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Review

The chemical landscape of tropical mammals in the Anthropocene

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ABSTRACT

Sixty years ago, Rachel Carson published her book *Silent Spring*, which focused the world's attention on the dangers of pesticides. Since that time human impacts on the environment have accelerated and this has included reshaping the chemical landscape. Here we evaluate the severity of exposure of tropical terrestrial mammals to pesticides, pharmaceuticals, plastics, particulate matter associated with forest fires, and nanoparticles. We consider how these environmental contaminants interact with one another, with the endocrine and microbiome systems of mammals, and with other environmental changes to produce a larger negative impact than might initially be expected. Using this background and building on past conservation success, such as mending the ozone layer and decreasing acid rain, we tackle the difficult issue of how to construct meaningful policies and conservation plans that include a consideration of the chemical landscape. We document that policy solutions to improving the chemical landscape are already known and the path of how to construct a healthier planet is discernible.

1. Introduction

Human actions have altered global environments in dramatic ways. For mammals in the tropics, their habitat is being destroyed at an increasing rate, with ~60 million ha (an area larger than Madagascar) of tropical primary forest lost between 2002 and 2019 (Weisse and Gladman, 2020). Our actions have led to the Earth's temperature increasing over land by 1.59 °C from the 1850–1990 period to the last 10 years, and temperature increase by the end of the 21st century is projected to exceed 1.5 °C (Bernard and Marshall, 2020; IPCC, 2021). Estimates suggest that the tropics will experience 10% greater warming than this global average (Graham et al., 2016). Given the magnitude of anthropogenic impacts, Crutzen and Stoermer (2000) suggested that we label the current geological epoch as the “Anthropocene” and this term is now widely used in academic and popular literature (Kalbitzer and Chapman, 2018; Lewis and Maslin, 2015).

The cutting of forests or production of greenhouse gases are very apparent as people see cleared fields, the smokestacks of industry, and melting glaciers, while also experiencing hotter summers; however, all human actions are not so easily seen. One of the best-known examples of human actions that have a cryptic influence was brought to the public's attention in 1962, when Rachel Carson wrote her book *Silent Spring* (Carson, 1962). This book focused on the detrimental effects of pesticides, which she advocated should be termed “biocides” because their effects are rarely limited to the pests they were intended to target. Her work, and the public interest it created, contributed to a change in the pesticide policy of the United States and a nationwide ban on dichlorodiphenyltrichloroethane (DDT) use in the agricultural industry (Hayes and Hansen, 2017).

While the release of anthropogenic chemicals into the environment has been further regulated since Carson's time, the threat remains, and environmental chemical contaminants continue to play a substantial

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role in shaping the Anthropocene. Pollution is the largest environmental cause of premature human death in the world. Over 9 million people died prematurely in 2015 from pollution related causes (Landrigan et al., 2018). This is three times the number of deaths caused by malaria, tuberculosis, and AIDS combined. Unfortunately, we do not have similar statistics for wildlife. However, given the magnitude of these human mortality statistics and since pollutants do not stay where they are applied, wildlife populations are likely experiencing similar impacts. In fact, the world has seen continuous growth in the amount and number of chemicals used with global sales projected to double by 2030. In 2017, sales totaled 5.68 trillion US dollars, making the chemical industry the world's second largest manufacturing industry (UNEP, 2019). Today, more than 140,000 unique synthetic chemicals have been made (Landrigan et al., 2018), and these chemicals end up in air, water, soil, plants, and biological tissues. Less than half of the top 5000 chemicals produced in the greatest volume have been tested for toxicity and safety (Landrigan et al., 2018). Despite this, many of these chemicals are found in the food we eat, air we breathe, and products we use every day, such as toothpaste and cosmetics. Given their quantity and the physico-chemical properties of most of these chemicals that make them volatile and persistent, it is not surprising that atmospheric transport deposits many synthetic chemicals in remote areas where they were never applied (Devi et al., 2015). Eventually, many end up distributed in all parts of every ecosystem.

The long-term effect of these chemical contaminants on ecosystems is only now being appreciated. For example, flying insect biomass has been documented to have declined by 80% over the last 30 years in Europe and this corresponds to a loss of more than 420 million birds (Hallmann et al., 2017; Inger et al., 2015; Karlsson et al., 2021). The vast majority of the studies examining the effects of chemical contaminants are concerned with human health and focus on temperate ecosystems. Yet, given the threatened status of many tropical species and the increasing encroachment of humans into what were previously remote tropical areas, there is an urgent need to understand the chemical landscapes experienced by tropical terrestrial mammals. This is even more urgent if one considers that the growth of chemical sales is projected to be the largest in emerging markets like Africa and the Middle East (UNEP, 2019).

The objective of our paper is to first evaluate the severity of exposure of tropical terrestrial mammals to pesticides, pharmaceuticals, plastics, particulate matter associated with forest fires, and nanoparticles. Second, we consider how environmental contaminants interact with one another, with the endocrine and microbiome systems of mammals, and with other environmental changes to produce an increased negative impact than might initially be expected. Finally, we tackle the difficult issue of how we can improve the situation and construct meaningful policies and conservation plans that include consideration of the chemical landscape. Here we build on past conservation success, such as mending the ozone layer and decreasing acid rain, and ask what approaches will be most successful for implementing positive change, including a focus on how academia can make a meaningful contribution.

2. The chemical landscape

2.1. Pesticides

Similar to the trends for anthropogenic chemicals as a whole, pesticide pollution is also getting worse, particularly in low- and mid-income countries that are often home to a high diversity of tropical mammals (Fig. 1). For example, approximately 2.3 billion kg of pesticides are used

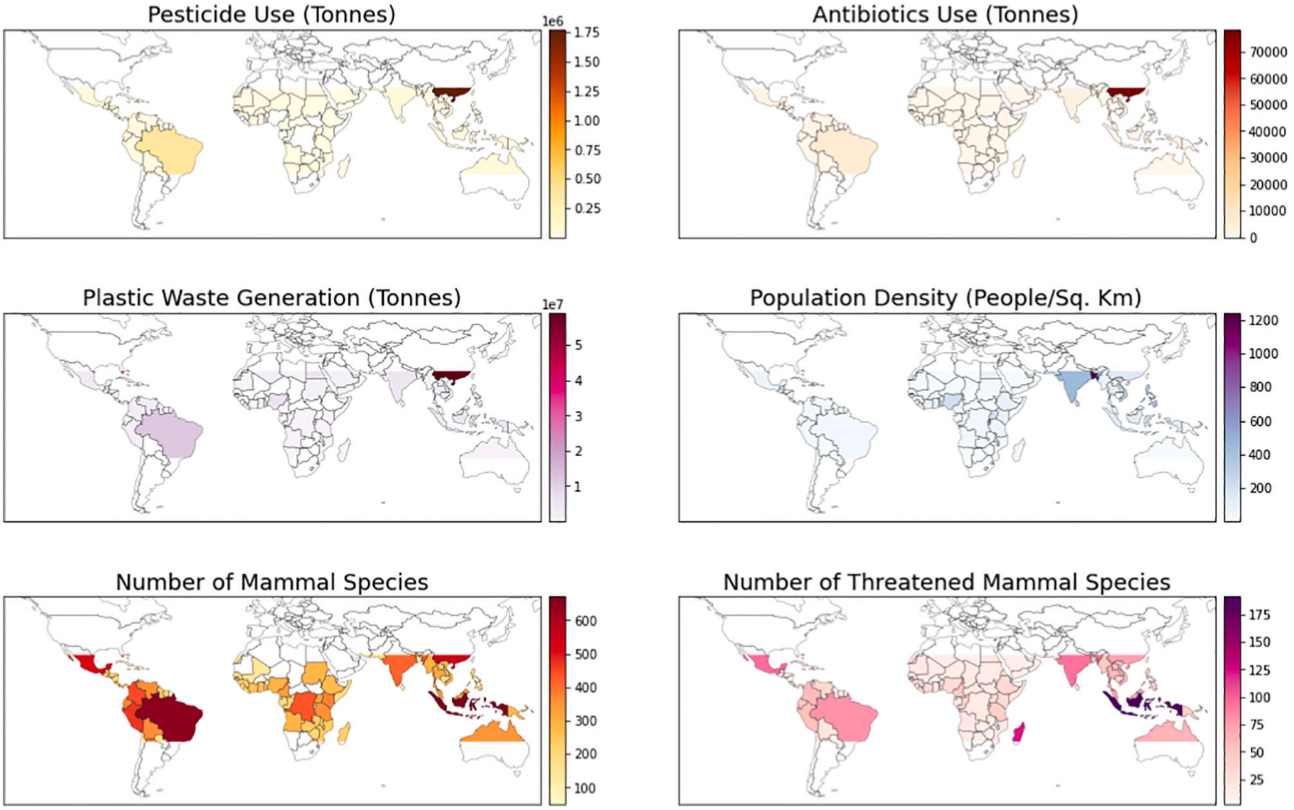

Fig. 1. Variation across tropical countries in: a) pesticide use (tons of pesticides used in agriculture in 2018), b) antibiotics used for livestock (tons), c) plastic (tons), d) population density (individuals/km^2), e) number of mammal species, and f) number of threatened mammal species. Data from pesticides - http://www.fao.org/faostat/en/#data/RP; antibiotics - https://resistancemap.cddep.org/AnimalUse.php; plastics - https://ourworldindata.org/plastic-pollution; https://worldpopulationreview.com/country-rankings/plastic-pollution-by-country; population density: https://data.worldbank.org/indicator/EN.POP.DNST. Data on the number of mammal and threatened mammal species from the IUCN.

each year (Hayes and Hansen, 2017). For tropical mammals there should be elevated concern because as high-income countries restrict the use of many environmentally-damaging chemicals, these same chemicals are either exported to or manufactured by mid-and low income countries and used with little restraint (Sanchez-Bayo and Hyne, 2011). Many of the older, more environmentally damaging pesticides that are banned in high-income countries (i.e., legacy pesticides) have expired patents allowing them to now be mass-produced in middle- and low-income countries, which can then be sold at cheaper prices than newer, presumably safer, chemicals (i.e., current-use pesticides) produced by foreign enterprises (Biscoe et al., 2004). Furthermore, environmental regulations are often scant or not enforced in many tropical countries (Landrigan et al., 2018). Additionally, chemicals like DDT and its metabolites persist for decades and continue to have environmental impacts long after its use, although degradation is faster in hot wet climates (Turgut et al., 2012). For example, the 21-year decline of Brazilian free-tailed bats (*Tacarida brasiliensis*) from an estimated 8.7 million to around a half a million in one cave system was attributed to DDT poisoning (Clark Jr, 2001).

While such examples illustrate the magnitude of what can happen, they underestimate the actual impact because wildlife research often neglects sublethal effects, researchers do not have the means to record premature deaths, and reporting is biased to dramatic events that are easily observed. As a result, it is currently not possible to obtain a general picture of the association between pesticide use and their threat to biodiversity conservation (Groh et al., 2022) and in general, the consideration of consequences of exposures only exists for human health risk assessment (Liao et al., 2020).

However, there are a number of studies demonstrating exposure. For example, frugivorous bats in Africa and the Americas have been shown to bioaccumulate organochlorine pesticides (Brinati et al., 2016; Stechert et al., 2014; Valdespino and Sosa, 2017) which causes tissue damage (de Oliveira et al., 2021). Organophosphates, pyrethroids and toxic metals were found in the tissues of lowland tapir (*Tapirus terrestris*) from Brazil (Medici et al., 2021) and eight different pesticides were found in samples from sloths (*Bradypus variegatus* and *Choloepus hoffmanni*) in Costa Rica (Pinnock, 2010). Liao et al. (2020) sampled soils in areas that were being used by endangered leopard cats (*Prionailurus bengalensis*) and detected 67 different pesticides.

Unfortunately, the health and fitness effects of such exposures are not known because wildlife populations are seldom monitored for substantial lengths of time relevant to the accumulation of sublethal affects that ultimately lead to premature death (Chapman et al., 2017; Hayes and Carsten, 2017). As a result, comprehensive information on the effects of exposure to pesticides for tropical wildlife are lacking. For example, only 5% of the world's bats have been evaluated with respect to their exposure to pesticides, with most of these studies conducted in the 1970s and 1980s on insectivorous bats in North America and Europe (Torquetti et al., 2020). However, recent research by our group across a series of tropical forests in Uganda and Costa Rica found significant levels of four groups of chemicals in air, including legacy pesticides, current-use pesticides, halogenated flame retardants, and organophosphate flame retardants (Wang et al., 2019). We followed up on these findings and sampled dung of howler monkeys (*Alouatta palliata*) in Costa Rica, and baboons (*Papio anubis*), chimpanzees (*Pan troglodytes*), red-tailed monkeys (*Cercopithecus ascanius*), and red colobus (*Piliocolobus tephrosceles*) in Uganda for the same groups of chemicals, many of which were found across all species (S. Wang et al., 2020).

Many of these chemicals have sublethal impacts on mammals and are known to disrupt the endocrine system and cause adverse developmental, immune, and reproductive effects (Matthiessen et al., 2018). Exposure at low levels will not result in mortality but could contribute to the extirpation of stressed populations through synergistic effects on immune function or reproduction, among other outcomes. For example, atrazine, the world's second most widely used pesticide, is known to cause decreased fertility in many species, including humans (Hayes and Hansen, 2017). The true contribution of chemical pollution, including pesticides, to health outcomes in both human and wildlife is likely underestimated because the adverse effects of many environmental contaminants are poorly understood and interactions among chemicals are rarely investigated.

2.2. Pharmaceuticals

Human use of pharmaceuticals leads to thousands of tons of biologically active compounds being dumped into the environment annually. In 2018, the global pharmaceutical market was valued at $1.2 trillion US with an annual growth rate of 3–6%. There are over 4000 different pharmaceuticals used globally for human and veterinary health care (Arnold et al., 2014). These compounds find their way into the environment at sites of production, when discarded without use, or once they are excreted by humans and domesticated animals. There is very limited research conducted evaluating the presence of these compounds in tropical environments (Kookana et al., 2014), but extrapolating from what is known from Europe and North America provides insights. Pharmaceuticals that are excreted are not usually degraded in sewage treatment plants. In the USA, 5–7 million tons of dry sewage are produced each year and 60% of this is used as fertilizer on cropland (Arnold et al., 2013; Arnold et al., 2014). Thus, we are spreading many active pharmaceuticals on the crops we eat. Globally, 20 million ha of farm land are fertilized with non-treated wastewater (Jiménez et al., 2009), an area just less than the size of the United Kingdom. Agricultural application of sewage from people is dwarfed by the use of livestock manure as fertilizers and 73% of all antimicrobial drugs sold are used on food animals (Van Boeckel et al., 2019). It is estimated that in North American the amount of antibiotics entering the soil with natural fertilizers attains the level of several kilograms per hectare (Gworek et al., 2021).

Estimates suggest that more than 105,000 tons of antimicrobial drugs will be administered to food animals by 2030, and it is expected that tropical countries like Brazil, India, China, and South Africa will nearly double their use by 2030 (Fig. 1) (Van Boeckel et al., 2015). In general, meat production plateaued in high-income countries in 2000 but has grown by 68%, 64%, and 40% in Asia, Africa, and South America, respectively (Van Boeckel et al., 2019). Meat production in Africa is expected to rise dramatically in the coming decade as many African countries are selling large amounts of land to meat producing businesses from countries that are capital-rich but lacking in suitable land for agriculture (Friis and Reenberg, 2010). For example, approximately 50 million ha of farmland in Africa, roughly the area of France, was appropriated by oil- or capital-rich but food-poor Middle-Eastern and Asian countries in 2009, with the products primarily destined for export (Lambin and Meyfroidt, 2011). In many cases, the area of land used in this way comprises a large proportion of the available agricultural land: in Uganda ~ 14%, Mozambique ~ 21%, and the DRC ~ 48% (Friis and Reenberg, 2010). This trend is partially driven by the increasing wealth of countries like China and India, and an associated increased preference for animal-based diets (Shimokawa, 2015).

For over 15 years there has been solid evidence that non-human primates are affected by pharmaceuticals. For example, in 2007 and 2008 it was shown that chimpanzees and gorillas are hosts to *Escherichia coli* resistant to human-use antibiotics (Goldberg et al., 2007; Rwego et al., 2008; Weiss et al., 2018). In Uganda, appreciable antibiotic resistance was primarily found for inexpensive antibiotics that were readily available over the counter without a prescription (Goldberg et al., 2007). However, while such single species case studies are available and many studies have highlighted the impacts of pharmaceuticals on aquatic organisms, especially fish (Lagesson et al., 2019), the general effects of pharmaceuticals on terrestrial mammals, especially in the tropics, have received almost no attention.

One of the clearest cases of pharmaceuticals causing population-level effects occurred on the Indian subcontinent, where the consumption of livestock carcasses that were medicated with diclofenac, a non-steroidal anti-inflammatory drug, resulted in the death of over 95% of Gyps vultures (*Gyps bengalensis*), one of the most common raptors across the Indian subcontinent (Cuthbert et al., 2014; Oaks et al., 2004). Prior to the veterinary use of this drug, Gyps vulture populations were so high (tens of millions of vultures from the three most common species, including *G. bengalensis*) they were considered a risk to aircraft populations (Cuthbert et al., 2014; Oaks et al., 2004). Despite this, diclofenac is presently the 12th best-selling generic drug globally with more than 1443 tons consumed by people annually (Acuña et al., 2015; Lonappan et al., 2016)

As with pesticide production, the manufacturing of pharmaceuticals is shifting to tropical countries, particularly India and Brazil. The consequences of the development of the pharmaceutical industry in tropical countries and the associated increased use of these chemicals are unknown. Historically, conservation biologists have responded to change and attempted to take corrective action after negative situations have occurred (Caughley, 1994; Chapman and Peres, 2001; Chapman and Peres, 2021); however, it is much more effective and less expensive if researchers can predict negative changes before they occur and proactively prevent population declines rather than restore populations. Thus, given the increased presence of pharmaceuticals in the environment in tropical countries, the close association of people and wildlife in the tropics, and the fact that these drugs are often designed to alter reproduction and behavior, research into pharmaceuticals in the tropics is warranted. Of particular concern is the fact that wildlife will be exposed to these drugs at all stages of life, including during development and as young infants, when animals are most susceptible to non-reversible organizational effects and do not have the metabolic capacity for detoxification.

2.3. *Plastics*

The world is producing a staggering amount of plastic: 402 million metric tons per year (Brahney et al., 2020) with production growing at 8.3% a year (Fig. 1) (Gavigan et al., 2020). Given this growth rate, production will double in only 9 years. Over 40% of this is single use plastics (Wright and Kelly, 2017) and globally only 9% of plastic produced were recycled in 2015 (Wu et al., 2021). Much of the world's discarded plastics ends up in landfills; however, 32% do not, and surprising amounts are found in the air we breathe and in the water we drink after breaking down into microplastics. Microplastics became a concern in oceanographic studies about a decade ago, as large amounts of plastics were easily found floating in the water column (Jacobsen et al., 2010). However, researchers have recently discovered that small plastic particles are a common component of dust and rainwater and are beginning to appreciate the magnitude of this deposition. For example, it is estimated that 132 plastic particles per m^2, which amounts to >1000 metric tons of plastic, are deposited each year on protected lands in the western United States (Brahney et al., 2020). Atmospheric transport of these particles means that they are found in remote regions far from their sources, such as pristine mountain habitats of the Pyrenes (95 km from a source) (Allen et al., 2019), the Arctic (Peeken et al., 2018), and the Tibetan Plateau (Allen et al., 2019). Furthermore, estimates suggest that 110,000 and 730,000 tons of microplastics are added annually to farmlands in Europe and North America, respectively (Nizzetto et al., 2016). As with pharmaceuticals, much of this plastic contamination on farmlands results from widespread application of sewage sludge from municipal wastewater treatment plants onto agricultural fields as fertilizer. Microplastic particles can be taken up by plant roots and transported into the stems of agricultural plants (Li et al., 2020). Thus, the use of sludge as fertilizer results in people ingesting plastics through their food crops. One estimate suggests that people consume about 39,000 to 98,000 plastic particles each year (Cox et al., 2019) and inhale between 10,000 and 100,000 particles a year (Prata et al., 2020). Another study discovered that globally people ingest an average of 5 g of plastic every week – the equivalent of a credit card (World Wildlife Fund, 2019). How much is consumed or inhaled by terrestrial wildlife is largely unknown but this is a concern particularly for animals that raid agricultural fields (Chapman et al., 2016; Cox et al., 2019). For example, a recent study of Asian elephants found that 32% of the dung samples contained plastic (Katlam et al., 2020).

The effects of such plastic consumption and inhalation are poorly understood, but particles can move across the gut lining and are found in all major organs. Microplastic fibers bioaccumulate in the lungs, which triggers inflammation (Gavigan et al., 2020). Chemicals leaching from plastic particles (e.g., BPA) can have endocrine-disrupting properties, potentially causing reproductive and developmental problems, while also being immunosuppressive, carcinogenic, neurotoxic, and disruptive to the gut microbiome (Bouwmeester et al., 2015; de Souza Machado et al., 2018; Prata et al., 2020; Yang et al., 2011). Because of their hydrophobic nature, microplastics act as an accumulator, making pollutants, such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and dichlorodiphenyltrichloroethane (DDT), all of which are highly toxic, carcinogenic environmental pollutants, more concentrated in organisms ingesting microplastics (Fackelmann and Sommer, 2019). Microplastics have also been shown to inhibit food assimilation (Straub et al., 2017), reduce body weight (Wright et al., 2013), and negatively impact growth and reproduction (Besseling et al., 2014).

In many tropical countries there is the added problem that since waste collection and disposal systems are poor, plastics are burned. Globally, approximately 70.2 million tons of plastic waste were burned in 2016, releasing almost 1 million tons of toxic aerosols - some of which likely contain highly toxic dioxins and furans - and the majority of this burning occurred in developing, often tropical, countries (Wu et al., 2021). These aerosols, which include small plastic particles, can cause an array of diseases when inhaled. To our knowledge, the extent to which wildlife inhale these aerosols and plastic particles has not been studied. Quantifying the magnitude of the exposure of tropical mammals to plastics and determining the sublethal consequences of this exposure may raise the alarm to an important issue that is negatively impacting wildlife populations.

2.4. *Forest fire particulate matter*

While most tropical mammal populations are removed from the air pollution and smog associated with cities, they experience the particulate matter associated with forest fires first hand. Fires in the tropics can encompass huge tracts of land and blanket even more extensive areas in smoke. For example, in 2015 Indonesia lost more than 2.6 million ha to fire, an area larger than Vermont, and estimates of forest damage are as great as 5 million ha (Harrison et al., 2016). The economic costs of these fires is estimated to have exceeded US$16 billion and the fires caused more than 100,000 premature human deaths (Chapman and Peres, 2021; Lee et al., 2017). These fires emitted huge amounts of particulate matter and carbon that wildlife inhaled. It is estimated that 11.3 Tg of carbon dioxide was emitted each day for 2 months during these fires. This amount exceeded the daily fossil fuel carbon dioxide emissions (8.9 Tg CO^2 per day) across the European Union (Huijnen et al., 2016). Smoke is composed of hundreds of chemicals, many of which are known to be harmful to health (Johnston et al., 2012). The particulate matter associated with fire has a range of health affects in mammals including cardiorespiratory mortality, exacerbation of respiratory and cardiovascular condition, inflammation, and oxidative stress (Johnston et al., 2012). Of course, the best estimate of mortality that can be attributed to landscape fire smoke deals with humans. Each year an estimated 339,000 deaths can be attributed to landscape fire smoke, with sub-Saharan Africa (157,000) and Southeast Asia (110,000) being the most affected regions (Johnston et al., 2012).

Fires in the tropics are projected to get worse. Fires associated with El Niño (ENSO) and Indian Ocean Dipole (IOD) climatic events are on the rise because of climate change. The frequency of extreme positive IOD events that promote fires in Southeast Asia and Australia is predicted to increase from one event every 17.3 years during the 20th century to one every 6.3 years in the 21st century (Cai et al., 2014; Hartter et al., 2012). We know that fires have a devastating impact on tropical forests as many are not fire adapted (Barlow and Peres, 2006; Harrison et al., 2009), but the effect of the haze and poor air quality on the surviving wildlife is largely unknown. An extensive review of the effects of smoke on the health and behavior of wildlife only found 41 relevant studies and of these only 16 dealt with mammals and three with tropical mammals (Sanderfoot et al., 2021). However, the consequences can be severe. For example, Singer et al. (1989) documented that smoke inhalation likely caused the death of 246 elk (*Cervus elaphus*). Given such examples and the documented health effect of fire on the human population, one would assume the health effect on wildlife is large. During the 2015 fires in Indonesia, air borne pollutants near Sebangau National Park, Central Kalimantan, reached 12 times what is considered a hazardous level and no doubt impacted the endangered orangutans and gibbons living there (Harrison et al., 2016). The orangutans in this area decreased the time they were active, while increasing fat catabolism that was unrelated to changes in caloric intake and thus their increased energy expenditure possibly represented an increased immune response (Erb et al., 2018)

2.5. *Will nanoparticles be the next major health concern for tropical mammal wildlife?*

One would think that after recognizing the importance of the message in Rachel Carson's *Silent Spring*, society would have learned the lesson that it is not a good idea to produce huge amounts of chemicals and release them into the environment prior to understanding their effects. However, it is clear that the lesson was not learned and the health effects of the recently emerging use of nanoparticles demonstrate this concern. Engineered nanoparticles are increasingly becoming an integral part of everyday life and are used in many sectors including agriculture, electronics, textiles, cosmetics (e.g., lipstick, sunscreen, and anti-aging creams), food products, medicine, and paints (Kwon et al., 2014; Phogat et al., 2016). The global nanoparticle market was valued at $14.7 billion US in 2015, and is projected to reach $55 billion US by 2022 and then grow at a compounded annual growth rate of 22% (Inshakova and Inshakov, 2017). In 2016 there were 1814 marketed consumer products containing nanoparticles and 8484 new patents filed (Ajdary et al., 2018; Inshakova and Inshakov, 2017). Estimates of the amount of all nanoparticles produced are unavailable. However, industrial production of carbon black, which is used to strengthen rubber, is estimated at 10 million metric tons, or equivalent to the weight of 6.3 million mid-sized cars. As a result, it is not surprising that exposure to nanoparticles has risen dramatically in the last few decades (Brohi et al., 2017). The wide use of nanoparticles has raised concerns about their negative impacts on human and wildlife health. How different nanoparticles produce toxic effects needs to be better understood (Ajdary et al., 2018; Jeevanandam et al., 2018). Nanoparticles can cross cellular barriers due to their extremely small size. Due to their large surface to volume ratio, they are very reactive in biological systems. These particles can damage tissues and cells, activate oxidative stress responses and expression of genes involved in inflammation, and accumulate in different tissues and organs, including the brain (Ajdary et al., 2018; Jeevanandam et al., 2018).

3. Effects on animal physiology: chemical stressors, endocrine disruption, and the microbiome

Unfortunately, with a few exceptions, the impact of chemical contaminants on wildlife are assessed one contaminant at a time and do not consider the general ecological circumstances in which the population occurs (e.g., is the population stressed). Yet, animals live in complex environments where they are being simultaneously exposed to multiple chemicals and are experiencing several ecological stressors (Groh et al., 2022; Torquetti et al., 2020). Given the pace at which anthropogenic habitat disturbance and climate change are occurring, these stressors are increasingly challenging wildlife (Groh et al., 2022). It is also unfortunate that often only dramatic effects, such as population die-offs like that described for the Gyps vultures in India, are considered sufficiently clear and significant to warrant publication (Cuthbert et al., 2014; Oaks et al., 2004). Yet medical research on people, and a few on wildlife, clearly demonstrates that most impacts will not cause immediate mortality, but rather will have sublethal negative effects, such as reduced reproduction, suppressed immune functioning, altered endocrine functioning, decreased foraging efficiency, or increased allostatic load that can lead to premature death from diseases like cancer (Brinati et al., 2016; de Oliveira et al., 2021; Erb et al., 2018).

Many pollutants (e.g., phthalates, alkylphenolic compounds, polychlorinated biphenyls, dioxins/furans, organochlorine pesticides, heavy metals) adversely affect development and physiology often by interfering with normal endocrine functioning (Zala and Penn, 2004). Such endocrine disrupting chemicals are ubiquitous in the tropics and are commonly found in the tissues of wildlife, even those living in isolated regions (Verreault et al., 2005). Exposure in mammals can cause a variety of effects, such as masculinized females and feminized males, reduced fertility, altered mating behaviors, increased aggression, and impaired spatial learning and memory (Zala and Penn, 2004). For example, long-tailed macaque monkeys (*Macaca fascicularis*) experimentally exposed to PCBs have a shorter attention span and cognitive impairment (Rice and Hayward, 1997; Rice and Hayward, 1999). While such experimental studies are useful in identifying an effect of exposure, what is needed is information on how such cognitive effects translate into decreased abilities to find food, mates, and sleeping sites in natural environments and how these effects influence population viability. We do know that Douc langurs (*Pygathrix nigripes*, *P. nemaeus*, *P. cinerea*) were exposed to dioxin (TCDD - agent orange) in Vietnam (Brockman et al., 2009) and that howler monkeys (*Alouatta pigra*) have been exposed to high levels of lead (Serio-Silva et al., 2015), but the population level effects of these exposures are unknown. The wildlife in Bwindi Impenetrable National Park, Uganda, a biodiversity hotspot and the location protecting about half the world's endangered mountain gorillas (*Gorilla beringei*), are exposed to DDT from leaves at levels above European and US maximum levels for medicinal plants (Amusa et al., 2021). The ring-tail lemurs (*Lemur catta*) of Beza Mahafaly Special Reserve in Madagascar are exposed to multiple organochlorine pesticides and heavy metals but the exposure is currently at a low level (Rainwater et al., 2009).

Pollutants are also likely to interact with the microbiome - the community of microscopic organisms that live in and on animals and influence many aspects of their physiology. Environmental exposures to chemical pollutants can alter host microbial communities through absorption, inhalation, and consumption, eliciting specific physiological responses from the nervous, endocrine, and immune systems (Peisl et al., 2018). For example, exposure to the pesticide chlorpyrifos resulted in a decrease in beneficial bacteria and increases in gut permeability and inflammation in mice (Yuan et al., 2019), as well as inducing obesity and insulin resistance (Liang et al., 2019). Giving these mice a broad-spectrum antibiotic affecting their gut microbiota reversed the effects. Examples of pesticides impacting the gut microbiome of wild animals are accumulating (Kakumanu et al., 2016; Lozano et al., 2018). Similarly, exposure to pharmaceuticals is associated with changes in the gut microbiome, especially for antibiotics (Suez et al., 2018). A range of additional pharmaceuticals are likely to influence the gut microbiome given the overall propensity for bacteria to metabolize a diverse suite of xenobiotics (Javurek et al., 2017). Few empirical data have linked pollutants, such as microplastics and nanoparticles, to changes in the gut microbiome, but potential mechanistic links have been identified (Fackelmann and Sommer, 2019).

The extent to which shifts in wild animal microbiomes associated with pollutants are a symptom of other health impacts of pollutants or augment health via novel pathways remains to be understood. Human studies have demonstrated that the gut microbiome degrades pharmaceuticals (Abdelsalam et al., 2020), studies of insects demonstrate microbially-conferred resistance to insecticides (Kikuchi et al., 2012), and a subset of naturally occurring microbes can degrade plastics (G.-H. Wang et al., 2020). However, there will be limits to these microbial services. The extent to which the microbial genes that provide these services are distributed across habitats and animal species is unknown, as is the capacity of the gut microbiome to change fast enough to keep up with environmental change. Additionally, in some cases, the byproducts of microbial degradation of chemical compounds can be as detrimental to hosts as the original compounds, if not more (Claus et al., 2017).

4. Interaction of pollution with other changing environmental factors

While pollution is a direct threat to animal health, it also interacts with a range of other anthropogenic impacts on habitats. To illustrate how chemical contaminants could interact with the changing environment, we consider a tropical system where primate populations inhabit forest fragments that are adjacent to agricultural land; a tropical system some of us have worked on for many years (Chapman et al., 1999; Chapman et al., 2013; Chapman et al., 2007a; Chapman et al., 2006c). Forest loss and fragmentation is a global problem affecting most tropical terrestrial mammals. Globally, ~60 million ha of tropical primary forest were lost between 2002 and 2019, with the most forest loss occurring in Brazil (24.5 Mha), Indonesia (9.5 Mha), and the Democratic Republic of the Congo (4.8 Mha) (Weisse and Gladman, 2020). This loss not only resulted in a reduction of forest area, but large tracts of forest were divided into progressively smaller fragments. Today, large areas of intact forest are rare and many species only inhabit small forest fragments in human-dominated landscapes (Benchimol and Peres, 2013; Estrada et al., 2017; Strier, 1994). In fact, areas of continuous tracts of forest larger than 500 km^2 suitable for large populations comprise only 20% of remaining tropical forests and these forests are disappearing at a rate of 7.2% each year (Potapov et al., 2017). Only 12% of these areas are protected (Potapov et al., 2017). In the next 50 years the number of fragments is projected to increase 33-fold and the mean size of these fragments will decline to between 0.25 and 17 ha (Taubert et al., 2018).

Forest fragmentation leads to reduction of forest area and dramatic increase in forest edge. These edges trap pollutants that are coming from adjoining agricultural and urban areas. In fact, pollutant concentrations can be up to 56% higher on the forest edge than in the interior (Weathers et al., 2001). As the land adjacent to the fragments will typically be used for agriculture and human settlement, the animals will likely experience a greater exposure to a range of chemicals, including plastics being disposed of by burning. Animals will also breathe air whose quality is affected by large regional fires and the many small fires set to prepare fields for planting or promote growth of new grasses for cattle. If the animals enter the agricultural land to crop raid, they will be directly exposed to pesticides and since crops are typically fertilized by applying animal dung (Jiménez et al., 2009), they are likely ingesting pharmaceuticals used to treat domesticated animals. Depending on the region, they may be stressed by hunters (Sales et al., 2020) and must deal with the stress of encountering dogs (Serio-Silva et al., 2019). In addition to the stress of this increased pollutant exposure, animals in these fragments can both have elevated parasite levels and a poorer diet compared to animals in continuous forest (Chapman et al., 2015; Chapman et al., 2007b; Chapman et al., 2006a). A study of endangered red colobus found that cortisol levels of animals in fragments, a hormone involved with the vertebrate stress response and general energy metabolism (Bercovitch and Ziegler, 2002; Creel et al., 2002), was 3.5 times that of animals from continuous forest (Chapman et al., 2006b). Teasing apart the impacts of such diverse, interacting perturbations will be exceedingly difficult, and would involve a very well-funded, interdisciplinary effort that is rarely seen. However, this does not alter the reality that these interactions are occurring in most human-altered ecosystems.

5. What needs to be done

Despite ample research demonstrating the negatives effects of chemicals released into the environment (Landrigan et al., 2018), strong public support for protecting the environment (Feinberg and Willer, 2013), inequitable distribution of exposure to toxic chemicals that calls for fairer treatment (Landrigan et al., 2018), and decades of legislation and litigation (Chiapella et al., 2019), it is clear society has failed to protect environmental health. Society is not effectively adopting a precautionary principle, rather it is allowing new chemicals and forms of environmental contaminants to be generated in huge quantities and only responding well after the negative consequences of these actions are made apparent, if even then.

Let us provide one example following an environmental contaminant from its creation to the present day. Many people will be aware of Bisphenol A, or BPA. This is a synthetic monomer and estrogenic compound that was first used in 1958 in polycarbonate plastics, epoxy resin linings of canned foods and beverage containers, and as dental sealants (Seachrist et al., 2016). It became well known because of public demand to have it removed from our water bottles. In 1982 it was shown to cause cancer in rats (Seachrist et al., 2016). In 2007, a panel of experts assembled by the National Institutes of Health (NIH) and the Environmental Protection Agency (EPA) in the United States reviewed the extensive research that was available and concluded that BPA is an endocrine disruptor and is likely associated with increased breast and prostate cancer (Seachrist et al., 2016). In 2008, Canada banned the use of BPA in products for infants (Lofstedt, 2013). In 2009, a review published in the Proceedings of the Royal Society B demonstrated health effects in a wide range of aquatic organisms. In 2012, the use of BPA was banned in baby bottles and infant formula packaging in the United States. Yet, it is still widely used globally. In 2003, more than 2.7 million metric tons of BPA were made and in 2015 production increased to 4.9 million metric tons. Over 90% of people tested in the US have detectable levels of BPA in their bodies (Seachrist et al., 2016) and the EPA estimates 500,000 kg leach into the environment each year. The market value of BPA production was expected to be USD $20 billion in 2020 (Grand Review Research, 2020). Thus, despite strong evidence concerning its dangers to the health of people and wildlife and strong public knowledge of its dangers (Lofstedt, 2013), this chemical is not only widely used, but its use is increasing. Together with BPA, the use of its replacements (i.e., BPS) is on the rise, despite studies showing rapid and negative health effects (Ferguson et al., 2019). This cycle, where a chemical is replaced with a substitute of equal, if not worse, environmental and health outcomes, is referred to as “regrettable substitution”. Like BPA and BPS, other examples include flame retardants like tris (1,3 dichloro-2-propyl) phosphate (TDCPP) or polybrominated diphenyl ethers (PBDEs) which were replaced with organophosphate esters.

Our evaluation of the exposure of terrestrial wildlife in the tropics to pollution-pesticides, pharmaceuticals, and plastics reveals a very diverse set of problems and point to a strong need to improve the overall governance of toxic chemicals globally. In tackling these problems much can be learned from past efforts to regulate chemical use (Chiapella et al., 2019) and from efforts to respond to acid rain, ozone depletion, and climate change (Grennfelt et al., 2020; Morrisette, 1989). International efforts to regulate acid rain and ozone depletion are considered by many to represent a success story, particularly in North America and Europe. In contrast, attempts to mitigate climate change are only now beginning to make progress (IPCC, 2014, 2021). Dealing with each of these issues required producing extensive **credible scientific information** delivered to the public and policy makers. The role of scientists has been as “honest brokers” (Pielke Jr, 2007).

To achieve similar sorts of advances with new environmental contaminants will require the **creation and coordination of teams and**

networks. The efforts to control air pollution and climate change required strong networks of scientists and policy makers to push politicians to initiate change (Grennfelt et al., 2020). These networks can present a unified voice to lobby support, change consumer preferences, and pressure industry. Given the diversity of the contaminants and their sources, the difficulty of monitoring wildlife health and population size, and the complex cultural landscape in which change will have to occur, the coordination of similar multidisciplinary teams of international collaborators will be essential.

The creation of credible scientific information will require the **development of long-lasting infrastructure** that both continuously monitor the impacts of environmental contamination and generate science-based policy options. With respect to acid rain, infrastructure to monitor atmospheric concentrations, cross-border transport, and deposition of air pollutants was established in 1970. The information derived from this monitoring formed the basis for the Convention on Long-Range Transboundary Air Pollution in 1979 and one of the first steps to meaningful regulation (Grennfelt et al., 2020). The infrastructure needed to monitor the impacts of environmental contamination on wildlife will require long-term monitoring of exposure and population dynamics at field stations around the globe. These field stations will result in collateral conservation gains (Sarkar et al., 2019). The time may be right to instigate such efforts as they can be coupled with the call for monitoring of emerging infectious diseases from wildlife following the coronavirus pandemic (Bernstein et al., in press).

Producing this information will require **training and mobilizing scientists** from around the world. Ultimately, while the benefits will be reaped globally, the ownership of the solutions must rest with the people who ultimately bear the costs and/or reap their benefits. Thus, significant investment must be placed in building the education, research, and management capacity in many tropical developing countries. This training must involve an education system that promotes a connection with nature and wilderness (Kareiva, 2008; Zaradic et al., 2009). Data on wildlife exposure does not stand on its own and needs to be contextualized to make it useful. Thus, researchers will need to spend considerable time in the field attempting to understand pathways of exposure and causes of population stress that could act in combination with contaminants to negatively impact populations (Sarkar and Chapman, 2021). Furthermore, to derive effective policy options, it often takes considerable effort and time in the field interacting with local communities to understand their needs and working with policy makers to realize their constraints (Chapman et al., in review).

Ultimately, scientists must **produce and communicate information that will effectively inform policy decisions and motivate action**. This requires that the information produced be salient (relevant and timely), credible (authoritative, believable, and trusted), and legitimate (developed via a process that considers the values and perspectives of all actors) in the eyes of researchers, policymakers, media, and agents that create action (Cook et al., 2013). The growing demand for better synergy between science and policy and the meaningful implementation of their recommendations has led to new environmental frameworks for both research and society (Völker et al., 2019; Watson et al., 2020). In particular, there is a move away from focusing on the gap between research findings and their implementation, towards more attention on properly contextualizing the lessons from successes, as well as challenges (Cvitanovic and Hobday, 2018; Toomey et al., 2017). Within the science-to-action context, 'communication strategies' are explicitly a part of a 'political strategy'. All too often environmental protection is poorly presented to society so that it appears to be a costly trade-off where social and economic opportunities are forfeited to achieve environmental protection that may or may not be needed. It is hardly surprising, therefore, that environmental protection is sometimes seen to be placed above the individual's welfare - the paycheck that comes at the end of the week or the amount of crop that can be produced to support a family. New and better ways of communicating with and educating the public, lobbyist, industry, and policymakers are needed – including a tool kit that converts scientific information into legally binding policy and action. One important component of this tool kit will be efforts to promote the co-creation of scientific knowledge and policy options between scientists and policy makers.

Today, wildlife's exposure to anthropogenic chemicals is greater than ever given the amounts being produced. New dangers are becoming recognized, such as those from microplastics and nanoparticles. However, many of the answers to the question of how to find policy options to contaminants are known and the path of how to construct a healthier planet is discernible. The question that needs to be asked is whether humanity has the will to do the right thing and forge a healthy and equitable future for people and wildlife.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence this work.

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