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SYSTEMATIC REVIEW

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Climate change as a wildlife health threat: a scoping review

Sabrina S. Greening[1*], Lucie R. Pascarosa[2], Avery L. Munster[2], Roderick B. Gagne[1] and Julie C. Ellis[1]

Abstract

Background The definition of wildlife health continues to expand with the recognition that health is more than the absence of disease. Practitioners are working to integrate concepts such as vulnerability, adaptation, and resilience into wildlife health research, surveillance, and management actions. Here, we performed a scoping review to identify scholarly articles from 2008 onwards with a focus on climate change impacts on wildlife health. Searches were conducted in Web of Science, Zoological Record, Scopus, Ovid CAB Abstracts, and ProQuest Dissertations and Theses. Articles were screened for relevance and fed into an AI-based thematic analysis that identified recurring themes across the literature. Each theme was manually reviewed and refined to help describe the scope and depth of existing literature, identify key themes, and assess potential knowledge gaps.

Results In total, 2,249 citations were retrieved of which 372 were included in further analysis after applying a set of inclusion/exclusion criteria. On closer inspection, 30.4% (113/372) of the papers were focused on climate-associated impacts on vector distribution. For this reason, two thematic analyses were performed, one which only included the subset of papers focused on climate change and vector distribution ($n=113$) and another including the remaining papers focused on climate-associated impacts on wildlife health ($n=259$). Amongst the subset of papers focused on vector distribution, top themes included concepts related to pathogen transmission dynamics, human/public health, and pathogen prevalence, while health papers focused on concepts related to increasing temperatures, species home ranges and distribution, and changing environmental variables.

Conclusions A large number of the papers retrieved in the literature search focused on how climate change impacts the distribution and abundance of host, vector, and pathogen species, remaining disease-centric in their approach. Papers including themes related to management actions were limited reflecting some uncertainty on how best to respond and prepare for climate change. Further discussion is needed on how wildlife health concepts can be used to help inform on-the-ground management actions in the face of climate uncertainty, this includes the collection of baseline health data and research into health metrics that could be used as indicators of resilience at the ecosystem level.

Keywords Wildlife Health, Resilience, Adaptation, Climate Change, Conservation, Vector Distribution, Thematic Analysis

*Correspondence:
Sabrina S. Greening
sgreenin@vet.upenn.edu
[1] Department of Pathobiology, Wildlife Futures Program, University of Pennsylvania School of Veterinary Medicine, New Bolton Center, 382 W. Street Road, Kennett Square, PA 19348, USA
[2] University of Pennsylvania School of Veterinary Medicine, 3800 Spruce Street, Philadelphia, PA 19104, USA

Background

Protecting and promoting wildlife health in the face of climate change is complex. Despite decades of climate research, there remains uncertainty surrounding the magnitude and scope of impacts climate change is having on many wildlife species [31]. Furthermore, climate change is exacerbating other concurrent anthropogenic

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threats to wildlife, such as habitat loss and land use change, compounding the threats faced by wildlife and the ecosystems they live in. An increased understanding of the climate-associated impacts on wildlife at multiple taxonomic, temporal, and spatial scales is critical for adaptive management and conservation [20, 37]. However, current research often focuses exclusively on how climate change will impact the emergence and transmission dynamics of infectious diseases, in particular, vector-borne diseases [34]. This is driven largely by the traditional disease-driven view of health (i.e., health is the absence of disease), but also likely reflective of the many health initiatives that remain human-centric, defining the singular role (and value of) wildlife as sources of emerging zoonotic disease. An alternative approach is research that focuses on how climate change will impact the health of wildlife. However, despite ongoing discussions, there remains ambiguity about what wildlife health means and how this translates into actionable management goals [29].

More recent wildlife health frameworks reflect our expanding understanding and definition of health – extending beyond disease and emphasising the interaction of biological, social, and environmental determinants and their impact on health [33, 38]. While there is growing recognition that wildlife health is more than just the presence or absence of disease, integrating concepts such as adaptation and resilience into health research remains limited. For wildlife populations, managing for resilience shifts the focus from population-based management towards ecosystem management, whereby strategies centre on maintaining system-level characteristics and processes [3] and strengthening the capacity of the system to respond to change through adaptation [6]. Therefore, it is important in adaptation research to have an understanding of the entire system in which the population of interest is a part of [15] in order to identify practical strategies that could help reduce the anticipated negative effects of climate change [16, 17]. A recent review found that only 1% of management recommendations designed to address climate-associated impacts on wildlife populations focused on aspects of health such as reproduction, survival, or disease and few recommendations representing local-scale management interventions [23]. Similar challenges are seen across much of animal health research, for instance, a review focusing on climate change impacts in livestock systems emphasised the importance of more detailed adaptation research to inform local, national, and regional policies to support livestock keepers in adapting to climate change more effectively [12]. The Intergovernmental Panel on Climate Change (IPCC refers to climate adaptation as the "process of adjustment to actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities" [18], while resilience is the "ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner" [18]. Over the past few years, there has been considerable growth in the number of wildlife management agencies that have developed and/or implemented climate adaptation plans. For example, the adaptation strategy first published in 2012 and updated in 2021 by the National Fish, Wildlife and Plants Climate Adaptation Partnership (NFWPCAP aims to provide a framework that enables decision-makers to take actionable steps towards building ecosystem resilience and maintaining ecosystem services in the face of climate change [27, 28]. Such frameworks identify practical strategies that can be used to reduce the anticipated negative effects of climate change. A previous study reviewed 16 adaptation strategies developed across the United States, Canada, England, Mexico, and South Africa, related to wildlife management and biodiversity conservation [26]. The strategies could be grouped into four broad categories: land and water protection and management, direct species management, monitoring and planning, and law and policy [26]. In many cases, the health impacts of climate change are not explicitly addressed in adaptation strategies or otherwise wildlife health is still only considered through a disease-centric lens.

Given the threat of climate change to wildlife health, it is important that wildlife research, surveillance, and management continue to evolve and integrate concepts such as resilience and adaptation. We hope this review will stimulate further thinking on how to add wildlife health to the climate agenda. We gathered literature focused on climate change and wildlife health and used an artificial intelligence (AI) thematic analysis to describe the scope and depth of existing literature, identify key research themes, and identify knowledge gaps.

Methods

A scoping review was conducted to assess the size (i.e., number of papers) and scope of research focused on climate change as a threat to wildlife health. This review does not intend to synthesize or evaluate all relevant studies, such as a systematic review, but instead aims to understand broad themes across the existing literature. The checklist provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR; [36]) was consulted to help ensure key items from the scoping review are reported. A copy of the completed checklist is provided as an Additional File. Once citations had been identified and screened by the authors, an AI-based thematic analysis was used as a preliminary tool to identify patterns across the research that may point toward potential themes and/or knowledge gaps.

Search strategy and screening

The literature searches were completed over several days starting from July 15 through to July 19, 2024. The search was conducted in five databases: Web of Science, Zoological Record, Scopus, Ovid CAB Abstracts, and ProQuest Dissertations and Theses. All searches were limited to all types of publications dated from 2008 onwards with no language restrictions. Only the article titles, abstracts, and keywords were queried using the search terms listed in Table 1. The search terms used to capture the concept of "health" were selected from a standard lexicon of threats to biodiversity conservation presented by Salafsky et al. [32], while search terms related to the concepts of "wildlife" and "climate" were discussed and selected by authors. All citations identified using the search strategy were imported into Endnote reference management software (version 21.4 Bld 18,113) where duplicates were removed using the Endnote "Find Duplicates" tool followed by a manual check to remove any duplicates that had been missed. The title and abstracts were then divided between two reviewers (LRP and ALM) and screened using a set of inclusion and exclusion criteria to determine their eligibility for use in the thematic analysis. Citations were included if studies (1) investigated or demonstrated the potential impacts of climate change on wildlife health outcomes, either at a population or animal level. If the title and abstract alone were not adequate to determine if the study should be included, the full text was used for screening. Citations were excluded if studies (1) reported a mortality and/or morbidity event associated with episodes of extreme weather (e.g., hurricanes, wildfires, or floods), (2) focused on the risk of zoonotic diseases to humans, (3) exclusively looked at captive animals (i.e., companion or zoo) or food production systems, (4) documenting pathogen presence/absence without assessing any impacts on wildlife health outcomes, (5) did not distinguish between climate change and other anthropogenic pressures, and (6) that discussed potential climate change impacts on their results but did not directly investigate climate change impacts. During the screening process, it became clear that a large proportion of the papers focused on ways that climate change impacts the distribution of disease vector species such as mosquitos, ticks, and flies. These papers were set aside for use in a second thematic analysis to evaluate if climate change was considered differently in papers focusing on wildlife health versus those focused on vector distribution. After the initial screening process, the remaining citations were checked by a third reviewer (SSG) to confirm the relevance of the remaining studies before accessing a PDF copy of each manuscript using EndNote's search for full-text tool. If EndNote was unable to retrieve the PDF and a PDF copy could not be obtained using a manual online search, the study was excluded from further analysis. Once the final number of papers for inclusion had been determined, linear regression models were used to help determine if the total number of papers increased by year with all models run using R statistical software (version 4.3.2 [30],).

Table 1 Search terms used to conduct a review of climate change research papers focused on wildlife health and climate change. Concepts were combined using "AND" as the Boolean operator

Concept	Keywords
Wildlife	"wildlife" OR "free ranging"
Health	"bacter*" OR "disease*" OR "fung*" OR "hazard*" OR "health*" OR "parasit*" OR "pollut*" OR "risk" OR "toxi*" OR "viral*" OR "virus*" OR "poison*"
Climate	"climate change" OR "global warming"

AI-based thematic analysis

PDF copies of each paper were imported into NVivo (version 14.23.3) where auto-coding was used to identify themes across the text. For the primary analysis focused on the impacts of climate change on wildlife health, the entire text was used whilst for the secondary analysis focused on vector distribution only the abstracts were used, reducing the computational time. The NVivo auto-coding feature uses a linguistic processing algorithm to generate a theme hierarchy based on reoccurring phrases in the data. To summarise, it detects themes by identifying noun phrases, grouping them under a broad parent theme, and assigning significance to themes based on how frequently each noun phrase appears [24]. Auto-coding was chosen over manual coding processes as it can provide insight across large sets of data more efficiently. The themes and noun phrases identified using auto-coding were reviewed manually (SSG) and refined by merging, moving, or deleting themes and noun phrases that were thought to be incorrect when interpreting them in context. Only a small proportion of the auto-coded themes and noun phrases were deleted, many of which were related to a study's methodology for example, themes such as "Linear regression" or "Bayesian analysis" were removed. Other auto-coded themes were deleted if the theme was identified in less than 5% of the papers and could not be merged with another theme. Merging was more commonly performed on noun phrases and only occurred if two themes or noun phrases could be linked by a common idea or could be considered one and the same. For example, the noun phrases "Public health" and "Human health" were merged to form a single noun phrase. Rarely was a new parent theme created manually with the exception of the "Species" theme which has "Moose (*Alces alces*)" and "White-tailed deer (*Odocoileus virginianus*)" nested as noun phrases. It was thought important to keep these noun phrases as they were found in high frequency throughout the papers related to climate change impacts on vector distribution however, they did not fit into any existing parent theme. Noun phrases were also moved from one parent theme to another. For example, the AI auto-coding placed the noun phrase "Habitat management and protection" under the "Habitat" theme before it was manually moved under the "Management" theme. It could be argued that this noun phrase could belong to both parent themes, however, "Management" was selected based on the interpretation of the text segments that had been assigned during the auto-coding process. In the end, very few edits were made to the auto-coded parent themes with most of the manual corrections centred around the movement of noun phrases.

Results

Search results

The literature search yielded 2,249 citations (after removing duplicates) of which only 372 (16.5%; 372/2,249) met the inclusion criteria after being screened by all three reviewers. Of these 259 (69.6%; 259/372) contributed to the analysis focused on climate change and wildlife health while 113 citations (30.4%; 113/372) made up the vector distribution subset (Fig. 1). The datasets analysed during the current study are available in the Scholarly Commons: The University of Pennsylvania's open-access institutional repository; https://repository.upenn.edu/handle/20.500.14332/60593. The number of citations retrieved varied across each year (Fig. 2) with results from the linear regression model suggesting that approximately 60% of the variance in the number of citations related to climate change and wildlife health could be accounted for by yearly changes ($R^2 = 0.637$; p-value = 0.0001). In comparison, yearly changes accounted for approximately 50% of the variance in the number of citations related to climate change and vector distribution ($R^2 = 0.498$; p-value = 0.0016).

AI-based thematic analysis—climate change and wildlife health

A total of 17 parent themes and 103 noun phrases were identified across the 259 citations focused on climate change and wildlife health (Table 2 and Supplementary Table 1). The top noun phrases identified across all the papers focused on concepts related to increasing temperatures ($n = 152$; 58.7% papers), species home ranges and distribution ($n = 108$; 41.7% papers), changing environmental variables ($n = 86$; 33.2% papers), animal body

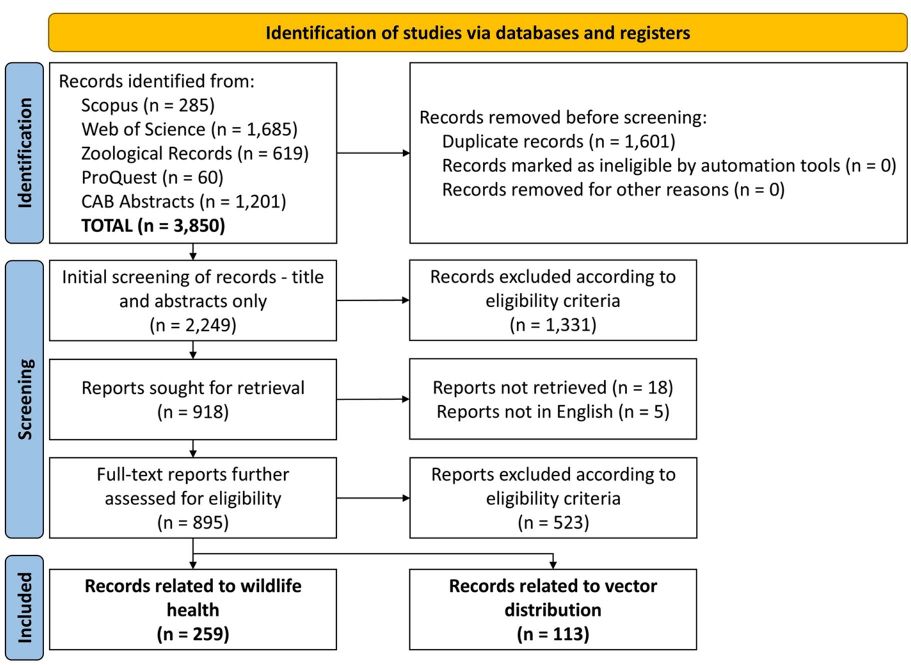

Fig. 1 Number of records yielded from the scoping review across five databases: Scopus, Web of Science, Zoological Records, ProQuest, and CAB Abstracts, and included in the thematic analyses

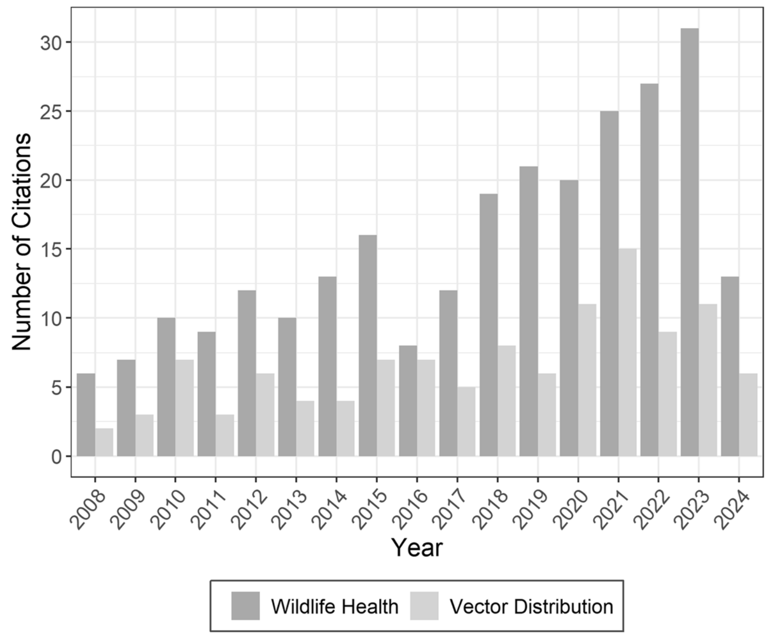

Fig. 2 A breakdown of the number of citations by year yielded from a scoping review looking at wildlife health and climate change (*n* = 259) and vector distribution and climate change (*n* = 113)

Table 2 A breakdown of the parent themes (*n* = 17) identified using AI-based thematic analysis including 259 papers related to climate change impacts on wildlife health. A full list of the noun phrases within each theme is presented in the Supplementary Material

Parent theme	No. of noun phrases in the parent theme	Top noun phrase in the parent theme	No. of papers with parent theme included (%)
Temperature	5	Increasing temperatures	175 (67.6)
Species	8	Amphibian and reptile species	173 (66.8)
Habitat	15	Habitat suitability	147 (56.8)
Population	8	Population response and trends	132 (51.0)
Variables	4	Changing environmental variables	128 (49.4)
Response	6	Physiological stress response	123 (47.5)
Distribution	3	Species home ranges and distribution	114 (44.0)
Body	3	Body condition	111 (42.9)
Disease	12	Infectious diseases	103 (39.8)
Survival	5	Reproductive success and survival	99 (38.2)
Water	3	Increasing water temperatures	91 (35.1)
Host	6	Host immunology	86 (33.2)
Effects	8	Direct effects	85 (32.8)
Level	6	Sea level	82 (31.7)
Human	3	Anthropogenic climate change	54 (20.8)
Parasite	5	Parasite prevalence	53 (20.7)
Management	3	Habitat management and protection	52 (20.1)

size and/or mass (*n* = 69; 26.6% papers), and increasing water temperatures (*n* = 68; 26.3% papers). When combining noun phrases, the top theme identified looked at different aspects of temperature including heat stress, extreme temperature events, winter temperatures, and critical temperature thresholds. Noun phrases identified across only a small proportion of the papers focused on concepts related to fungal diseases ($n=5$; 1.9%), critical habitats ($n=6$; 2.3% papers), genetic effects/impacts ($n=6$; 2.3% papers), proliferative kidney disease ($n=6$; 2.3% papers), and climate policies and planning ($n=7$; 2.7% papers). When combined, the theme with the fewest number of noun phrases captured concepts related to management including habitat management and protection.

AI-based thematic analysis—climate change and vector distribution

Across the 113 papers focused on vector distribution, a total of 13 parent themes and 58 noun phrases were identified (Table 3 and Supplementary Table 2). The top noun phrases focused on concepts related to pathogen transmission dynamics ($n=46$; 40.7% papers), human/public health ($n=46$; 40.7% papers), pathogen prevalence ($n=32$; 28.3% papers), *Ixodes spp.* ($n=27$; 23.9% papers), and tickborne pathogens ($n=27$; 23.9% papers). The top theme identified when considering the combined frequency of noun phrases captured within each theme included aspects related to pathogens including the identification of many pathogen species, namely *Yersinia pestis*, *Babesia* spp., *Borrelia* spp., and *Rickettsia* spp. Noun phrases identified across only a small proportion of the vector distribution papers focused on concepts related to vector abundances ($n=2$; 1.8%), vector biology and/or ecology ($n=2$; 1.8%), vector competence ($n=3$; 2.7%), host immune competence ($n=4$; 3.5%), and *Rhipicephalus* spp. ($n=4$; 3.5%).

Discussion

This scoping review provides insight into how climate change is being integrated into the wildlife health literature. In total, 2,249 citations were retrieved from the literature search and after applying a set of inclusion/exclusion criteria, a total of 372 papers were used in one of two thematic analyses. In many of the papers excluded from the analysis, climate change was not considered the focus of the paper but rather added as a discussion point that reflects on how research findings might be impacted by climate change. Across the papers included in further analysis, it became clear that over one-third of papers were related to the distribution of different vector species including mosquitoes, ticks, and flies. For this reason, two thematic analyses were performed. Vector-borne diseases are expected to increase with climate-associated changes in vector density, activity periods, life cycles, and geographical distribution. The World Organisation for Animal Health (WOAH) has highlighted this growing concern in its latest "Animal Health Situation Worldwide" report [4]. However, similar to the dominant "public health" theme found across the papers focused on climate change and vector distribution in this study, much of the concerns related to vectors remain on impacts to human and livestock diseases with the importance of wildlife species limited to their role as reservoir hosts. Many of the papers also assume that the impact of climate change on vector distribution will result in a universal increase in infectious disease although in many cases this is likely an oversimplification. The disease process relies on many interacting factors between the host,

Table 3 A breakdown of the parent themes ($n=13$) identified using AI-based thematic analysis including 113 papers related to climate change impacts on vector distribution. A full list of the noun phrases within each theme is presented in the Supplementary Material

Parent theme	No. of noun phrases in the parent theme	Top noun phrase in the parent theme	No. of papers with parent theme included (%)
Pathogens	9	Pathogen transmission dynamics	85 (75.2)
Host	8	Host population density	56 (49.6)
Ticks	9	Ixodes spp.	54 (47.8)
Human	2	Human/public health	51 (45.1)
Disease	3	Zoonotic diseases	42 (37.2)
Health	6	Wildlife health	41 (36.3)
Control	4	Surveillance systems	36 (31.9)
Wildlife	3	Wildlife habitats	28 (24.8)
Factors	3	Environmental factors	27 (23.9)
Virus	4	Tick-borne encephalitis virus	26 (23.0)
Range	2	Range expansion or shifts	26 (23.0)
Species	2	Moose (*Alces alces*)	15 (13.3)
Vector	3	Vector biology and ecology	7 (6.2)

the pathogen and/or vector, and their environment all of which will be impacted by climate change in different ways, leading to declines or shifts in disease just as often as increases [22, 35].

Several themes not related to disease emerged across the papers focused on wildlife health and climate change including "temperature" as the top theme. This is a good indication that many of the papers focus on more than just infectious diseases and are looking at other health impacts such as heat or thermal stress although a more in-depth breakdown of the themes is needed to see if this theme recently emerged or can be found across all the study years. It is also important to note that climate change is not limited to increases in temperature alone. Other stressors such as changing precipitation patterns will also impact health and disease, and these stressors have not been captured in any of the themes [13]. The focus on temperature could reflect the uncertainty inherent in future climate predictions. These uncertainties add to the challenge of managing for climate change and emphasise the importance of spreading the risk by using a diversity of management strategies and having a means by which the impact, or any potential unintended consequences, of each strategy can be evaluated both in the short- and long-term [3, 10].

The top theme across the papers focused on the effects of vector distribution and climate change focuses on different aspects related to the "pathogen" including pathogen prevalence. This may reflect the importance of disease and/or pathogen surveillance systems in wildlife health. Documenting the presence or absence of pathogens has always been central to surveillance, however, there is growing recognition that surveillance systems must move beyond simply "putting points on a map" or "doing surveillance for surveillance sake" and instead be used to help generate information that can support evidence-based recommendations for the protection and promotion of healthy wildlife populations [5, 8]. For example, the collection of long-term baseline health data including information on pathogen occurrence is rarely prioritised, making it difficult to track trends over time, disentangle climate-associated impacts, and draw evidence-based conclusions.

Wildlife exists in complex systems and how health is quantified or assessed can vary depending on the definition of health being used and at what scale you are looking at. This variation in scale is captured in the theme focused on "levels" with some papers looking at an individual or species level versus others that look at a population or community level. Quantifying health at different scales plays a huge role in determining how health is measured and moving beyond a focus on disease processes. For example, health metrics such as blood chemistry are focused on an individual animal while at a species level metrics such as population counts or species interactions are more important [2, 21]. Several individual-based health metrics were identified as themes including body condition, body size or mass, physiological stress responses, and host behavioural responses, while it is not clear what other metrics were used to study health impacts across the different levels. Identifying wildlife health metrics, across different levels, allows actionable health frameworks that can scale from the animal (e.g., targeted antibiotic use) to the ecosystem (e.g., providing corridors of connectivity between optimal habitats). These approaches can move us beyond the detection of pathogens and their pathology towards healthy wildlife [1].

Understanding health effects at different levels can help identify relevant health metrics and targets, which is critical to guide potential management actions that may be used to reach those targets [14]. In a review of 261 studies looking at health assessments for population monitoring in noncaptive vertebrate species, the most common metrics used included taxa blood analysis, body composition assessments, physical examination, and faecal analyses however, only a limited number of papers discussed how these metrics could be used to inform decision-making processes without further integrating a physiological or ecological understanding of species resilience [21]. In addition, these metrics are all focused on the individual level whereas wildlife management often occurs at the population level or above, with a recent shift to adaptive management approaches at the ecosystem level as a way of managing for resilience. Taking an ecological perspective on management is a more holistic approach compared to using single species to guide decision-making as it considers the problem in context including both important ecological interactions and interactions at the human-wildlife interface (Mascia et al., [25]. It is also necessary to explain in more details the inclusion (eligibility) criteria and reason why large proportion of the articles were excluded from the study. Consequently, please address potential concerns that may arise from th2003). Additional themes, concerned with indirect effects, long-term effects, cascading effects, or sublethal effects, further highlight some of the challenges in defining and measuring wildlife health and the potential additive effects of climate change on health which are often not considered in health frameworks.

When examining the themes identified in this study, it is important to consider the limitations both in the search strategy and AI-based thematic analysis. A variety of keywords were used to capture the central concepts: wildlife, health, and climate change. However, with any search strategy, it is hard to assess the scope and magnitude of papers that have been missed or the biases introduced by the keywords. This may be of particular importance when considering the expanding definition of wildlife health and how defining health is complicated by the different terminology used across disciplines. For example, an ecologist may be more likely to use terms such as "fitness" instead of "health." Nevertheless, it is important to note that out of the 2,249 records that resulted from the literature search, only 16.5% (372/2,249) remained after applying the eligibility criteria suggesting that the search terms could have been further assessed to help narrow the search and reduce the number of papers that were outside the scope of this review. A large proportion of the papers were removed during the inclusion/exclusion process because they discussed how climate change would potentially impact their findings, particularly concerning the prevalence of pathogens and/or diseases, but did not directly investigate climate change impacts on wildlife health outcomes. These papers highlight the difficulty in assessing the impact of climate change without a large amount of retrospective or baseline data for both health and climate. The eligibility criteria may have also resulted in papers being excluded from the thematic analysis inappropriately, however, having such criteria is important to help standardise the inclusion/exclusion process between reviewers.

It is also important to acknowledge that by using an AI tool for auto-coding themes, there is a risk of misclassification as the algorithm is based on pattern recognition and lacks human insight or context. In this study, many of the auto-coded noun phrases were either moved into different themes or broken down/split to create a new noun phrase. For example, the noun phrase "body temperature" was initially included under the theme "temperature" but was combined with the noun phrases "body size/mass" and "body condition" to create a new parent theme with the understanding that they are all related to physiological measurements. This highlights the importance of manually reviewing the themes. Nevertheless, the use of AI auto-coding followed by a manual review still takes considerably less time than manually coding the themes and showcases how AI tools can facilitate the initial stages of qualitative data analysis, especially in cases where there is a large amount of data. An important next step in this analysis would be to build a thematic map or network to start exploring the relationships between codes and themes [7]. For instance, in this analysis, moose (*Alces alces)* were one of only two wildlife species identified in a theme; however, on further exploration, you can see that all the papers identified under the theme "moose" are also captured under the themes related to "increasing temperatures" and "*Dermacentor* tick species". This is unsurprising given the evidence for increasing winter tick (*Dermacentor albipictus*) burdens due to increasing temperatures and its impact on calve survival [9, 19] and adult cow reproduction rates [11]. A thematic map would also help reflect the complexity of wildlife health and further highlight potential knowledge gaps. For example, "increasing temperatures" was the top noun phrase but it remains unclear if these papers assessed the impact of increasing temperature on disease agents or direct effects on the wildlife host.

Overall, this review highlights how much of the climate and health research has focused on investigating changes in the geographical or altitudinal distribution of pathogens, parasites, and vectors. The importance of this research cannot be understated however, more needs to be done to link these changes to wildlife health outcomes. To do this, a crucial next step would be to identify relevant health metrics and targets that could be used to assess health across different levels of an ecosystem. Furthermore, our ability to untangle the impacts of climate change amid other anthropogenic threats that are acting synergistically is difficult without long-term baseline health data and robust climate predictions.

Conclusion

As the term "wildlife health" continues to evolve, it is important to discuss the various factors that contribute to wildlife health, particularly as climate change presents a threat with considerable uncertainty. The thematic analysis presented in this study reveals what central ideas are driving wildlife health research and where the potential gaps may lie. The findings show that wildlife health is complex and operates at many different levels. This complexity has been captured in many of the recent definitions; however, health metrics that can be used to help inform on-the-ground management actions or build resilience are still missing and instead the focus has been on how climate change may impact species distribution. It is clear that successful wildlife management needs to incorporate climate change into the response to other health threats and to implement strategies that mitigate impacts related to climate change. Doing so requires research to determine how wildlife can withstand climate driven threats and how management of wildlife can help achieve healthy and resilient populations.

Abbreviations

PRISMA-ScR	Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews
AI	Artificial Intelligence
IPCC	Intergovernmental Panel on Climate Change
NFWPCAP	National Fish, Wildlife and Plants Climate Adaptation Partnership

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12917-025-04516-2.

Additional file 1. PRISMA_ScR_Checklist.pdf. A completed checklist provided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR; Tricco et al., 2018) showing what key items from the scoping review are reported.

Additional file 2.

Authors' contributions

All authors (S.S.G., L.R.P., A.L.M., R.B.G. and J.C.E.) participated in the design of the scoping review and provided intellectual contributions in interpreting the results and writing the discussion, before reading and approving the final manuscript. Further, L.R.P. and A.L.M. performed the literature searches and completed the initial screening, while S.S.G. completed the secondary screening, performed the thematic analysis, and was the major contributor to writing the manuscript and preparing the figures.

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Data availability

The citations yielded from the scoping review and analysed during the current study are available in the Scholarly Commons: The University of Pennsylvania's open-access institutional repository, https://repository.upenn.edu/handle/20.500.14332/60593.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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