of non-vulnerability. In other words, the species' population adaptability (Box 2) is insufficient to contrast the negative effects of prevailing climatic conditions.

Of course, there are other aspects apart from the biological and environmental data discussed here. Accordingly, the assessments indicated here should be complemented by already developed questionnaires that aim to assess social local knowledge and use, applying regulations, policies, development plans, social vulnerability, and land ownership (e.g., SAVS and Integrated Climate-Biodiversity Frameworks (Newell *et al.* 2022)). Only in this way, critical socioeconomic factors shaping the social adaptive capacity (IPCC 2001), and thus the implementation of conservation measures, can be effectively taken into account. Uncertainty in metrics quantified during experimental, ecological or social observations are included at such questionnaires. Additionally, while we consider all the assessments equally important to define clear vulnerability stages and the necessary actions, managers may discuss with experts, along with affected interests and the broader public, which assessments are feasible given the socioeconomic context of each evaluation (Rhodes et al. 2022), and which goals or biodiversity elements need to be prioritized.

Stage-dependent actions

As vulnerability levels should be identified during the proposed assessments at climatically threatening sites, specific conservation measures will be needed (Figure 3). A wide range of management strategies may be applied depending on the vulnerability stage.

For weakened populations, habitat management strategies – such as increasing shelter, shade, or water availability (Scheffers *et al.* 2014)) - or isolation measures, like reducing the interactions with stressors, may help prevent or reduce climatic vulnerability. If this stage is expected to be temporary, reinforcement or assisted reproduction might be necessary to support the population through this period. Ecosystem services and functions restoration can also reduce the vulnerability (Mawdsley *et al.* 2009). For example, populations of commercially valuable species should not be harvested while "weakened", as they are less able to sustain such pressure. However, at this step, *weakened populations* can often be highly resilient and recover their numbers after climatic disturbances (e.g., heat waves, dry spells). Actions to improve such recovery can include enhancing key resources (Griffith *et al.* 1989) or improving habitat connectivity (Jangjoo *et al.* 2016), to facilitate immigration from source populations, particularly from nearby protected areas (Antonelli 2023), which could enhance genetic exchange and potentially resilience. Critically, engaging local communities in conservation programs while integrating both species and societal needs will be needed to ensure long-term persistence under climate change scenarios (Pörtner *et al.* 2023).

For intolerant populations, which are inherently exposed to deleterious conditions, in-situ selection, captive breeding programs, and restocking of tolerant individuals (e.g. genetic management (Frankham *et al.* 2019)) or assisted immigration of more tolerant variants from other locations may become essential (Fritts *et al.* 1997).

Non-resilient and unadaptable populations, will likely require off-site conservation measures. Habitat suitability models can identify locations where the population might persist (Araújo & Peterson 2012; Gomides *et al.* 2021), potentially guiding the creation of wildlife corridors and even assisted migration to more suitable areas (Camacho 2010). For such populations, assessments of the potential effects on target sites for translocation become essential (Schwartz *et al.* 2012). A broader strategy could involve establishing a connected network of climate-resilient protected areas (Alagador *et al.* 2014; Hoffmann *et al.* 2019) to facilitate persistence of non-resilient populations. In extreme cases, ex-situ conservation actions, such as maintaining populations in zoological or botanical gardens, may be necessary (Hobohm & Barker 2023). Ultimately, captive maintenance and reproduction programs or genetic material preservation (e.g., germ/sperm banks) can play a role in the long-term conservation of populations and their genetic value (Hoffmann *et al.* 2015). However, while captive programs can save highly threatened species, they may be impractical for many due to genetic, behavioral, or disease-related challenges (Mawdsley *et al.* 2009) and the lack of basic knowledge on its reproductive biology.

These guidelines enable decision-makers to get an idea of widely recommended climate adaptation measures based on the stage of vulnerability level and to engage appropriate specialists for each task (Arribas *et al.* 2012; Dawson *et al.* 2011; Foden & Young 2016; Willis *et al.* 2015). Ultimately, they can also help identify which populations might need to be left unmanaged or deemed unsalvageable (Gilbert *et al.* 2020). The complexities of the legal context of many administrations may entail that managers need to consider the existing types of procedural flexibility to apply such measures (Rhodes *et al.* 2022) .

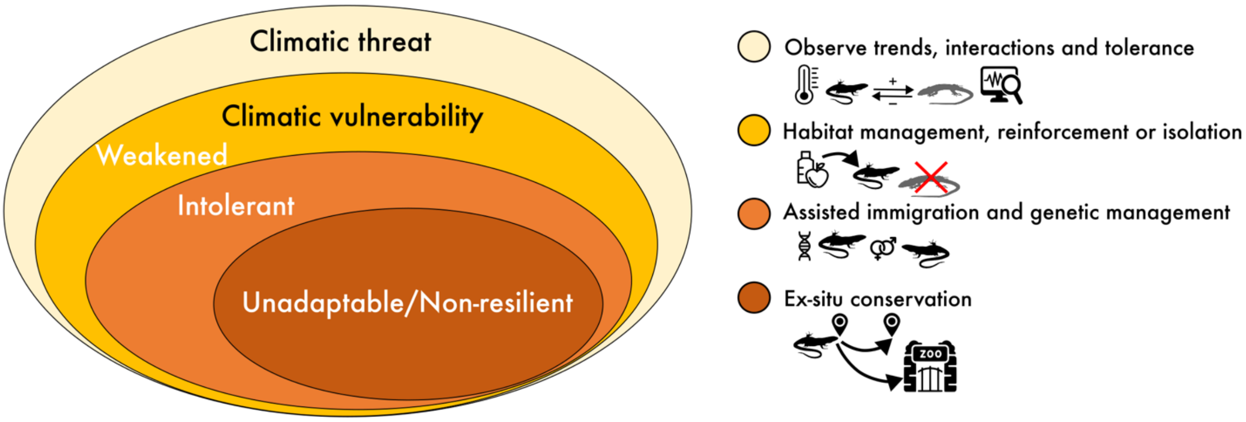

Figure 3. Hierarchical relationships between the concepts of site climatic threats, the climatic vulnerability stages of populations, and examples of suggested general research and conservation actions for each climatic vulnerability stage.

5. CONCLUSIONS

We present a conceptual and operational framework designed to organize biodiversity conservation efforts against the climatic extirpation of populations of relevant species. By clarifying key concepts (climatic responsibility, climatic threat, climatic vulnerability), our framework offers a precise yet accessible perspective for managers and funders to guide resource allocation toward the sites and populations that need it most.

The CTRR identifies specific locations requiring assessment and provides a transparent tool to facilitate dialogue and coordination among managing jurisdictions and technicians. It is based on easily understandable and communicable concepts (value under climatic threat, urgency of action, certainty of threat) and is calculated with minimal technical complexity. Because the CTRR ranks sites across customizable geographic scales and species lists, it can guide decisions related to the protection, restoration, or acquisition of land parcels, helping align local actions with regional and global biodiversity and sustainability strategies. The CTRR should trigger on-site, criterion-driven assessments—described herein—to determine climatic vulnerability ranks for affected biological populations, and to derive appropriate actions to reduce such vulnerability. Our proposed approach requires pre-conservation research phases, which we believe should be an integral part of grants aimed at supporting climate adaptation in biodiversity conservation.

Box 1. Multifaceted Impacts of Climate Change on Biodiversity.

Climate change drives long-term shifts in precipitation, temperature, and water availability, while also increasing the frequency and intensity of extreme events such as heatwaves, droughts, and storms (e.g.,(IPCC 2001; Santos *et al.* 2024)). These changes affect all aspects of biodiversity. Organisms respond through altered behavior and physiological processes, shifts in microhabitat use, reproductive timing, migration patterns, and geographic distributions (Camacho 2012; Kubelka *et al.* 2022; Vitasse *et al.* 2021). Consequences of these shifts include reduced periods of optimal conditions for key activities, mismatches between reproductive events and food availability, habitat quality loss, reduced ranges due to physiologically imposed barriers, and range shifts toward cooler latitudes or higher elevations that may lead to the displacement of native species in those areas (Camacho *et al.* 2024; Denney *et al.* 2020; Iler *et al.* 2021; Sinervo *et al.* 2010). Climate change also promotes the spread of invasive species and pathogens better suited to altered environments, further threatening already declining native biodiversity in fragmented habitats (García-Rodríguez *et al.* 2023; Paniw *et al.* 2022).

Human-induced land-use changes—such as deforestation, agricultural expansion, urbanization, and other forms of land conversion—interact with climate pressures to amplify their individual impacts (Bezrukova et al., 2024; Law et al., 2022). These combined forces accelerate habitat loss and conectivity in vulnerable ecosystems, where species often rely on narrow ranges of temperature, freshwater availability, oxygen levels, or pH conditions (Wernberg et al., 2024; Jeleva et al., 2023). For climatically vulnerable populations, the cumulative effect of these stressors reduces the spatial and temporal availability of suitable habitats and essential resources, leading to diminished performance, genetic diversity and weakening their adaptive capacity and resilience (PhD., 2022). Further details are published on extensive reviews of climate change impacts on species (E.g. Pernetta 1995; Pörtner *et al.* 2021).

Box 2. Measuring climatic vulnerability components in a nutshell.

Climatic sensitivity

Climatic sensitivity represents how negatively a population or species will react to changes in climate (IPCC 2001). It depends on how climate change affects different traits at the individual level (e.g., tolerance, fitness, behaviour, reproduction), influences population growth rates and survival (Huey & Berrigan 2001), shapes the outcome of ecological interactions and ultimately affects the population's abundance and viability (Gaston *et al.* 2009). Ways to estimate species' climatic sensitivity are diverse (Pacifici *et al.* 2015). Many trait-based approaches compare species' phenotypes (i.e., heat tolerance physiological thresholds, morphology, etc.) with expected climatic conditions to assess climatic risk. Yet, the methods to measure phenotypic traits, capture climatic variation, and integrate them to predict changes in vulnerability are undergoing strong conceptual development (e.g., (Camacho *et al.* 2023a; Kearney & Porter 2009; Kingsolver & Buckley 2017; Parratt *et al.* 2021; Pinsky *et al.* 2019; Rezende *et al.* 2020; Sinervo *et al.* 2010; Terblanche *et al.* 2011).

Sensitivity has also been estimated by models that correlate climatic variables with either geographic changes in the frequency of species' occurrences (Araújo & Peterson 2012;

Kling *et al.* 2020; Lobo 2016) or with temporal trends in local population size, sometimes combining both (Pacifici *et al.* 2015; Wheatley *et al.* 2017), or indexing them at the community level (Hespanhol *et al.* 2022). Such models may include the effects of negative interactors, like predators, competitors, or diseases (e.g., on species' distribution or abundance. However, some studies focus either on mapping sites whose climatic conditions will remain suitable for the species (Araújo & Peterson 2012) or on forecasting the expected demographic outcome for a specific population (Paniw *et al.* 2019). Despite its utility, such an extensive toolbox requires careful consideration, and estimating a species' population climatic sensitivity demands specialized expertise due to technical complexities and uncertainties (e.g., (Jarnevich *et al.* 2015)). This limits their generalizability to other populations or species.

Climatic exposure

Exposure is commonly measured as the expected change in the macroclimate (e.g., average atmospheric temperature and precipitation) of locations where species occur (Chowdhury *et al.* 2021; Foden *et al.* 2013; Mancini *et al.* 2024; Patiño *et al.* 2016). However, macroclimatic variables (a.k.a bioclimatic, (Hijmans *et al.* 2005)) present at least two fundamental problems for this use. First, they are affected by uncertainty arising from the multiple proposed climatic scenarios for the future (Beaumont *et al.* 2008; Hossain *et al.* 2019), and second, they do not actually represent the precise conditions that individuals will experience (Geiger *et al.* 2009; Vives-Ingla *et al.* 2023). Instead, these variables often represent averaged climatic conditions of a region of at least 1x1 km size for 20 years. Nonetheless, macroclimatic variables are often used for climatic vulnerability assessment assuming that, except for microclimatic refuges, microhabitat conditions will be strongly driven by the regional climate (Geiger *et al.* 2009).

However, estimates of individuals' actual exposure to those conditions are complicated by multiple factors (species' behaviour, morphology, phenology, interactions with other species). For example, individuals frequently shift their microhabitat use (Porter *et al.* 1973) or phenology (Lorite *et al.* 2020). These changes enable them to mitigate their exposure to hazardous conditions. Similarly, morphology (i.e., body size and shape, fur cover, colour, etc.) affects how species integrate microclimatic conditions into body conditions (Porter & Gates 1969). There are tools to integrate the microhabitat scale conditions (Kearney & Porter 2009; Lembrechts *et al.* 2019) with hard-to-obtain species' traits such as morphology and physiology, particularly tolerance. While morphological data are among the first obtained for any newly described species and widely available (Etard *et al.* 2020) the latter are unavailable for most species (Camacho *et al.* 2024).

Additional complexity in measuring exposure arises from different definitions of exposure that disagree on whether including tolerance plasticity (e.g., (Williams *et al.* 2008) or not (e.g., (Dawson *et al.* 2011)). Tolerance plasticity is an intrinsic feature of physiological tolerance, which may increase tolerance through exposure-driven acclimation processes (Clusella-Trullas & Chown 2014), or decrease it due to exposure to continuous stress (Rezende *et al.* 2014). It can also vary or not in association with geographic gradients in climate (Clusella-Trullas & Chown 2014; Gutiérrez-Pesquera *et al.* 2022). Thus, tolerance plasticity, by definition, influences climatic sensitivity and should be part of that component rather than exposure (Riddell *et al.* 2018). Lastly, a significant constraint of most climate change exposure estimates is the predictive time frame, which often extends many decades into the future (Murali *et al.* 2023; Vaz-Canosa *et al.* 2023). Such far-ahead projections may impair prompt action because typical budgetary timeframes of climate adaptation programs are often limited to up to 6 years (e.g., LIFE Programme (European Commission 2020)).

Climatic adaptability

The third classic component, climatic adaptability, combines two concepts that should be separated: evolutionary adaptive potential and ecological resilience (Seaborn *et al.* 2021). Both are essential to evaluating climatic vulnerability (Hughes *et al.* 2007; Moritz & Agudo 2013), see glossary). Yet, while evolutionary adaptive potential might facilitate resilience (e.g., (Kellermann & van Heerwaarden 2019)), these concepts represent fundamentally different processes and are estimated by radically different methods (e.g., (Diniz-Filho *et al.* 2019; Gunderson 2000). Accordingly, they may be impossible to parameterize jointly. Measuring trait adaptative potential often requires intraspecific studies of genetic variability (Bürger & Lynch 1995) and geographic (Morley *et al.* 2009) and/or intergenerational (Martin *et al.* 2023) variation in particular traits or their plasticity (Diaz *et al.* 2021). In turn, quantifying ecological resilience involves identifying the capacity of a population to recover demographic parameters after catastrophic shifts (Capdevila *et al.* 2020) or recover original levels of evaluated ecological functions for ecosystems (e.g., pollination; (Oliver *et al.* 2015)). This may depend on different species traits (e.g., their capacity to escape and return later; having resistance forms, or high reproductive output) and on landscape parameters (e.g., connectivity, available resources, (Cumming 2011)). Therefore, we suggest updating the definition of climatic vulnerability, including resilience as a distinct fourth component of climatic vulnerability (see section 3).

Glossary:

Administrative climatic responsibility: the legal authority (and potential obligation) of a land management or conservation agency to adapt its management practices to climate change.

Climatic adaptation measures: research and conservation actions necessary to diagnose climatic vulnerability and protect a species or population from climatic extirpation.

Climatic niche range: The range of climatic conditions a species requires to survive, given biotic and abiotic interactions and dispersal limitations (Hutchinson 1957).

Climatic threat. The situation when climatic conditions experienced in the present or near future exceed the known range of tolerated conditions for a species.

Climatically threatening site: sites whose present or near future climatic conditions fall beyond the historical climatic niche of any species that inhabit it.

Climatic threat exposure: proportion of known sites where a climatic threat has been detected for either a species or a region.

Climatic Threat Rank (CTR): calculated for sites across any geopolitical administration. Helps identifying sites that impose a higher level of threat to its inhabitant species.

- **Value** = proportion of native species in each administrative scale (site, administration) of a given species pool requiring management.
- **Urgency** = the average of Climatic Threat exposure calculated for the species existing in a site or region.

- **Certainty** = for a site, it is the maximum among the proportions of climatic scenarios that indicate climatic threats for the species inhabiting this site. These proportions are estimated for a range of climatic variables. For a region, it is calculated as the average certainty calculated across sites and species.

Climatic Threat and Responsibility Rank (CTRR): can be calculated for regions or any geopolitical administration. Helps identifying where to direct economic resources for climatic adaptation measures. It depends on the same three additive variables as CTR. While sites with higher CTR should be prioritized to receive actions/funds from the responsible administration, administrations managing lands with higher CTRR should be prioritized to receive funds and undertake climatic adaptation measures.

Realized historical niche range: the range of climatic conditions observed at locations occupied by all the wild populations of a species. It is calculated with historical datasets of climatic variables (i.e., observed before present time).

Fundamental niche range: The range of climatic conditions in which the species could survive if it was not further limited by biotic interactions or its own dispersal capacity (Hutchinson 1957).

Population's climatic adaptive capacity: its capacity to use inner trait variation to maintain or increase population size by changing the population's value in traits essential for dealing with climatically induced changes (adapted from (Catullo *et al.* 2015)).

Population's climatic resilience: the biological properties of a population that allows it to recover to its original status after a catastrophic climatic event (large reductions in population size or distribution range) (Gunderson 2000).

Population's exposure to climate change: the amount of change in climatic variables likely to be experienced by a species at a given site. Exposure depends on the rate and magnitude of climate change in such a site and whether the species is present at the site periods when relevant climatic variables are acting (e.g., if it has not migrated seasonally before). Most assessments of future exposure to climate change are based on climatic projections from correlative niche models (Dawson *et al.* 2011).

Relevant species: organisms (i.e., animals, plants, fungi, etc) identified under applicable laws as requiring management for their conservation

Species' adaptive capacity: The overall tendency of a species for intergenerational trait variation across its multiple populations, in response to a selective factor.

Species' climatic resilience: The overall resilience measured across multiple populations or estimated due to traits widespread within this species.

Species' exposure to climate change: The number of sites at which a species experiences climatic changes multiplied by the amount of climatic change experienced at each.

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