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Ecosystem Sentinels as Early-Warning Indicators in the Anthropocene

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Abstract

We are already experiencing the rapid pace of environmental change in the Anthropocene, necessitating the development of new tools and techniques for measuring changes in ecosystem dynamics. Sentinel species, from birds to invertebrates, have been used to provide insights into ecosystem function, as leading indicators of risk to human health and as harbingers of future change, with implications for ecosystem structure and function. Here, we offer an update to previous research identifying marine top predators as indicators of ecosystem change and examine terrestrial sentinels and the latest research on sentinels of pollution and human health. Using ecosystem sentinels enables rapid response and adaptation to ecosystem variability and environmental change in part because they may be easier to observe and in part because they may serve as leading indicators of ecosystem change. While there may not be a given taxon that is best suited as sentinels, we highlight how to select the most effective sentinels, including examples of when sentinel species have been incorporated into management. Choosing a suite of appropriate sentinels will both give insight into ecosystem processes and can help manage changing ecosystems into the future.

Contents

1. INTRODUCTION

We have entered a new era known as the Anthropocene, in which human-induced changes are having a greater impact on species and ecosystems than natural variability (1). Understanding these rapid changes has become critical for mitigating deleterious ecological and economic effects such as loss of commercially valuable species (2) or increased human–wildlife conflict (3). If we can respond to environmental change by developing responsive management frameworks, we can mitigate monetary losses from ecosystem services while still protecting threatened species. Ecosystem sentinels (i.e., a species that responds to ecosystem variability and change in a timely and measurable way and that can indicate an otherwise unobserved change in ecosystem function) (4) have become increasingly important not only to monitor environmental change (4) but also to inform management of potential ecosystem response (5). With anthropogenic change hastening alterations in land development and ocean use, as well as increasing variability in climatic processes and animal population dynamics (6), indicators that respond rapidly in a clear, visible, and measurable way are becoming increasingly necessary (4).

Ecosystem sentinels offer a valuable perspective for identifying ecosystem tipping points, quantifying human impacts on ecosystems, and assessing the efficacy of conservation or management efforts. However, sentinels are still frequently found as a buzzword in the literature rather than as an actual scientific or management tool (4). The rates of sentinel use in the literature and even in management application have increased rapidly over the past decade (**Figure 1**), thus highlighting their potential utility (5). Such growth in use mirrors the history of similar terms such as flagship species (7), keystone species (8), umbrella species (9), focal species (10), and conservation proxies (11), all of which have helped define modern-day conservation biology. Here, we offer an updated

Anthropocene: our current era, in which human-induced changes are having a greater impact on species and ecosystems than natural variability

Ecosystem sentinel: a species that responds to ecosystem variability and/or change in a timely and measurable way and that can indicate an otherwise unobserved change in ecosystem function (e.g., stream invertebrates)

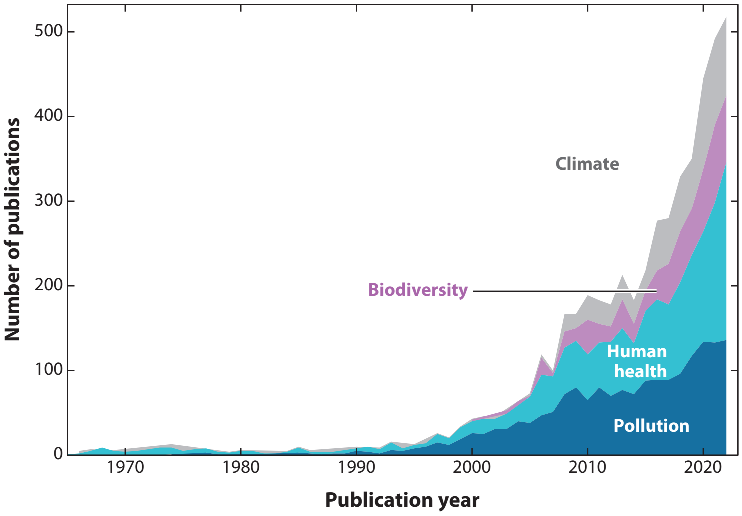

Figure 1

Timeline of sentinel type in terms of number of publications per year using the Web of Science, searching for "climate" OR "biodiversity" OR "human health" OR "pollution" AND "species" AND "sentinel" NOT "satellite" in the title, abstract, or keywords.

vision for how different types of ecosystem sentinels can be used to better monitor, manage, and conserve socio-ecological systems.

Ecosystem sentinels can include leading sentinels of future ecosystem response, when a species might be the first to respond, or an elucidating sentinel, when there are unmeasured or unstudied components of an ecosystem about which the sentinel provides information (4). In this review we expand on the definition of Hazen et al. (4) to include sentinels of human health and pollution that offer indication of human health concerns from exposure to biological, chemical, or physical hazards. Thus, we focus on four categories of sentinels rapidly increasing in use (**Figure 2**): (*a*) sentinels of human health, (*b*) pollution sentinels, (*c*) sentinels of abiotic conditions and biotic interactions, and (*d*) biodiversity sentinels.

Anthropogenic impacts can also have synergistic effects across sentine types; for example, climate change can increase biodiversity loss and rates of disease spread, increasing the value in a network of sentinels (**Figure 2**).

With the rapid pace of change, and the increased use of ocean and terrestrial ecosystems by humans, there is a pressing need for tools like ecosystem sentinels to improve our understanding of ecosystem response and change in the Anthropocene. Monitoring ecosystem sentinels, both multiple individuals and multiple measurements, provides a unique array of data that can indicate environmental change across multiple timescales, from hours to centuries (4) (**Figure 3**). While there remains much debate about the utility of such proxies in representing underlying ecological processes (11, 12), proxies can be both cost-effective and conservation effective when budgets for monitoring and management are limited. As human impacts continue to grow in the Anthropocene, ecosystem sentinels may offer the first warning signs that management intervention is needed (see examples in **Figure 4**).

Indicator: can be used like a sentinel species to indicate something about the environment; can also refer to the time series or data collected from a sentinel species (e.g., sea lion pup count)

Flagship species: a charismatic species that can be used to advance and coordinate conservation and management efforts (e.g., Bengal tiger)

Keystone species: an organism that plays a disproportionately large role in ecosystem structure and function (e.g., sea otter)

2. HISTORY OF SENTINELS

The canary is among the first examples of a sentinel species in the modern world. Beginning in the latter half of the nineteenth century, canaries were used as reliable sentinels for toxic gasses, such

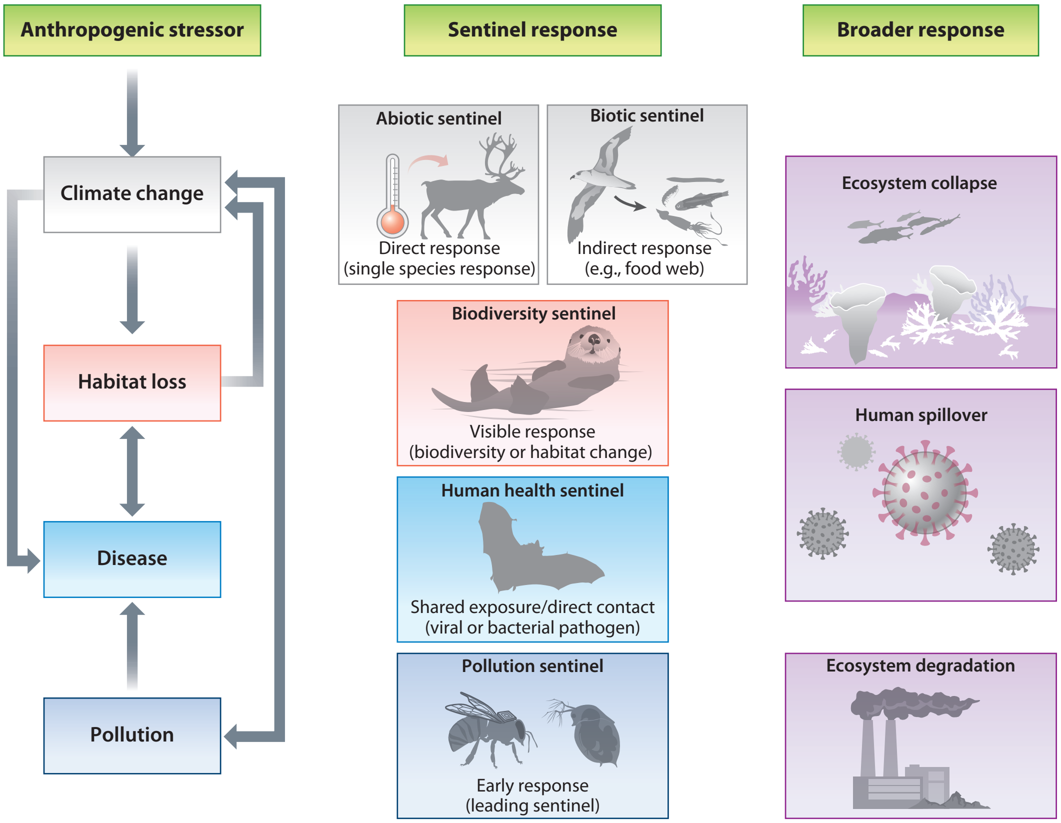

Figure 2

Flowchart of stressor–sentinel–ecosystem response. Sentinels offer a novel pathway for ecosystem information to reach ecologists and decision-makers. Abiotic sentinels identify the response of a single species to warming temperatures before ecosystem response. Biotic sentinels identify changes in the trophic landscape via ecological interactions such as predator and prey. Biodiversity sentinels identify changes in biodiversity or habitat before they have broader ecosystem effects. Anthropogenic sentinels can be sampled individuals or individual response to pollutant load that may provide early warning to humans or ecosystems. Human health sentinels are useful for identifying when a disease or toxin is likely to have direct translation from ecosystem to human-specific effects. Each species is chosen as a sentinel because they react as early-warning indicators or easily observable changes before there are broadscale effects such as ecosystem shift or collapse (abiotic, biotic, and biodiversity sentinels), human spillover (human health sentinel), or degraded ecosystems (pollution sentinel).

as carbon monoxide (CO), in coal mines. By 1911, their use was part of mining regulations. The extraction and processing of coal as part of mining operations resulted in significant quantities of CO generated via oxidation. Early experiments indicated that while other species (e.g., rabbits, chickens, dogs, mice) could serve as biotic CO sensors, canaries were the optimal sentinels (24). A canary's small size, high metabolism, and conspicuous behaviors made it an excellent leading indicator of CO that, if ignored, could prove lethal to humans (CO is lethal to humans at concentrations >400 ppm for 3 h) (25). Canaries were used as biotic CO detectors until they were replaced by electronic devices in 1986, a 100-year tenure as a sentinel species.

Seabirds have a similarly long history as ecosystem sentinels, as indicators of ecosystem productivity and environmental pollution (26). In the early twentieth century, Robert Cushman Murphy (27) of the American Museum of Natural History suggested that seabirds could be used to assay characteristics of the ocean. The University of Washington's P. Dee Boersma has been advocating

Umbrella species: a species that when protected can directly or more commonly indirectly protect many other species (e.g., giant panda)

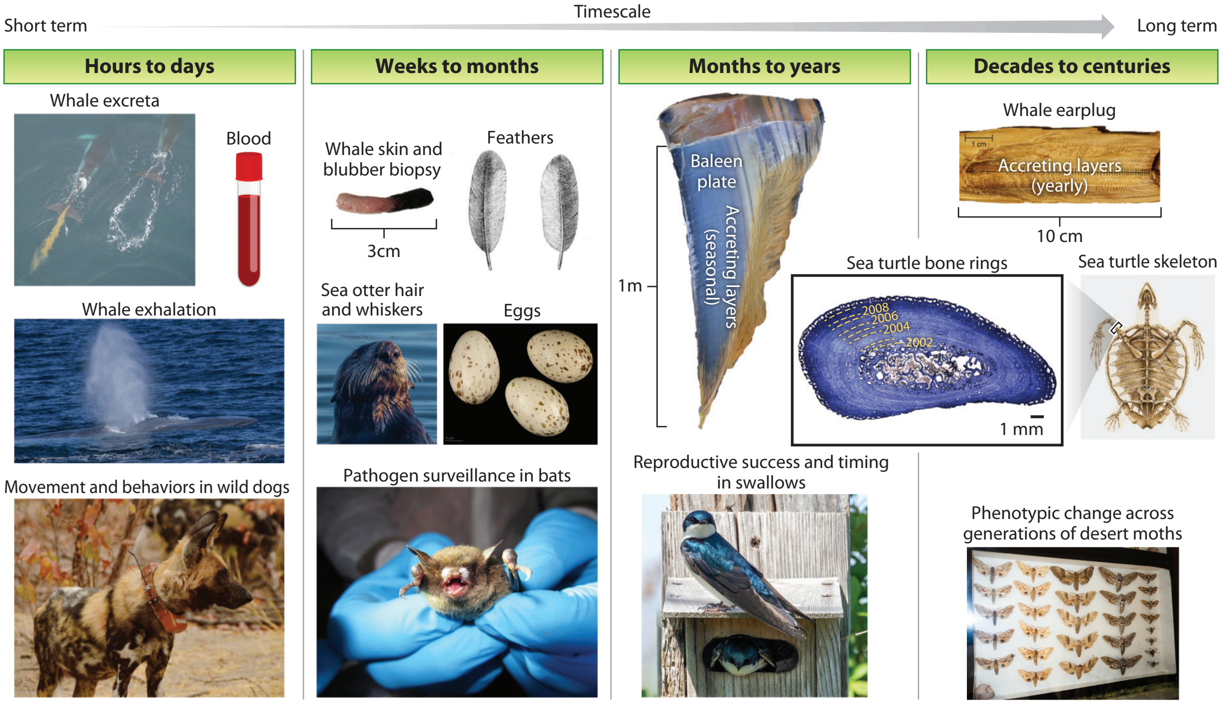

Figure 3

Different measurements can reference different timescales of sentinel response. For example, bodily fluids can be monitored for recent changes in stress, pollutants, and pathogens while long-term study populations and museum collections are more useful for detecting changes at multiyear scales. Certain tissue types can be particularly valuable because they store interdisciplinary sentinel information; for example, blood can be used to monitor stress, reproduction, pollutants, and pathogens. These animal sentinels can be used to detect changes in marine or terrestrial systems, and some groups that require both systems (e.g., seabirds and pinnipeds) can monitor both. Images of whale excreta, exhalation, and skin and blubber; sea otter; and baleen plate created by Matthew Savoca. Photo of wild dog taken by Briana Abrahms. Image of sea turtle bone rings reproduced from figure 2 in Reference 13 (CC BY 3.0). Image of whale earplug image reproduced from figure 1 in Reference 14 (CC BY 4.0). Image of sea turtle skeleton reprinted with permission from Dawn Witherington. Eggs image adapted from Roger Culos/Wikipedia (**https://commons.wikimedia.org/wiki/File:Gallirallus_philippensis_MHNT.ZOO.2010.11.69.7.jpg**) (CC BY-SA 4.0). Feather illustrations adapted from Philip Sclater/Wikipedia (**https://commons.wikimedia.org/wiki/File:Machaeropterus_deliciosus_feathers_1862.jpg**) (public domain). Image of swallow adapted from Rhododentrites/Wikipedia [**https://commons.wikimedia.org/wiki/File:Tree_swallows_at_a_nest_box_in_JBWR_(24844p).jpg**] (CC BY-SA 4.0). Photo of bat adapted from Steve Taylor/US Fish and Wildlife service (**https://www.flickr.com/photos/usfwshq/8509677349/**) (public domain). Image of desert moths adapted from Thomas Quine/Wikipedia [**https://commons.wikimedia.org/wiki/File:Collection_of_desert_moths_(49189265101).jpg**].

for seabirds, specifically penguins, as marine sentinels for half a century. Her work has demonstrated that pelagic birds can serve as indicators for oceanography, climate, and pollution (18), and has instigated the use of seabirds as sentinels globally (28). Seabird illness can also be a useful indicator of harmful algal blooms leading to domoic acid (DA) poisoning. Aberrant behaviors occur prior to death, and this symptom of DA poisoning inadvertently made its way into pop culture as the presumed cause of the aggression and disorientation depicted in Alfred Hitchcock's 1963 film, *The Birds* (29).

There are numerous records of wildlife illnesses as early-warning sentinels of human disease. Among the first known examples is the hypothesis that Alexander the Great died from West Nile virus encephalitis, which was presaged by dead and dying corvids (30). Over 2,000 years later, corvids have again served as sentinels of West Nile virus (31). Disease surveillance of bat

Focal species: a species that is targeted because of its broader importance, such as economic, ecological, or conservation (e.g., polar bear for climate change)

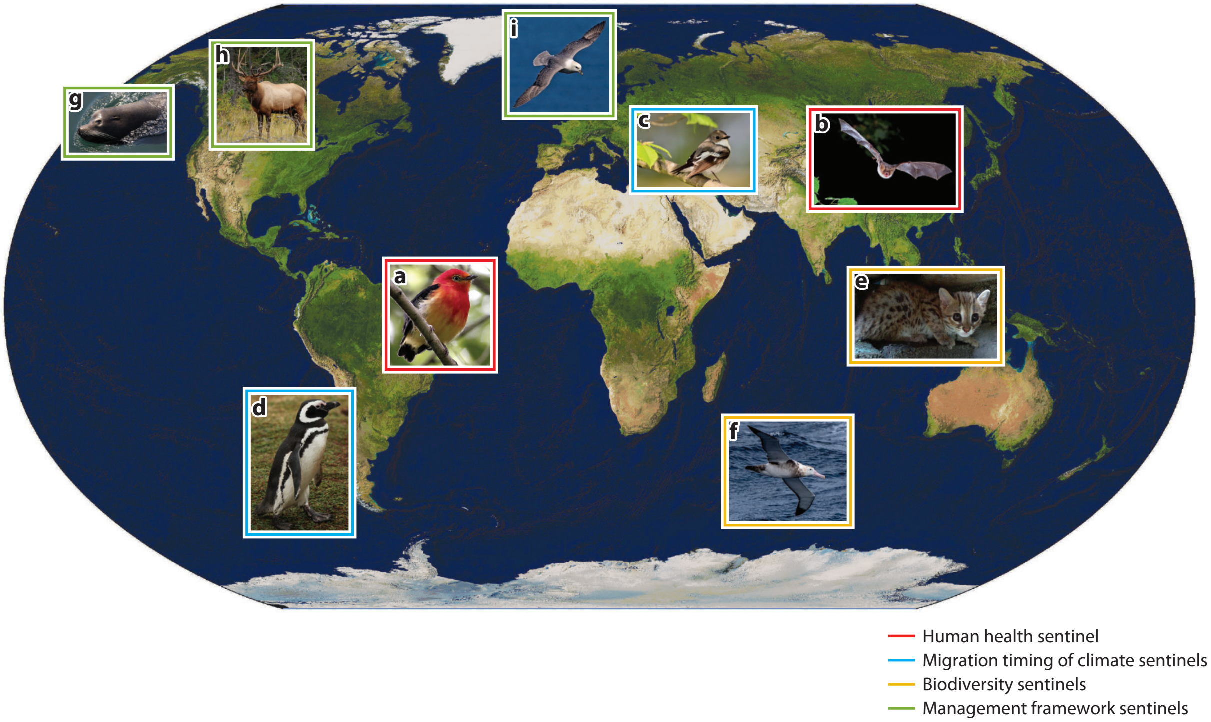

Figure 4

Highlighting examples of ecosystem sentinels around the world. Red boxes indicate human health sentinels, such as (*a*) the band-tailed manakin (*Pipra fasciicauda*), which accumulates mercury from illegal mines across the tropics of Central and South America (15), and (*b*) bats (*Myotis myotis*) surveilled as reservoirs of infectious diseases with spillover potential in China (16). Blue boxes indicate change in the migration timing of climate sentinels such as (*c*) the European pied flycatcher (*Ficedula hypoleuca*) from Europe (17) and (*d*) the Magellanic penguins (*Spheniscus magellanicus*) from Chile as sentinels of oceanographic conditions (18). Orange boxes indicate biodiversity sentinels, such as (*e*) the Sunda leopard cat (*Prionailurus javanensis*) from Sundaland islands responding to habitat loss (19) and (*f*) the wandering albatross (*Diomedea exulans*) responding to illegal fishing vessels (20). Green boxes indicate sentinels that have been incorporated into a management framework, such as the (*g*) California sea lion (*Zalophus californianus*) pupping rates in the California Current integrated ecosystem assessment (21), (*h*) elk (*Cervus canadensis*) as one of many sentinels for the health of the Yellowstone ecosystem (22), and (*i*) the northern fulmar (*Fulmarus glacialis*) for indicators of pollution in the North Sea (23). Panel *a* adapted from Hector Bottai/Wikipedia [**https://en.wikipedia.org/wiki/Band-tailed_manakin#/media/File:Pipra_fasciicauda_-_Band-tailed_manakin_(male).JPG**] (CC BY 4.0). Panel *b* adapted from C. Robiller/Wikipedia [**https://commons.wikimedia.org/wiki/File:Wikipedia-Bats-001-v01.jpg**] (CC BY 4.0). Panel *c* reprinted under the Pixabay free use agreement. Panel *d* adapted from Liam Quinn/Wikimedia [**https://commons.wikimedia.org/wiki/File:Magellanic_Penguin_at_Otway_Sound,_Chile_(5521272498).jpg**] (CC BY-SA 2.0). Panel *e* adapted from Ridho Illyasa/Wikipedia (**https://en.m.wikipedia.org/wiki/File:Prionailurus_bengalensis_in_Indonesia_02.jpg**) (CC BY 2.0). Panel *f* created by Matthew Savoca. Panel *g* created by Elliott Hazen. Panel *h* adapted from Membeth/Wikipedia (**https://en.wikipedia.org/wiki/Elk#/media/File:Jasper.Wapiti-Hirsch.P1033401.jpg**) (CC0 1.0). Panel *i* adapted with permission from Andreas Trepte (**https://www.avi-fauna.info/**) (CC BY-SA 2.5). World map adapted from Ian Macky (**https://ian.macky.net/pat/map/world/world_bluemarble.jpg**).

populations has reentered public consciousness following the COVID-19 pandemic, but bats have been monitored for zoonotic pathogens for decades (e.g., coronaviruses, hemorrhagic fevers, rabies) (16, 32). Climate change is expected to increase disease spillovers from wildlife reservoirs to livestock and humans, which will make sentinel species even more important for monitoring these events in the future (33).

While there are many examples of animal sentinels through time, frogs are emerging as the canaries of the Anthropocene (34). Amphibians are extremely sensitive to environmental changes

Figure 5

The idiom "canary in the coal mine" has been suggested as the origin for the animal sentinel concept. When oxygen was low or toxic gasses were too high in underground mines, a dead canary would indicate unhealthy conditions for the crew. Figure reproduced with permission from Reference 25.

with their porous skin and reliance on both aquatic and terrestrial habitats. These factors allow amphibians such as frogs to act as sentinels for most forms of anthropogenic change, including disease, pollution, biodiversity, and climate (35). Without rapid amelioration of these threats, however, we may lose these ecosystem sentinels altogether (36).

3. TYPES OF SENTINELS

3.1. Sentinels of Human Health

The iconic "canary in the coal mine" (**Figure 5**; Section 2) is the most well-known example of a nonhuman organism providing direct early sentinel warning to humans of a shared risk from an environmental health hazard. As the sentinel concept is extended to other hazards and species, as well as consideration of their value to assess ecosystem change rather than primarily human health risk, two outstanding questions are whether and how we can link an animal sentinel event to human health. Identifying this linkage is the primary driver of sentinel ability for disease and human health.

In the case of canaries in coal mines providing warning to miners of the risk of exposure to CO and other toxic gasses (see Section 2), there were several critical aspects that connected the animal to the human. The first aspect was shared environmental exposure, with both miners and canaries breathing the same air (although miners did have the option to put on a respirator to prevent further exposure, a key action step to be taken if the canaries started showing symptoms). This shared exposure makes the animal reactions more relevant to human health. The second aspect was the consideration of differential exposure (greater in animals than in humans) to the hazard:

Conservation proxy: a species that when protected can indirectly protect other species that may be less easy to protect; similar to an umbrella species

Biodiversity: number of species or ecological traits that occupy a given ecosystem

Canary in the coal mine: a type of leading sentinel that shows a response earlier than other important components of the ecosystem

Shared environmental exposure: when both a sentinel and another species are facing the same risk or threat (e.g., canaries and coal miners breathing the same air)

Differential exposure: when a sentinel and another species or ecosystem component have different levels of contact with a threat or virus

Susceptibility: the likelihood that an individual exposed to a threat is affected by the threat

Recognizability: whether an effect from exposure and susceptibility are actually easy to observe; also contributes to the effectiveness of a sentinel

If the canary stayed in their cage in one area of the mine, they would have, due to lesser mobility, greater exposure to toxic substances in the area compared with miners who were moving between different areas of the mine. Another differential in their exposure was physiological, as canaries have a much higher respiratory rate than humans, resulting in greater and more rapid uptake of and impact by the toxic gases (37).

The third aspect was the possibility of differential susceptibility to the hazard for canaries compared with that for humans. This could be due to differences in metabolic pathways; the structure of the avian respiratory system, which includes air sacs (38); and metabolic rates. Factors like exposure and susceptibility can interact to result in differential latency (time from exposure to outcome) between nonhuman species and humans, which meant that the health effects seen in the canary (change in behavior, including singing) occurred prior to miners noticing the toxic effects in themselves. The fourth aspect was recognizability, with the change in behavior being characteristic enough for the miners to correctly identify the problem before they developed their own symptoms from CO exposure.

We can use these same criteria of shared exposure routes and differentials in exposure, susceptibility, latency, and recognizability to identify species and taxa most likely to show sentinel ability and to inform the examination of the relevance to human health. An important aspect of animals serving as sentinels for humans is how the animal sentinel data can inform human health risk assessment (for both abiotic and biological hazards) or ideally serve as a precursor to potential human impacts. A traditional approach to human health risk assessment is to determine what hazards are in a particular environment (hazard identification), how much exposure are humans experiencing (exposure assessment), how potent is the hazard in question and what health effects does it cause (dose response), and overall, how great is the risk to human health (risk characterization) (39).

Animal sentinels can help with hazard identification through analysis of samples from living or dead specimens. Samples can be tested for chemical toxicants and the presence of infectious agents. An example of wildlife sentinel events leading to the identification of a new infectious hazard (to both humans and animals) was the sudden die-off of crows and other birds, including birds kept in zoos, in New York City's Bronx Zoo, heralding the first appearance of West Nile virus in the Western Hemisphere (40). Once a hazard is identified, animal sentinels can also play an important role in assessing exposure by allowing for direct measurements of the levels of a chemical or the frequency of pathogens in the animal and using that information to help estimate human exposure in a particular area. One twist to exposure assessment is that for many toxicants, human exposure occurs through ingestion of animal-sourced foods (such as meat or dairy) containing the toxic substance (or pathogen). In such cases where humans are consuming contaminated fish, meat, or dairy products, animals may serve as both sentinels and vectors for human health risk (41).

While animal sentinels have been used extensively to detect chemical hazards in the environment, the increasing global frequency of zoonotic disease outbreaks and pathogen emergence has focused our attention on wildlife reservoirs of viruses and other pathogens that could have pandemic potential. The current epizootic of avian influenza, with widespread mortality in both wild and domesticated animals, is reinforcing the need to monitor animal disease outbreaks for risk to both animals and humans (42). Bats constitute the major reservoir for significant zoonotic diseases, including severe acute respiratory syndrome (SARS), Middle East respiratory syndrome, Marburg virus infection, and potentially SARS CoV-2. This finding has led to increased monitoring of bat populations to detect sentinel evidence of infection, following the paradigm described above of hazard identification and exposure assessment (43).

Another potential value of animal ecosystem sentinels to human health that deserves additional development by the field of comparative medicine is that such animals can serve as natural animal models for assessing the relationship between exposure in the environment and the development of human disease. These natural animal models have served as an important axis of discovery; for example, there are indications that reactions by aquatic wildlife to human psychotherapeutics may shed light on the human health effects of such chemicals (44). The relative utility of sentinels for human health derives from the fact that much human disease surveillance is passive and reactive, waiting for cases to come to medical attention and then be reported to public health. Collecting data from animal sentinels can illuminate upstream drivers of disease risk, including changes in biodiversity, animal outbreaks of infectious disease, the spread and abundance of vectors, and the effect of toxic substances on reproductive health (45).

Finally, there is growing recognition of the dangers to human populations of changes in global and local biodiversity. While the relationship between ecosystem biodiversity and risk of infectious disease exposure to humans remains controversial, there is evidence that biodiversity change can be associated with increasing infection risk from vector-borne and zoonotic diseases (46). Therefore, animals that are sentinels for biodiversity could also provide an important indicator of human health, specifically about how ecosystem decline augments infection risk (47). Climate change in general is increasingly associated with changes in infection risk, with much of this change attributed to movement or range expansion of arthropod and mammalian vectors into heavily inhabited areas (33, 48). Tracking the movement of host populations will be important in terms of quantifying changes in human–animal contact patterns and, consequently, risk of zoonotic disease transmission (49). Based on the volume of published scientific reports, evidence exists that the use of animal sentinel data to promote both animal and human health will continue to grow rapidly, supported by the increasing acceptance of the One Health concept, which stresses connections between human, animal, and environmental health (50).

3.2. Pollution Sentinels

All ecosystems are affected by the multifaceted chemical signature of modern civilization. Despite the pervasiveness of pollutants, we still struggle to understand their extent and effects in part because >50,000 of the >350,000 registered synthetic chemicals are relatively unknown to the scientific community, as their formulae are proprietary (51). This gap in knowledge impedes monitoring and mitigation efforts. With several notable exceptions (e.g., ghost fishing gear, oil spills), anthropogenic pollutants are also difficult to detect in the environment. This multifaceted problem necessitates approaches that can detect, track, and monitor the effects of pollutants in the environment. As a result, there is a long history and deep literature of pollution sentinels (**Figure 5**; Section 2). Wildlife serves a unique role in pollution monitoring by allowing rapid assessment of environmental contamination that may have human and ecosystem impacts (52).

Human-modified natural pollutants are naturally occurring elements or compounds emitted as a by-product of human activity or where human activity enhances the bioavailability of an element or compound in the environment. Excess nutrient subsidies (e.g., bioavailable nitrogen or phosphorus) to aquatic systems can cause eutrophication and hypoxia that can affect ecosystem health and services. Sessile invertebrates are common sentinels of eutrophication (53), and fish behavior (e.g., avoiding hypoxic regions) has also been used to indicate eutrophic deoxygenation (54). Excess nutrient loading can also lead to harmful algal blooms. Paralytic shellfish toxins (PSTs) are a group of >50 compounds produced by dinoflagellates, as well as some cyanobacteria and diatoms. Saxitoxin is a PST that can cause mortality at low concentrations across a wide range of organisms, including humans (oral LD_{50} for humans is 5.7 μg/kg). As a result, many species targeted by commercial fisheries are regularly monitored for lethal and sublethal (e.g., changes in foraging behavior or predator avoidance) responses to PSTs (55). This is an example of pollution sentinels used as early-warning indicators of human health effects. DA, produced by diatoms in the genus *Pseudo-nitzschia*, can have neurotoxic effects on mammals and birds. Shellfish and forage fish, such as northern anchovy (*Engraulis mordax*), are well-developed bioindicators of DA (56). The California sea lion (*Zalophus californianus*), an anchovy predator, is used as a sentinel of DA exposure because it is a particularly sensitive species (57). Changes in sea lion behavior, morbidity, and mortality have been linked to DA in the California Current food web, and their sensitivity can warn of impending ecosystem and fisheries disruption (57).

Biomonitors: data from a species or multiple species that are used to monitor the contaminants present in the environment integrated over a specific period of time

Perfluoroalkyl and polyfluoroalkyl substances (PFASs): a class of over 1,000 chemicals that are long-lasting and widely used; are dangerous for both ecosystems and humans

Heavy metals (e.g., mercury, cadmium, arsenic, lead) occur naturally in the environment, but extractive activities (e.g., mining, fossil fuel burning and processing) increase environmental concentrations by several orders of magnitude. Lead poisoning occurred on a global scale via atmospheric deposition of tetraethyl lead added to gasoline through the mid-twentieth century, and wildlife sentinels were vital in detecting this pollution (58). Lead ammunition remains a threat, and raptors have been integral in monitoring this pathway of lead pollution into the food web (59). For example, research on bald eagles (*Haliaeetus leucocephalus*) and golden eagles (*Aquila chrysaetos*) in North America has revealed that food webs in the central migratory flyway are more polluted than those on the Atlantic and Pacific coasts (59). In addition to wildlife, domesticated animals have been recently recognized as sentinels of lead pollution (60). As with lead, mercury is considered a global pollutant, with regional hotspots often occurring due to mining or trophic accumulation; monitoring faunal concentrations of neurotoxic mercury is essential, particularly in understudied systems. For example, fish are used as sentinels of mercury in deep-sea food webs (61), and birds' mercury levels are used as indicators of illegal gold mining in the Amazon rainforest (15).

Synthetic pollutants are complex molecules created by humans. Any detection of these substances in the environment represents a form of pollution, regardless of their concentration. Dichlorodiphenyltrichloroethane (DDT) is one of the most infamous synthetic pollutants known to degrade ecosystems. Birds have been used as biomonitors of DDT since the mid-twentieth century (see Section 2), and raptors continue to serve as sentinels of this pollutant (62). Similarly, numerous species, including invertebrates, fish, mammals, and birds, have been used as sentinels for pollution by polychlorinated biphenyls and flame-retardant polybrominated diphenyl ethers (63, 64). Perfluoroalkyl and polyfluoroalkyl substances (PFASs) are a group of >10,000 compounds that lack class-based regulation and have recently received increasing public concern. Wildlife, including ticks (65), birds (66), fish (63), and mammals (67), and domesticated animals (68) have been recently proposed as PFAS sentinels. Sentinel species have also been used to track modern pharmaceuticals in the environment (44). One successful example involves the widespread use and subsequent restriction of diclofenac (a livestock analgesic) and the decline and recovery of vultures in India and Pakistan (69). Finally, sentinels have been used to track synthetic polymers (i.e., plastics), which are ingested by thousands of species, including humans (70). Seabirds provided the first warning that plastics polluted our oceans (71), and they have been sentinels of small plastic debris ever since (72). Programs around the world have been either initiated or proposed to use sentinel species to track plastic pollution in the marine environment (73, 74).

Anthropogenic pollution permeates every facet of the planet; however, not all pollution has a chemical signature. Sensory pollution such as noise, light, and olfactory pollution have become commonplace (75). While sensory pollution can, for the most part, be directly observed, the question remains whether ecosystem changes could be revealed more from a sentinel than from direct measures of sensory pollution. Sensory pollution can affect animal behavior, and thus the potential exists for sentinels of sensory pollution to serve as indicators of broader ecosystem disruption. Several recent examples demonstrate how artificial light and noise can influence animal behavior, with rippling consequences for ecosystems (76). Further exploration of sensory pollution sentinels may prove fruitful.

From snails to whales, pollution sentinels have played a crucial role in advancing our understanding and facilitating mitigation efforts (59). However, our comprehension of risks still lags behind the true threat that pollutants pose (77). Moreover, organisms are rarely subjected to pollutants in isolation; exposure to contaminant cocktails often have unanticipated, synergistic effects. Recently, however, there have been calls, treaties, and actions to address ubiquitous anthropogenic contaminants (51). Pollution sentinels will remain essential for tracking progress toward these goals.

3.3. Sentinels of Abiotic Conditions and Biotic Interactions

Changing ecosystem conditions can lead to critical ecological and economic losses, such as when changing species distributions lead to an increase in human–wildlife conflict (3), altered opportunities for resource harvest (78), or barriers for burgeoning industries such as tourism (79). Detecting the first signs of ecosystem change can speed up management responses and ideally stem ecological and economic losses (80). Climate and ecosystem sentinels offer us the ability to detect these rapid ecosystem responses and respond accordingly, and can ideally identify changes before they occur (4, 5).

For example, marine mammals have been proposed as ecosystem sentinels because of their regular migrations, visibility, and strong response to ecosystem states (81). In the past decade, marine mammals have had increased interaction with fisheries on both US coasts [North Pacific humpback whales (*Megaptera novaeangliae*) and North Atlantic right whales (*Eubalaena glacialis*)] and have experienced climate-induced unusual mortality events [California sea lions (*Z. californianus*) and gray whales (*Eschrichtius robustus*)] (82). Loss of sea ice has also been linked to changes in migration timing (83), increased foraging opportunities, and, as a result, body condition in bowhead whales (*Balaena mysticetus*) and gray whales (83). In the past decade, we have also seen marine mammals, including humpback whales in California (84), right whales in New England (85), fin whales (*Balaenoptera physalus*) in the Mediterranean (86), and multiple baleen whale species in the North Sea (87), shift their foraging habitats to new areas. These shifts have included significant ecological impacts alongside increased whale mortality and economic losses due to fishery closures (84, 85), yet we still have not quantified how these changes may be indicative of ecosystem cascades. Even without direct evidence of shifting prey species, these shifts in top predator habitats suggest ecosystem regime changes as the result of a changing climate, yet the near-global synchrony in these responses remains unexplained.

Sentinel species can respond to an abiotic change or a biotic change, either before other ecosystem components or more conspicuously so that ecosystem changes can be identified early (4). For example, eutrophication-driven hypoxia can have significant ecological and economic effects, and sentinels have been proposed as early-warning indicators for ecosystem shift or collapse (88). With top predators predicted to make exploratory trips to new ecosystems as climate variability and change create novel habitats (89), such movements could be important indicators of biotic changes underlying ecosystem shifts. Broad-scale processes like climate change and hypoxia can be difficult to ameliorate directly through management, but sentinels can give insight into additional potentially cumulative stressors that could be addressed through mitigation. Changes in the timing of ecosystem processes can also be detected by phenological sentinels, a subset of abiotic or biotic sentinels whose life-history events are timed to specific environmental triggers. For example, migrating birds have shifted their timing earlier in the season as a result of changes in the start of springtime greening (17). By using the first detected responses to changing conditions, additional management intervention could mitigate change or at least economic losses from impending change.

Shifts in timing or location of top predator behaviors, including arrival in an ecosystem, novel foraging grounds, or shifts in reproduction habitat, may render existing efforts at conservation or management (e.g., protected areas, seasonal closures) ineffective (90). Phenological sentinels that have behaviors timed to specific environment or ecosystem conditions (91) can provide an indication that ecosystems are transitioning sooner or later to productive systems in ways that might require additional management intervention (92). Early-warning indicators of ecosystem tipping points could be the most powerful types of sentinel information because they would allow for proactive rather than reactive management, which is more costly (93). However, detection of clear early-warning indicators of ecosystem tipping points has been difficult at broad scales (94). Top predators are some of the most responsive indicators of ecological tipping points. California sea lion pup production is an indicator of nonlinear shifts in sea surface temperature patterns (21) and mass gain in the northern elephant seal (*Mirounga angustirostris*) is an indicator of future population trajectories (95). These early-warning indicators are often easier to detect posthoc; for example, seabird reproductive success provided the first warning of an ecosystem effect of delayed upwelling in the California Current (4).

3.4. Biodiversity Sentinels

A substantial body of literature describes certain animal species as indicators of broader biodiversity as an implicit or explicit function of habitat quality or ecosystem health (96). In such cases, variation in the presence of these biodiversity sentinels across space or time is related to variation in the richness or abundance of other species within the ecological community. Importantly, the mechanisms underlying such relationships between sentinel species and their communities may vary substantially among sentinel species. A sentinel species may have high requirements for habitat quality, suggesting that when they are present there is high-quality habitat available for other species as well (97); alternatively, a sentinel species may be an ecosystem engineer that increases overall habitat quality (98); or a sentinel species may have strong ecological relationships such as predation, mutualism, or competition with multiple species within the community (99). Regardless of the mechanism, the presence or absence of the sentinel species can be a useful proxy for the occurrence of a suite of other species that indicate how changes in habitat quality or prey resources, for example, affect multiple components of the ecosystem.

Numerous examples of biodiversity sentinels that span multiple taxa have been documented, though the identification of such sentinels dominates in terrestrial systems. For instance, the presence of desert tortoises (*Gopherus agassizii*) and kit foxes (*Vulpes macrotis*) in the Mojave Desert, United States, is positively correlated with higher species richness across multiple taxa, including birds and reptiles, and therefore both species have been suggested as surrogates to identify land areas for protection (100). Similarly, the probability of occurrence of certain predatory fish species is correlated with increased species richness and diversity in fish assemblages in eastern European riverine systems (101). Terrestrial birds are perhaps the taxon most widely used as biodiversity sentinels because of their conspicuousness and ease of detection (96, 102). As one example, site occupancy of eagle owls (*Bubo bubo*) in the Italian Alps reliably indicates biodiversity among a range of bird, amphibian, and reptile species (103).

The richness of multiple species within a sentinel guild has also been used to indicate broader trends in biodiversity. For example, in British Columbia, Canada, woodpecker richness positively correlates with both tree species richness and broader bird species richness across time as a function of forest health and harvest practices (104). In this case, the woodpecker richness is likely an indicator of diverse habitat that benefits multiple bird species. Similarly, in China and Japan, cuckoo (*Cuculus canorus*) richness and occurrence were positively correlated with bird species richness across space (105). Finally, the presence of a suite of five butterfly species was the most reliable indicator of increased species richness within the broader butterfly guild across mountainous areas of the western United States (106).

Such biodiversity sentinels have both basic and applied uses and are particularly valuable in regions undergoing rapid environmental change. The use of a biodiversity sentinel allows researchers and managers to assess ecosystem-wide impacts of human disturbance more cost-effectively without the need to survey many individual species. Moreover, suites of biodiversity sentinels that indicate complementary components of biodiversity within an ecosystem may be particularly valuable for surveying impacts across a wider breadth of habitat and ecosystem functioning. Similar to the concept of umbrella or surrogate species in conservation, protecting the habitats used by one or more biodiversity sentinels can protect a broader suite of additional species (100). Biodiversity sentinels offer a unique role in monitoring studies because they provide information at the ecosystem level, can help us understand community-level impacts of environmental change, and can inform conservation efforts aimed at protecting vulnerable species and ecosystems. Loss of habitat or increases in ecosystem stressors (e.g., pollution) can also be indicated by a change in biodiversity sentinel behavior, habitat, or population trend.

Phenology: a field of study focused on changes over time and periodic or cumulative biological phenomena

3.5. What Factors Make Specific Ecosystem Sentinels More Useful for Monitoring, Conservation, or Management?

Life-history characteristics, like functional importance or ecological mechanism, are often used to justify the choice of a specific sentinel species as ecosystem indicators (4). Top predators are often identified as sentinels because they are thought to be more sensitive and indicative of change at lower trophic levels (4, 99). For example, the diet, distribution, and phenology of whales such as blue whales (*Balaenoptera musculus*), humpback whales (*M. novaeangliae*), and sperm whales (*Physeter macrocephalus*) are strongly driven by environmental variables like sea surface temperature and sea ice, as well as the distribution and abundance of prey populations (107). Conversely, mesopredators have been argued to be appropriate sentinels because they hold an intermediate trophic position that is affected by both bottom-up and top-down changes in trophic levels (19). For example, smaller carnivores like the eastern spotted skunk (*Spilogale putorius*) were found to be more sensitive to environmental and anthropogenic change than were larger carnivores in the Blue Ridge Mountains of the eastern United States (108). Part of the lack of clarity between these two positions is that most studies rely on local context-dependent research in evaluating sentinels. In a recent meta-analysis, Clark-Wolf et al. (5) analyzed 206 sentinel studies and found that sentinel predictive performance did not vary across taxa or study system. Rather, species that were more closely trophically linked to ecosystem components served as better sentinels. Thermoregulation was also found to be an important life-history characteristic in defining sentinel responses, as ectotherms were slightly more sensitive to environmental and ecosystem change than endotherms (5). Sentinels were also more sensitive to changes in abiotic conditions like air temperature than to changes in habitat. These sensitivities may be a direct response to abiotic conditions or may instead be a response to abiotic-driven changes to prey species.

One advantage of long-lived and large-bodied species such as top predators as sentinels is that they offer multiple scales of response due to the ability to measure multiple behavioral, physiological, and population responses, in some cases simultaneously (**Figure 3**). California sea lions are one such example where a rapid behavioral response was an important indicator of delayed productivity in the California Current (4). Although it was not recognized as a broader ecosystem signal at the time of detection, pup production is another important metric of forage availability (21). Additionally, sea lion scat has been used as an important indicator of changes in forage species composition (109). Whisker and blubber samples could be added to get an additional scale of inference on the changes in diet composition and ultimately food availability. This scale of sentinel response ultimately influences the sentinel's efficacy (**Figure 3**); for example, fine-scale temporal responses were shown to have more sentinel-skill than broader-scale temporal or spatial responses (5). Ultimately, identifying the spatiotemporal scale underlying sentinel ability is critical when developing sentinel-based management or conservation plans.

Ecological interactions can also be important for informing the utility and applicability of a sentinel species (4, 5, 99). Species that were more tightly connected with their resource, like predators, were more effective ecosystem sentinels than species that were predicting other co-occurring species that were not trophically related (5). These findings are supported by a recent meta-analysis of raptor species that found that they were better biodiversity indicators when strongly linked to the resources that they were predicting (99). For example, northern goshawks (*Accipiter gentilis*) are good indicators of avian biodiversity through their role as predators (110), but not necessarily in all cases. Nontrophic ecological interactions, like competition or parasitism, may also inform sentinel applicability but have yet to be thoroughly studied. For example, kittiwake (*Rissa tridactyla* and *R. brevirostris*) breeding success in the Bering Sea–Aleutian Island ecosystem was negatively related to abundance of pink salmon (*Oncorhynchus gorbuscha*), a competitor for prey resources (111). In parasitism, common cuckoos (*C. canorus*) are useful indicators of host biodiversity through their role as avian brood parasites (105). Other positive ecological interactions, such as mutualism or ecological engineering, may also present new ways to examine the use of sentinel species to predict the environment or ecosystem.

Other important characteristics of a sentinel are visibility, being easily monitored, and having a clear and measurable response to ecosystem perturbations (4). For this reason, colonial breeding seabirds are often used as sentinel species. For example, Cassin's auklets (*Ptychoramphus aleuticus*) breed in large colonies, allowing for a suitably long time series and repeated measures of egg-laying and chick rearing. A year of complete reproductive failure served as an indicator of ecosystem response to delayed productivity in the California Current (4). Although plenty of other signals, including changes in copepod communities, were identified after the fact (4), the conspicuousness and the clarity of response made seabirds the first sentinel of change. With the advent of new tools and technologies, additional species that have been cryptic in response are becoming more widely usable (112). For example, wandering albatrosses (*Diomedea exulans*) fitted with radar-sensing tags have been used to identify potential illegal fishing practices in the Southern (Antarctic) Ocean (20), and changes in savannah herbivore movement patterns have been successfully linked to poaching activity (113).

With the field of sentinel science expanding rapidly, it is also important to clearly identify the limitations of various sentinels. Factors such as adaptation, population trends, and nonstationarity in the species–environment–stressor relationship may obfuscate the utility of sentinel ability. For example, a range contraction could be the result of population decline; conversely, a range expansion could be the result of a population increase, which may be viewed as a behavioral change in a sentinel context. Similarly, if a sentinel species historically relied on a single prey species but shifts its diet to a new prey species in the region, the responses to ecosystem changes may look different from responses in the past. In sum, sentinel ability needs to be continually explored and reassessed, as multiple scales of natural variability and anthropogenic stress could change sentinel response signals in the future.

4. EXAMPLES OF SENTINELS IN PRACTICE

There are only a few examples of sentinels in practice, so here we highlight two case studies of the application of sentinel species to provide a framework for future implementation.

4.1. Greater Yellowstone Ecosystem

The US National Park Service established the Vital Signs Monitoring Program in the early 2000s to help increase scientific research on natural resources to support science-informed management in its national parks (114). These vital signs are a set of physical, chemical, and biological indicators that are integral to understanding the ecological and cultural health of national park ecosystems and how they are impacted by stressors. Following this, there has been an effort to combine long-term monitoring projects in the Greater Yellowstone Ecosystem (GYE) to monitor ecosystem processes, known as the Collaborative Vital Signs project (22). Researchers have published their findings in special journal issues on GYE indicators (115) and on GYE amphibians as indicators (116). For example, Yellowstone National Park (YNP) monitors key natural resource indicators such as water quality, plant communities, and amphibians (22). The trajectories of 21 of these vital signs are summarized using more than 50 indicators in YNP's vital monitoring signs reports (117). These collaborative, interdisciplinary reports highlight the threats to and the status of these vital signs, including for species like bison (*Bison bison*), elk (*Cervus canadensis*), grizzly bears (*Ursus arctos horribilis*), trumpeter swans (*Cygnus buccinator*), and whitebark pine (*Pinus albicaulis*) (see table 1 in 22). These vital signs have helped characterize the recovery of iconic GYE animals, such as bald eagles (*H. leucocephalus*) and grizzly bears, and ecosystems like Soda Butte Creek, which was contaminated from mine-related metals (22). In general, these reports focus on the effects of physical monitoring signs (e.g., temperature, snowpack melt) on biological indicators rather than use biological indicators to understand other harder-to-monitor species or ecosystem health (22, 115, 117). Moreover, it is unclear how these vital signs are collectively used to inform management decisions on a broader scale.

A more collective, systematic approach to inform management in the GYE is the Wildland Health Index (WHI), which evaluates trends in ecological vital signs (118). The WHI identifies and monitors vital signs for judging ecosystem health, analyzes current trends and creates projections, and communicates these results to managers effectively using a stoplight scorecard or report card (119). In these stoplight scorecards, the colors red, yellow, and green are used to communicate the trends and magnitude of vital signs (see figures 1 and 11 in 119). These systematic evaluations of large ecosystems are becoming more popular, with notable examples in the Everglades (120) and Chesapeake Bay (121) ecosystems. Hansen & Phillips (119) created a WHI for the GYE that highlights the changes in snowpack, stream flow, temperature, and forest health and the ecosystem impacts on increasing or stabilizing populations of large mammals like gray wolves (*Canis lupus*), bison, and grizzly bears and on the decline of native fish like cutthroat trout (*Oncorhynchus clarkii*) and Arctic grayling (*Thymallus arcticus*) (see table 2 in 119). We look forward to future application of the WHI in the GYE, in addition to quantifying how biological indicators monitor environmental and ecosystem change, and more explicit ecological forecasting based on these quantified relationships (5).

Amphibians are one suite of species that have been used to monitor environmental and ecosystem change in the GYE (122). Amphibians are sensitive gauges of ecosystem health (122). Environmental stressors like climate change, habitat alteration, invasive species, and disease have caused declining amphibian populations globally (35) and locally within the GYE (122). Because of this, wetland ecosystems and a suite of amphibian species, including indicators like western tiger salamanders (*Ambystoma mavortium*), western toads (*Anaxyrus boreas*), and boreal chorus frogs (*Pseudacris maculata*), have been continuously monitored in the GYE since 2006 (122). These long-term monitoring programs have shown that amphibians are indicators of ecosystem change due to their sensitivity to drought (123, 124), to perturbations from wildfires and beaver-induced flooding (125), and to wetland restoration (126, 127). For example, boreal chorus frog breeding occupancy is strongly related to wetland availability, where years with larger snowpacks and runoff from snowmelt drive wetland habitat (122). As temperatures increase and wetlands dry out in the future, scientists and managers in the GYE are recommending integrating datasets for ecological forecasting and further coordinated monitoring of biological indicators dependent on wetlands (e.g., trumpeter swans, moose, bats, passerines) (116). Thus, the GYE provides a suite of examples of how sentinel species may be effectively used to monitor terrestrial ecosystems.

4.2. Northern California Current Ecosystem

In 2008, the US National Oceanic and Atmospheric Administration developed the integrated ecosystem assessment (IEA), an approach to marine ecosystem–based management that consists of setting management goals, identifying and analyzing trends in indicators, and evaluating future ecosystem scenarios for better management (128). Similar to the vital signs program in the GYE, a major component of IEAs is identifying biophysical, ecological, and socioeconomic indicators that capture the status and trends of ecosystems (129). Indicator trends are captured in ecosystem status reports, which evaluate how marine ecosystems are changing (e.g., Alaska, Gulf of Mexico, West Hawai'i). For example, the Northeast Fisheries Science Center monitors the state of the ecosystem for the Gulf of Maine and the Georges Bank to better meet fishery management objectives by using a combination of indicators, including ecosystem stability, seafood production, protected species bycatch, commercial profits, and recreational opportunities (129). In addition, due to long-term marine monitoring in the Northwest Atlantic, indicator species such as zooplankton, larval fish, and adult fish diversity were incorporated. IEAs in this region have been operationalized by conceptual modeling to illustrate the connections between indicators and fisheries in this ecosystem. Qualitative network modeling has also been used to show the effects of management and environmental scenarios on fish stocks (129).

The Northwest Fisheries Science Center (NWFSC) monitors ocean ecosystem indicators to understand the marine survival of Pacific salmon and to predict salmon returns (130). Scientists use a suite of indicators based on an ecosystem-based understanding of bottom-up and top-down factors that affect salmon survival, including climate and atmospheric data; local biophysical indicators like sea surface temperature and salinity; and biological indicators like copepods, ichthyoplankton, and chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*) abundance (130). Currently, bottom-up ecological indicators, such as ichthyoplankton and copepod abundance and biodiversity, are used to measure good conditions for salmon survival (130). For example, winter ichthyoplankton, an important fat-rich food source, is strongly related to juvenile chinook and coho salmon survival (131). Potential top-down indicators are predatory fish; for example, salmon marine survival was negatively correlated with Pacific hake (*Merluccius productus*) abundance and positively correlated with forage fish, turbidity, and Columbia River flows (132). Future research directions may use more top-down and ecosystem-based indicators that describe food web interactions to predict salmon survival (130). In addition, the NWFSC consolidates these indicator trends in ocean ecosystem conditions into a stoplight report card. Recently, unprecedented climatic and ecosystem shifts, temporal nonstationarity, and ecosystem complexity have been found to limit the success of these ecosystem-based forecasts (133). Solutions to these issues could include improving the use of indicators with iterative near-term ecological forecasting (134) and developing management systems that are robust to forecast uncertainty (133).

Given the number of indicators being used in management (sometimes in the hundreds), it could be relevant to develop ways to evaluate larger trends in ecosystems across many indicators. Two methods are the WHI (118) and the Ocean Health Index (135), where multiple indicators are integrated into higher-level summative metrics that are useful to policymakers using stoplight graphs. While this allows for ecosystem evaluation across many indicators (see figure 11 in 119), it may still be unclear to policymakers how to assess ecosystem states when diverging responses are seen across higher-level metrics. Structured decision-making is a formal process that can address complex issues in management that may be valuable in these cases (136).

5. THE FUTURE OF SENTINELS

The future need for sentinel species is only likely to increase as rates of change and cumulative effects of stressors on terrestrial and marine ecosystems interact in new and novel ways. Combining ecosystem sentinels with Earth observations may allow greater inference, specifically correlations between animal presence and ecosystem response [e.g., normalized difference vegetation index in the terrestrial lens (137) versus chlorophyll *a* in the marine system (138)] to provide a more holistic assessment of ecosystem health. Inclusion of a specific sentinel species and a measurable response may give better insight into ecosystem impacts than remotely sensed data alone (139). Genomics such as environmental DNA could provide novel insights into ecosystem health whether overall biodiversity is measured or whether cryptic indicator species are identified with genetic samples (140). Sentinel data can be integrated into multiple scales of decision-making: Static management measures can be triggered for reassessment when there is a decline in a key species targeted for protection, when indicators such as genetics for returning salmon can adaptively close or limit a fishery, or ideally when allowing changes in sentinel data to trigger automated decision-making via dynamic management (141).

Measurements from pollution sentinels can be linked to ecosystem and human health risk thresholds (thus intersecting with disease sentinels) that, if exceeded, trigger management action. For example, contaminants are tangential to fisheries management at present; as pollutant loads are known to affect population trajectories (142) and health outcomes of wildlife and humans, pollution sentinels could be key to efficiently monitoring the ecosystem for concerning levels of persistent or insidious pollutants. Disease outbreaks can be present in animal populations weeks before first detection, allowing spread to occur undetected before preventative action could take place (45). Rapid and broadly implemented sentinel screening could detect virus or disease prevalence alongside transferability to human populations, providing a unique early-warning indicator of future outbreak.

6. OPEN DATA AND REPRODUCIBILITY IN SENTINEL SCIENCE

Both the discovery of new sentinels and the implementation of management based on known sentinels will benefit from the adoption of open science practices by ecologists and resource managers (143). Consider the cuckoo (105), woodpecker (104), and penguin (18) examples discussed above. The field work required to describe these sentinels required 6, 10, and 40 years, respectively. In an era of rapid climate change and accelerating biodiversity loss, relying on decade-plus studies should be cause for concern. Therefore, in addition to time- and resource-intensive new data collection, steps should also be taken to facilitate reanalysis and synthesis of existing ecological data. Other scientific fields have successfully adopted this approach of leveraging open science to accelerate research and implementation. For example, in biomedical research, drug development also relies on decade-long studies to discover, develop, and test new compounds. But widespread adoption of open science practices like FAIR (findable, accessible, interoperable, and reusable) data principles (144) facilitated rapid computational experiments that screen for the most likely candidates before moving on to more time- and resource-intensive experiments and trials (145).

In addition to impeding scientific discovery, inaccessible data are also a major obstacle for evidence-based conservation and environmental management (146). Sentinel research must make its way into the hands of policymakers and resource managers to make conservation impacts, as it has in the GYE and Northern California Current ecosystem. However, a substantial fraction of conservation research does not inform or aid implementation (147). This knowledge–action gap can be addressed through open science practices, such as data sharing and open access publications (148).

Within ecology, open science practices are slowly gaining traction, but approximately half of published datasets remain incomplete or otherwise unusable (149). Encouragingly, some forms of biodiversity data are increasingly aggregated and standardized in data repositories, which promotes reanalysis and synthesis. These include the Global Biodiversity Information Facility for species occurrence (150) and Movebank for animal movement (151). Despite these advances, data archiving and sharing norms remain far from consensus. As a consequence, biodiversity data aggregation alone (prior to analysis) can take years of effort from large teams. The substantial resources required to assemble, for example, the Arctic Animal Movement Archive (152) and the Antarctic Tracking Data Project (153) are indicative of the outstanding challenges to reanalysis and synthesis. Increasing adoption of open science practices will reduce these barriers, promote sentinel research, and facilitate utilization by practitioners.

Further, harmonization of methods (e.g., sampling/collection, analysis, reporting) is becoming increasingly vital as datasets become larger and richer. To detect changes over time or impacts on species and ecosystems, studies of sentinels need to have standardized procedures. Without such harmonization, conclusions about trends or risks can be inaccurate. With the emergence of plastic debris as a global pollutant of concern, researchers have scrambled to outline standardized methods so that data and results are comparable across research teams (154). The power of standardization can be seen with OSPAR's development of the northern fulmar (*Fulmarus glacialis*) as a sentinel of plastic pollution in the marine food web (23). This long-term monitoring program has shown a change from industrial to consumer plastics in the food web over time and projects that plastic in fulmar stomachs will decline below their determined ecological quality threshold by 2054 (73).

7. CONCLUSION

The planet is changing rapidly due to human influence, and we are struggling to understand these changes, let alone mitigate or reverse them. These novel challenges to understanding the rate and step functions of change in global ecosystems (6) require novel data on ecosystem structure, health, and function (4, 5). While these data can and should be focused on the ecosystems themselves, nonhuman animals offer specific advantages, including rapid and more comprehensive assessment of emergent threats at a broader range of locations, times, and conditions than direct surveillance of mechanistic processes allows. Here, we show how stressors can act as compound drivers of sentinel response. The recent literature has provided examples and tested the efficacy of ecosystem sentinels, but we lack a coherent framework to get from raw sentinel data to decision-making for ecosystem, animal, and human health that is desperately in need of investment. We highlight examples where ecosystem sentinels provide valuable information to management bodies, but most of these examples are qualitative information–driven goals rather than quantitative thresholds for management response. Incorporating ecosystem sentinels alongside existing management approaches can offer early warnings of ecosystem change that can improve our ability to rapidly react to novel ecosystem conditions. With concern comes opportunity, as we could ensure that data on ecosystem sentinels become part of the conservation and management fabric in the Anthropocene.

SUMMARY POINTS

1. Ecosystem sentinels are species that respond rapidly to ecosystem change (i.e., a leading sentinel), are easier to observe than other ecosystem components (i.e., an elucidating sentinel), or both.
2. Here, we highlight the role of ecosystem sentinels in our understanding of changes in human health, anthropogenic pollution, abiotic conditions and biotic interactions, and biodiversity in the Anthropocene, with the Anthropocene considered the current geologic epoch beginning in the mid-twentieth century when human impacts on ecosystems outpaced natural variability.
3. Human health sentinels not only can detect zoonotic diseases in a nonhuman host before they transfer to human hosts but also can give an idea on the rates of change that may make certain strains of viruses or bacteria more likely to have human infection potential. Human health sentinels can also detect other environmental health hazards, such as chemicals, with risk shared by nonhuman animals.
4. Pollution sentinels can aggregate pollutants and show effects based on their habitat use and trophic position, giving a better idea of how pollutants travel through food webs.
5. Sentinels of abiotic conditions and biotic interactions can indicate when physical or ecological changes may have ecosystem effects. Biodiversity sentinels can assess ecosystem state or even health, including the relevance of biodiversity change to human health.
6. The use of ecosystem sentinels in practice is still emerging, and we highlight how management structures can be built to include ecosystem sentinels.
7. Including ecosystem sentinels in management can uniquely identify changes in ecosystem structure and function before they have broader impacts.

FUTURE ISSUES

1. Decreasing surveys on land and at sea due to cost and staffing concerns is putting increased pressure on developing alternative approaches toward ecosystem management in the Anthropocene.
2. There are large stores of data on ecosystem sentinels that are not available in public repositories, which limits our ability to identify and implement sentinel-based management.
3. Current examples of ecosystem sentinels in management are largely in North America and there is a great need to expand these approaches to other parts of the world.
4. Incorporating more nuanced approaches of pollution and human health sentinels could provide an early-warning system for broader human and ecosystem impacts.
5. The role of citizen science (e.g., eBird, iNaturalist) offers an exciting opportunity to observe novel patterns in sentinel movement that we have not fully harnessed.

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AUTHOR CONTRIBUTIONS

All authors contributed to the writing of this manuscript, contributed equally to outlining, and contributed to editing the final manuscript and figures. E.L.H. composed **Figures 1** and **2** and wrote Sections 1, 3.3, 5, and 7. M.S.S. drafted **Figure 3** and Sections 2 and 3.2. T.J.C.-W. drafted Section 4. P.M.R. drafted Section 3.1. M.C. drafted Section 6. B.A. wrote Section 3.4.

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