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Impact of Climate Change on Biodiversity and Implications for Nature-Based Solutions

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Abstract

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The Intergovernmental Panel on Climate Change (IPCC) provides regular scientific assessments on climate change, its implications, and potential future risks based on estimated energy matrixes and policy pathways. The aim of this publication is to assess the risks climate change poses to biodiversity using projected IPCC climate scenarios for the period 2081–2100, combined with key species-sensitivity indicators and variables as a response to climate change projections. In doing so, we address how climate-change-driven pressures may affect biodiversity. Additionally, a novel causal relationship between extreme ambient temperature exposure levels and the corresponding effects on individual species, noted in this paper as the Upper Thermal-Tolerance Limit and Species Sensitivity Distribution (UTTL-SSD), provides a compelling explanation of how global warming affects biodiversity. Our study indicates that North American and Oceanian sites with humid continental and subtropical climates, respectively, are poised to realise temperature shifts that have been identified as potential key tipping-point triggers. Heat stress may significantly affect approximately 60–90% of mammals, 50% of birds, and 50% of amphibians in North American and Oceanian sites for durations ranging from 5 to 84 days per year from 2080. In the humid temperate oceanic climate of European sites, the climate conditions remain relatively stable; however, moderate cumulative effects on biodiversity have been identified, and additional biodiversity-assemblage threat profiles exist to represent these. Both the integration of IPCC-IUCN profiles and the UTTL-SSD response relationship for the species communities considered have resulted in the identification of the projected threats that climate pressures may impose under the considered IPCC scenarios, which would result in biodiversity degradation. The UTTL-SSD responses developed can be used to highlight potential breakdowns among trophic levels in food web structures, highlighting an additional critical element when addressing biodiversity and ecosystem concerns.

Introduction

The Understanding the localised impacts of climate change projections on ecosystems is of the utmost importance for nature conservation strategies aiming to adapt to local climatic processes [1]. Increases in heat-related stress can result in a variety of effects, including increased metabolic rates, behavioural changes, and/or mortality [2,3,4,5]. The potential consequences of climate change on biodiversity in the long-term, and the transitional phases in the mid-term, are insufficiently known [6]. The literature confirms that mid- and long-term predictions on the effects of climate pressures on biodiversity, within local and regional scales, exhibit complex interactions, multiple drivers of change, and involve complex food webs with spatial variations in ecosystems [7,8,9,10,11,12,13] (Table A1). Changing climate conditions are caused by multiple factors and compounding bioclimatic pressures [14], such as temperature increases and changes in the water cycle. The combined stressors of drought and extreme heatwaves, as predicted by climate scenario models, could have a high, and often negative, impact on organisms' physiology [15,16,17]. Ref. [18] showed that, if the monitored variation in thermal-tolerance levels for species continues, naturally adaptive responses in thermal limits from organisms will have a limited potential to serve as an adaptation strategy for most species' preservation. This has particular relevance, given the unprecedented rate of contemporary climate change. The resultant potential ecological regime shift, denoted by impacts observed as tipping points in external bioclimatic drivers and ecosystem responses, stands to cause a major change in ecosystems' structure and/or function [19]. Ref. [20] used catastrophe theory to detect a regime shift for marine species; in doing so, he concluded that ocean warming will cause potentially irreversible regime shifts in ecosystems on a global scale. A mechanism that could reduce the risk of overheating is physiological thermal tolerance, such as the reversible change known as acclimation [21]. Moreover, exposure of ectotherms to combined heat stress and drought can exacerbate physiological stress of organisms through additive effects [22,23]. Given the likelihood of increasing single and combined heat stressors with a limited pathway for species' adaptation, particularly given the rate of change predicted, particular attention is given to these elements within this application.

As there stands to be considerable potential for severe shifts in biodiversity composition and ecosystem functioning due to climate change, there is a need to assess the progress of climate adaptation in areas for nature conservation, resulting in an applied Nature-based Solution (NbS) [24,25]. Some of these studies consider ecological indicators to assess biodiversity conservation potential. Several authors have developed estimations on the potential effects of projected climate pressures on ecosystems [7,26,27,28,29]. Ref. [30] developed a model to assess the efficiency of NbS by coupling local IPCC bioclimatic projections with management plans for NbS sites. This application used UN Sustainable Development Goals (SDGs) for metrics and assessment purposes [31].

Readily applicable methodologies for evaluating biodiversity vulnerability levels to projected bioclimatic pressures are available, particularly those which can account for climate resilience solutions and adaptation strategies. However, to the best of our knowledge, studies in the existing literature have not attempted to conduct an analysis of NbS based on existing threats to biodiversity and long-term bioclimatic projections for the period 2081–2100—the core application considered in this work. As extremes become more common and intensify, investigating global assessments of climate change in relation to extreme heat stress, drought, and precipitation events requires key datasets compiled from scientific sources, and for this data to be carefully considered in future model risk assessments [32,33,34].

Our study shows the novel relationship between Upper Thermal-Tolerance Limit and Species Sensitivity Distribution (UTTL-SSD), where critical temperatures provide compelling insights into how climate change stands to affect biodiversity. This analysis aims to assess the effectiveness of NbS sites by enhancing an impact model, incorporating local IUCN biodiversity threats to vertebrates and invertebrates, and establishing connections with IPCC bioclimatic projections. This adds to the body of evidence concerning the role that an NbS plays in adaption strategies regarding the increasing bioclimatic pressures associated with climate biodiversity threats.

Within the scope of this paper, we consider biodiversity in the general sense, regarding it as encompassing species diversity, as well as structural and functional elements within ecological systems. It is acknowledged that biodiversity assessments are inherently complex and rely on an intricate understanding of ecosystem composition and relationships, and this study does not delve into the nuances of the ecosystems considered. Within our analysis, the term biodiversity is used to indicate a terminus point for pressures and climate-change system drivers and NbS influences, which are related to species diversity and structural or functional implications on ecological systems. As such, biodiversity is defined as the diversity or richness within species, between species, or of the habitat and ecosystems, in line with the ICBD definition (The International Convention on Biological Diversity).

In our paper, the IPCC bioclimatic variables and IUCN spatial data are used to (1) analyse global NbS sites and the projected increases in bioclimatic variables in climate classification systems, focusing on mean annual temperature, heat waves (i.e., days warmer than 35 °C and 40 °C annually), max 5-day precipitation, consecutive dry days, and sea level rise; (2) judge the impact of bioclimatic processes on biodiversity in different climate zones and at multiple trophic levels; and (3) gain evidence for the role played by NbSs in adapting to climate change while considering biodiversity. The outcomes and impact measures of this assessment can be used to inform planning processes, improve and enhance resilience, or promote measures for the conservation of biodiversity. NbS sites from Europe, Oceania, and North America are utilised, with various global regions represented in the database being developed, and they are shown to have a range of impacts.

Methodology

The selection criteria for the NbS sites considered are primarily driven by a desire to maintain similarity and comparability. The criteria were based on their functionalities, namely, providing flood protection, serving socioeconomic growth, possessing a high intrinsic value for biodiversity and healthy ecosystems, regulating emissions, erosion reduction, and serving the wellbeing of humans [30]. Four Köppen–Geiger climate zones for the present day (1980–2016) have been selected [35]. These are located in Europe, Oceania, and North America [36,37,38], Figure A1. This was performed with the acknowledgement that tropical ecosystems are most vulnerable to climate change and will likely suffer the greatest impacts. Integrating local threat profiles with projected bioclimatic changes allows for effective nature conservation planning and climate adaptation at the NbS site.

The flow of data processing and analysis in the proposed Bioclimatic–Biodiversity Impact model (BBI) model is outlined in Figure 1, and consists of three methodological steps. Step 1 consists of building the IPCC Sixth Coupled Model Intercomparison Project (IPCC CMIP6) [39], IUCN biodiversity threats [40], and GlobTherm datasets [18,41] for the sites.

In Step 2, present-day IUCN biodiversity threats are analysed for the relevant climate zones to create a biodiversity sensitivity map, which is then evaluated within the context of the IPCC projections under emissions scenarios SSP1-2.6 and SSP5-8.5. Furthermore, the GlobTherm data are analysed to construct the Potentially Affected Fraction (PAF) of species groups to temperature extremes using the sigmoid shape Upper Thermal-Tolerance Limit and Species Sensitivity Distribution (UTTL-SSD) response relationship [42,43].

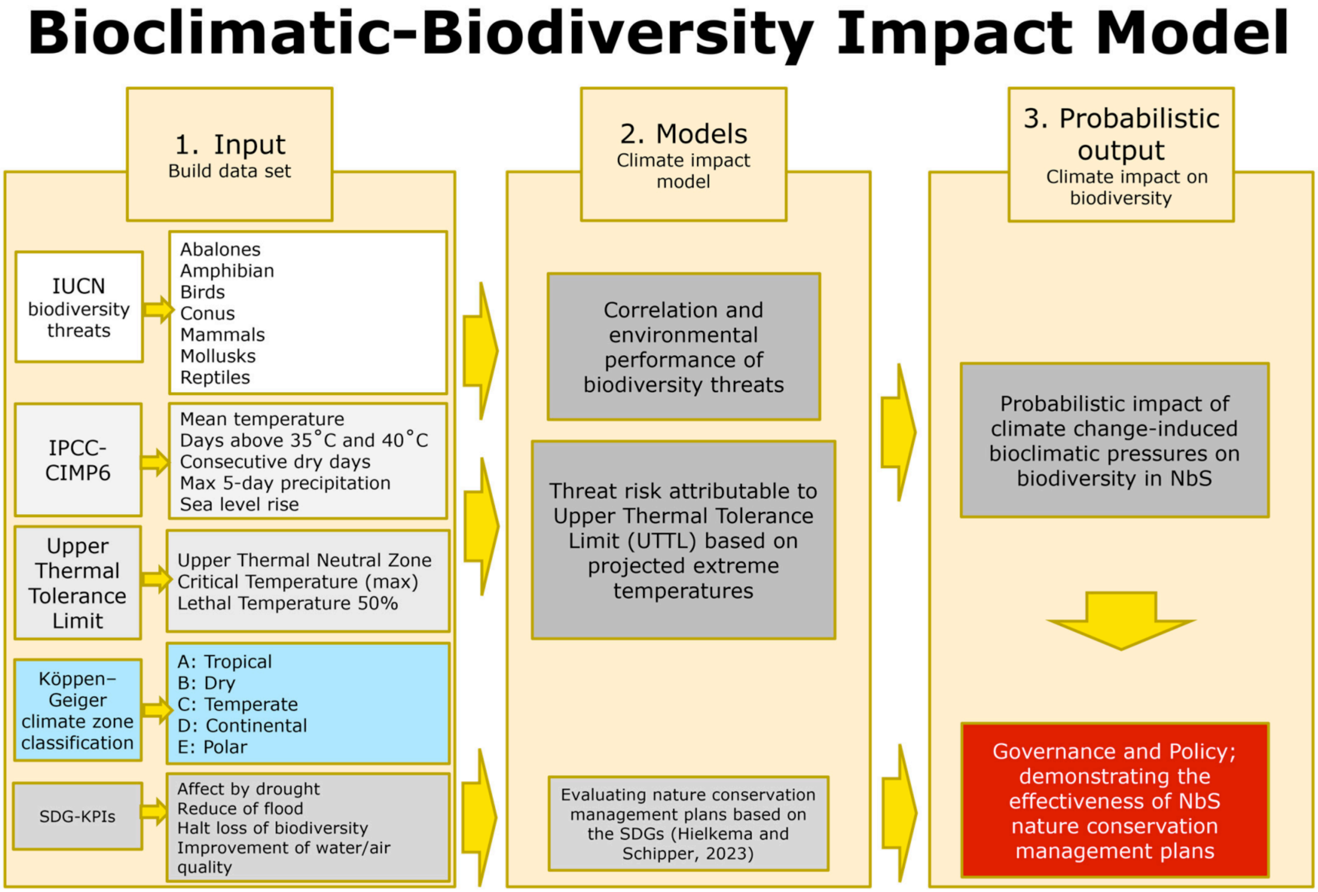


Figure 1. Schematisation of the BBI model. The diagram outlines the flow of processed data from the IPCC climate change-induced variable on the IUCN biodiversity threat used to assess potential biodiversity degradation and places these in relation to local vulnerabilities to demonstrate effectiveness management plans in Köppen–Geiger climate zone projections for 2081–2100 [30].

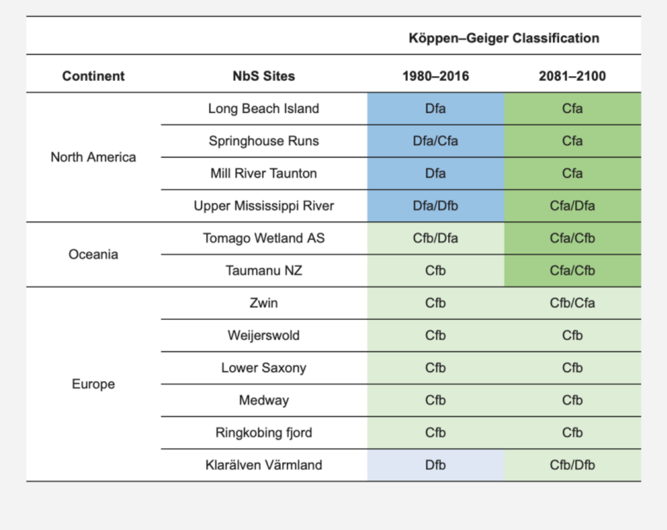
In Step 3, forecasts of probabilistic outputs are produced by correlations, tipping points, and food-web interactions for external bioclimatic drivers for selected species per region. It provides insights on potential biodiversity degradation in NbS sites and ranks these in relation to local biodiversity threats and vulnerabilities, demonstrating the effectiveness of management plans in climate zone projections for 2081–2100. Finally, the IPCC-SSD relationship demonstrates the effectiveness of management plans, considering the bioclimatic projections.

2.1. Building the Datasets

The IPCC model predictions are based on five scenarios, two of which are used in this body of work, namely, the SSP1-2.6 and SSP5-8.5 scenarios. Scenario SSP1-2.6 represents low greenhouse gas emissions and CO2 emissions declining to net zero around or after 2050, followed by global net negative CO2 emissions. Scenario SSP5-8.5 represents very high greenhouse gas emissions and CO2 emissions of about double the current levels by 2050 [39]. Utilising the lower and upper emission pathways allows for a thorough assessment of the full spectra of IPCC scenarios and to identify all threatened areas under best- and worst-case situations. The IPCC offers spatial data from CMIP6 for a range of bioclimatic variables, temporal domains (both historical data and projections), and Shared Socio-economic Pathways (SSP) [44]. Bioclimatic data were collected for mean annual temperature (in degrees °C), days warmer than 35 °C and 40 °C annually (biases adjusted using ISIMIP3 method [45]), max 5-day precipitation (in mm), consecutive dry days (CDDs) and sea level rise (SLR; in meters). In addition to SSP1-2.6 and SSP5-8.5 scenarios, bioclimatic data were collected for the baseline periods 1850–1900 (for mean temperature) and 1995–2014 (for precipitation, drought, and sea level rise). These data were collected as averages over the NbS site surface area. From the baseline and projection datasets, the changes in bioclimatic variables between periods were calculated manually.

Local biodiversity threat profiles were produced, based on the IUCN biodiversity-threat spatial data and species' thermal-tolerance limits. Firstly, the IUCN provides spatial data for threatened species and the direct threats to species. The IUCN connects threats for different species groups to the bioclimatic pressures via the IUCN Threats Classification Scheme (version 3.3. retrieved on 8 March 2022 https://www.iucnredlist.org/resources/threat-classification-scheme) [40]. Key factors of note used in this study are temperature increases and extremes, storms and pluvial flooding, droughts, and habitat shifting and alteration (sea level rise included; Table A2). The IUCN data were modified in the same process as described by [46,47], and used to generate a spatial biodiversity sensitivity map. Following the IUCN species distribution data [40], species were selected based on the overlap of their distribution with the coordinates of the NbS sites under consideration. Additionally, the species had to be scored as extant, native, and resident, so that invasive species were excluded. This ensured that species not adapted to local climate conditions were not evaluated and did not skew the evaluation of native ecosystems. Ten key species groups that play a central role in several ecosystem services were selected, namely, amphibians [48]; birds, fish, and mammals [49]; reptiles, insects, and arachnids [21]; and, lastly, abalones and conus for coastal areas or mollusks for river catchments [50]. The sensitivity of biodiversity assemblages to bioclimatic pressures was evaluated based on the count of local species threatened by the bioclimatic pressure.

Secondly GlobTherm database [18,40] was used, which represents a composite dataset of thermal-tolerance limits of species globally. The dataset consists of marine, fresh water, and terrestrial organisms and assesses the ecological impact of temperature in Oceania, North America, and Europe. The data cover land, marine, fresh water, and brackish water biomes, representing 10 taxonomic groups. The Upper Thermal-Tolerance Limit (UTTL) was then defined by considering the measure of upper thermal tolerance that allows the greatest taxon coverage. The limits considered were the Upper Thermal Neutral Zone (UTNZ), Critical Thermal Maximum (CTmax), or the Lethal Temperature for 50% (LT50) depending on species group. The UTNZ and CTmax describe critical temperatures at which key ecological functions are lost, such as locomotion and the ability to gain nutrition or maintain basal metabolism for UTNZs (only applicable for endotherms). LT50 describes lethal temperatures at which mortality in 50% of individuals occurs, where mortality is considered as the death of the entire individual or a portion thereof, such as leaf die-off in a tree [40]. UTTL data points were selected for the climate zones (for the period 1980–2016) of the NbS sites per continent (Table 1).



		Köppen–Geiger Classification	
Continent	NbS Sites	1980–2016	2081–2100
North America	Long Beach Island	Dfa	Cfa
	Springhouse Runs	Dfa/Cfa	Cfa
	Mill River Taunton	Dfa	Cfa
	Upper Mississippi River	Dfa/Dfb	Cfa/Dfa
Oceania	Tomago Wetland AS	Cfb/Dfa	Cfa/Cfb
	Taumanu NZ	Cfb	Cfa/Cfb
Europe	Zwin	Cfb	Cfb/Cfa
	Weijerswold	Cfb	Cfb
	Lower Saxony	Cfb	Cfb
	Medway	Cfb	Cfb
	Ringkobing fjord	Cfb	Cfb
	Klarälven Värmland	Dfb	Cfb/Dfb

Table 1. Overview of the climate zones in NbS sites in 1980–2016 and 2081–2100 following the Köppen–Geiger climate classification scheme. Abbreviations: Dfa = humid continental climate with hot summer; Dfb = humid continental climate with warm summer; Cfa = humid subtropical climate areas; Cfb = temperate oceanic climate areas. Different colors show the changes in the zones in the 21st century.

2.2. Climate Impact Model

2.2.1. Upper Thermal-Tolerance Limit and Species Sensitivity–Response Relationship

In the second step of the BBI model, the relevant adverse effects of emerging threats can be assessed for a Potentially Affected Fraction (PAF) of species [51,52]. As the PAF includes the variation in sensitivity among all species tested, it gives a more ecologically relevant indication of the risk of an environmental pressure. This approach shifts away from a binary 'risk' or 'no-risk' evaluation for the most sensitive species, and rather addresses the likelihood that different effects are predicted based on a statistical analysis of all species tested [42]. In our study, the PAF of species was converted into SSD curves to use causal relationships between temperature exposure level and effects realised for individual species. The SSDTOOLS package was used to plot SSD curves in R statistical software version 4.2.2 [53], and the curve represents the best fit of the data to the sigmoid function [54,55,56]. The SSD curves consist of at least six species; if this was not possible, the SSD curve was omitted. From these SSD curve calculations, the Upper Thermal-Tolerance Limit sensitivity of species' tipping points was derived as the percentage of species threatened above 35 °C and 40 °C.

2.2.2. Correlating IPCC Projections with IUCN Data

The direct threats to species in NbS sites were correlated with the projected changes in bioclimatic pressures using the Spearman's correlation coefficient [57]. The Spearman correlation coefficient p is a measure of the strength and direction of monotonic association between two independent variables. The interpretation of the Spearman correlation relies on several factors: the closer p is to +1 or −1, the stronger the monotonic relationship. A Spearman's correlation was run to determine the relationship of selected IPCC SSP1-2.6 and SSP5-8.5 variables for temperature, drought, and precipitation with the number of species threatened by the respective IUCN biodiversity threat. Correlating IPCC projections with IUCN data gives insights into the effects of projected changes in bioclimatic pressures on local biodiversity in NbS sites. A positive correlation (bioclimatic pressure has threatened many species and is projected to increase until 2100) indicates the climatic pressure poses a threat of biodiversity loss in the NbS site.

2.3. Probabilistic Climate Impact on Biodiversity

The effect of heat stress on an ecosystem as a whole can be simulated by integrating projected heat stress among species with food web interactions. Simplified food webs were constructed for East Australian, North American, and European NbS sites to simulate the predicted effects of temperature rise on various trophic levels [58,59]. This is performed by utilising only the species groups considered and detailed above. The interactions were based on the SSP5 climate scenario and the percentage estimates of species within a given species group which are threatened by heat stress, as shown in the UTTL-SSD curves.

The degree to which NbS for Nature Conservation Management (NCM) plans consider climate change scenarios and address their impact on biodiversity is key to determining how such plans contribute to the active or potential conservation of threatened species. NCM plans must not only be appointed for species currently under threat, but should also include species potentially threatened as a result of changing bioclimatic conditions. To this end, forecasts resulting in probabilistic outputs were produced using PAF and an analysis of biodiversity threat profiles to external bioclimatic drivers for selected species groups; this was repeated for each considered region. Plotting resultant thermal-tolerance limits of species regarding the UTTL-SSD response relationship provided insights into possible tipping points and biodiversity degradation as a result of external bioclimatic drivers due to the effects of global warming on ecosystems. In line with [30], the NCM plans of the 12 considered sites were compared using the UTTL-SSD response relationship to determine the degree to which climate change is considered and affecting these sites. This is performed to enhance the BBI model and assess the vulnerability of biodiversity in NbS sites for different climate zones in relation to climate change scenarios. Additionally, we also correlated predicted changes and how they may be affecting local biodiversity. The statistical Spearman's correlation is more limited as it does not describe potential tipping points, but it can highlight the local bioclimatic pressures of concern for nature conservation planning.

Results

3.1. Building Datasets

Twelve NbS sites are selected across Northwest Europe (six), Eastern North America (four), and East Oceania (two), including six coastal sites and six river sites. The NbS sites are located in four different climate zones following the Köppen–Geiger climate classification for the present day (1980–2016) and the future (2081–2100) (Table 1). Some North American and Oceanian NbS sites considered are located in multiple climate zones, due to the sites' location and low level of confidence in prescribing only one climate zone. When looking at current and 2081–2100 classifications, projected climate change results in the zones altering for most of the NbS sites.

The IPCC CMIP6 model projects great bioclimatic variabilities among NbS sites and continents (Table A3 and Table A4). In the European NbS sites, most significant projected changes are longer periods of drought (CDD, SSP1: 0.28–2.08 days; SSP5: 1.44–8.49 days) and more extreme precipitation (max. 5d, SSP1: 3.40–7.47%; SSP5: 14.16–19.78%). In North American NbS sites, the temperature rises (mean annual, SSP1: 2.29–2.78 °C; SSP5: 5.74–6.99 °C) and precipitation intensifies (max5d, SSP1: 5.23–7.63%; SSP5: 17.42–21.51%) most significantly. Sea level may rise most at the coast of Long Beach Island (North America), with changes from 0.69 m (SSP1) to 0.97 m (SSP5), while at the other coastal NbS sites, sea level rises were documented from 0.4 m (SSP1) to 0.7 m (SSP5). In absolute numbers, North American sites are projected to experience higher levels of precipitation and fewer consecutive dry days than Europe (under SSP5; $F(2, 9) < 5.2$, $p < 0.05$). Conversely, Europe is set to experience longer dry periods and a stronger increases in consecutive dry days compared to North American sites under SSP5 ($p = 0.07$) and Oceanian sites under both SSP1 ($p = 0.04$) and SSP5 ($p = 0.06$). Precipitation increases similarly in Europe compared to North American and Oceanian sites under SSP1 ($F(2, 9) = 4.619$, $p = 0.36$) and SSP5 (NA: $p = 0.05$, OC: $p = 0.54$). Extreme temperatures—that is, days warmer than 35 °C and 40 °C—will be more likely in North American and Australian sites, with rare events in Europe. Under SSP5 especially, extremely hot days will be more frequent.

The biodiversity sensitivity maps (Figure 2) show the number of species threatened for North American, Oceanian, and European areas and for temperature extremes, storms and flooding, droughts, and habitat shifting and alteration. The biodiversity sensitivity maps show that North American NbS sites are threatened by the combination of drought, temperature, precipitation, and habitat shifting and alteration, with mostly mammals and birds coming under pressure. European NbS sites are threatened by the combination of temperature, droughts, and habitat shifting and alteration, with mostly birds, mammals, and mollusks under pressure. Oceanian NbS sites are threatened by the combination of temperature, precipitation, drought, and habitat shifting and alteration, with mostly birds and mammals under pressure. It is important to note that in the majority of cases where species are coming under threat, it is a result of habitat shifting and alteration. This holds especially true for birds and mammals. For birds, this is most notable in Springhouse Runs stream and Tomago Wetland, where large numbers of bird species are threatened, due to habitat shifting and alteration.

3.2. Bioclimatic Impact on Biodiversity

Forecasts generating probabilistic outputs are made through the application of the Potentially Affected Fraction. Subsequently, an analysis of biodiversity threat profiles and climate projections for selected species groups is generated per region. Figure 3, Figure 4, Figure 5, Figure A2, Figure A3 and Figure A4 show the SSD curves generated for the UTTL–SSD response relationship for different species groups per continent. To provide insights in species degradation aspects linked to projected extreme temperature, the figures show the 35 °C and 40 °C lines, indicating that species on the left side experience heat stress at those temperatures (not indicated for aquatic species). The UTTL-SSD curves show many species groups are sensitive to heat stress, indicating a potentially dramatic decline in species in NbS sites due to frequent heatwaves in North America and Oceania.

In North America, many species have a thermal-tolerance level below 35 °C (Figure 3 and Figure A2), while temperatures among NbS sites are projected to exceed 35 °C for 5-to-24 days in 2100 under SSP1 and 33-to-84 days under SSP5 (Table A4). Approximately 60% of mammals and 50% of birds have a UTNZ lower than 35 °C and approximately 45% of amphibians have a maximum CTmax lower than 35 °C. The majority of species have a thermal-tolerance level below 40 °C, but 40+ °C days are much less frequent.

In European sites, extreme warm days are not projected to be frequent. It is only under SSP5 where 0 to 9 days are expected to exceed temperatures of 35 °C (Table A3). Approximately 70% of birds and mammals (combined) have a UTNZ lower than 35 °C (Figure 4 and Figure A3).

In Oceanian sites, extreme warm days are only projected to occur in Tomago Wetland (Table A4), while many species have a thermal-tolerance level below 35 °C (Figure 5 and Table A4). Temperatures exceed 35 °C on 14 (SSP1) to 41 days (SSP5) and temperatures exceed 40 °C during 1 (SSP1) to 7 days (SSP5). Approximately 90% of mammals and 55% of birds have a UTNZ below 35 °C and approximately 60% of amphibians have a CTmax below 35 °C. In total, 100% of these species have a temperature tolerance below 40 °C.

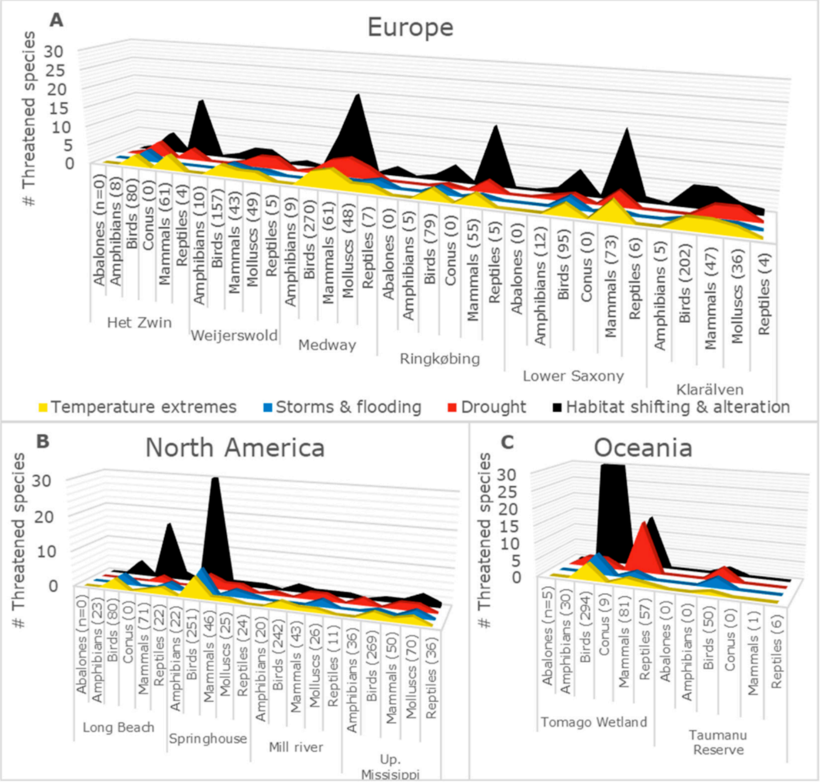


Figure 2. Number of threatened species of abalones, amphibians, birds, conus, mammals, mollusks, and reptiles in NbS sites in Europe (A), North America (B), and Oceania (C) due to temperature extremes, storms and flooding, droughts, and habitat shifting and alteration. The total number of endemic species present in the IUCN database is given in parentheses.

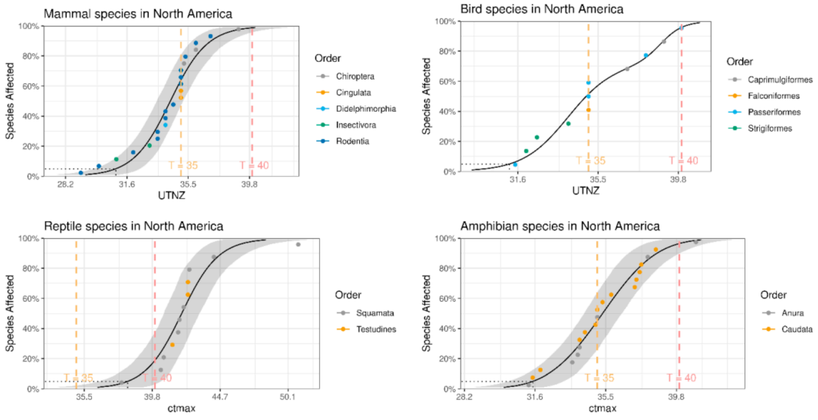


Figure 3. The Species Sensitivity Distributions for North America. The UTNZ and CTmax SSD–response relationship of invertebrate and vertebrate species is shown as sigmoid curves [40]. The percentage of affected species at temperature (°C) is represented by the solid black line, with the model-averaged 95% confidence interval indicated by the shaded band, and the 5% affected species threshold by the black dotted line. In 2100 in North America, the ambient temperatures are projected to exceed 35 °C for 5–25 days (SSP1) and 33–85 days (SSP5) and to exceed 40 °C during 0–2 days (SSP1) and 5–22 days (SSP5). Note that large group of species show high sensitivity to the extreme temperatures projected in 2100.

The outcome of correlating the current biodiversity threats with the projections of changing bioclimatic pressures mean annual temperature, max 5-day precipitation, and droughts (CCD) gives no clear positive correlations among all sites considered on a global scale (Table A5). However, on regional scales, moderate (rho > 0.4), strong (rho > 0.6), and very strong (rho > 0.8) positive correlations were found for precipitation and drought among European NbS sites and future climate zones Cfa (North America and Oceania) and Cfb (Europe). Positive correlations highlight an imbalance in the climate pressures of concern, where biodiversity in some sites, per continent or climate zone, stand to be particularly vulnerable and exceptionally influenced under the considered projected intensifying climate conditions. For instance, in Europe, drought is projected to intensify, particularly in NbS sites where biodiversity shows sensitivity to droughts (rho (6) = 0.78, p = 0.06)—as is the case for the Medway Catchment and Het Zwin.

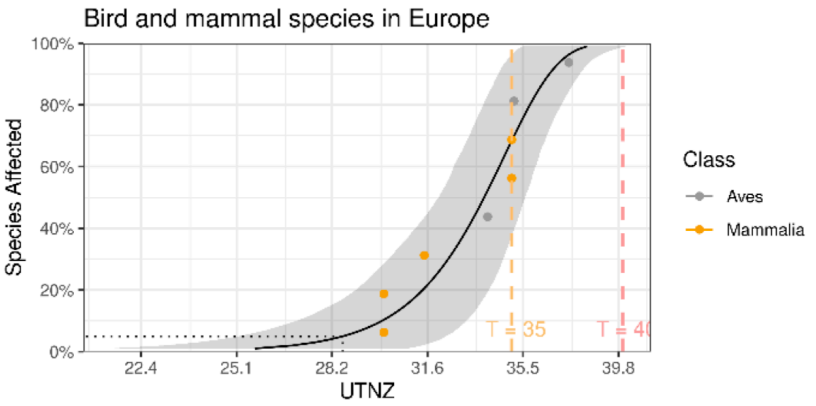


Figure 4. The Species Sensitivity Distributions for Europe. The UTNZ SSD–response relationship of vertebrate species is shown as sigmoid curves [40]. The percentage of affected species at temperature (°C) is represented by the solid black line, with the model-averaged 95% confidence interval indicated by the shaded band, and the 5% affected species threshold by the black dotted line. In 2100, in Europe, the ambient temperatures are projected to exceed 35 °C for 0–1 days (SSP1) and 0–9 days (SSP5) and exceed 40 °C during 0 days (SSP1) and 0–2 days (SSP5). Note that while many species show high sensitivity to extreme temperatures, the projections show extreme temperature will be very uncommon in 2100.

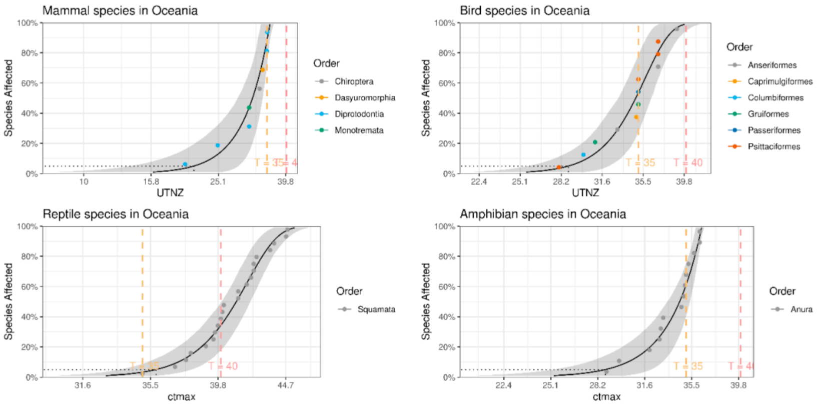
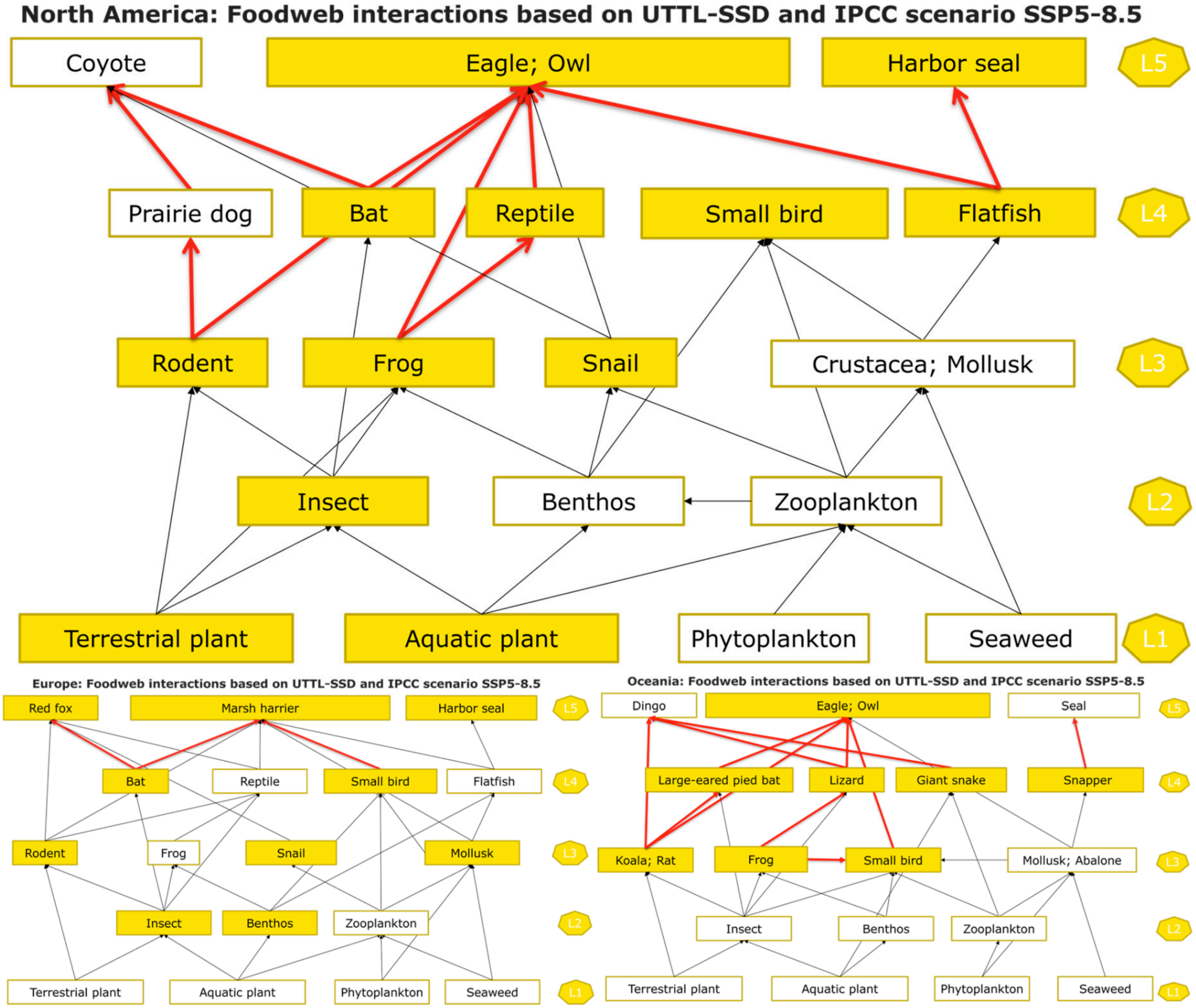


Figure 5. The Species Sensitivity Distributions for Oceania. The UTNZ and CTmax SSD–response relationship of invertebrate and vertebrate species is shown as sigmoid curves [40]. The percentage of affected species at temperature (°C) is represented by the solid black line, with the model-averaged 95% confidence interval indicated by the shaded band, and the 5% affected species threshold by the black dotted line. In 2100, in Oceanian sites, the ambient temperatures are projected to exceed 35 °C for 0 and 14 days (SSP1) and 0 and 41 days (SSP5), and to exceed 40 °C for 0 and 1 days (SSP1) and 0 and 7 days (SSP5). Note that large group of species show high sensitivity to extreme temperatures, which are projected to occur frequently only in East Australia in 2100.

3.3. The Effect of Intensifying Climatic Conditions on Ecosystems as a Whole

The effect of heat stress among species was integrated with food-web interactions based on the percentage estimates of species affected by heat stress (Figure 6). This assessment aims to indicate what percentage of a certain species group stands to be at risk and potentially removed from the food-web dynamics, or at least significantly reduced. The majority of potentially affected food-web interactions exist amongst the higher trophic levels. These extreme temperature pressures are indicative of a dramatic decline in species by limiting food-web interactions and, potentially, overall biomass. Extinction events are seldom reversible without considerable conservation efforts; if caused by persistent and increasingly severe climactic pressures, reversibility or mitigation is highly unlikely. This highlights that through heat waves, a reduction in the number of species and trophic levels is realised, which has a direct impact and influence on the number of key species characteristics.



North America: Foodweb interactions based on UTTL-SSD and IPCC scenario SSP5-8.5

Europe: Foodweb interactions based on UTTL-SSD and IPCC scenario SSP5-8.5

Oceania: Foodweb interactions based on UTTL-SSD and IPCC scenario SSP5-8.5

Figure 6. Visualisation of food-web interactions at risk among key species groups in North America (top), Europe (bottom left), and Oceania (bottom right). Arrows show predator–prey interactions, with red arrows indicating prey is under pressure due to extreme temperatures. Thresholds result from extreme temperature IPCC projections for 2081–2100 under scenario SSP5-8.5 and UTTL-SSD response relationships. Species groups without UTTL-SSD data are shown in white.

In Oceanian sites, considerable impacts on biodiversity are caused by extreme temperatures, based on the UTTL-SSD curves and IUCN data. However, drought and habitat shifting and alteration also have a profound impact on the populations of birds, mammals, and amphibians. Multiple species experience a cumulative risk of extreme temperatures and drought, namely, species of the genus bat Vespadelus, frog Pseudophryne, and pigeon Hemiphaga, based on the UTTL-SSD and IUCN data assessments, and the bird species Larus bulleri, koala Phascolarctos cinereus, and bat Pteropus poliocephalus, based on the IUCN data assessment. In North America and Europe, UTTL-SSD and IUCN datasets showed no matching species or genus. Based on the IUCN dataset, in North America, cumulative impact by extreme heat and drought did exist for mollusks Cyclonaias tuberculate, Lampsilis cariosa, Ligumia recta, and Margaritifera margaritifera, and the skunk Mephitis mephitis. In European sites, heat and drought impact the bats Eptesicus serotinus, Myotis nattereri, and Plecotus auratus, and mollusk Margaritifera margaritifera.

Discussion

When considering the effects of changing climatic conditions in NbS sites, one should not only look at the multiple scales that the impacts of climate change have on biodiversity, but also the consequences that the cumulative impacts have in relation to increasing climate pressures on ecosystems. These bioclimatic changes are also dependent on the behavioural and evolutionary mechanisms of species, available connectivity to other habitats, species interactions, and range shifts in the environment that are impacting ecosystems [9]. These shifts in ecosystems, coupled with habitat degradation induced by phenomena such as sea level rise, wildfires, alterations in stream temperature, and shifts in species distributions, pose significant challenges and impose significant stressors [7,8,10,12].

The aim of this publication is to assess the risks posed to biodiversity from referenced IPCC scenarios in response to climate change, utilising key species-sensitivity indicators and variables. In doing so, we address how climate-change-driven bioclimatic pressures may affect biodiversity based on the IPCC-IUCN-profiles and using the UTTL-SSD response relationship for species groups. Ref. [60] expresses a need to use climate change projections to take action on heat waves, extreme precipitation events, and extreme droughts, a claim reaffirmed through this body of work. However, a novel point of concern that has been raised is how are NbS nature-conservation management plans integrating climate change and impact scenarios in the context of biodiversity? Using these relationships and their impacts in medium- and long-term projections would be needed to support or inform the conservation of (potentially) threatened species in the face of climate pressures. This study highlights the fact that the conservation of these species in the currently denoted NbS sites may not be possible.

Models have been developed to provide response profiles and quantify the impacts of bioclimatic pressures on species distribution [61]. These response profiles are considered “fingerprints”, and are indicative of which species are affected by changing subsets of climate pressure variables and which are not [35]. Ref. [62] have suggested that conservation plans need to explore the relationships between biodiversity and ecosystem dynamics in response to climate extremes to understand the implications of systems being disrupted by periodic extreme events. To do so, further emphasis is needed on the development or larger applications of predictive models that consider the interactions between atmospheric processes, behavioural and migration patterns, and ecosystems. Such coupled models would allow for a prediction of the effectiveness of niche-model interventions over alternative frameworks for site-specific investigations, thereby building resilience and allowing for more comprehensive predictions of climate change’s impacts on ecosystems [25,63,64].

Previous studies have shown that the relative proportion of species threatened, from the IUCN Red List in combination with IUCN predictors, is a relevant indicator to assess climate change effects on bioclimatic variables and biodiversity. However, most studies were not conducted for NbS sites over multiple transects based on climate zones. In our study, the global IPCC climate projections are coupled to today’s IUCN biodiversity threats to enhance understanding regarding the effectiveness of applying NbSs for climate adaptation and biodiversity conservation. The method of migrating species to support or replace declining population structures is not analysed within the scope of this study; however, it will likely play a significant role in shifting populations and replacing those no longer suited to certain regions. An analysis on foreign species migrating due to shifting habitats and suitability ranges is outside of the scope of this research, as to gather this information would require a critical analyses into food-web dynamics and the supplantation of endemic species, potentially leading to structural and functional shifts in ecological composition. This shifting of biomes has been cited to result in waves of what would now be considered as invasive species and drastic alterations to food webs, especially in 2080–2100 timelines.

4.1. NbS Nature-Conservation Management Planning

The BBI model incorporates projections on future bioclimatic pressures through species threat profiles that show species vulnerabilities based on empirical research, as well as UTTL-SSD response relationships, to highlight species tipping points for temperature extremes, highlighting bioclimatic pressures that need to be the focal point of nature conservation planning. In North American sites, climate conditions are projected to transition from a humid continental climate to a more humid subtropical climate. Temperatures are expected to increase by 2 °C to 7 °C, with a higher frequency of heat waves. Biodiversity in four NbS sites is especially threatened by heatwaves, particularly for species of higher trophic levels, with heat stress significantly affecting approximately 60% of mammals, 50% of birds, and 45% of amphibians for durations ranging from 5 to 84 days per year from 2080. Additionally, the intensification of droughts and precipitation events, habitat shifts and alterations, and the cumulative effects thereof, pose significant threats to mammals and birds, among other species. Examination of the nature-conservation management plans of the North American NbS sites reveals a significant deficiency in planning for increased resilience to rising temperatures, precipitation, and drought [30], indicating a need for substantial improvements.

In Oceanian sites, climate conditions are projected to shift from a temperate oceanic climate to a more subtropical climate. Frequent heatwaves are expected, as well as intensified precipitation events, particularly in the NbS site in New Zealand. Biodiversity in two NbS case studies, again mainly those of higher trophic levels, faces considerable threats from heatwaves, with heat stress affecting approximately 90% of mammals, 55% of birds, and 60% of amphibians significantly for durations of 14 to 41 days annually, from 2080. Furthermore, the intensification of droughts, precipitation events, and habitat shifts and alterations, along with cumulative effects, threatens birds and mammals, among other species. While nature conservation management plans for the Oceanian NbS sites in this region do address these concerns and aim to enhance resilience to increasing bioclimatic pressures, the potentially high percentage of species that will experience heat stress remains alarming.

In European sites, climate conditions are projected to remain relatively stable, with only the Klarälven Varmland site experiencing a shift from a humid continental climate to a more temperate oceanic climate. However, droughts and precipitation events are expected to intensify. While birds and mammals in this region are sensitive to heat waves, such events will remain rare in the European sites. Biodiversity is nonetheless sensitive to temperature increases, and the intensification of droughts, precipitation events, and habitat shifts and alterations pose threats to birds, mammals, and mollusks. Examination of the nature conservation management plans for the European NbS sites indicates that there are strategies in place to address concerns related to increasing temperatures, precipitation, and habitat shifts. However, there is a notable lack of planning to enhance resilience to intensifying droughts, necessitating significant improvements in these areas.

4.2. Effects of Temperature Rise on Biodiversity

There is a realistic chance that, even under the most ambitious action scenario SSP1-1.9, global warming will exceed 1.5 °C in the next decade; even 2 °C is within reach, based on emissions scenarios SSP3-7.0 and SSP5-8.5 [65,66]. However, the IPCC projects additional extreme warming hereafter. NbS sites are widely applied as a climate adaptation strategy; however, they are not always applied in an effective manner, and often only in the consideration of floods. Some studies have used global datasets, with a temporal resolution including historical periods and extending to future time horizons by including a post-processing of climate simulations [67]. We have shown that biodiversity is threatened due to more frequent extreme temperatures, based on the UTTL-SSD response relationship, temperature projections under scenarios SSP1-2.6 and SSP5-8.5, and empirical data on species threats.

Many species groups that are threatened by projected extreme-temperature conditions reside in higher trophic levels (Figure 6), potentially destabilising the balance of food webs and consequently reducing ecosystem self-regulation and increasing the risk of biodiversity loss. Further intensive investigations on the effects of climate change and resulting probabilistic redistributions of ecosystems and habitats on Earth would be useful to study the multi-scale implications of climate impact responses. Based on such studies, as we demonstrated in our examples, the internal UTTL-SSD response relationship can be related to habitat-based SSDs for ecological risk assessment of global-warming-induced tipping points.

Ref. [68] suggest that disruptions to ecological assemblages caused by climate change will be abrupt, and the result of resilience breakdowns. Within any given ecological assemblage, the exposure of most species to climate conditions beyond their realised niche limits occurs almost simultaneously. Based on our study of the biodiversity assemblages, biodiversity threats and projections for bioclimatic projections suggest serious biodiversity breakdowns within several ecosystems in North America and East Australia, which is further substantiated with the UTTL-SSD response relationships. The impact may be undervalued due to the cumulative effects of extreme temperature and droughts on biodiversity in combination with habitat alterations.

4.3. Cumulative Impacts on Biodiversity

The striking conclusions based on the UTTL-SSD response relationship can be seen as a metaphor for the sensitivity of the species, linked to other extreme weather events. Our study highlights the need for research on species tipping points for the climate pressures of droughts, extreme precipitation, and sea level rise. Changing climate conditions are caused by a chain of effects and compounding bioclimatic pressures [14], such as changes in temperature and the water cycle. However, there is no empirical evidence for biodiversity showing a tipping response to all environmental drivers; trying to formulate or suggest a “manageability” that is, in fact, not feasible is still advised in many cases, and is adverse to conservation targets [69]. The applied BBI model shows the temporal changes in composition and the spatial changes in the UTTL-SSD response relationship of climate zones. By using the UTTL-SSD response relationship in the climate Köppen–Geiger zones, the number of affected species interactions in an ecological ecosystem may be clarified. Still, because of the cumulative bioclimatic and anthropogenic pressure on biodiversity, the species tipping response will be hard to pinpoint.

Sensitive species are often negatively impacted, due to cumulative bioclimatic pressures, as seen in North American and East Australian sites, where climate zones shift from humid continental climate conditions to a more humid subtropical climate. The impact is most notably felt by populations of amphibians, birds, mammals, and fish, placing these at high risk of impacts resulting from habitat changes. This is especially pronounced for the Tomago Wetland, as it shows high percentages of threatened species. As sensitive species are exposed to risks caused by extreme high temperature and further so by cumulative effects, these shifts are expected to have reasonable impacts on multiple populations.

It is reasserted that tropical ecosystems are most vulnerable to climate change. In these climate zones, temperature shifts have been identified as a key tipping point and trigger for amphibian, bird, and mammal decline, while thresholds may be exceeded for cumulative effects of hot days above 35 °C during prolonged periods of drought. Drought-adaptation condition mechanisms exist in the combination of ecological processes, physiological strategies, and morphological habitat changes [22,70]. However, when droughts, extreme temperature, and heatwaves occur together, biodiversity elements show considerable differences regarding drought tolerance and species mortality throughout the food web [71,72,73,74].

Conclusions

This paper illustrates the benefits of integrating IPCC climate change pathways with IUCN biodiversity threats and upper thermal-tolerance levels for a range of species groups. It demonstrates that doing so enhances the degree to which climate resilience is considered in nature conservation planning for NbS sites and can highlight issues with implementation strategies for medium- and long-term periods. By applying the Bioclimatic–Biodiversity Impact model, the causal relationship between extreme ambient temperature exposure level and the level of effect on individual species can be explored. In doing so, a compelling explanation of how climate change affects species can be developed. The bioclimatic projections suggest serious biodiversity breakdowns within several ecosystems in North American and East Australian NbS sites under scenarios SSP1-2.6 and SSP5-8.5 in 2081–2100. This is further substantiated with the analysis conducted using the UTTL-SSD response relationships and the future climate predictions for these regions. The UTTL-SSD response to extreme ambient temperature has been identified as a key tipping-point trigger for many species of amphibians, birds, and mammals in their respective food webs. The UTTL-SSD responses can be used to highlight potential risk among trophic levels in food web structures. Our results indicated the potential destabilisation of food webs, particularly links within the higher trophic levels. To better align the ambitions and conservation targets of NbS sites, NCM plans must better consider the multiple pressures on the horizon resulting from climate change and the pending crises related to this. NCM plans that seek to protect threatened species cannot effectively do so without the incorporation of coupled stressors represented in various policy pathways, and focusing on those pathways remains realistic, despite current levels of action or inaction. Further investigations are needed regarding the effects and tipping points for climate pressures (e.g., drought) on biodiversity and the resulting probabilistic redistributions of ecosystems and habitats on Earth.

Appendix A: Table 1A, Figure A1, Table A2, Table A3, Table A4, Figure A2, Figure A3, Figure A4, Table A5.

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