nature climate change

Progress

https://doi.org/10.1038/s41558-023-01608-5

Climate change as a global amplifier of human–wildlife conflict

Received: 30 March 2022

Accepted: 13 January 2023

Published online: 27 February 2023

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Climate change and human–wildlife conflict are both pressing challenges for biodiversity conservation and human well-being in the Anthropocene. Climate change is a critical yet underappreciated amplifier of human–wildlife conflict, as it exacerbates resource scarcity, alters human and animal behaviours and distributions, and increases human–wildlife encounters. We synthesize evidence of climate-driven conflicts occurring among ten taxonomic orders, on six continents and in all five oceans. Such conflicts disrupt both subsistence livelihoods and industrial economies and may accelerate the rate at which human–wildlife conflict drives wildlife declines. We introduce a framework describing distinct environmental, ecological and sociopolitical pathways through which climate variability and change percolate via complex social–ecological systems to influence patterns and outcomes of human–wildlife interactions. Identifying these pathways allows for developing mitigation strategies and proactive policies to limit the impacts of human–wildlife conflict on biodiversity conservation and human well-being in a changing climate.

Anthropogenic global changes imperil global biodiversity, ecosystem functioning and human well-being. Climate change is recognized as a dire planetary threat but the interacting and potentially amplifying effects of climate change in conjunction with other anthropogenic pressures are less understood. Human–wildlife conflict—broadly defined as direct, non-extractive interactions between humans and wildlife with adverse outcomes for one or both parties[1]—is one such phenomenon amplified by climate change. Human–wildlife conflict takes many forms, including direct injury to people and wildlife and damage to personal property or livelihood losses and has dire consequences for social–ecological systems[2]. For instance, human–wildlife conflict is a leading contributor to the regional decline and extinctions of large mammals[3], triggering the transformation of entire ecosystems[4]. At the same time, negative interactions with wildlife directly threaten human lives, compound economic and livelihood insecurity and cost the global economy billions of dollars annually[2]. As climate change reshapes resource availability and human and animal behaviour alike, a growing body of evidence reveals that climate change itself often plays a powerful role in exacerbating human–wildlife conflict around the globe[1]. However, consideration of climate change as an underlying driver of human–wildlife conflict has largely been missing from its discourse[1]. Recognizing the connection between climate change and human–wildlife conflict is essential for anticipating, and ultimately addressing, new and intensified human–wildlife interactions in the twenty-first century and beyond.

Climate-driven human–wildlife conflicts are becoming more visible, as a function of both long-term climate change and increased frequency and severity of extreme climate events, compelling an increase in research attention[1]. Understanding the processes, and not simply the patterns, underlying climate-driven conflicts requires elucidating the causal pathways along which climate change creates, alters or intensifies conflict. Articulating these pathways across a diverse array

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 https://doi.org/10.1038/s41558-023-01608-5

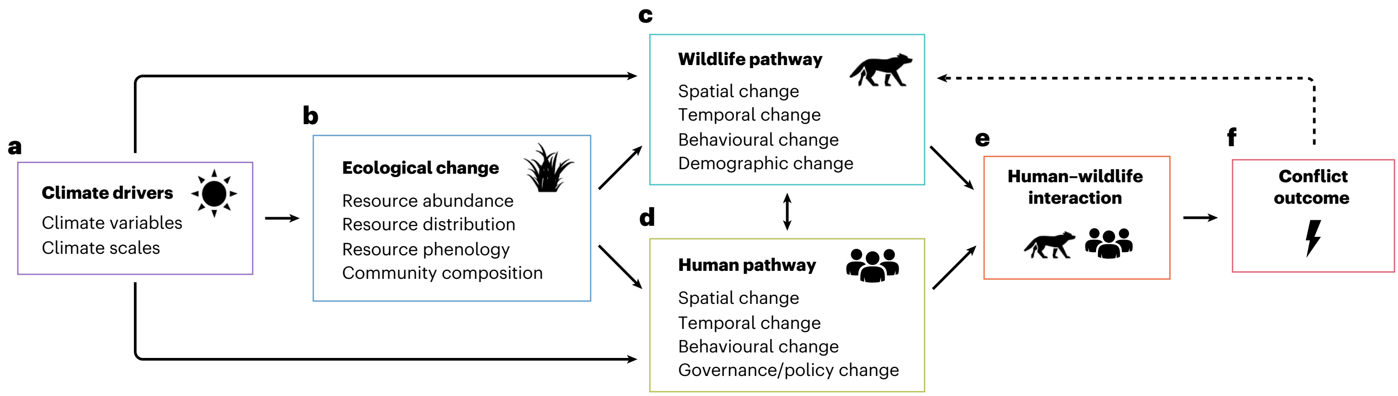


Fig. 1 | A conceptual framework to describe how climate drivers propagate through social–ecological systems to impact human–wildlife conflicts. Arrows indicate directions of influence. A prerequisite for any human–wildlife conflict to arise is the co-occurrence of wildlife and human activities, the patterns of which are indirectly and directly shaped by social, ecological and climate drivers. **a**, Climate drivers, such as ambient temperature or rainfall, drive changes in the availability of resources such as food or habitat. **b**, Altered resource availability and other ecological changes can modify patterns of animal behaviour, distributions or demography and influence where and how people choose to work, live and recreate. Climate drivers can also elicit direct responses from people and wildlife, unmediated by ecological changes. **c**–**f**, Such responses by animals (**c**) or people (**d**) can increase or alter interactions (**e**) that lead to negative outcomes (**f**). The dashed line demonstrates one of many potential feedbacks between diagram components.

of systems will allow us to (1) identify common drivers across systems, (2) better predict conditions under which conflicts are likely to emerge and (3) target effective interventions and policies that address both the drivers and the outcomes of conflict.

Here, we review three decades of research to demonstrate that climate change is exacerbating human–wildlife conflict globally (Methods are provided in the Supplementary Information). We present a new framework for considering how the impacts of climate change interact with complex social–ecological systems to shape human–wildlife interactions. By applying our framework to a systematic review of case studies[5], we identify a diverse suite of environmental, ecological and social pathways through which climate change alters human and wildlife systems and intensifies conflict. Finally, we show how considering climate-driven conflicts is critical for informing policy and management efforts to prevent or mitigate human–wildlife conflict in an era of rapid environmental change.

Conceptual framework

Our framework considers climate as an underlying driver of human–wildlife interactions via its effects on multiple components of a social–ecological system (Fig. 1).

Climate drivers

Variation in climate sets the stage for variation in life on Earth, structuring ecological patterns such as species distributions and community compositions (Fig. 1a). Climate change is characterized by changes in the mean and variability of atmospheric (for example, precipitation), terrestrial (for example, snow depth) and oceanographic (for example, sea surface temperature) conditions[6]. Anthropogenic climate change has already resulted in long-term directional changes in climate[6], increased interannual variability in climate conditions[7] and increased frequency and severity of acute climate events[8]. For example, warming temperatures are driving ice-free winters in freshwater lakes[9], glacial melting[10] and long-term aridification in parts of the world[11]; interannual variance in climate indices in the north Pacific Ocean has grown substantially since the 1970s[7]; and catastrophic marine heatwaves throughout the world's oceans[12] and extreme precipitation and flooding events in arid regions[13] are increasingly occurring. People and wildlife alike will be increasingly exposed to the impacts of these changes as global warming is predicted to exceed 1.5–2 °C this century[6].

Ecological change

Climate is a key limiting determinant of resources which produces a range of ecological changes, including changes in resource abundance, distribution, phenology and community composition[14] (Fig. 1b). Changes in temperatures and precipitation can alter the abundance and distribution of primary resources across both terrestrial and aquatic systems, which can have cascading effects across communities and ecosystems[15,16]. Many biotic resources also have life history events that occur during discrete environmental conditions, which are impacted by changes in climate. This can generate mismatches in the timing of events between resources and the people or wildlife that depend on them[17]. Climate-driven changes in resource distributions, abundances and phenologies can scale up to affect community composition[18,19]. For example, climate change may limit resources, thereby altering competitive dynamics between species[20], or may make conditions favourable for new species to invade[21], leading to altered communities. Similarly, climate change has shifted the distribution of disease vectors and facilitated the emergence of infectious diseases, leading to broad changes in host–pathogen interactions[15,22]. Such climatic and ecological changes in turn drive a suite of responses by both humans and wildlife.

Wildlife pathways

Climate change influences a broad range of animal behavioural and ecological processes, from the scale of individuals to populations to communities. The pathways through which climate-driven changes in wildlife ecology can alter human–wildlife interactions include impacts on (1) spatial distribution, (2) temporal patterns, (3) behaviour and (4) demography (Fig. 1c).

Spatial distribution. Climate change and associated disturbances in the abiotic and biotic environment reshape the available niche space for wild animals[20,23]. As animals seek more suitable habitat, the distribution and density of populations change and the degree of overlap with anthropogenic land uses and human activities may also change. This reshuffling of wildlife distributions across broad landscapes represents one of the most important pathways through which climate change alters human–wildlife interactions and was present in 69% ($n = 34$) of the case studies that we examined. In addition to range shifts, climate change may open new opportunities for species in previously unsuitable areas, leading to the expansion of species' ranges and thus generating new human–wildlife interactions in these areas[24].

 https://doi.org/10.1038/s41558-023-01608-5

BOX 1

Bharal and snow leopards, Nepal

An understanding of the complex pathways linking climate to human–wildlife interactions can help to explain why some areas may be seeing long-term rises in conflict independent of demographic changes in wildlife or human populations. In the Himalayas, mean annual temperatures and rainfall are increasing, leading to increased snowmelt and encroachment of forests into higher elevations[88]. In response to climate-driven reductions in forage at high altitudes, bharal (also known as blue sheep; *Pseudois nayaur*) have shifted distributions to lower elevations near human villages, where they forage on crops. In turn, snow leopards (*Panthera uncia*) have followed bharal to lower elevations, leading to increased livestock predation by leopards and retaliatory killings of leopards by local people[88,89]. Future climate models predict that both bharal and snow leopard habitat will decrease, which is expected to accelerate current conflict[90].

Such conflicts have serious consequences for people and wildlife in the Himalayas. Crop foraging and livestock depredation can be economically devastating for agricultural producers, with up to 12% of livestock holdings killed by carnivores each year (25–50% of average per capita income)[88]. This economic loss leads to hostility and killing of snow leopards and other carnivores[89]. Retaliatory killing is a considerable conservation threat to the endangered snow leopard, accounting for 55% of snow leopard mortality every year[91]. Given recognition that such conflicts are likely to continue or rise in this region in the future, several mitigation approaches have been recommended, including implementation of a livestock compensation programme, a conservation education programme, and a local and participatory community-based climate change adaptation programme[88]. Such cases are instructive of potential problems and solutions as climate change continues to transform our landscapes.

BOX 2

African elephants, Tanzania

Recognition of climate as an underlying driver of human–wildlife interactions is valuable for conflict mitigation; conversely, failure to recognize the role of climate in conflicts can have undesired consequences. In West Kilamanjaro, Tanzania, a severe drought in 2009 caused elephants to forage on crops, leading to increased resentment among villagers[26]. The situation was compounded by reduced tolerance for wildlife damage due to increased livelihood insecurity during drought. Moreover, resentment towards elephants was exacerbated by a history of antiparticipatory conservation programmes, spurring the marginalization of villagers by non-governmental organizations and governmental agency efforts to expand elephant populations[26]. To reduce conflict, villagers tried short-term mitigation actions but after drought conditions rendered these ineffective against crop raiding, villagers resorted to retaliatory killing of elephants. Describing their feelings of disempowerment, one villager said, “We became very furious and said let the government choose either people or elephants”[26].

Since then, several near-term changes have occurred. However, recognition of climate as a contributing factor will help characterize the scale of conflict and inform its management. Droughts and related conflict are not just temporary, one-time events but are rather patterns indicative of a longer-term trend and conservation programmes must be designed to match this longer-term time frame. Conflicts are likely to be exacerbated during droughts; appreciation of this link may help agricultural producers prepare by implementing mitigation tactics preventatively or help institutions plan for increased conflict mitigation spending during droughts. Drought forecasts are increasingly available and may be incorporated into conflict mitigation policies. Conversely, incorporating human–wildlife interactions into both social and ecological climate vulnerability assessments will benefit animal and human communities alike.

Conversely, when changes in climate contribute to shifts in resource distributions or scarcity, animals may relocate to human-dominated areas in search of alternative resources (Box 1). For both tapir (*Tapirus bairdii*) in Mexico[25] and elephants (*Loxodonta africana*) in Tanzania[26] and Kenya[27], droughts led animals to move into villages in search of food or water, which then led to crop damage and subsequent retaliatory killings (Box 2).

In addition to tracking shifting resources, animals may also adjust their spatial distribution as they seek out more favourable abiotic conditions for ease of movement or thermoregulation in ways that alter human–wildlife interactions. In the northern hemisphere, several studies have shown that large ungulates are more likely to shift to lower elevations and move along linear features such as roads and railroad tracks in years with deep snow, leading to increased vehicle collisions[28,29]. Notably, land transformation due to flooding, fire, snow and sea ice melt reshapes the extent and distribution of available space for animals, forcing them into new spaces that may increase interactions with humans. In Sumatra, for instance, forest fires following an El Niño-induced severe drought drove tigers (*Panthera tigris*) and Asian elephants (*Elephas maximus*) into the buffer zone of a protected area, resulting in at least one human death[30].

Temporal patterns. Climate-driven changes in the timing of wildlife activity at seasonal or daily time scales can also alter interactions with humans and were documented in 12% ($n = 6$) of case studies. Changes in the timing of events like hibernation or migration may change the nature of human–wildlife interactions. As the temperature has warmed and the length of black bears' (*Ursus americanus*) active season has grown longer, bears have sought out additional resources in anthropogenic areas and experienced greater human-caused mortality[31]. In blue whales (*Balaenoptera musculus*), a marine heat wave led to changes to migration timing that caused the whales to remain in a high ship-strike area for much longer than usual, elevating risk exposure to vessel collisions[32,33]. Although not documented in the case studies, animals may also adjust their diel activity patterns to better thermoregulate amidst changes in daytime temperatures under global warming, which may affect human–wildlife interactions. If animals increase their nocturnal activity, for example, they may have fewer direct negative interactions with people during the daytime or in other cases they may cause more damage to property or livestock if people are asleep and unable to prevent the damage[34]; indeed, carnivore attacks on livestock occur predominantly at night in many systems[35,36]. Changes in the timing of resource availability (phenology) due to climate change can also alter the seasonal timing of wildlife activity and behaviour and influence interactions between humans and animals. In Asiatic black bears (*Ursus thibetanus*), for instance, temperature-related timing of leaf-out determines post-hibernation resource availability and likelihood of attacks on humans, ultimately resulting in bear culling[37].

Behaviour. Behaviourally mediated pathways are an important avenue through which climate change alters human–wildlife interactions and their outcomes, cited in nearly half of the case studies (45%, 22 studies). Most notably, climate-driven fluctuations in resource availability alter the foraging behaviour and diet of animals, such as prey-switching from wild prey to livestock[38,39]. Animals that typically avoid human disturbance may be more likely to take risks, such as foraging on anthropogenic food sources, when their body condition is poor and their options are limited. For example, drought-induced reduction in vegetation cover makes it harder for ambush predators like lions (*Panthera leo*) to hunt[40]. Combined with reduced prey availability, this change in habitat structure and prey accessibility led to an increase in lion attacks on livestock in Botswana during drought[41]. Across the Arctic, climate change is reducing sea ice that polar bears (*Ursus maritimus*) rely on for hunting, leading to increased use of terrestrial habitat, increased starvation and reduced demographic rates in polar bears[42]. More hungry bears on the landscape have increased negative human–polar bear interactions, involving property damage, life-threatening encounters and bear killings[43,44]. Churchill, Manitoba—the 'polar bear capital of the world'—is a hotspot for these incidences, which tripled from 1970 to 2005 as a direct consequence of declines in sea ice[43].

In addition to affecting diet and foraging patterns, climate change may also affect animal activity budgets, reshaping how animals allocate their time to different activities in an altered environment. Ectotherms spend more time active when temperatures are higher, for example, which may expose them to greater contact with humans or their pets[45]. Changes to the physical environment may also mediate reactive antipredator responses of animals to perceived risk from humans and alter the nature of human–wildlife interactions, as when reduced vegetation cover during drought made brown snakes (*Pseudonaja textilis*) more aggressive in response to approaches by humans[46].

Demography. Climate-driven changes to wildlife demography may also alter patterns of human–wildlife interactions and were cited in 10% ($n = 5$) of studies. In cases where climate change makes environmental conditions more favourable for wildlife populations, increases in abundance may generate or exacerbate negative interactions with humans, as competition drives animals to exploit anthropogenic habitat and resources. For example, warming temperatures on Islay Island, Scotland, have created more favourable breeding conditions for barnacle geese (*Branta leucopsis*) and a long-term rise in goose population abundance has driven grassland damage that is costly to sheep farmers[24]. Furthermore, climate change could also alter the age and sex structure of populations through its effects on survival and reproduction. These changes might affect conflict, if certain age classes (for example, juveniles) are more likely to engage in conflict given fitness trade-offs and energetic demands related to their life stage[47]. For example, severe drought increased prey vulnerability in a South African reserve, with impacts on lion survival and fecundity[48]. As a result, there was an increase in the number of subadult male lions, which are more likely to have negative interactions with people as they disperse outside protected areas[47].

Human pathways

The effects of climate change on where people live, work and recreate can impact the degree to which humans and wildlife interact. These effects occur across scales from individuals, communities and institutions. Climate change shapes human–wildlife interactions through several human pathways, including altering people's (1) spatial distribution, (2) temporal patterns, (3) behaviour and (4) governance and policy (Fig. 1d).

Spatial distribution. Changing climate conditions can lead people to adjust their spatial patterns of landscape use, with broad implications for human–wildlife interactions. Spatial changes were the most cited human pathway, identified in 14% ($n = 7$) of case studies. At the local scale, this pathway often involves climate impacts on activities such as subsistence livelihoods and food production. Subsistence agricultural production—including both pastoralism and crop agriculture—is one of the human livelihoods that has historically been most impacted by negative human–wildlife interactions[2] and climate change can amplify these conflicts by exacerbating resource scarcity on shared landscapes. Climate conditions, such as drought, that impose resource stress on crops and livestock often lead people to extract natural resources from protected areas more heavily, which can lead to increased encounters between people and wildlife. In Kenya, for example, drought conditions led farmers to increase use of protected areas for cattle grazing and crop production, which resulted in higher levels of human–wildlife conflict[49,50]. Climate-driven human–wildlife interactions arising from changes in spatial patterns of human activities not only threaten wildlife but can also be detrimental to people. In South Sudan, fatal attacks by crocodiles (*Crocodylus niloticus*) on humans and livestock peak during the dry season, when herders move livestock to riverbanks to access water and pasture[51]. With ongoing desertification and the increased frequency of drought in this region, crocodile attacks are expected to rise over time due to climate change[51].

Beyond the impacts on patterns of subsistence resource use, climate change may also make new regions accessible to extractive industries and use by large corporations, with adverse effects on human–wildlife interactions. For example, declining sea ice due to climate change has opened previously inaccessible Arctic waters to shipping and fossil fuel extraction and Arctic shipping is expected to increase substantially in the coming decades[52,53]. Increased vessel traffic and noise poses threats to marine mammals[54] and their prey[53]. These marine mammals constitute an important subsistence resource for local Indigenous communities, such that climate-driven increases in shipping traffic and resource extraction will negatively impact Indigenous livelihoods in the Arctic[55].

Temporal patterns. Climate change can also alter the timing of human activities, especially human labour, that can reshape human–wildlife interactions. This pathway was identified in 8% ($n = 4$) case studies. Conflicts arising from altered human timings largely result from a shift in the temporal availability of resources shared between people and wildlife, thereby exacerbating negative interactions. For example, on the US West Coast, a marine heat wave and harmful algal bloom resulted in a delayed fishing season that overlapped with the timing of whale migrations[56]. These events contributed to record numbers of whale entanglement in fishing gear, leading to whale mortality and economic losses for fishers (Box 3)[56,57]. Long-term directional change may also precipitate a change in temporal patterns of human landscape use in ways that influence interactions with wildlife. For example, long-term sea ice decline in the Arctic has extended the navigation season for shipping, commercial fishing and oil and gas exploration and opening of the Northern Sea Route is projected to lengthen by 70–80 days by 2080, prolonging the exposure of marine wildlife to threats[55].

Behaviour. In addition to altering the spatiotemporal distribution of their activities due to climate change, people may also change their behaviours, a pathway cited in 10% ($n = 5$) of studies. For instance, during a drought in the Gir forest of India, livestock farmers brought their livestock into compounds and houses for additional protection from depredation by Asiatic lions. This greater proximity between livestock and humans, intended to mitigate depredation risk, drew lions into human dwellings and increased lion attacks on people[47]. Beyond livelihood activities, shifts in recreation patterns due to climate change can also influence human–wildlife interactions. For example, higher temperatures increase beach visitation and swimming activity by people, leading to increased bite incidences with white sharks (*Carcharodon carcharias*)[58,59] and alligators (*Alligator mississippiensis*)[60].

https://doi.org/10.1038/s41558-023-01608-5

BOX 3

Humpback and blue whales, Pacific Ocean

Proactive management that considers climate as an underlying factor in human–wildlife interactions will help promote positive outcomes for both parties. An innovative example is California's Whale Entanglement Risk Assessment and Mitigation Program (RAMP) in the northeast Pacific Ocean. During 2014–2016, a marine heatwave drove an ecosystem-state shift from a cold, krill-dominated regime to a warm, anchovy-dominated regime[56]. In response, humpback whales (*Megaptera novaeangliae*) switched prey from krill to anchovies, doubling the probability of whales being inshore and placing them in greater spatial overlap with the California Dungeness crab fishery[56,57]. In addition, a heatwave-induced toxic algal bloom delayed the opening of the fishery to coincide with the timing of whales migrating up the coast[56]. The confluence of these factors led to a historic high of 50 whales being entangled in fishing gear in 2015 compared with an average background rate of 10 entanglements per year and involved unprecedented entanglements of endangered blue whales (*Balaenoptera musculus*).

In response, the state of California developed RAMP—a series of seasonal risk assessments based on near real-time climate, ecosystem and fishery factors[56]. This programme is at the vanguard for explicitly incorporating climate indices into risk assessment to proactively manage either wildlife populations or human activities to avoid or mitigate undesired human–wildlife interaction. Additionally, a West Coast Whale Entanglement Working Group was created to encourage participatory engagement by commercial fishers, state and federal managers, conservationists and scientists to evaluate and mitigate entanglement risks and educate the public[56]. This approach recognizes that environmental changes driven by an extreme climate event were at the root of the rise of entanglements that led to a major shift in management of California's most lucrative fishery. Now, more proactive, participatory and dynamic management that explicitly takes climate into account as an underlying factor in conflict is used to address this issue in an era of rapid climate change[57].

Climate-driven changes in disease prevalence can also induce behavioural changes in people, domesticated animals and wildlife alike that affect conflict. In Iran, for instance, hoof disease, which is affected by aridity, limits the ability of livestock to flee predators and is correlated with increased leopard (*Panthera pardus*) predation on livestock. As a result, conflict with leopards is projected to be mediated by disease dynamics under future climate scenarios in this region[61]. Such disease-related cases highlight the fluidity between wildlife and human pathways, as changes in livestock behaviour do not fit neatly into either category. The outcomes of climate-driven disease spread as a human–wildlife conflict pathway are underexplored in the literature but will be increasingly important as climate change increases the emergence of infectious diseases worldwide[22].

Economic and livelihood effects of climate change can reduce the ability of people to sustain economic losses from wildlife. Reduced tolerance for wildlife—that is, acceptance of risks from sharing spaces with wildlife[62]—can in turn lead people to change their behaviour in ways that exacerbate negative human–wildlife interactions. Although hypothetical, under these conditions a costly positive feedback loop may emerge between climate and conflict that is mediated by economic or livelihood insecurity[26]. Heightened rates of economic and personal losses from wildlife due to climate change may exceed the threshold of what people are willing or able to tolerate[63] and may further exacerbate negative interactions[63]. In the context of carnivore predation on livestock or crop destruction by large herbivores during drought, for example, lower tolerance has led to increased retaliatory killings by subsistence farmers (Box 2)[26].

Governance and policy. We found no case studies documenting a change in human–wildlife conflict arising from climate-related governance or policy. However, policies intended to address or mitigate the impacts of climate change drive large-scale changes in land use around the world, which can have unforeseen consequences for human–wildlife interactions. In some cases, climate change adaptation or mitigation policies could alleviate negative outcomes—for example, discouraging development in the wildland–urban interface to mitigate wildlife risk may also reduce livestock predation by carnivores[64]. Conversely, some climate change policies could unintentionally exacerbate negative human–wildlife interactions. For instance, climate change adaptation or mitigation policies may inadvertently drive human–wildlife conflict if they increase spatial or temporal overlap between humans and wildlife, which could occur as people are relocated from areas affected by sea level rise or wildfire risk or under some reforestation and forest protection for carbon offset scenarios. Whether and how climate change mitigation and adaptation policies have unforeseen consequences on human–wildlife conflict is an area for future research and is important to consider alongside other equity concerns[26,65,66].

Interactions and feedbacks

The aforementioned pathways can alter human–wildlife interactions additively, synergistically or antagonistically. In many cases, simultaneous human and wildlife responses to climate change can reshape conflict through both human and wildlife pathways. Research from Kenya, for example, suggests that hot and dry weather influences the behaviour of both African wild dogs (*Lycaon pictus*) and pastoralists, bringing them into greater contact and resulting in higher wild dog mortality rates[67]. The differential costs and benefits of climate change to humans and wild animals may also disrupt coexistence via interacting pathways. In Chile, milder winters have led to growth in guanaco (*Lama guanicoe*) populations, while more arid conditions have reduced availability of preferred livestock forage availability. The flexible diet of the guanacos gives them a competitive advantage over livestock, which has led to increased competition for vegetation forage with livestock ranchers[68]. Seemingly unrelated pathways may also align to exacerbate negative human–wildlife interactions in ways that may not be as readily predicted, generating a perfect storm of conditions (Box 3)[56].

Climate-driven human–wildlife conflict can also initiate feedbacks by reshaping the pathways elucidated above, as the outcomes of conflict may alter the spatiotemporal distribution, density or behaviour of people and animals (Fig. 1). For example, the killing of polar bears in response to increased presence on land has contributed to lower bear population densities and thus conflict[69]. Conflict and associated management responses may also alter human risk tolerance or exert selective pressure on animals, for example, further reshaping the nature of human–wildlife interactions[70]. Climate-driven human–wildlife interactions could potentially have cascading consequences for ecosystems that scale up to affect the global climate, although it will be difficult to anticipate and document such feedbacks in complex systems. Regardless, it is important to recognize the coupled nature of human-modified ecosystems and global climate change as we manage human–wildlife interactions.

Finally, we underscore that the vulnerability of both wildlife and human populations to negative interactions will also interact with their overall vulnerability to climate change. The negative outcomes of agricultural loss to wildlife, for example, will be felt most strongly in communities where people are already suffering from climate change-related resource scarcity[26]. Similarly, wildlife populations may not be able to compensate for anthropogenic sources of mortality if these populations are already threatened by other climate change impacts[69]. Overall, these complexities highlight the need for interdisciplinary, localized approaches to elucidate the underlying social–ecological dynamics of a given system.

Outlook and future directions

Defining the pathways through which climate change impacts human–wildlife interactions allows us to identify common trends across systems, predict the emergence of new or intensified interactions and develop effective conservation and policy measures.

Trends and gaps

Our systematic review revealed an extraordinary breadth of systems in which climate-driven conflicts are occurring worldwide (Figs. 2 and 3). Further, the number of studies empirically linking climate change to increased human–wildlife conflict has quadrupled in the last decade compared with the previous two decades (Fig. 3b). Climate-driven conflicts were documented across all continents except Antarctica, with a geographic emphasis in Africa and North America that may reflect a bias in research effort (Fig. 3). Conflicts involved five major wildlife taxa (birds, fish, mammals, reptiles and invertebrates), spanning body sizes from 2.5 mg (mosquitos) to 6,000 kg (African elephant). Mammals were the most commonly studied taxa, which may reflect the fact that mammals are heavily implicated in human–wildlife conflict[2] and/or research biases generally widespread in wildlife ecology and conservation[71]. In addition, most documented climate-driven interactions involved terrestrial species (82%, 40 studies), with relatively little research in aquatic systems. Given the ubiquitous impacts of climate change and human–wildlife interactions across terrestrial and aquatic systems[6,72], our review underlines the need for future research into the impacts of climate change on interactions within a broader range of taxa and systems.

Several common drivers and pathways emerged across systems. Temperature and precipitation were the primary climate variables associated with changes in human–wildlife interactions, cited in over 80% of case studies. Climate-driven exacerbation of resource scarcity was the single-most cited ecological mechanism amplifying conflict, with changes in resource abundance (74%, 36 studies) and distribution (31%, 15 studies) frequently underlying conflict. Most climate-driven conflicts were attributed to wildlife responses to climate change, rather than human responses. The relatively few human pathways documented in the literature may reflect a shortage of research on the linkages between socioeconomic drivers of human–wildlife interactions and environmental change, highlighting a priority area for future research. Understanding such multifaceted mechanisms necessitates multidisciplinary research teams and offers opportunities to broaden participation in the research process by including traditional ecological knowledge when characterizing the local to regional impacts of climate change[68].

The forms of conflict documented in our review highlight the severe consequences of climate-driven conflicts on human and wildlife communities. The most commonly reported conflict outcomes were physical injury or mortality to people (43%, 21 studies) and wildlife (45%, 22 studies) and loss of food production (45%, 22 studies). Although human–wildlife disease transmission as a form of conflict was beyond the scope of our review, increase in infectious disease spread is also a well-documented consequence of climate change[15,22,67]. Many of the case studies evaluated explicitly reported impacts on economically vulnerable pastoral communities, providing another example of how the world's already marginalized communities bear many of the impacts of climate change. These findings underscore the high stakes of climate-driven conflicts and highlight that there are important issues of environmental justice at play, in addition to those pertaining to wildlife conservation.

While our review revealed clear mechanisms through which climate change amplifies human–wildlife conflict, the opposite may also be true in certain contexts. Additionally, climate-driven range shifts or population declines may reduce conflict intensity to the point that conflict management strategies that were previously not feasible, such as payments for ecosystem services, could be reconsidered. Future studies should remain aware of the potential for climate to alleviate negative human–wildlife interactions, as doing so can strengthen our capacity to make effective management decisions.

Predicting conflicts

By incorporating an understanding of climate into conservation planning, scientists and managers can better predict and manage emerging patterns of human–wildlife conflicts. Anticipating where and when conflicts are likely to occur is key for proactive management, such as prioritizing locations to implement conflict mitigation schemes. In areas prone to droughts or megafires, for example, climate projections of those extreme events can be used to develop early warning indicators of subsequent human–wildlife interactions. Forecasts of rapid climate-driven environmental change, like increasingly severe droughts[6] or the opening of the Arctic[52], could be used to reveal locations most likely to experience elevated human–wildlife encounters. Predictions of climate refugia for wildlife could identify where hotspots of conflict may shift under continued warming[43]. Likewise, given associations like increased livestock predation and presence of carnivores in human-dominated areas during La Niña dry years in arid regions of North and South America[73,74], predictions of El Niño/Southern Oscillation indices could help predict when wildlife are more likely to come into conflict with people[75].

Explicit consideration of the human pathways connecting climate change to human–wildlife interactions would also improve predictions of conflicts. Climate change will probably alter human population distributions in and near important wildlife habitats, for example, through rural–urban migrations or accelerating migrations toward the edges of protected areas[76]. Considering how wildlife distributions are predicted to change alongside how people may move in response to climate change will shed light on where humans and wildlife interact more often in the future. Furthermore, understanding how climate change impacts human tolerances for wildlife will lead to better predictions of negative human–wildlife interactions in the future[26].

Proactive policies

Conflict policy that recognizes the multiple, interacting paths to conflict will be more effective at addressing its root causes and policy-makers can draft proactive policies based on conflict pathways laid out in this review to ensure that they do not overlook critical causes or instances of conflict. For example, recognizing that water scarcity was at the root of conflicts, one case study in Central America recommended setting out artificial water troughs in tapir habitat to help tapirs cope with droughts and compete for water set aside for livestock and agriculture[25]. Increasing local awareness about the influence of climate change on human–wildlife interactions, such as a correlation between specific climate conditions and increased conflicts, could also help mitigate them[38]. For instance, ref. 77 and ref. 73 both note that educating local communities about the relationship between hot or dry climate conditions and encounters with crocodilians and black bears, respectively, would reduce threatening interactions.

Given the rapid pace of climate change, policies will need to embrace the dynamic nature of human–wildlife conflicts, especially in a changing climate, and be capable of adjusting to changing conditions. In the marine environment, dynamic ocean management is gaining traction as a 'climate-ready' strategy for protecting species whose

https://doi.org/10.1038/s41558-023-01608-5

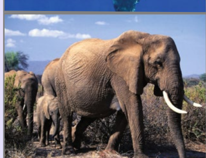
	System		Climate driver	Pathway	Conflict outcome	Reference
Long-term change		Polar bears; Canada	Warming leading to delayed sea ice freeze-up	Polar bears spend more time on land, seek out new food sources	Conflicts involving property damage, life-threatening encounters or bear killings triple over 30 years	43
Long-term change		Bharal (blue sheep) and snow leopards; Nepal	Warming; decreased snowfall	Bharal forage at lower elevations; snow leopards follow bharal as prey	Increases in bharal crop foraging, livestock and income loss from snow leopard depredation and retaliatory killing	88
Long-term change		Barnacle geese; Scotland, UK	Warming	Geese populations increase with improving foraging and breeding ground conditions	Conflict with farmers, including economic damage to farmland	24
Long-term change		Guanacos; Chile	Aridification	Milder winters increase guanaco populations; drier summers reduce grazing resources	Increased resource competition between guanacos and livestock; income loss for ranchers	68
Acute event		Humpback and blue whales; Eastern Pacific Ocean	Marine heatwave	Whales move inshore and delayed fishery opening increases spatial and temporal overlap between whales and fishery	400% increase in whale entanglements in fishing gear, leading to whale injury and mortality, and fishery closures*	56
Acute event		African elephants; Tanzania	Drought	Elephants move towards villages for food and water; reduced human tolerance of wildlife due to food and economic insecurity	Elephants destroy crops and pipes; retaliatory killing	26
Acute event		White sharks; South Africa	Strong El Niño leading to high air and sea surface temperatures	White sharks shift distribution nearshore; people spend more time in water	360% increase in shark bite incidences*	58
Acute event		Baird's tapir; Mexico	Drought	Tapirs enter villages looking for water	Increased tapir sightings in villages; tapirs destroy crops; retaliatory killing	25
Weather		African wild dogs; Kenya	Air temperature	Wild dogs and humans change space use in hot weather, increasing spatial overlap	Increased wild dog mortality from retaliatory killing and disease exposure from domestic dogs	67
Weather		Nile crocodiles; South Sudan	Air temperature; rainfall	Shepherds move livestock to river in hot and dry seasons	Increase in human and livestock attacks; 23 people killed between 2018 and 2020	51

Fig. 2 | Key examples of climate-driven human–wildlife conflicts in the literature. Long-term changes represent changes in climate conditions over multiple decades; acute climate events represent extreme deviations in climate conditions over days to years; weather represents variability in climate conditions over minutes to months. Asterisks in acute event–conflict outcomes indicate conflict rates in a single year compared with average background rates. Data from refs. [24–26,43,51,56,58,67,68,88]. Credits: polar bears, Openverse/USFWSAlaska, under a CC BY 2.0 license; blue sheep, Openverse/ComputerHotline, under a CC BY 2.0 license; snow leopard, Openverse/Macpedia, under a CC BY 2.0 license; geese; Openverse/peter.v.b, under a CC BY 2.0 license; guanacos, Openverse/deensel, under a CC BY 2.0 license; humpback whale, E. Lyman/HWS and NOAA (MMHSRP permit no. 932-1905) under a CC PDM 1.0 license; elephant, Openverse/flickrfavorites, under a CC BY 2.0 license; shark, Openverse/Elias Levy, under a CC BY 2.0 license; tapir, Openverse/Rictor Norton and David Allen, under a CC BY 2.0 license; African wild dogs, Openverse/PaulBalfe, under a CC BY 2.0 license; Nile crocodile, Openverse/fotopamas, under a CC BY 2.0 license.

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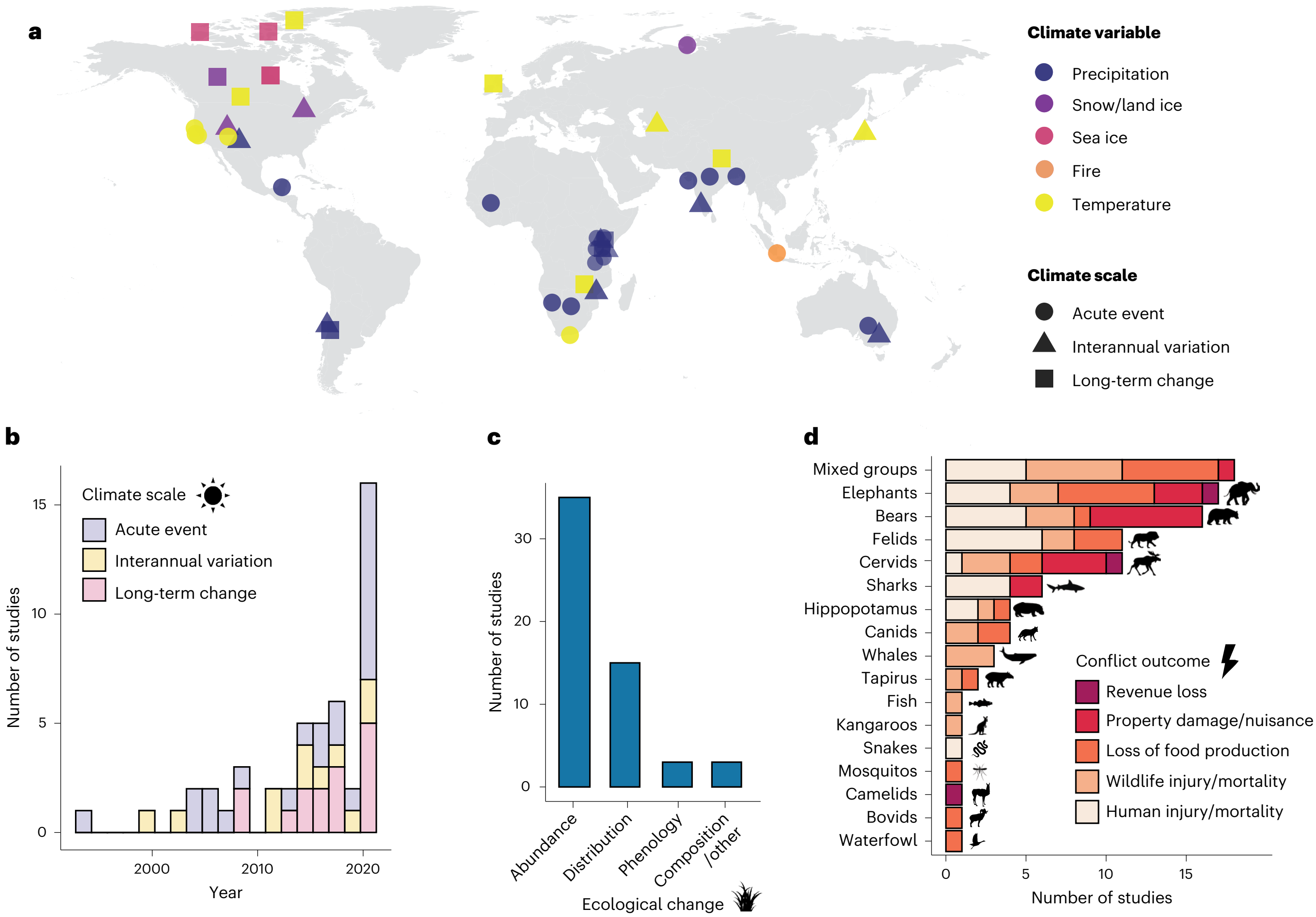

Fig. 3 | Synthesis of climate-driven human–wildlife conflicts documented in the literature. a, Geographic locations of studies. Colours indicate the primary essential climate variable identified as a driver of conflict; shapes indicate the scale of climate variation. **b**, Number of studies published by year, coloured by the scale of climate variation. **c**, Number of studies reporting changes in resource abundance, resource distribution, resource phenology and/or community composition or other ecological change underlying conflict. **d**, Number of studies on wildlife taxa involved in conflict, coloured by conflict outcome. The data used to generate this figure are provided in ref. [5]. Methods are provided in the Supplementary Information.

exposure to anthropogenic threats change rapidly by adjusting management dynamically in response to shifting biological, environmental or socioeconomic conditions[78]. Mobile protected areas[79] and dynamic fisheries closures[80] are prime examples of dynamic management being operationalized to reduce climate-driven human–wildlife interactions (Box 3). Although dynamic management is less widely considered in terrestrial wildlife management, examples such as seasonal road closures to reduce animal–vehicle collisions exist and opportunities for broader implementation are ripe[81].

Implications for land management

Climate-driven shifts in both human and wildlife populations will likely create more porous boundaries between lands managed for different purposes, such as between protected areas and nearby non-protected areas or between publicly and privately owned lands. Transboundary conservation initiatives could coordinate management across jurisdictions, such as national parks and privately owned forests, to develop a coherent conflict mitigation programme that spans the spatial scales within which conflict is occurring now and in the future under climate change[82]. Specific measures include directing funds for protected area management toward conflict mitigation efforts immediately outside of protected areas, where levels of human–wildlife interactions may increase due to climate change[49,67]. Managers could also limit certain agricultural practices near climate refugia for threatened wildlife species, using a suite of financial incentives to offset the opportunity costs to farmers[83]. Transboundary initiatives would also address the growing calls by conservation practitioners to mainstream the management of human–wildlife conflict and to incorporate human–wildlife coexistence into global conventions and regional programmes[84].

Integrating climate adaptation and conflict mitigation

Climate vulnerability assessments or adaptation strategies rarely discuss human–wildlife interactions[85] but our review makes clear that both need to explicitly encompass conflict mitigation to address the dire impacts imposed on both people and wildlife. Policies aimed at adapting to direct climate-related risks and risks from human–wildlife conflict can be mutually beneficial and together may seek to avoid synergistic effects that amplify human and wildlife vulnerability to climate change. For example, planting native vegetation along riparian areas to prevent erosion could be prioritized in locations that would also serve as refugia for wildlife from human-dominated areas. Revenue from wildlife tourism in conservancies could supplement funding to offset costs from climate change on livelihood practices of vulnerable human communities[86]. Recent evidence demonstrating that megafauna provide a wide range of climate adaptation benefits, such as by increasing vegetation and soil carbon stocks, further underscores the potential synergies between climate change adaptation and human–wildlife conflict mitigation[87].

Conclusions

Human–wildlife conflict is an inherently dynamic challenge, made even more complex by the myriad effects of climate change. Our framework and review illustrate that the pathways linking climate to conflict can be intricate and often unexpected (Box 1) and that ignoring connections between climate and conflict can exacerbate outcomes (Box 2). Participatory, dynamic management strategies that incorporate climate information to foresee likely climate-driven human–wildlife interactions hold promise for preparing for and mitigating conflicts as the climate continues to change (Box 3). As the impacts of climate change on humans and wildlife become increasingly salient, interdisciplinary explorations of the complex pathways through which climate reshapes social–ecological processes and outcomes will be vital for developing both effective and socially just policies for biodiversity conservation, human–wildlife conflict and climate adaptation.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All case study data derived from the systematic literature review are available at https://github.com/Abrahms-Lab/Climate-Conflict-Review and archived via Zenodo (https://doi.org/10.5281/zenodo/7502350).

Code availability

All R code used for analyses is available at https://github.com/Abrahms-Lab/Climate-Conflict-Review and archived via Zenodo (https://doi.org/10.5281/zenodo/7502350).

References

1. Abrahms, B. Human–wildlife conflict under climate change. *Science* **373**, 484–485 (2021).
2. Nyhus, P. J. Human–wildlife conflict and coexistence. *Annu. Rev. Environ. Resour.* **41**, 143–171 (2016).
3. Ripple, W. J. et al. Extinction risk is most acute for the world's largest and smallest vertebrates. *Proc. Natl Acad. Sci. USA* **114**, 10678–10683 (2017).
4. Estes, J. A. et al. Trophic downgrading of planet Earth. *Science* **333**, 301–306 (2011).
5. Abrahms, B. et al. Data from: Climate change as an amplifier of human–wildlife conflict. *Github* https://github.com/Abrahms-Lab/Climate-Conflict-Review (2022).
6. IPCC *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, 2021).
7. Sydeman, W. J., Santora, J. A., Thompson, S. A., Marinovic, B. & Lorenzo, E. D. Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California. *Glob. Change Biol.* **19**, 1662–1675 (2013).
8. Wang, G. et al. Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nat. Clim. Change* **7**, 568–572 (2017).
9. Filazzola, A., Blagrave, K., Imrit, M. A. & Sharma, S. Climate change drives increases in extreme events for lake ice in the Northern Hemisphere. *Geophys. Res. Lett*. 47, e2020GL089608 (2020).
10. Marzeion, B., Cogley, J. G., Richter, K. & Parkes, D. Attribution of global glacier mass loss to anthropogenic and natural causes. *Science* **345**, 919–921 (2014).
11. Martin, J. T. et al. Increased drought severity tracks warming in the United States' largest river basin. *Proc. Natl Acad. Sci. USA* **117**, 11328–11336 (2020).
12. Laufkötter, C., Zscheischler, J. & Frölicher, T. L. High-impact marine heatwaves attributable to human-induced global warming. *Science* **369**, 1621–1625 (2020).
13. Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A. & Maher, N. More extreme precipitation in the world's dry and wet regions. *Nat. Clim. Change* **6**, 508–513 (2016).
14. Walther, G.-R. et al. Ecological responses to recent climate change. *Nature* **416**, 389–395 (2002).
15. Pecl, G. T. et al. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* **355**, eaai9214 (2017).
16. Lin, D., Xia, J. & Wan, S. Climate warming and biomass accumulation of terrestrial plants: a meta-analysis. *New Phytol.* **188**, 187–198 (2010).
17. Kharouba, H. M. & Wolkovich, E. M. Disconnects between ecological theory and data in phenological mismatch research. *Nat. Clim. Change* **10**, 406–415 (2020).
18. Marinovic, B. B., Croll, D. A., Gong, N., Benson, S. R. & Chavez, F. P. Effects of the 1997–1999 El Niño and La Niña events on zooplankton abundance and euphausiid community composition within the Monterey Bay coastal upwelling system. *Prog. Oceanogr.* **54**, 265–277 (2002).
19. Kardol, P. et al. Climate change effects on plant biomass alter dominance patterns and community evenness in an experimental old-field ecosystem. *Glob. Change Biol.* **16**, 2676–2687 (2010).
20. Prugh, L. R. et al. Ecological winners and losers of extreme drought in California. *Nat. Clim. Change* **8**, 819–824 (2018).
21. Sorte, C. J. B., Williams, S. L. & Zerebecki, R. A. Ocean warming increases threat of invasive species in a marine fouling community. *Ecology* **91**, 2198–2204 (2010).
22. Muehlenbein, M. P. Human–environment interactions, current and future directions. *Hum. Environ. Interact.* **1**, 79–94 (2012).
23. Sinervo, B. et al. Erosion of lizard diversity by climate change and altered thermal niches. *Science* **328**, 894–899 (2010).
24. Mason, T. H. E., Keane, A., Redpath, S. M. & Bunnefeld, N. The changing environment of conservation conflict: geese and farming in Scotland. *J. Appl. Ecol.* **55**, 651–662 (2018).
25. Pérez-Flores, J., Mardero, S., López-Cen, A., Contreras-Moreno, F. M. & Pérez-Flores, J. Human–wildlife conflicts and drought in the greater Calakmul Region, Mexico: implications for tapir conservation. *Neotrop. Biol. Conserv.* **16**, 539–563 (2021).
26. Mariki, S. B., Svarstad, H. & Benjaminsen, T. A. Elephants over the cliff: explaining wildlife killings in Tanzania. *Land Use Policy* **44**, 19–30 (2015).
27. Mukeka, J. M., Ogutu, J. O., Kanga, E. & Roskaft, E. Spatial and temporal dynamics of human–wildlife conflicts in the Kenya Greater Tsavo Ecosystem. *Hum. Wildl. Interact.* **14**, 255–272 (2020).
28. Popp, J. N., Hamr, J., Chan, C. & Mallory, F. F. Elk (*Cervus elaphus*) railway mortality in Ontario. *Can. J. Zool.* **96**, 1066–1070 (2018).
29. Olson, D. D. et al. How does variation in winter weather affect deer–vehicle collision rates? *Wildl. Biol.* **21**, 80–87 (2015).
30. Nyhus, P. & Tilson, R. Agroforestry, elephants, and tigers: balancing conservation theory and practice in human-dominated landscapes of Southeast Asia. *Agric. Ecosyst. Environ.* **104**, 87–97 (2004).
31. Laufenberg, J. S., Johnson, H. E., Doherty, P. F. & Breck, S. W. Compounding effects of human development and a natural food shortage on a black bear population along a human development–wildland interface. *Biol. Conserv* **224**, 188–198 (2018).
32. Blondin, H., Abrahms, B., Crowder, L. B. & Hazen, E. L. Combining high temporal resolution whale distribution and vessel tracking data improves estimates of ship strike risk. *Biol. Conserv.* **250**, 108757 (2020).

 https://doi.org/10.1038/s41558-023-01608-5

33. Abrahms, B. et al. Dynamic ensemble models to predict distributions and anthropogenic risk exposure for highly mobile species. *Divers. Distrib.* **25**, 1182–1193 (2019).
34. Gaynor, K. M., Hojnowski, C. E., Carter, N. H. & Brashares, J. S. The influence of human disturbance on wildlife nocturnality. *Science* **360**, 1232–1235 (2018).
35. Kabir, M., Ghoddousi, A., Awan, M. S. & Awan, M. N. Assessment of human–leopard conflict in Machiara National Park, Azad Jammu and Kashmir, Pakistan. *Eur. J. Wildl. Res.* **60**, 291–296 (2014).
36. Soto, J. R. *Patterns and Determinants of Human–Carnivore Conflicts in the Tropical Lowlands of Guatemala* (Univ. of Florida, 2008).
37. Honda, T. & Kozakai, C. Mechanisms of human–black bear conflicts in Japan: in preparation for climate change. *Sci. Total Environ.* **739**, 140028 (2020).
38. Mukeka, J. M., Ogutu, J. O., Kanga, E. & Røskaft, E. Human–wildlife conflicts and their correlates in Narok County, Kenya. *Glob. Ecol. Conserv.* **18**, e00620 (2019).
39. Kuiper, T. R. et al. Seasonal herding practices influence predation on domestic stock by African lions along a protected area boundary. *Biol. Conserv.* **191**, 546–554 (2015).
40. Funston, P. J., Mills, M. G. L. & Biggs, H. C. Factors affecting the hunting success of male and female lions in the Kruger National Park. *J. Zool.* **253**, 419–431 (2001).
41. Schiess-Meier, M., Ramsauer, S., Gabanapelo, T. & Konig, B. Livestock predation—insights from problem animal control registers in Botswana. *J. Wildl. Manag.* **71**, 1267–1274 (2007).
42. Wilder, J. M. et al. Polar bear attacks on humans: implications of a changing climate. *Wildl. Soc. B* **41**, 537–547 (2017).
43. Towns, L., Derocher, A. E., Stirling, I., Lunn, N. J. & Hedman, D. Spatial and temporal patterns of problem polar bears in Churchill, Manitoba. *Polar Biol.* **32**, 1529–1537 (2009).
44. Schmidt, A. & Clark, D. 'It's just a matter of time:' lessons from agency and community responses to polar bear-inflicted human injury. *Conserv. Soc.* **16**, 64 (2018).
45. Koenig, J., Shine, R. & Shea, G. The dangers of life in the city: patterns of activity, injury and mortality in suburban lizards (*Tiliqua scincoides*). *J. Herpetol.* **36**, 62–68 (2002).
46. Whitaker, P. B. & Shine, R. Responses of free-ranging brownsnakes (*Pseudonaja textilis*: Elapidae) to encounters with humans. *Wildl. Res.* **26**, 689–704 (1999).
47. Saberwal, V., Gibbs, J., Chellam, R. & Johnsingh, A. Lion–human conflict in the Gir Forest, India. *Conserv. Biol.* **8**, 501–507 (1994).
48. Ferreira, S. M. & Viljoen, P. African large carnivore population changes in response to a drought. *Afr. J. Wildl. Res.* https://hdl.handle.net/10520/ejc-wild2-v52-n1-a1 (2022).
49. Masiaine, S. et al. Landscape-level changes to large mammal space use in response to a pastoralist incursion. *Ecol. Indic.* **121**, 107091 (2021).
50. Kiria, E. *A Spatial Multi-criteria Analysis of Land Use, Land Cover and Climate Changes on Wildlife Ecosystems Planning and Management in Meru Conservation Area* (Chuka Univ., 2018).
51. Benansio, J., Demaya, G., Dendi, D. & Luiselli, L. Attacks by Nile crocodiles (*Crocodylus nilotticus*) on humans and livestock in the Sudd wetlands, South Sudan. *Russ. J. Herpetol.* https://doi.org/10.30906/1026-2296-2022-29-4-199-205 (2022).
52. Melia, N., Haines, K. & Hawkins, E. Sea ice decline and 21st century trans-Arctic shipping routes. *Geophys. Res. Lett.* **43**, 9720–9728 (2016).
53. Ivanova, S. V. et al. Shipping alters the movement and behavior of Arctic cod (*Boreogadus saida*), a keystone fish in Arctic marine ecosystems. *Ecol. Appl.* **30**, e02050 (2020).
54. Hauser, D. D. W., Laidre, K. L. & Stern, H. L. Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proc. Natl Acad. Sci. USA* **5**, 201803543–201803546 (2018).
55. Hovelsrud, G. K., McKenna, M. & Huntington, H. P. Marine mammal harvests and other interactions with humans. *Ecol. Appl.* **18**, S135–S147 (2008).
56. Santora, J. A. et al. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nat. Commun.* **11**, 536 (2020).
57. Samhouri, J. F. et al. Marine heatwave challenges solutions to human–wildlife conflict. *Proc. R. Soc. B* **288**, 20211607 (2021).
58. Chapman, B. K. & McPhee, D. Global shark attack hotspots: identifying underlying factors behind increased unprovoked shark bite incidence. *Ocean Coast. Manag.* **133**, 72–84 (2016).
59. Burgess, G., Buch, R., Carvalho, F., Garner, B. & Walker, C. in *Sharks and Their Relatives II: Biodiversity, Adaptive Physiology, and Conservation* (eds Carrier, J. C. et al.) 541–565 (CRC Press, 2010).
60. Woodward, A. R., Leone, E. H., Dutton, H. J., Waller, J. E. & Hord, L. Characteristics of American alligator bites on people in Florida. *J. Wildl. Manag.* **83**, 1437–1453 (2019).
61. Khorozyan, I., Soofi, M., Ghoddousi, A., Hamidi, A. K. & Waltert, M. The relationship between climate, diseases of domestic animals and human–carnivore conflicts. *Basic Appl. Ecol.* **16**, 703–713 (2015).
62. Treves, A. & Bruskotter, J. Tolerance for predatory wildlife. *Science* **344**, 476–477 (2014).
63. Carpenter, S. Exploring the impact of climate change on the future of community-based wildlife conservation. *Conserv. Sci. Pract.* **4**, e585 (2022).
64. Nisi, A. *Cryptic Neighbors: Connecting Movement Ecology and Population Dynamics for a Large Carnivore in a Human-dominated Landscape* (Univ. California, 2021). .
65. Asiyanbi, A. P. A political ecology of REDD+: property rights, militarised protectionism, and carbonised exclusion in Cross River. *Geoforum* **77**, 146–156 (2016).
66. Dawson, N. M. et al. Barriers to equity in REDD+: deficiencies in national interpretation processes constrain adaptation to context. *Environ. Sci. Policy* **88**, 1–9 (2018).
67. Rabaiotti, D. et al. High temperatures and human pressures interact to influence mortality in an African carnivore. *Ecol. Evol.* **11**, 8495–8506 (2021).
68. Vargas, S. P., Castro-Carrasco, P. J., Rust, N. A. & F, J. L. R. Climate change contributing to conflicts between livestock farming and guanaco conservation in central Chile: a subjective theories approach. *Oryx* **55**, 275–283 (2021).
69. Heemskerk, S. et al. Temporal dynamics of human–polar bear conflicts in Churchill, Manitoba. *Glob. Ecol. Conserv.* **24**, e01320 (2020).
70. Schell, C. J. et al. The evolutionary consequences of human–wildlife conflict in cities. *Evol. Appl.* **14**, 178–197 (2021).
71. Clark, J. A. & May, R. M. Taxonomic bias in conservation research. *Science* **297**, 191–192 (2002).
72. Ravenelle, J. & Nyhus, P. J. Global patterns and trends in human–wildlife conflict compensation. *Conserv. Biol.* **31**, 1247–1256 (2017).
73. Zack, C. S., Milne, B. T. & Dunn, W. Southern oscillation index as an indicator of encounters between humans and black bears in New Mexico. *Wildl. Soc. Bull.* **31**, 517–520 (2003).
74. Acosta-Jamett, G., Gutiérrez, J. R., Kelt, D. A., Meserve, P. L. & Previtali, M. A. El Niño Southern Oscillation drives conflict between wild carnivores and livestock farmers in a semiarid area in Chile. *J. Arid. Environ.* **126**, 76–80 (2016).
75. Timmermann, A. et al. El Niño–Southern Oscillation complexity. *Nature* **559**, 535–545 (2018).
76. Wittemyer, G., Elsen, P., Bean, W. T., Burton, A. C. O. & Brashares, J. S. Accelerated human population growth at protected area edges. *Science* **321**, 123–126 (2008).

77. Powell, G., Versluys, T. M. M., Williams, J. J., Tiedt, S. & Pooley, S. Using environmental niche modelling to investigate abiotic predictors of crocodilian attacks on people. *Oryx* **54**, 639–647 (2020).
78. Maxwell, S. M. et al. Dynamic ocean management: defining and conceptualizing real-time management of the ocean. *Mar. Policy* **58**, 42–50 (2015).
79. Maxwell, S. M., Gjerde, K. M., Conners, M. G. & Crowder, L. B. Mobile protected areas for biodiversity on the high seas. *Science* **367**, 252–254 (2020).
80. Pons, M. et al. Trade-offs between bycatch and target catches in static versus dynamic fishery closures. *Proc. Natl Acad. Sci. USA* **119**, e2114508119 (2022).
81. Oestreich, W. K., Chapman, M. S. & Crowder, L. B. A comparative analysis of dynamic management in marine and terrestrial systems. *Front. Ecol. Environ.* **18**, 496–504 (2020).
82. Mason, N., Ward, M., Watson, J. E. M., Venter, O. & Runting, R. K. Global opportunities and challenges for transboundary conservation. *Nat. Ecol. Evol.* **4**, 694–701 (2020).
83. Dickman, A. J., Macdonald, E. A. & Macdonald, D. W. A review of financial instruments to pay for predator conservation and encourage human–carnivore coexistence. *Proc. Natl Acad. Sci. USA* **108**, 13937–13944 (2011).
84. Ej, N. G. et al. *A Future for All: The Need for Human–Wildlife Coexistence* (UNEP, 2021).
85. Lankford, A. J., Svancara, L. K., Lawler, J. J. & Vierling, K. Comparison of climate change vulnerability assessments for wildlife. *Wildl. Soc. Bull.* **38**, 386–394 (2014).
86. Syombua, M. *An Analysis of Human–Wildlife Conflicts in Tsavo West-Amboseli Agro-Ecosystem Using an Integrated Geospatial Approach: A Case Study of Taveta District* (Univ. of Nairobi, 2013).
87. Malhi, Y. et al. The role of large wild animals in climate change mitigation and adaptation. *Curr. Biol.* **32**, R181–R196 (2022).
88. Aryal, A., Brunton, D. & Raubenheimer, D. Impact of climate change on human–wildlife–ecosystem interactions in the Trans-Himalaya region of Nepal. *Theor. Appl. Climatol.* **115**, 517–529 (2013).
89. Aryal, A., Brunton, D., Ji, W., Barraclough, R. K. & Raubenheimer, D. Human–carnivore conflict: ecological and economical sustainability of predation on livestock by snow leopard and other carnivores in the Himalaya. *Sustain. Sci.* **9**, 321–329 (2014).
90. Aryal, A. et al. Predicting the distributions of predator (snow leopard) and prey (blue sheep) under climate change in the Himalaya. *Ecol. Evol.* **6**, 4065–4075 (2016).
91. Nowell, K., Li, J., Paltsyn, M. & Sharma, R. *An Ounce of Prevention: Snow Leopard Crime Revisited* (Traffic Report, 2016).

Acknowledgements

We are grateful to A. Zimmerman and L. Withey for providing early feedback on our manuscript. We thank our institutions for supporting this work. L.W. was supported under an NSF Graduate Research Fellowship.

Author contributions

B.A. conceived of the work and led the writing. B.A., T.J.C.-W., E.J., A.M., A.C.N., K.R. and L.W. performed the systematic literature review. All authors contributed writing, edits and ideas to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-023-01608-5.

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Peer review information *Nature Climate Change* thanks Maria Paniw and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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Last updated by author(s): May 6 2022

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☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
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☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No code or software was used for data collection.
Data analysis	We used R version 4.1.0 to analyze the case study data derived from the systematic literature review.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

All case study data derived from the systematic literature review and R code used for analyses are available at https://github.com/Abrahms-Lab/Climate-Conflict-Review and are archived via Zenodo (DOI: 10.5281/zenodo/7502350).

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We conducted a systematic literature review to identify and synthesize cases reporting empirical relationships between climate change and human-wildlife conflict.
Research sample	The research sample was published case studies in the literature reporting empirical relationships between climate change and human-wildlife conflict.
Sampling strategy	We identified potential literature using two processes: 1) a Web of Science search and 2) a snowballing process of citations in relevant papers. For the Web of Science Search, we used two search strings to identify candidate studies that documented instances of human-wildlife conflict (search string one) being mediated by climate variables (search string two). The first search used the topic string (human-wildlife* OR human$ wildlife OR human-animal* OR human$ animal$ OR anthropogenic wildlife or anthropogenic animal$) AND AB=(conflict* OR depredation OR hunt*OR poach* OR disturb* OR livestock OR attack* OR injur* OR interact* OR clash* OR encounter* OR ship strike* OR raid* OR predat* OR damag* OR econom* OR problem*OR destruction OR bit$* OR retaliator*OR deat* OR dead* OR destroy*). Search string two used the topic string (climate OR temperature* OR heat OR rain* OR cold OR "environmental change" OR drought* OR flood* OR warm* OR melt* OR El Niño OR season* OR southern oscillation index OR ENSO OR summer OR winter OR weather). Search strings targeted research abstracts and we restricted results to research journals within relevant topics using the search string (Anthropology OR Behavioral Sciences OR Biodiversity Conservation OR Ecology OR Environmental Sciences OR Environmental Studies OR Evolutionary Biology OR Fisheries OR Forestry OR Marine & Freshwater Biology OR Ornithology OR Zoology). We based the selection of relevant topics on an initial exploratory analyses of search results from all research topics. The Web of Science search generated 2,813 articles. We used a backwards and forwards snowballing process to identify papers that may have been overlooked in the Web of Science search. In backwards snowballing, we identified candidate references that were cited within a paper meeting our inclusion criteria below. In forwards snowballing, we identified candidate articles in Web of Science that cited a paper meeting our criteria. Snowballing generated 136 articles. The combined processes generated a total of 2,949 records which were subsequently screened for inclusion.
Data collection	We initially screened records for duplicates and empiricism, yielding 409 records that were screened in further detail. We included case studies based on the criterion that they demonstrated an empirical link between a climate variable and human-wildlife conflict incidences. We defined human-wildlife conflict as direct, non-extractive interactions between humans and wildlife with adverse outcomes for one or both actors. To focus on studies linking climate change to conflict, we further refined our dataset to studies that related conflict to either interannual climatic variation (e.g., El Niño Southern Oscillation index), acute climatic events (e.g., severe drought, marine heatwave), or long-term directional climate change (e.g., global warming, sea ice decline). While climate change impacts sub-annual climatic variation as well, the confounding factors of life history patterns make it difficult to definitively attribute any changes in human or wildlife behavior and ecology to climate change, and we therefore excluded studies relating conflict to sub-annual climatic variation. This resulted in a final dataset of 49 case studies. For each case study, we recorded the following metadata: year of publication, study location, system (terrestrial, aquatic, or marine), and focal wildlife species. We next applied our conceptual framework to each case study to record the following information: the Essential Climate Variable identified in the conflict based on categorizations by the Global Climate Monitoring System, which describe the physical, biological, and chemical attributes of Earth's climate; climate scale (interannual, acute event, or long-term); conflict outcome (human or wildlife injury/mortality, loss of food production, revenue loss, and personal property damage); ecological changes (resource abundance, phenology, distribution, community composition/other, or none identified); and wildlife and/or human pathways identified.
Timing and spatial scale	Web of Science studies were searched 1950-2021, although the first record that met our inclusion criteria was published in 1994. The spatial scale of our study is global.
Data exclusions	We excluded case studies that did not meet our inclusion criteria as described above.
Reproducibility	We provide the data and code to fully reproduce the analyses/figures from the systematic literature review.
Randomization	Not applicable as this was a systematic literature review.
Blinding	Not applicable as this was a systematic literature review.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging