8 Interactions between Climate Change and Contaminants

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CONTENTS

KEY LEARNING OBJECTIVES

1. Climate change and contaminants act as cumulative stressors on wildlife health.
2. Climate change increases the release and cycling of contaminants in the environment.
3. Climate change will alter contaminant levels in wildlife, causing various impacts on individual health.

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IMPLICATIONS FOR ACTION

1. Standardized, long-term monitoring programs are needed to identify how changes in climate are impacting contaminant concentrations in wildlife.
2. Supplementing existing long-term wildlife-monitoring programs with climate change, contaminants, and wildlife health measures will allow us to assess how multiple stressors may cumulatively impact wildlife health.
3. Future research should focus on the interactive effects of climate change and contaminant levels at an ecosystem-level scale to better understand how contaminants released from climate change can move through the environment and impact wildlife.

INTRODUCTION

The loss of biodiversity is an urgent issue in the Anthropocene as we approach a tipping point or planetary boundary beyond which recovery is difficult (1,2). Two of the greatest risks to wildlife, of the nine identified planetary boundaries, are climate change and toxic contamination (3,4). Understanding the interactive effects of climate change and chemical pollution on wildlife is a great challenge that requires multidisciplinary approaches that integrate ecotoxicology, environmental chemistry, and remote sensing.

The effects of climate change on contaminant cycling are complex and interactive; they include different processes, such as transformations (5–7), biological uptake (8,9), transport by air, snow or ice, and ocean currents (10–13), biotransport (14,15), and biomagnification (16). Moreover, these trends can differ geographically depending on differences in climate, contamination, and wildlife.

The influence of climate change on wildlife can be separated into direct mechanisms (heat stress) and indirect mechanisms, such as bottom-up processes (changing diet) and top-down processes (changing predators; 17–20). Each of these mechanisms can interact with toxic contamination. For example, since most contaminants are obtained via diet, climate-related bottom-up processes that influence diet may lead to higher levels of contaminants if the new prey, itself, feeds at a higher trophic position. At the same time, in the face of environmental perturbations, contaminant exposures may exacerbate effects of climate change through interfering with the ability of wildlife to respond to indirect and direct threats due to climate change.

In this chapter, we examine the interactive effects of climate change and contaminants on wildlife health. First, we examine the abiotic effects of climate change on contaminants, as well as biotic effects on wildlife via diet changes.

Next, we examine how contaminants may influence resilience to climate change, with an emphasis on endocrine disruption. Finally, we discuss two case studies in Arctic and alpine regions where climate change is occurring more rapidly than anywhere else on the globe. While this chapter focuses primarily via a wildlife lens, the general trends and circumstances are also relevant to domestic species.

CHANGE IN ABIOTIC FACTORS INFLUENCING CONTAMINANT LEVELS

GLACIERS, SEA-ICE AND PERMAFROST

The impacts of climate change are greatest in Arctic and alpine habitats, where warming is twice the global average and critical cold habitats are in rapid decline (8,21,22). We have lost over 50% of the world's glaciers, 30% of Arctic sea ice, and a large portion of permafrost, with ice-free summers predicted to occur before 2050 (23). This dramatic ice loss can lead to the mobilization of high levels of contaminants that have been deposited in cold regions in glaciers, sea ice, and permafrost. At the same time, many contaminants produced in warmer climates are brought by air and water currents to colder climates where they are then deposited, a process known as the "Grasshopper Effect" (24–27). Such contamination is of concern because of the high levels that biomagnify through the food web and bioaccumulate in top predators (28). Because many biomagnifying contaminants are lipophilic (i.e., dissolve in fats), they pose a risk to Arctic species that have large fat reserves as an adaptation for living in a colder climate, but also to northern communities who harvest Arctic predators as important traditional foods (29).

Glacial runoff from melts can interact with cold condensation, contaminating surrounding watersheds due to the minimal volatilization loss from cold runoff waters, limited catchment retention owing to low soil organic matter within such catchments, and the rapid channeling of the runoff from the glacier surface (30–32). Alpine areas in western North America are one region where contaminants, such as persistent organic pollutants (POP) and mercury, from Asia or industrial regions of North America, can be transported atmospherically and deposited (30,31,33), potentially contaminating wildlife and people that eat fish from alpine lakes (34,35). For example, the 1960–1980 global cold cycle trapped contaminants in glaciers, but these contaminants would have likely melted out by 1980 (12,34,35). Nonetheless, local processes coupled with ongoing POPs deposition in cold environments mean that significant levels of POPs remain in alpine environments worldwide (12,32,34,36). Thus, understanding the role of melting glaciers in contaminant levels in biota will be of increasing importance in a changing climate (Case Study 8.1).

Sea ice plays a key role in Arctic marine ecosystems, and many of the most threatened Arctic species are pagophilic, which means they depend on ice for some or all of their annual cycle (53,54). Sea ice can provide a platform for hunting,

CASE STUDY 8.1 ALPINE GLACIERS IN WESTERN CANADA

Contaminants that are resistant to degradation, including many POPs, occur in remote alpine habitats like the Alps and Rockies, partially due to scavenging by snow crystals, possibly via adsorption or entrapment (24,37,38). High levels in glacial runoff have been particularly evident in western North America, partially due to atmospheric transport from Asian sources (24,34,39). Half of the world's glaciers outside of the Antarctic and Greenland ice sheets have melted since 1950 (40), meaning pollutants trapped in alpine glaciers can melt out and accumulate in nearby water bodies. Indeed, most of the "legacy" pollutants in alpine lakes originated from the organochlorine era (1950–1970) and have since melted out of glaciers (35,41,42).

Pollutants released from glacial melt can bioaccumulate and biomagnify through lacustrine and riverine food webs and reach high levels in fish and their predators (43,44). Indeed, elevated pollutant levels in fish and mussel tissues, including insecticides such as toxaphene and industrial pollutants such as Polychlorinated biphenyls (PCBs) occur even in locations far removed from contaminant sources (45–47). For example, zebra mussels (*Dreissena polymorpha*) from Lake Iseo, Italy, had high levels of Dichlorodiphenyltrichloroethane (DDT) from a glacial-melting event, which led to mistimed sperm release relative to egg release (46). Likewise, trout from glacier-fed lakes in the Rockies had high levels of DDT (200 ng/g), which can then biomagnify in their predatorspredators, such as osprey (Pandion haliaetus). Indeed, DDT levels are expected to be above 20ug/g for osprey feeding exclusively on DDT levels are expected to be above 20 ug/g for osprey (*Pandion haliaetus*) feeding exclusively on trout in glacial-fed lakes, well above the levels associated with a 15% reduction in eggshell thickness and effects on embryonic viability (5 ug/g; 34,35,44,48,49). Thus, climate-induced glacial melting can lead to high contaminant levels in wildlife, including piscivorous birds that are feeding at a similar trophic level as humans.

Although melting glaciers were historically a source of contaminants, particularly during the melt following the 1950–1980 cool period after the organochlorine era (see above, and Figure 8.1 in 35), current levels in alpine glaciers are very low compared to global hotspots. Moreover, the portions of alpine glaciers that are now melting out predate the Industrial Revolution (50). For example, legacy pollutant levels in osprey were not associated with glacier coverage in an alpine region (34). Although high levels in some lakes may be due to historical melting, as well as the concentration of levels deposited over large glacier areas into small downstream lakes, ongoing melting is unlikely to lead to the high levels of pollutants seen in the late 20th century. Recent investigations of contaminant release have shifted, however, to other chemicals of concern, such as pharmaceuticals, plastics, and surfactants (51,52).

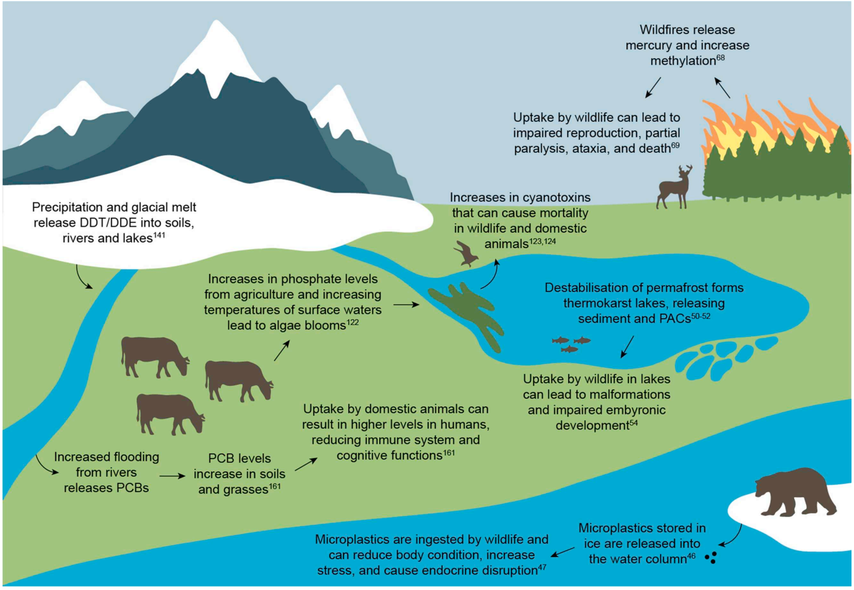

FIGURE 8.1 Example of how climate change can influence contaminant movements across different environmental compartments, and the interactive affects this movement can have on the health of wildlife and domestic animals. For each example, we highlight one contaminant that is well-studied in that context, but the same mechanism is often implicated for many different contaminants.

reproduction, travel, refuge from predators and during melt, acts to inject freshwater and nutrients that enable blooms in primary productivity (53–55). However, a dramatic decline in Arctic sea-ice cover is underway as a result of climate change, with ice-free summers predicted to occur before 2050 (21,56). Reduced ice cover can increase wildlife exposures to other anthropogenic stressors, such as increased industrial development, shipping activity, and contaminants (21,57). Indeed, sea ice can act as a sink, source, and transport medium for many contaminants (see also Case Study 8.2; 58–60). For example, microplastics can be deposited in sea ice during formation, and then transported long distances to remote regions such as the Arctic (60,61). As climate change exacerbates sea-ice melt, these contaminants can then be remobilized, thus increasing their availability in the environment (Figure 8.1; 62). Once ingested by biota, microplastics can cause a myriad of impacts, including reduced growth, reduced body condition, increased stress, endocrine disruption, reduced reproductive success, and even death (reviewed in 63). Thus, understanding how sea ice acts as a source of contaminants to wildlife is an important step to better understand how climate change may impact contaminant concentrations in wildlife.

Permafrost thaw and the melting of land ice is the largest change in the Arctic attributable to rising temperatures in soil and terrestrial environments (80), and this change is occurring across the circumpolar Arctic (81). For example, using satellite imagery, Lewkowicz and colleagues (82) found a 60-fold increase in retrogressive thaw slumps (large catastrophic thaw features) on Banks Island (Northwest Territories, Canada) between 1984 and 2015. The destabilization and slumping of permafrost, forming thermokarst lakes, is releasing sediment to downstream lakes and waterways as well as to the Arctic Ocean from coastal erosion (82–84). This release can increase both primary (released from permafrost) and secondary (released from sediment erosion, altered hydrological flow, or increased runoff caused by permafrost thaw) sources of contaminants to terrestrial and marine environments in the Arctic (reviewed in 6). For example, thermokarst lakes in the Canadian Arctic were found to contain higher concentrations of metals and polycyclic aromatic compounds (PACs) released by thaw slumps (85). PACs are highly toxic to wildlife and have been found to cause cardiac and skeletal malformations, as well as impaired embryonic development in fish, frogs, and birds (Figure 8.1; 86). Importantly, thermokarst responses to climate warming are not uniform and vary regionally within the circumpolar Arctic in relation to local landscape factors (87,88). Thus, monitoring the quantity and rate that contaminants are released from permafrost, and how this may pose a risk to wildlife species, is important to examine on a region- and species-specific basis.

Lakes

Freshwater ecosystems have been altered by climate change, with many lakes drying up via evaporation and thermokarst development, and others affected by altered precipitation patterns (32,89–91). Moreover, the ice-free period is increasing in many polar regions, influencing the stratification and biogeochemistry of lakes (92–95). Together, these processes increase the light available in the water column, influencing levels of dissolved organic carbon (DOC) and contaminant levels in lakes (96,97). Specifically, DOC can bind to methylmercury (MeHg), the most bioavailable and toxic form of mercury, and facilitate its dissolution into the water, increasing the amount of bioavailable MeHg to wildlife (98,99). MeHg is a powerful neurotoxin that can cause reproductive impairment (e.g., the suppression of sex hormones, the underdevelopment of gonads), neurological effects (e.g., partial paralysis, ataxia) and have fatal effects in vertebrates (Figure 8.1; 100–102). Importantly, MeHg can biomagnify the food web; thus, organisms at all levels may suffer severe health effects (28). The complex interactions between DOC and mercury cycling make it difficult to understand how physical changes to lakes might influence the breadth of contaminants' impact on the environment and wildlife.

Wildfires

In terrestrial ecosystems, wildfires play an important role in the life cycle of many plants in forest systems. However, the frequency of wildfires in some regions, exacerbated by particular forest-management regimes, has increased in recent decades. Moreover, regions such as the Arctic tundra, where forests historically have been rare (103–105), are also expected to experience an increase in wildfire frequency (105–107). Increased forest fires have complex effects on contaminant cycling. As climate change increases the frequency and intensity of wildfires, the burning of peatlands is expected to increase, thus releasing mercury into the environment, especially as methylation rates of mercury increase with temperature (Figure 8.1; 100). Wildfire suppression can also lead to outbreaks of pests, such as the mountain pine beetle (*Dendroctonus ponderosae*) in western North America, which are further exacerbated by climate change when warmer winters lead to reduced beetle deaths during overwintering (108). Increased use of pesticides, such as monosodium methanearsonate (MSMA), to control these beetles can alter the abundance and distribution of beetle species and their predators, such as woodpeckers (108). Understanding how wildfires impact the introduction of contaminants into the environment is crucial to managing wildlife health and populations.

PRECIPITATION

Climate change–induced shifts in precipitation patterns can impact the transport and remobilization of contaminants. For example, Lu et al. (109) conducted a leaching experiment on a tailings deposit in northern Norway to examine how temperature and precipitation changes due to climate change may impact heavy metal leaching from the tailings. The authors found that higher precipitation rates alone cause metal leaching from the tailing, but that increasing temperature and precipitation rates synergistically increase metal leaching, causing higher amounts of contaminants to be released from the tailings deposit. Further, Zhu et al. (110) show that increasing precipitation rates in the mid-Atlantic Ocean result in higher contaminant concentrations in surface waters, where contaminants likely come from both surface and sediment runoffs and sewage overflows. Additionally, increased precipitation rates can cause further sea ice, glacier, and permafrost melt, thus exacerbating the release of contaminants from those stores (see section *Glaciers, sea-ice and permafrost*). Leached contaminants, such as cadmium, cause a range of health issues in wildlife. For example, in Colorado, USA, cadmium from ore-mining has contaminated soils and is taken up and highly biomagnified by willows (*Salix* spp.), an important winter food source for the white-tailed ptarmigan (*Lagopus leucurus*; 111). As the ptarmigans age and continue to feed on willows, cadmium will bioaccumulate in their tissues, especially in kidneys, weakening skeletal integrity, causing renal failure, and even leading to death once the cadmium has reached its toxicity threshold (100 mg/kg; 111). These interactions emphasize the importance of assessing multiple factors when examining the interactions between climate change and contaminant concentrations, especially when trying to assess risks to wildlife.

DIET CHANGES

Warming ocean temperatures and sea-ice loss due to climate change have resulted in significant prey shifts in several Arctic marine predators (17,112,113), with potential impacts on contaminants. For example, Øverjordet et al. (114) examined mercury concentrations in two seabird species, black-legged kittiwakes (*Rissa tridactyla*) and dovekies (*Alle alle*), in Svalbard and found that mercury levels in black-legged they were lower in years that they fed at lower trophic levels. The authors suggested that this situation was a result of lower sea-ice concentrations, where in years with less sea ice, black-legged kittiwakes would have less access to relatively high trophic-level prey (e.g., ice-associated Arctic cod; *Boreogadus saida*) that generally have higher mercury concentrations (16,115). Moreover, changes in sea-ice or prey populations can cause various Arctic biota to have prolonged periods of fasting (i.e., increased reliance on fat stores), which can lead to the release of more fat-soluble contaminants into the body. Sea-ice concentrations can also influence the diet of terrestrial mammals. For example, Andersen et al. (116) examined POP concentrations in Arctic foxes (*Vulpes lagopus*) from Svalbard, Norway, in 1997–2013, and found that POP concentrations increased with higher proportions of marine diet (e.g., ringed seal; Pusa hispida) than terrestrial diet (e.g., Svalbard reindeer; Rangifer tarandus platyrhynchus). Specifically, the authors found that concentrations of beta- Hexachlorocyclohexane (β-HCH; an isomer of the insecticide lindane), increased with increasing sea-ice cover, suggesting higher β-HCH levels in marine prey. This shows that climate-induced diet changes can influence contaminant levels in complex ways (Case Study 8.2).

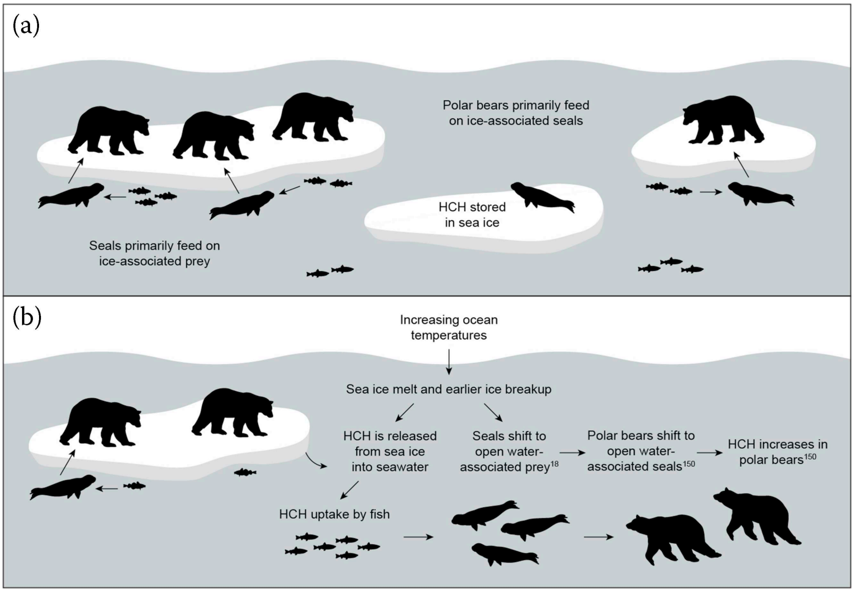

FIGURE 8.2 Example of how climate change can influence hexachlorocyclohexane (HCH) in an Arctic food web, where panel A represents "normal" climate conditions 9/25 and panel B represents climate-induced increases in ocean temperatures.We highlight HCH because it is well-studied in this context, but the same mechanism is often implicated for many different contaminants.

CASE STUDY 8.2 DIET CHANGES IN RINGED SEALS AND POLAR BEARS

Ringed seals and polar bears (*Ursus maritimus*) are ecologically, economically, culturally, and nutritionally significant in the Arctic, and they are a primary food source in many Arctic communities (64,65). However, as an ice-dependent species, climate change-induced changes in ocean temperatures and sea-ice concentrations can impact ringed seal and polar bear diets, and ultimately, contaminant concentrations in their tissues. Indeed, there is evidence that ringed seals and polar bears across the Arctic are changing their diet, likely as a result of warming temperatures and changes in sea ice (18,66–69). For example, in western Hudson Bay (Nunavut, Canada), ringed seal diet shifted from ice-associated Arctic cod to a sub-Arctic species, capelin (*Mallotus villosus*), through 1991 to 2006, likely as a result of changes in water temperatures and sea ice in this region (18). As most contaminants in these predators are likely obtained from diet, shifts in diet can play an important role in contaminant levels in this species.

Indeed, Braune et al. (16) examined changes in the feeding ecology of polar bears from Hudson Bay from 1991 to 2007 and found that several chlorinated and brominated contaminants (e.g., β-HCH, PCBs, Polybrominated diphenyl ethers PBDEs) increased over time due to shifts in diet to more open water-associated species because of earlier sea-ice breakup (Figure 8.2). Similarly, Gaden et al. (70) observed that ringed seals from the Canadian Arctic had higher concentrations of organochlorines (OCs) in years of earlier ice break-up, likely related to shifts in diet. Looking at the food web as a whole, McKinney et al. (71) examined temporal changes in OCs in a Canadian Arctic marine food web, including seals and polar bears, and found that contaminants were generally higher in ice-free seasons, but also that the presence of more contaminated, transient, or sub-Arctic species during ice-free seasons may also alter contaminant concentrations in the food web. Thus, climate change can cause shifts in diet that may alter contaminant levels, but may also cause more contaminated species to shift northward, which may increase environmental levels in the region (72).

Currently, knowledge on contaminants in ringed seal prey is limited, and results vary spatially and temporally. For example, Pedro et al. (73) and Braune et al. (16) sampled Arctic cod and capelin from different regions in Nunavut, Canada, and found that mercury concentrations were consistently higher in Arctic cod than capelin. However, when examining POPs, this relationship is less clear. While Braune et al. (16) found that PCB concentrations were also higher in Arctic cod than capelin, Pedro et al. (73) found the opposite: PCBs levels in capelin were higher than in Arctic cod from the same region. These differences are likely related to the migratory behavior of these fish species, and as climate change continues to shift species distributions northward (74), understanding the role of species shifts on contaminants throughout the Arctic food web will be of increasing importance.

Climate change-induced changes in contaminant concentrations in ringed seals and polar bears can also impact Indigenous communities who rely on these predators for sustenance. Indeed, in eastern Greenland, Sonne et al. (75) estimated that subsistence hunters that regularly consume ringed seals and polar bears may exceed the tolerable daily intake of PCBs and chlordane pesticides by approximately five-fold. Moreover, Quinn et al. (76) modeled exposure to PCBs in Indigenous women and estimated that women who consume an entirely traditional diet (i.e., seal blubber) have 15–150 times higher body burdens of PCBs than women who consume imported foods. PCBs can cause severe health effects in humans, including cancer, reduced immune-system function, and lower cognitive abilities (77). While it can be difficult to model how climate change and contaminant levels in food webs will change over time, models that consider emissions, transport, and fate of contaminants under changing climate conditions will be useful to examine how these cumulative effects may impact Arctic biota and the people that harvest them (78). Hickie et al. (79) modeled the accumulation of POPs in ringed seal blubber using data from the Canadian Arctic and found that their ability to eliminate many POPs, along with a fast juvenile growth rate and population turnover, allows this species to respond rapidly to contaminant changes. Thus, ringed seals are a useful indicator species to monitor spatial and temporal trends in POPs and other contaminants, while also providing data for risk assessments for Indigenous communities in the north (79).

IMMUNOCOMPETENCE AND ENDOCRINE DISRUPTION

Contaminants can disrupt endocrine systems and cause altered reproductive behaviors in wildlife (117). Two mechanisms by which climate change is impacting wildlife populations are first, by a mismatch in the timing of breeding and environmental cues (17,118), and second, increased parasitism and disease (19,119). For example, PCBs and PBDEs both mimic thyroid hormones and bind readily to the carrier proteins in gulls (120). This may compromise the ability of individuals to respond to environmental change and lead to reduced reproductive success (121). Infectious diseases and parasites have caused the population collapse of many wildlife species, including white-nose syndrome in North American Myotis bats and Batrachochytrium dendrobatidis on amphibians (119). At the same time, many contaminants can alter the immune status of wildlife, leaving them at greater risk for these diseases (122,123).

Endocrine Disruption

Primary productivity can respond rapidly to increases in energy associated with climate change, while animals at higher trophic levels may use other cues to determine optimal timing of breeding (17,118). For example, in Arctic seabirds, a phytoplankton bloom immediately following the departure of sea ice sets a timeline that dictates the food available for offspring (55). Seabirds must be able to time their egg-laying approximately one month ahead of time to match the period of highest energy demands (i.e., chick-rearing) with the peak in prey availability (when the most energy can be obtained for the least energy spent; 17). Climate change can cause ice to melt more rapidly than seabirds are able to respond, creating a mismatch between the time for chick-rearing and the peak of food availability, leading to unsustainable levels of energy expenditure (17). Contaminants such as per and poly-fluoroalkyl acids can disrupt thyroid hormone homeostasis in seabirds (16,124), which are associated with avian thermoregulation. It is predicted that warming temperatures due to climate change may affect avian thermoregulation and endocrine regulation, especially processes regulated by thyroid hormones (125). Therefore, the effects of climate change on endocrine and thyroid function may be exacerbated by contaminants. Moreover, the brain is particularly sensitive to contamination (126,127), potentially influencing behavioral responses to climate change. For example, neonicotinoid pesticides alter the behavior of migratory songbirds, which may exacerbate mismatches between historical migratory tendencies and current peaks in food availability (the mismatch hypothesis; 128,129). A major factor in determining the resilience of wildlife to climate change is their behavioral plasticity (or flexibility) to accommodate changes in food availability. However, contaminants may disrupt hormones (and related biomarkers) that allow such behavioral plasticity.

Immune Disruption

Many human and wildlife parasites and diseases will increase in response to climate change, although others are expected to go extinct (130). For example, avian cholera, human and avian malaria, and Rift Valley Fever have increased their distribution with climate change (130), while increased mosquitoes and blackflies on warm days has led to increased mortality in seabirds and birds of prey (19,131). Many contaminants cause immune disruption at environmentally relevant levels in the lab (132); however, this effect is less studied in natural environments. Moreover, wildlife living in highly toxic environments, such as the Baltic Sea, Saint Lawrence Estuary, and Great Lakes, had high rates of lesions and diseases during the organochlorine era and shortly thereafter (133–135). Thus, contaminant-induced immune deficiencies in wildlife may reduce their plasticity when responding to novel diseases facilitated by climate change.

CARCINOGEN EXPOSURE AND NEOPLASIA RISKS

Contaminant concentrations in the environment are continuously increasing, by exacerbated weather patterns and natural disasters, or by shifts in contaminant bioavailability and cycling (136,137). Animals are increasingly exposed to these environmental contaminants, many of which are carcinogenic, which lead to the deteriorating health of populations. Contaminants like polycyclic aromatic hydrocarbons (PAH) and HCH have adverse effects on immune system function and can cause the development of neoplasms (abnormal tissue growth) in animals, which may become malignant (137–140). Contaminants may further act as endocrine disruptors or cause oxidative damage to DNA in vertebrates leading to the development of various forms of cancer (138).

For example, PAHs were linked to liver lesions in winter flounder (*Pleuronectes americanus*) and cancerous tumors in Saint Lawrence Estuary belugas (*Delphinapterus leucas*) in habitats with contaminated sediments (141–143). Cancer was the main cause of death in the Saint Lawrence Estuary belugas, and researchers identified 21 types of cancers, the most prevalent consisting of intestinal tumors (143). The authors attribute the high rate of cancer in belugas (27%; comparable to cancer rates in humans) to their diet and feeding strategies: belugas disturb sediments to feed on invertebrates, which have been shown to be highly contaminated by PAHs produced by aluminum-smelting factories in proximity to the Saint Lawrence Estuary (143,144). Further, wildfires are another important source of PAHs, and their frequency is expected to increase as climate change progresses (106,145). Thus, climate change is an additional environmental stressor that can work to weaken immune systems in wildlife, making animals more vulnerable to disease. Climate change and pollutants, therefore, work synergistically as threats to animal health (139,140).

TOXIC ALGAE BLOOMS

Marine heatwaves doubled between 1982 and 2016, and they are expected to increase rapidly in the near future (146). Similarly, inland waters are warming at 0.13°C per decade with 99% showing warming trends (147). These warming trends in marine and terrestrial environments, are especially extreme events, are negatively affecting aquatic animals, causing increases in coral bleaching (148), die-offs (149), and the need to search over long distances for dwindling food (150). Moreover, these responses can persist long after the heat waves subside (151). One of the greatest impacts of warming waters is increased toxic-algae blooms. For example, 68% of lakes have experienced more algae blooms since satellite imagery started, while only 8% declined (152). Similarly, harmful algal blooms in marine environments are expected to increase with ocean stratification (153).

In terrestrial environments, increased nutrient loading has led to a global increase in freshwater algal blooms (147). Higher levels of nutrients (particularly phosphate) from intensive agriculture, coupled with warmer surface waters and increased stratification and eutrophication, can lead to increases in cyanobacteria, the main algae involved in harmful freshwater algae blooms. For example, overflowing hog farms following Hurricane Florence led to large blooms in North Carolina (154). Cyanobacteria produce a variety of cyanotoxins that are harmful to fish and humans alike, and can cause large-scale mortality of fish, domestic livestock, and birds (Figure 8.1; 155,156).

In the marine environment, roughly 200 species of phytoplankton cause harmful algal blooms, and future impacts are difficult to predict. Indeed, poisoning from "red tide" was recorded in 731 in Japan and the 1500s in the Gulf of Mexico (157). Yet, some forms of harmful algal blooms have only been described in the last 40 years (157). Toxins produced during these algal blooms, such as domoic acid and saxotoxins, can cause mass die-offs of fish, seabirds and marine mammals, including large-scale mortality of endangered species (158–160). No change in marine harmful algal blooms has been detected globally, although trends are difficult to detect because of the many taxa involved, regional differences in reporting, awareness of novel toxins, and because many reports are anecdotal or based on impacts to poisoned species (157). Changes in temperature, salinity, stratification, light, storm intensity, and ocean nitrification and acidification are all likely to influence future algae bloom trends and wildlife health in complex and unpredictable ways (153).

DOMESTIC ANIMALS

This chapter has illustrated the variety and magnitude of climate change and contaminants interactions by focusing on wildlife. Domestic animals, however, will also be affected, in turn affecting humans. Some of the impacts described for wildlife will be the same for domestic animals. For example, just as precipitation and warming will increase wildlife exposure to freshwater toxic algae, contaminants in drinking water or immunosuppressive chemicals, domestic animal exposures will increase as well. These will have implications for human health when domestic animals enter the human food chain or when agriculture waste products enter soil and waterways. There may also be effects that are unique to domestic animals. For example, as climate change impacts the prevalence of certain infectious diseases, so too might the use of veterinarian use of veterinary drugs and chemicals, with subsequent risks of increased meat contamination (161). Livestock foods may be increasingly plagued by mycotoxins, which are expected to become more prevalent in crops with climate change (162). Additionally, while increased flooding of agriculture areas can redistribute environmental pathogens and contaminants, but contaminants, it may also disperse fuels and chemicals that are usually safety stored on farms or nearby areas. For example, increased flooding in urban and industrial areas has been shown to increase contaminant concentrations in domestic cows' milk on nearby farms, likely due to higher levels in the grasses on which they feed (163). Domestic animal health-adaptation strategies must, therefore, include consideration of direct effects of contaminants on animal and public health, as well as how changes in exposure to chemicals contaminants may interact with and modify other climate change related health effects.

SUMMARY AND FUTURE DIRECTIONS

Climate change and toxic contaminants interact in complex and unpredictable ways. As climate change continues, contaminants will continue to be released by ice melt, wildfires, erosion, precipitation, and more. As wildlife respond to these changes by shifting their diet or range, contaminant concentrations may be altered further. These changes can result in a variety of impacts, including neurological effects, altered stress and hormone levels, endocrine disruption, and mortality. While it can be difficult to model how climate change and contaminant levels will change and interact over time, models that consider sources, transport, and fate of contaminants under changing climate conditions will be useful to examine how these cumulative effects may impact wildlife and the people that harvest them. Although wildlife species can be used as indicators of changes in climate or contaminants, studies rarely examine both. Much more work is needed to better understand how wildlife health will continue to be impacted by contaminants in the context of exacerbating climate change. In the short term, bioremediation solutions can reduce the overall quantity of pollutants that wildlife are exposed to during their lifecycle. Future research should focus on examining the interactive effects of climate change and contaminants at an ecosystem-level scale to more accurately assess how these two threats interact and impact wildlife and the environment.

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