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Advances in Assessing Wildlife Vulnerability to Climate Change: A Postprint

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Date: 2017-11-01T00:00:00+00:00

Abstract

Vulnerability assessment constitutes an important component of research on climate change impacts on wildlife, and identifying wildlife vulnerability is crucial and fundamental for adapting to and mitigating climate change effects. Conducting vulnerability assessments of wildlife under climate change aims to identify species susceptible to climate change and clarify the factors driving species vulnerability; such assessment results facilitate human understanding of climate change impacts on wildlife and provide a scientific basis for formulating conservation strategies for wildlife adaptation to climate change. For wildlife (at the species level), vulnerability denotes the degree to which species are affected by climate change, encompassing three major components: exposure, sensitivity, and adaptive capacity. Specifically, exposure comprises external factors arising from climate change, such as temperature, precipitation, and extreme weather events; sensitivity is influenced by species-specific factors, including interspecific relationships and tolerance; adaptive capacity refers to the ability of species to reduce climate change impacts through self-adjustment, such as migration or dispersal to suitable habitats, plastic responses, and evolutionary responses. This review examines recent methods for assessing wildlife vulnerability under climate change, compares the differences in indicators selected by each approach, summarizes methods for handling uncertain indicators encountered in vulnerability assessment, and discusses the application of vulnerability assessment results in strategies for wildlife adaptation to climate change. By synthesizing wildlife vulnerability assessment methods, this study aims to provide reference approaches for assessing the vulnerability of China's wildlife resources under climate change.

Full Text

Preamble

ACTA ECOLOGICA SINICA ChinaXiv Partner Journal Vol. 37, No. 20 Oct., 2017 DOI: 10.5846/stxb201607301564

Overview of Methods for Assessing the Vulnerability of Wildlife to Climate Change

Li J, Liu F, Zhang Y, Xue Y D, Li D Q. Overview of methods for assessing the vulnerability of wildlife to climate change. *Acta Ecologica Sinica*, 2017, 37(20): 6656-6667.

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Abstract

Vulnerability assessment is a critical component of research on climate change impacts on wildlife. Identifying wildlife vulnerability is fundamental to adapting to and mitigating the effects of climate change. The primary objectives of vulnerability assessments are to identify species susceptible to climate change and to clarify the factors driving species vulnerability. Assessment results enhance our understanding of climate change impacts on wildlife and provide a scientific basis for developing adaptive conservation strategies. Vulnerability represents the degree to which species are affected by climate change and comprises three core elements: exposure, sensitivity, and adaptive capacity. Exposure encompasses external factors driven by climate change, such as extreme weather events. Sensitivity reflects intrinsic species characteristics, including interspecific relationships. Adaptive capacity refers to a species' ability to adjust and reduce climate change impacts through mechanisms like migration to suitable habitats, phenotypic plasticity, and evolutionary responses. This review synthesizes recent assessment methods for wildlife vulnerability under climate change, comparing the indicators selected by each approach and examining how vulnerability assessment results inform adaptive conservation strategies for wildlife. We also summarize approaches for handling uncertainty in vulnerability assessments, aiming to provide methodological references for evaluating the vulnerability of China' s wildlife resources in the context of climate change.

Keywords: climate change; vulnerability; exposure; sensitivity; adaptive conservation strategies

Introduction

Climate change represents a major global environmental issue of widespread international concern. The Intergovernmental Panel on Climate Change (IPCC) assessment reports confirm that global warming is an undeniable reality, with

human activities being the primary cause of widespread temperature increases over the past century. From 1880 to 2012, global temperatures rose by approximately 0.85°C, while temperatures increased by 0.72°C. The resulting increase in greenhouse gases and consequent global warming have drawn growing attention to impacts on global biodiversity [2-3]. Climate warming has significantly affected biodiversity, with substantial observational evidence demonstrating profound impacts on species' geographic distributions [4-5], population dynamics [6-7], phenology (including breeding periods and migration distances) [8-9], and evolution [10-11], with these effects projected to intensify in the future [12-13]. If the trend of climate warming is not effectively curbed, the United Nations Framework Convention on Climate Change (UNFCCC) warns that biodiversity protection will face severe challenges, with temperature increases [14] potentially causing 15%-35% of species to go extinct [15]. Although predictions regarding the extent and rate of climate-driven extinctions remain debated, the accelerating trend of biodiversity loss due to climate warming has been widely documented [16-17].

In response to global climate change, how to develop effective biodiversity conservation strategies has become a hot topic among governments, ecologists, and the public. Vulnerability assessment is essential for understanding climate change impacts on wildlife. The International Union for Conservation of Nature (IUCN), IPCC, and related organizations, along with the United States and European Union, are actively conducting vulnerability assessments to establish scientific strategies for wildlife adaptation to climate change, ultimately providing robust support for effective climate response and wildlife conservation [3,18-21]. China's Biodiversity Conservation Strategy and Action Plan (2011-2030) also prioritizes climate change impacts on wildlife [22]. However, research in this field remains at an introductory stage, with insufficient understanding of assessment methods [23]. This paper reviews recent international methods for assessing wildlife vulnerability under climate change to provide methodological references for evaluating China's wildlife resources.

1. Concept of Vulnerability

The IPCC provides a comprehensive definition of vulnerability as the degree to which a system is susceptible to or unable to cope with adverse effects of climate change, comprising three components: exposure, sensitivity, and adaptive capacity [24]. Exposure refers to the degree of climate change stress on a system, sensitivity is the degree to which the system is altered by this stress, and adaptive capacity is the system's ability to adjust to climate change. Enhanced adaptive capacity reduces vulnerability [25]. For wildlife, vulnerability similarly includes these three components [26-27]. Exposure encompasses external factors resulting from climate change, including direct impacts like extreme weather and indirect effects such as altered habitat structure and sea-level rise [29-31]. Sensitivity is influenced by intrinsic species factors such as interspecific relationships and genetic diversity [28-29]. Adaptive capacity represents a species' ability to

reduce climate change impacts through adjustments like migration to suitable habitats, plastic responses, and evolutionary reactions [32-33].

2. Significance of Vulnerability Assessment

Vulnerability assessment provides the scientific foundation for developing effective climate adaptation strategies for species [30] and identifies the factors driving species vulnerability [28]. Assessments primarily address two questions: identifying species vulnerable to climate change and clarifying the causes of vulnerability. This process helps researchers and decision-makers understand climate change impacts, map vulnerability distributions, and formulate corresponding adaptive protection strategies. Vulnerability assessment is considered the starting point for all climate adaptation planning [30], enabling the identification of susceptible species and enhancement of their adaptive capacity.

3. Vulnerability Assessment Methods

Wildlife vulnerability assessment under climate change is a relatively new research field with limited methods. Existing literature categorizes assessment approaches into three types: bioclimatic envelope models, mechanistic niche models, and vulnerability index assessments [27,30,34].

3.1 Bioclimatic Envelope Model Assessment

Based on spatial niche theory, bioclimatic envelope models assess species vulnerability by predicting distribution ranges. These models can accurately determine current species distributions and project future changes [35-38]. By comparing current potential distribution areas with future projections, species vulnerability is inferred: large range contractions or minimal overlap between current and future distributions indicate significant climate impacts [39-41]. Lawler et al. used these models to project climate change impacts on vertebrates, finding that at least 81%-83% of species would experience distribution changes and some would disappear [42]. Sinerov et al. predicted that Mexican lizard extinctions would reach 14.5%-46.2% by 2080 [43]. Pearson et al. analyzed impacts on U.S. endemic amphibians and reptiles, projecting extinctions in 6%-9% of species under low emissions and 11%-15% under high emissions scenarios [44]. Marine organisms face similar threats; Poloczanska et al. studied 1,066 marine species, finding significant distribution changes in 81% [45]. Similar results have been reported for species like the Australian koala (*Phascolarctos cinereus*), Pacific walrus (*Odobenus rosmarus divergens*), Himalayan snow leopard (*Panthera uncia*), and Chinese giant panda (*Ailuropoda melanoleuca*), all facing substantial habitat loss and accelerated extinction risk [37,49-50].

However, climate change does not always reduce habitats. Some species may benefit from warming and expand their ranges, such as the Asian needle ant (*Pachycondyla chinensis*), American bullfrog (*Rana catesbeiana*), and European rotan (*Perccottus glenii*), which show potential for global or local expansion [53].

While bioclimatic envelope models accurately predict species distributions, using them alone to assess vulnerability has limitations [40,54]. These models primarily consider climatic factors, often overlooking important biotic and abiotic factors like species' environmental tolerances, species interactions, dispersal and evolutionary capacity, and geographic heterogeneity, which can affect predictive accuracy [40].

3.2 Mechanistic Niche Model Assessment

Mechanistic niche models, developed from field observations of population dynamics, physiological tolerance thresholds, and dispersal models, analyze extinction probabilities under future climate scenarios. These models, including population viability analysis (PVA), assess vulnerability by examining species' physiological tolerance ranges, dispersal ability, and population dynamics [27,30,55]. For example, Naveda-Rodríguez et al. combined distribution models with Vortex models to analyze Andean condor (*Vultur gryphus*) extinction risk, identifying habitat loss as the primary threat [56]. Jenouvrier et al. found that warming temperatures would reduce viability of Antarctic emperor penguin (*Aptenodytes forsteri*) populations [57]. Physiological tolerance-based assessments recognize that animals' environmental tolerance limits constrain distributions [58], with most ectotherms restricted to lowland tropical rainforests [59], marine ectotherms expanding toward poles and equators [60], and island insects limited to lower elevations [61]. Schloss et al. assessed mammal vulnerability in the Western Hemisphere using dispersal capacity, concluding that climate change velocity exceeds dispersal rates for many species, preventing 9% of mammals from adapting through dispersal [62].

Mechanistic niche models require highly accurate species-specific information (e.g., physiological tolerance ranges, dispersal ability, population structure) that is often difficult to obtain, necessitating extensive research [27,63].

3.3 Vulnerability Index Assessment

Vulnerability indices assess species vulnerability by scoring sensitivity, exposure, and adaptive capacity indicators. This is the most widely used method for global wildlife climate change vulnerability assessment [30]. Indices integrate extensive species information from literature, databases, expert opinion, and model projections [55,64]. To simplify this work, researchers and institutions have developed frameworks and systems.

The Climate Change Vulnerability Index (CCVI), developed by the U.S. conservation organization NatureServe, assesses vulnerability of North American species over 50 years [54,64,66]. The index comprises four components: (1) direct exposure to future climate change (temperature, precipitation); (2) indirect exposure (sea-level rise, habitat change); (3) species sensitivity (physiological tolerance, species interactions); and (4) adaptive capacity. Tuberville et al. applied CCVI to assess 50 amphibian and reptile species in the southeastern U.S.

dune ecosystem, finding 14.5% would become moderately vulnerable and 46.2% would remain stable [34]. Similar assessments of 168 bird species in California's Sierra Nevada found 62 species moderately vulnerable and 9 highly vulnerable, with alpine and aquatic birds most at risk [67]. Mammals like pumas (*Puma concolor*), white-tailed deer (*Odocoileus virginianus*), and Gambian giant pouched rats (*Cricetomys gambianus*) showed moderate vulnerability [68].

Although CCVI provides comprehensive indicators, its primary limitation is geographic restriction to North America, preventing broader application. However, its thorough indicator framework offers valuable reference for other regions.

The Climate Change Vulnerability Assessment (CCVA) framework, developed by the U.S. Environmental Protection Agency (EPA), evaluates threatened and endangered species vulnerability [73]. The framework consists of 20 current stress indicators (population size, distribution, life history) and 20 climate impact indicators, each scored for credibility. Integrated scores determine final vulnerability assessments for species like the golden-cheeked warbler (*Dendroica chrysoparia*), Mexican spotted owl (*Strix occidentalis lucida*), and Mount Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*) [73-74]. Moyle et al. modified indicators to assess native and invasive fish vulnerability in California, finding climate change would significantly alter regional fish communities [75]. Gardali assessed endangered California birds, integrating vulnerability with endangerment levels to prioritize conservation actions [65]. The EPA framework is relatively simple and produces credible results for well-studied endangered species, though its focus on threatened species limits its scope.

The System for Assessing Vulnerability of Species (SAVS), developed by the U.S. Forest Service, uses questionnaires to survey climate change impacts on terrestrial vertebrates [76]. The questionnaire addresses habitat alteration, phenological changes, and species interactions. Applied to 49 vertebrates in New Mexico, SAVS identified highly vulnerable species with low resistance and less vulnerable species with greater resilience [76-77]. The framework predicts strong climate impacts on regional habitats and physiology, with many species becoming highly vulnerable, such as the Sonoran pronghorn (*Antilocapra americana sonoriensis*) and Morafka's desert tortoise (*Gopherus morafkai*), whose populations are projected to decline significantly [78].

The Standardized Index of Vulnerability and Value (SIVVA), developed by NatureServe, addresses sea-level rise impacts on coastal lowland biodiversity [79]. SIVVA adds indicators like economic value and salinity to better reflect coastal species characteristics. Applied to Florida's lowland wildlife, SIVVA recommended priority conservation for species like Key deer (*Odocoileus virginianus clavium*) [80]. Compared to other habitats, some endangered species on Florida's reef islands show poor adaptive capacity and dispersal limitation, making them unable to cope with climate change. The Miami blue butterfly (*Cyclargus thomasi bethunebakeri*) faces extinction risk, with low probability of successful protection [81].

4. Vulnerability Index Indicators

Climate change affects wildlife in multiple dimensions, but all methods commonly use sensitivity, exposure, and adaptive capacity as assessment indicators [26,76]. However, no universal standard exists for indicator selection [34].

Sensitivity indicators include habitat specialization, physiological tolerance, genetic diversity, phenology, migratory status, population trends, habitat loss, management policy changes, dietary versatility, and species interactions. Species with high habitat specialization face greater extinction risk if their dependent habitats are severely affected by climate change. Similarly, species heavily reliant on human protection and management are more vulnerable than independent species.

Exposure indicators encompass temperature and precipitation changes, extreme weather events, dispersal barriers, and non-climatic stressors like disease, pollution, and land use. Regions with substantial temperature increases, altered rainfall patterns, and frequent extreme weather will significantly impact species. Human infrastructure or natural barriers blocking migration routes further exacerbate vulnerability.

Adaptive capacity indicators include dispersal ability, phenotypic plasticity, evolutionary potential, and habitat availability in projected ranges. Climate model predictions of future suitable habitat changes and food availability inform adaptive conservation strategies.

Indicator selection should be flexible and tailored to specific regions and species [34,65,75]. The greatest challenge is data availability, as only a few well-studied species have sufficient information for comprehensive assessment [26,34]. Climate change impacts occur rapidly, and by the time complete data are collected, habitats may be lost and species may face extinction [26,75].

For data-limited species, information can be estimated through: (1) literature review, (2) data from related species, (3) expert opinion, (4) experimental or field observations [30,55,65], and (5) historical climate data as proxies for physiological tolerance [64,82]. Some indicators like genetic diversity may remain incompletely understood [26,73]. Frameworks like CCVI allow flexible indicator use—assessments remain valid if most sensitivity indicators are addressed [64]. Uncertainty in climate change science is inherent, and vulnerability assessments represent approximate vulnerability levels rather than precise quantifications [75].

Table 1 Factors of climate change vulnerability addressed in different evaluation methods

Factor	CCVI index	EPA framework	SAVS system	CCVA framework
Sensitivity				
Specialized habitat	√	√	√	√
Migrate ability	√	√	√	√

Factor	CCVI index	EPA framework	SAVS system	CCVA framework
Biotic interaction/dependence	√	√	√	√
Phenology	√	√	√	√
Physiological tolerances	√	√	√	√
Genetic diversity/evolvability	√	√	√	√
Past/current population trends	√	√	√	√
Past/current habitat loss	√	√	√	√
Policy/management changes	√	√	√	√
Dietary versatility	√	√	√	√
Migratory status	√	√	√	√
Exposure				
Temperature/precipitation change	√	√	√	√
Changes in extreme weather	√	√	√	√
Barriers to dispersal	√	√	√	√
Non-climatic stressors	√	√	√	√
Climate model projections	√	√	√	√
Future habitat change in projected range	√	√	√	√
Food availability in projected range	√	√	√	√
Availability within new range	√	√	√	√

Note: The CCVA framework defines these as adaptive capacity factors.

5. Application of Vulnerability Assessment Results

Vulnerability assessments primarily aim to propose adaptive conservation strategies that mitigate adverse climate change impacts on wildlife [55]. Applications include:

- 1. Identifying vulnerability factors:** Effective adaptive conservation requires understanding current pressures (primary threats) and species sensitivity to these pressures [28,73]. Vulnerability assessments enable managers to modify conservation strategies adaptively through long-term monitoring, reducing human disturbance, and strengthening invasive species surveillance [55,83-84].
- 2. Identifying vulnerable species:** Assessments screen for priority conservation species that cannot adapt through dispersal or evolution [78]. Adaptive strategies like constructing ecological corridors can reduce climate change impacts for species requiring human intervention to overcome dispersal barriers [31].
- 3. Assessing vulnerable habitats:** Models predicting current and future suitable habitats can identify areas where habitat loss or degradation will occur, enabling targeted restoration, management, and monitoring to prevent habitat decline [86-87].

4. **Finding refugia:** Model projections can identify areas where suitable habitats remain stable or where currently unsuitable areas become suitable in the future. These climate refugia require enhanced protection and management, with planned corridors to reduce migration obstacles [88-89].
5. **Evaluating protected area effectiveness:** Gap analysis can assess whether existing protected areas cover current and future suitable habitats [2,90], informing adjustments to protected area networks and improving connectivity and overall conservation capacity [91-92].
6. **Informing IUCN Red List assessments:** Climate change vulnerability assessments can inform threatened species classifications in the IUCN Red List, increasing international attention and promoting conservation action [93].

6. Conclusion

Climate change uncertainty and limited wildlife knowledge pose challenges to vulnerability assessment. However, frequent extreme climate events in recent years [94] provide clear evidence that climate change is occurring and affecting China's wildlife [97-98], including observed shifts in avian fauna [99], altered phenology in insects and amphibians [100], potential rodent outbreaks [101-102], and local species extinctions [103].

Current Chinese research primarily uses models to predict future suitable habitat changes, focusing on single species like giant pandas [49-50], wild camels [104], Sichuan hill partridges [108], and snow leopards [89], or multiple species groups including birds [96], amphibians [109], and ungulates [110]. These studies often overlook small-scale impacts and biological factors like species interactions and life history traits, despite local climate disasters potentially having more severe consequences [111-112].

Research on wildlife vulnerability assessment under climate change remains limited in China, with most studies considering only current pressures while ignoring future climate impacts, and lacking effective techniques for developing adaptive conservation strategies [23]. We recommend that Chinese researchers and managers:

1. Establish long-term wildlife monitoring systems (population dynamics, geographic ranges) to support vulnerability assessments. While comprehensive biodiversity databases like North America's NatureServe are not yet feasible, 自然保护区-scale data platforms with sharing mechanisms could be developed.
2. Enhance climate change monitoring and prediction capabilities, establishing mechanisms to prevent extreme climate impacts on wildlife.
3. Learn and adopt new vulnerability assessment methods, establishing indicator systems suitable for Chinese wildlife to evaluate vulnerability under

future climate scenarios.

4. Analyze wildlife adaptive processes and capacities (migration, evolution) to support adaptive conservation strategies.
5. Improve adaptive management practices and reduce anthropogenic factors exacerbating climate change impacts.
6. Strengthen public education and awareness.

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