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

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Abstract

Biodiversity is cornered by human habitat alteration and eroded by climate change. Protecting it urgently requires efficient allocation of conservation resources to protect vulnerable species and ecosystems. However, conservation decisions are often hindered by fragmented governance and a disconnection between policymakers, funders, managers and scientists. To address this, we propose the Climatic Threat and Responsibility approach to help allocating 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; (2) Climatic Vulnerability, which encompasses species' sensitivity, exposure, adaptability, and resilience; and (3) Administrative Climatic Responsibility, 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 conservation value under climatic threat, the urgency to act, and the certainty of climatic threat. Based on these notions, we present an R-based algorithm that maps species-specific exposure to climatic threats and, accordingly, ranks sites' climatic threat toward its inhabiting species. Besides, it summarizes these threats across geopolitical regions to compare administrations' climatic responsibility to preserve biodiversity. This system leverages species' realized climatic niches and multiple climatic scenarios (2020–2040). Finally, we propose a trait-based ranking system to classify climatic vulnerability for local populations and guide adaptation actions. This framework is intended to complement traditional climatic vulnerability assessments by flagging sites and populations for which such assessments should be prioritized. By uniting conservation practitioners, policymakers, and scientists, this framework aims to streamline adaptation funding and policies in a rapidly changing climate.

1. Introduction

Defending biodiversity against climatic impacts urges swift allocation of conservation funds among research and nature conservation administrators (e.g., the European Climate-adapt partnership)(Ferraz *et al.* 2021; Habibullah *et al.* 2022). In turn, administrators must strategically allocate these limited resources. To do so, they need to prioritize locations, species, and appropriate adaptation measures (e.g., This requires administrators, relevant managers, and scientists to speak a common language (e.g., Li *et al.* 2023) to identify and prioritize conservation targets and ensuing adaptation measures.

Instead, while 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), 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). Such situation has led to key terms, such like climatic vulnerability, climatic risk, or threat, being used as synonyms, while representing different things depending on the author (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).

Determining where to direct adaptation funds is complicated by competing priorities for conservation actions. 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), and for the ecological functions of local assemblages (Auber *et al.* 2022). In addition, we find the global aim of keeping the abundance of populations to healthy levels in view of lowering extinction risk (Conference of the Parties to the Convention on Biological Diversity 2022). Within the 2050 Goals of the Global Biodiversity Framework, all such facets of biodiversity are mentioned. Even if there is agreement on prioritizing the conservation of phylogenetic diversity, ecosystem services, or ecological functions, the question of which species, service, or function to prioritize may remain unresolved (Camacho 2010). Nonetheless, it is accepted that populations are the fundamental 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). Thus, directing resources towards climatically threatened populations of relevant species arguably contributes to a multi-dimensional 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 1) requires implementing so costly approaches that often only one or some 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 populations, despite the fact that climatic vulnerability varies geographically (Gunderson and Leal, 2012; Camacho et al., 2023). While endemic species with narrow distributions are generally the more vulnerable, assessments that tag species as climatically vulnerable or not may obscure regional differences. 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 is rarely feasible across an entire species' range (Wheatley et al., 2017). Finally, the technicalities of methods clash with the practicalities of funding allocation and on-the-ground conservation efforts (Clusella-Trullas *et al.* 2021; Tulloch *et al.* 2016). Firstly, the climatic vulnerability components are undergoing an intense process of redefinition and refinement (e.g., Beever *et al.* 2016; Seaborn *et al.* 2021, Hespanhol; 2022; see Box 1). In second instance, climatic vulnerability maps created through Species Distribution Models (SDMs) 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 SDMs utility in guiding conservation planning (Ferraz *et al.* 2021). Additionally, uncertainties in climate projections further complicate assessments, raising concerns about their reliability (Carvalho et al. 2022). Yet, 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).

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Nonetheless, funding and implementing climatic vulnerability assessments remains critical for ensuring the persistence of populations imperiled 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., biologists, veterinarians), they often lack the practicality needed by conservation practitioners and policymakers. Given the multidisciplinary nature of the climatic problem, we contend that more accessible frameworks are needed. Such frameworks should help science and policy agreeing upon how to geographically allocate climatic adaptation funds for biodiversity conservation. Likewise, these frameworks should enhance communication across administrative levels, helping managers and experts prioritize where to act and determine appropriate conservation measures . Herein, we present a tool to address these challenge, beginning with the clarification of 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). Protecting those species involves determining relative responsibilities and derived action burdens across administrations, and thus funding allocation becomes more complex. Herein, we aim to provide guidance for such authorities to help them better coordinate their adaptation strategies.

To navigate these complexities, we introduce the concept of **administrative climatic responsibility**, defined as the legal authority (and potential obligation) of a land management or conservation agency to adapt its management practices to climate change. Typically, such responsibilities are 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 (Reside et al., 2018;

Camacho, 2020). Of course, strategies that promote these objectives may indirectly support biodiversity conservation. Yet, to this aim, we argue that it is needed to sharply identify sites and “relevant” species’ populations affected by climate change, and that managers should receive adaptation funds commensurate with three key factors: (1) the number of relevant species under climatic threat (see definition below), (2) the number of climatically threatening sites for these species’ that the administration manages, and (3) the certainty that these species are under climatic threat at such sites. Based on that premise, a tool that maps the geopolitical distribution of these factors should help conservation funders and administrators determine relative responsibilities and burdens more efficiently and effectively (more details in section 2.1).

Here, “relevant” species include organisms (i.e., animals, plants, fungi, etc) identified under applicable laws as requiring management for their conservation. Under most legal regimes, relevant species will include those deemed threatened on international or local scale (e.g., IUCN red list species), keystone species, and/or otherwise of ecological and/or socioeconomic interest. In situations of lack of guidance and potential for conflict among managers about such value determinations in the context of climate change, it is essential that determinations by managers of “relevant” species should be subject to (1) standards clearly delineating conservation goals, and (2) procedures that seek to reconcile` conflicting goals between jurisdictions (Camacho 2020). We do not mean that administrative climatic responsibility should only be calculated by estimating the climatically threatened populations of relevant species to protect and sites to act under each geopolitical jurisdiction. Still, this estimate should be an essential component to calculate the administrative responsibility, and its related burden, of protecting biodiversity against climate shifts.

To operationalize the use of climatic administrative responsibility, 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)).

In general, **climatic threat** refers to climatic conditions at a location that could, potentially, put one or more species’ populations at a serious disadvantage. 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 climatic ranges in which the species is observed. Such 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, 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., many invasive species). Second, populations located at climatically threatening sites may still not be climatically vulnerable because this information only addresses one of the three components of climatic vulnerability (Exposure, see Box 1). 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 (IPCC 2001). In this case, again, the harm is not known for climatically threatening sites without further site-specific investigations. Finally, models often label sites of *modelled* geographic distributions, 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.

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 due conservation actions. Populations' tolerance and exposure to hazardous climatic conditions will often vary across a species' geographic range (Gunderson & Leal 2012). Thus, inferring the climatic vulnerability of entire species using estimates made for a single or a few populations likely introduces artefactual under-or-overestimations of the whole species' climatic vulnerabilities. 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. In contrast, defining a **climatically vulnerable species** poses several difficulties (see Box 1). It could be defined as one 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 can be too much to guarantee its persistence. We expect that managers and technical experts agree on what to do at each case. Cautionarily, we propose that the case when any vulnerable species, according to the IUCN, is found under climatic threat exposure should be enough to immediately start due assessments and protection actions (described in Section 3). In the following section, we outline how to identify climatically threatening sites and compare climatic responsibility to allocate climatic adaptation funds for species' conservation.

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. 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). First, the algorithm is applied to all the species and sites of a respectively prespecified pool and geographic boundaries (Figure 1, Panel 1). As example, think of IUCN's endangered species list, or a list of endemic plants or cattle breeds existing across a country's provinces. For each species, the algorithm estimates the populations exposure to climatic threat and then rank each site's level of climatic threat. Then, these calculations are summarized across the selected geopolitical subdivisions, applying the same criteria to compare the climatic responsibility of different subdivisions to manage species from the selected pool. Specifically, the algorithm proceeds as follows:

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

Our algorithm first estimates the limits of the realized climatic niche range of each species 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 (Figure 1, Panel 2). This information can be obtained from available distribution 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 layers for the recent past (e.g., 1979-2013, as in our example, and the near term (2021-20240). The algorithm extract climatic values for the selected variables are extracted from 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 niche of that species for those variables and are obtained from a recent past climatic database (1979-2013)(Karger *et al.* 2017). Then, 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 2011-2040 (Brun *et al.* 2022). In each of those sites, the expected values are extracted from six different climatic scenarios. 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 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.

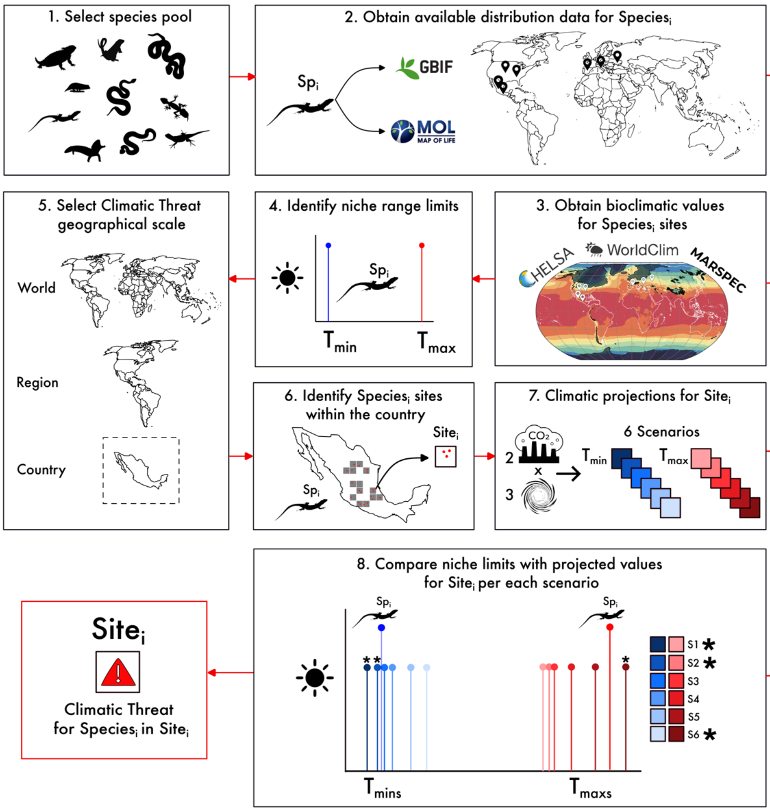

Figure 1. Steps to identify Climatic Threat. *The algorithm begins with a list of species (Species pool, Panel 1) and proceeds for each species (Sp$_i$), climatic variables (e.g., temperature, represented by the sun icon) and site (Site$_i$), shown here for a single case for simplicity. Note that more than one climatic variable can be selected (e.g., rainfall, maximum temperature, etc.). Species geographic locations are retrieved from online database (e.g., GBIF and Map of Life are showed as commonly used, Panel 2) and matched with climatic data (e.g., Chelsa, WordCLim and Marcspecn icons are showed*

as commonly used), to extract temperature values at those locations. From these, the minimum and maximum temperature limits are identified (i.e., realized thermal niche extreme values, Panel 4). Next, users select the geographical scale for the Climatic threat mapper (Panel 5). In this example we do it at the country scale selecting a random country (Mexico) where the species occurs. The species locations are aggregated following the climatic database geographic resolution (e.g.,10 km^2). The sites depicted in the figure map are much bigger for visual clarity (Panel 6). For each site, future temperature projections (2011–2040) are generated 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 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 $Site_i$.

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 for sites occupied by a single relevant species, too, by simply entering a list of one species.

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 focus only on reportedly occupied sites where climatic conditions are expected to reach beyond a species' realized 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, enabling both governmental and non-governmental organizations to allocate resources efficiently and address urgent biodiversity threats in alignment with their current missions.

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 the studied region (Figure 2, Panel 3):

- **Administrative Value:** the proportion of species pool found within the administration (e.g., region, country, province etc.).
- **Administrative Urgency:** the average CT_{exp} for species within the administration.

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

Sites or administrative regions with higher ranks, calculated through this method, represent areas of greater biological value under more urgent and certain need of climatic adaptation measures. The CTRR can be applied to any species pool and it is equally appliable to both animal and plant taxa, provided reliable distribution data are available. 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. 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. 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 distribution 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).

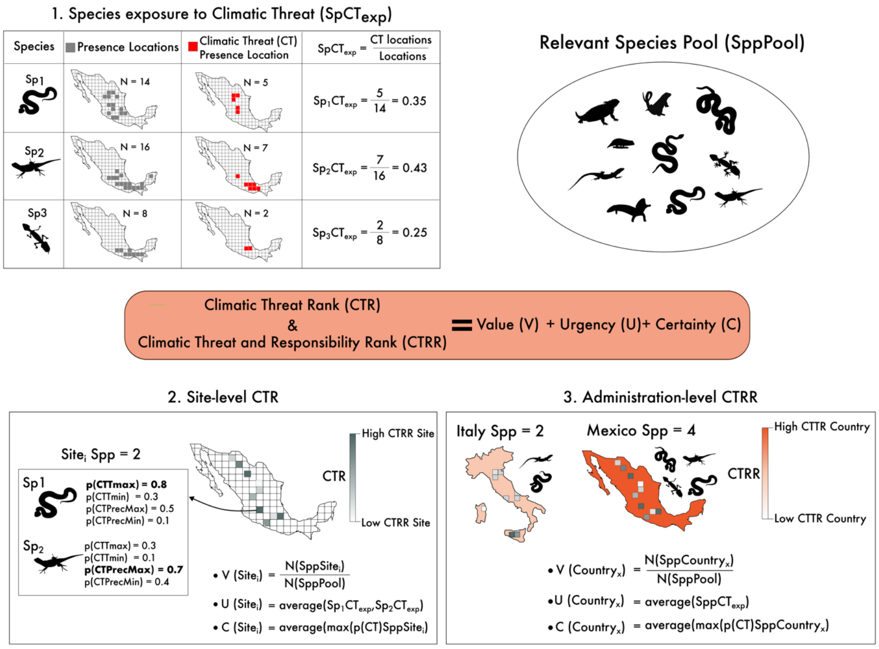

Figure 2. Ranking Climatic Threat Exposure for species and Climatic Threat and responsibility for sites and geopolitical administrations. *Panel 1 depicts how to calculate species exposure to climatic threat ($SpCT_{exp}$), that is the proportion of climatically threatening sites out of all known presence 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. The algorithm works with pixels of the resolution provided by the climatic database (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 to researchers, policymakers, and funders, hopefully facilitating agreement and coordinated action.

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 identifying areas where there are more relevant species under more realistic climatic threat. 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.

If an administration identifies climatically threatening sites within its jurisdiction, it should start multidimensional assessments of the climatic vulnerability of the corresponding relevant species populations. This entails leveraging both field research and available online data on species tolerance, or frameworks to guide 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, we outline below a set of essential assessments that can guide further tailored conservation actions:

- **Thermohydroregulation assessment.** This evaluation aims to determine whether the population is able to avoid deleterious abiotic conditions and obtain enough water or humidity to reproduce and maintain its population (Paquette & Hargreaves 2021).
- **Interaction assessment.** This assessment identifies whether climate-induced changes 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).
- **Adaptability assessment.** This is necessary to identify, if possible, more tolerant individuals, or neighboring populations, that could allow the 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).
- **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).

With these assessments, it is possible to objectively rank climatic vulnerability at any given site and take corrective measures, accordingly. The assessments identify stages of climatic vulnerability that progressively escalate toward the climatic extirpation of a population. Each stage includes factually demonstrable elements derivable from the previous described assessments and justify particular types of adaptation interventions. We propose four proposed stages of climatic vulnerability for a population:

1. **Weakening.** A population's climatic vulnerability reaches the 'Weakening' stage 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 (Sinervo *et al.* 2010)). These conditions, sometimes named *pejus* conditions (Pörtner *et al.* 2023), increase populations susceptibility to negative biotic interactions (Paquette & Hargreaves 2021) or reduce key resources for population growth (e.g., food or suitable shelter, (Gomides *et al.* 2021)). Accordingly, to identify this stage, tolerance data and models of the hydrothermal environment, including available refuges, are necessary.

2. **Intolerance.** A population's climatic vulnerability reaches the 'Intolerance' stage when exposure to physical conditions in a site overcomes the species' sensitivity (Box 1), even when the individuals are sheltering. This situation can potentially kill (Cowles & Bogert 1944) or sterilize individuals (van Heerwaarden & Sgrò 2021). It occurs whenever minimum available temperatures in local shelters reach the 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 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 1) is insufficient to contrast the negative effects of prevailing climatic conditions.

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 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 ensuring 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).

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).

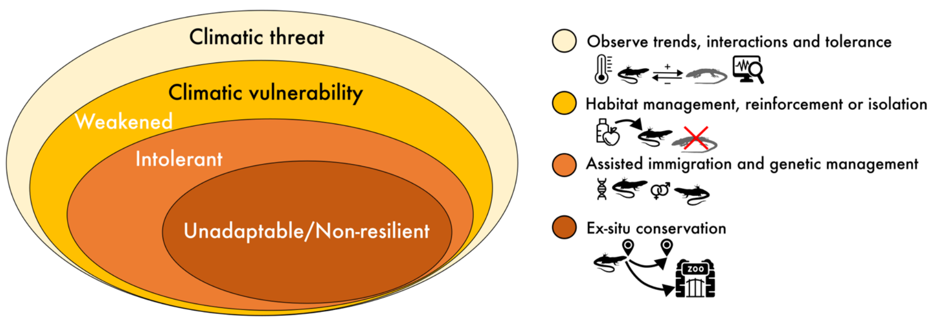

Figure 3. Hierarchical relationships between the concepts of site climatic threats, the climatic vulnerability stages of populations, and examples of suggested general research and conservation actions for each climatic vulnerability stage.

5. CONCLUSIONS

We have proposed a framework of concepts and operations designed to make effective biodiversity conservation efforts against climatic erosion. We expect our clarifications will help managers and funders balancing resource allocation toward needed sites and species' populations. Our Climatic Threat and Responsibility Rank identifies specific locations to act, and provides a tool for dialogue among managing jurisdictions. Finally, the key assessments, vulnerability ranks, and actions should help managers communicate with technical experts. Through this framework, we aim to catalyze more efficient and effective allocation of resources, faster implementation of conservation strategies, and greater integration of biodiversity concerns into global climate adaptation planning.

Box 1. Measuring climatic vulnerability components in a nutshell.

Climatic sensitivity

Climatic sensitivity represents how negatively a population or species will react to changes in climate (Dawson *et al.* 2011; Seaborn *et al.* 2021; Williams *et al.* 2008). It depends on how climate change affects different traits at the individual level (e.g., tolerance, 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 thresholds, morphology, etc.) with expected climatic conditions to assess levels of 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 species' behaviour, morphology, and phenology. 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) 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.

Historical realized 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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