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A Planetary Health Approach to Study Links Between Pollution and Human Health

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Abstract
The purpose of this review is to provide an understanding of the links between pollution and human health, pollution and planetary health, and planetary health and human health from the perspective of the anthropogenic activities that have had the most significant impact on these relationships including food pollution, transportation, and electricity production-related pollution, consumerism-related pollution, and agriculture-related pollution. The literature tells us that most pollution is being driven by anthropogenic activities used to sustain our species, our economies, and our consumption-based lifestyles. These activities and their subsequent pollution are driving at least eight of the nine planetary boundaries and are having profound impacts on both human and planetary health to the peril of the survival of many species including our own. Given that the two core planetary boundaries, climate change and biodiversity loss, have been crossed, and that the IPCC 2018 report calls for emissions reductions of 45% from 2010 levels by 2030, reaching net zero around 2050 to limit global warming to 1.5 °C, it would seem that avoiding catastrophe and meeting the basic needs of the global populace will require nothing less than a rapid reduction of fossil hydrocarbon use in addition to a drastic reduction in ruminant meat consumption. Further research is needed, however, the urgency of the current planetary state requires action and, therefore, applied and outcomes research of initiatives that address these issues.

Keywords Planetary health · Planetary boundary · Pollution human health · Climate change · Anthropocene

Introduction

The focus of this review will be on (i) the current state of global pollution and (ii) chemical pollution as a planetary boundary, and their relationships to human health.

Pollution has always accompanied humans. Indoor air pollution from inadequately ventilated open fires has existed since humans created the first fires. [1] Metal forging may have been the first occupational exposure as indicated by core samples of glaciers in Greenland which reveal increased levels of pollution associated with metal production in the early Greek, Roman, and Chinese civilizations. [2] Glacial analysis reveals that environmental lead levels nadired only once in the last 2000 years. This was a result of an interruption of metal production that accompanied the economic and population collapses during the Black Death pandemic. [3]

As the total human population has increased, pollution has likewise grown sharply. As of 2015, pollution was responsible for 16% of all deaths globally, and an estimated 9 million premature deaths, making it the largest cause of morbidity and premature mortality due to environmental causes. [4]

Humans, from the beginning of our existence, have used the natural resources of the planet to feed, clothe, and house ourselves. The abundance of natural resources including the soil, water, plants, animals, and most especially, fossil fuels, have allowed us to emerge as a dominant species. The two events that have resulted in the most anthropogenic pollution are The Agricultural Revolution and the Great Acceleration, "which refers to the most recent period of the proposed Anthropocene epoch during which the rate of impact of human activity upon the Earth's geology and ecosystems is increasing significantly." [5] It is now commonly accepted that

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human activities have driven the Earth into the Anthropocene, a new geological epoch. The suggested start date of the Anthropocene and The Great Acceleration coincides with the industrial revolution and the invention of the steam engine in 1784. [5]

The Great Acceleration and humanity's dramatic impact on the natural planetary systems upon which we depend would not have been possible without cheap and plentiful fossil fuels. While the use of fossil fuels has made possible the improvement of the health of the average global citizen over the past century, planetary health has declined dramatically, as evidenced by climate change and increased levels of pollution of all kinds. Human activities have inspired an unprecedented and profound transformation of the natural world, particularly within the last 300 years. Since the industrial revolution and the global population boom, the terrestrial biosphere has been converted to one marked by human endeavors. What was once a mostly wild, untouched land [6] has been transformed by agriculture, manufacturing, and human settlements into an anthropogenic biosphere in which over half of the Earth's ice-free land is now range- and croplands, and dense settlements with over half the global population now living in cities. [7] As a result, "the health gains achieved in the past 50 years of global economic development could be reversed by 2050 due to the consequences of climate change" [8] and the negative human and planetary health impacts of human-derived pollution will continue to rise.

Current State of Global Pollution and Its Impacts on Human and Planetary Health

Planetary health refers to "the health of human civilization and the state of the natural systems on which it depends". Planetary health characterizes the connections between "human-caused disruptions of Earth's natural systems and the resulting impacts on human health " [9] and is a critical discipline for understanding the links between pollution and human health, pollution and planetary health, and planetary health and human health.

Most pollution is being driven by anthropogenic activities used to sustain our species, our economies, and our consumption-based lifestyles. These activities and their subsequent pollution are having profound impacts on both human and planetary health. As such, the focus of this review will be divided into the categories of:

- Food Pollution
- Transportation and Electricity Production-Related Pollution
- Consumerism-Related Pollution
- Agriculture-Related Pollution

Food Pollution

Food pollution is generally defined as "the presence in food (or associated with food) of toxic chemicals, elements, or compounds and/or biological contaminants which are not naturally present in food, or are above their natural background levels for those chemicals which are naturally found in some foods." [10]

The Global Burden of Disease study tells us that globally, in 2017, dietary risks and their consequent non-communicable diseases (NCDs) were responsible for 22% of all deaths and 15% of all disability-adjusted life years (DALYs) among adults. The dietary risks include both low consumption of healthy foods (nuts and seeds, milk, and whole grains) and high consumption of unhealthy foods (sugar-sweetened beverages, processed meat, sodium-laden foods, and red meat). [11] However, what is often not discussed is that food is often a vector for many chemical pollutants that are both persistent in the environment and impact death and disability from NCDs in ways that are additive or perhaps synergistic [12]. Of the 21 compounds designated as persistent organic pollutants (POPs)[1] by the Stockholm Convention [13], the primary exposure to humans, for at least 11, is through food, primarily animal foods [13].

As an example, the link between meat consumption and cancer incidence may be, in part, due to the presence of carcinogenic contaminants on or in it. A study of meat (beef, chicken, and lamb), which tested for 33 carcinogenic pollutants [14], revealed that "no meat sample was completely free of carcinogenic contaminants and the differences between organically and conventionally produced meats were minimal." Because environmental contamination by POPs is ubiquitous, organic food production practices are unable to prevent contamination. This is alarming given that researchers also examined the safe limits of meat consumption for the given population and found that current patterns of meat consumption exceed them. According to the authors, "These limits are set according to the levels of contaminants which is directly associated with a relevant carcinogenic risk. Strikingly, the consumption of organically produced meat does not diminish this carcinogenic risk, but on the contrary, it seems to be even higher, especially that associated with lamb consumption." [14]

Endocrine-disrupting chemicals have been linked to the rising incidence and prevalence of multiple diseases over the

[1] "Persistent organic pollutant-persistent organic pollutants (POPs) are organic compounds that are resistant to environmental degradation through chemical, biological, and photolytic processes. Many POPs are currently or formerly used as pesticides, solvents, pharmaceuticals, and industrial chemicals. Although some POPs arise naturally, most are man-made. POPs typically exhibit high lipid solubility and, as such, bioaccumulate in fatty tissues. They also tend to exhibit great stability in the environment, exerting their negative effects on the environment via long-range transport and bioaccumulation, often times, in the food chain." [9]

last 50 years. Many POP's have endocrine-disrupting properties, including bisphenol A (BPA), some organochlorines, polybrominated flame retardants, perfluorinated substances, alkylphenols, phthalates, pesticides, polycyclic aromatic hydrocarbons, alkylphenols, solvents, some cleaning products, air fresheners, hair dyes, cosmetics, sunscreens, and some metals. Endocrine disruptors act primarily through estrogen and estrogen-related receptors. They also induce oxidative stress through modulation of nitric oxide and act epigenetically through DNA methylation [15] leading to a host of diseases and developmental defects including breast, prostate, and testis cancers; diabetes; obesity; autism; Parkinson's disease; Alzheimer's; Amyotrophic Lateral Sclerosis (ALS); Multiple System Atrophy (MSA); and decreased fertility and endometriosis. [16]

Because of their ubiquity, human exposure to POPs starts before conception. Effects on sperm and ova can impact a child's health. During pregnancy when maternal fat stores are mobilized, the fetus can be exposed through the placenta and postnatally via breast milk. [17]

Maternal exposures to POPs can result in modifications to fetal genes that not only affect the health of the infant throughout its life but that can be transmitted to daughter cells and passed down for as many as 4 generations. [18–20] An example of this was seen when a group of researchers exposed pregnant rats to the insecticide methoxychlor and the fungicide vinclozolin. Decreased sperm production and increased male infertility in the exposed male pups were noted as a result of epigenetically altered genes. Even without additional exposures, these adverse effects persisted in 90% of the males in the four subsequent generations. (21) This effect has also been seen in humans. One study examined newborns with mothers who smoked daily during pregnancy. The newborns of smoking mothers had 6073 locations of epigenetic DNA modification. Almost half of these alterations occurred at gene sites which were associated with the nervous system and lung development, cleft lip and palate, and smoking-related cancers. In another analysis, these DNA modifications persisted even in older children. [18, 21] Perinatal exposure (in the womb or during breastfeeding) to background dioxin levels can permanently impair semen quality in adult male offspring. [22]

Because POPs are often lipophilic, they bioaccumulate and pass through the food chain. This biomagnification leads to POP levels in organisms at the top of the food chain that are hundreds of magnitudes of order higher than at the lowest plant trophic level. [23, 24] Unfortunately, human babies are often at the highest trophic level. Through pregnancy and breastfeeding, mothers can pass as much as 20% of their lifetime accumulated load of POPs to their infants. [25] Serum concentrations of perfluorinated alkylate substances (PFAS) in infants can be up to 30% higher on a monthly basis with exclusive breastfeeding as compared to partial breastfeeding. [26] Reduction of maternal POP burden to the infant through breastfeeding may contribute to the protective effect of breastfeeding for breast cancer. [27]

Human exposure to POPs most often comes from the ingestion of food (mainly fish, meat, and dairy products). Exposure also occurs through inhalation and dermal absorption, though to a lesser extent. Toxic substances persist in nearly all bodies of water and are absorbed by microplastics, all too commonly found in water as well. [28, 29] The chemical constituents of plastics, in addition to the chemicals and metals they absorb, bioaccumulate in the marine life that consumes them, [30–33] eventually climbing the food chain to humans. These microplastics and their accompanying contaminants are of concern given their links to cancer development. [34, 35]

Glyphosate is the most commonly produced herbicide globally. [36] Because of its recent implication in a well-publicized case of non-Hodgkin lymphoma, it is worth addressing independently. [37] In 1987, US farmers and ranchers applied 6–8 million pounds [38] of the chemical and by 2014, that had increased to 240 million pounds annually. [39, 40] In 2015, the International Agency for Research on Cancer (IARC) classified glyphosate, the active ingredient in Roundup®, as "probably carcinogenic to humans" (Group 2A) based on "limited evidence of carcinogenicity in humans for non-Hodgkin lymphoma and "convincing" evidence that glyphosate also can cause cancer in laboratory animals." [36] Most human exposure is through residential use and diet and evidence exists that toxicity of glyphosate-based herbicides (GBHs) persist despite most exposure levels meeting low, set safety limits. [41]

While glyphosate has historically been perceived as non-toxic, according to Mesnage et al. [42], because of synergy with other ingredients, Roundup® was 125 times more toxic than glyphosate by itself. These authors wrote: "Despite its relatively benign reputation, Roundup® was among the most toxic herbicides and insecticides tested." [43]

Meyers, et al., in their consensus statement regarding concerns overuse of GBHs, concluded that "glyphosate and its metabolites are widely present in the global soybean supply; human exposures to GBHs are rising; and that regulatory estimates of tolerable daily intakes for glyphosate in the United States and European Union are based on outdated science." [44] Residues of glyphosate and one of its metabolites have also been found in processed foods, such as bread. Testing conducted in the UK in 2012 found that 27 out of 109 samples of bread contained glyphosate residues at or above the set safety limit of 0.2 mg/kg [45].

Because multiple different pesticides have similar mechanisms of action, it is possible that synergistic and/or cumulative effects of consuming small amounts of various pesticides through food pose risks to health, however, this remains unclear. [46, 47]

Food Waste Impact on Planetary Health

According to United Nations (UN) Food and Agriculture Organization estimates, about 1.3 billion tons or one-third of all food produced is lost or wasted on an annual basis worldwide. [48] Food losses occur all along the supply chain; however, in developed nations, approximately 30% is lost at the retail and consumer levels and another 20% is lost at the time of harvest, sorting, and grading [49].

In the US in 2015, 30.3 million tons of food waste went to landfills, representing 22% of all municipal solid waste (MSW) landfilled, making it the single largest component of MSW in landfills. [42, 50] In 2017, MSW landfills in the US emitted approximately 14.1% of all human-related methane, a potent greenhouse gas that can trap heat 34 times more effectively than carbon dioxide. [50] According to a report from the UK, the carbon footprint of food waste in landfills is equivalent to that of one-fifth of all the cars on the road in the country. [51] Interestingly, moving from the standard US diet to a lacto-ovo vegetarian diet would roughly reduce emissions to the same extent as eliminating all retail- and consumer-level food losses (30% vs 28%). [52]

Transportation and Electricity Production-Related Pollution

Worldwide, in 2015, fossil fuels accounted for 79.7% of the total primary energy supply [53] and by 2040, rapid growth in developing countries is expected to increase global energy demand by a third. It is anticipated that fossil fuels will still provide approximately 75% of total primary energy supply in that year. [54] In 2015, 33.2% of US electricity came from coal, 32.7% from natural gas, 20% from nuclear power while only 13% came from renewable energy sources. In the transportation sector, oil accounts for 92% of all consumption. [55] Globally, in 2015, 65.24% electricity was produced from coal, oil, and natural gas. [56]

Despite their positive impacts on our standard of living, fossil fuels have significant negative human and planetary health impacts because they are the primary source of local air pollution as well as carbon dioxide (CO_2) and other greenhouse gases. [56]

Human Health Impacts

The combustion of fossil fuels for electricity production, heating, transportation, and industry creates the majority of air pollution worldwide. [57] Eighty-five percent of airborne particulate matter (PM) pollution, and almost all sulfur dioxide and nitrogen oxide emissions are the result of fossil fuel combustion for energy and biomass burning in high- and middle-income countries and low-income countries, respectively. [58]. Mercury, black carbon, polycyclic aromatic hydrocarbons (PAH), and volatile chemicals that form ground-level ozone (O3) are also emitted in the process. Additionally, large-scale open burning of crop residue and wood in rural regions can increase air pollution in cities during winter and autumn months, by 25–59%. [59]

According to the World Health Organization, “particulate pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead are the six major air pollutants which harm human health.” [60] These, along with other suspended materials such as dust, fumes, smokes, mists, gaseous pollutants, volatile organic compounds, PAHs, and halogen derivatives in the air cause vulnerability to many diseases including cancer, respiratory diseases, and arteriosclerosis with long-term exposure. [61] Additionally, short-term exposure peaks of these pollutants can cause exacerbation of bronchitis, asthma, and other respiratory diseases [61]

Air pollution levels also cause neurological complications in exposed populations. A link has now been made between (ALS) and long-term exposure to traffic-related air pollution. [62] There also appears to be a relationship between air pollution and neurobehavioral hyperactivity, criminal activity, and age-inappropriate behaviors, with some studies revealing that aggression and anxiety in megacities correlate with high levels of air pollutants. [62, 63] Suicide has been linked to air pollution levels [64] and increased risk of adolescent psychotic experiences. [65]

There is also now evidence that link between exposure to air pollution and risk of autism spectrum disorders (ASD) may actually be causal in nature. [66] Some studies have also revealed relationships between air pollution exposure and fetal head size in late pregnancy, fetal growth, and low birth weight, [67] and stunted growth [68].

Evidence also suggests a significant association between increased particulate matter (PM) exposure and the risk of diabetes. It appears that burden of diabetes attributable to air pollution, for 2016, was approximately 3.2 million incident cases diabetes and about 8.2 million years of healthy life lost. [69]

While the negative health impacts of air pollution are often well-known, what is often less recognized is the magnitude of the problem. According to the WHO, globally, 91% of people live in areas where the air quality does not meet the WHO Guideline for healthy air and over half live in areas with air quality so poor that it does not meet even the minimum standards. [70] For example, approximately 300 million children breathe air that exceeds international pollution guidelines by at least six times [60]. Among global risk factors for mortality, air pollution ranks fifth and is only exceeded by lifestyle factors: poor diet, high blood pressure, tobacco exposure, and high blood sugar. [70] In 2016, air pollution was responsible for up to two-thirds of environmentally related years of life lost [71] and contributed to nearly 1 in 10 deaths globally in 2017 [70], making it the number one environmental risk factor, far surpassing other environmental risks such as unsafe water and lack of sanitation. [70]

Indoor (household) air pollution is also a significant environmental-related risk factor for human health. In 2017, 47% or 3.6 billion people were exposed to indoor air pollution from the use of solid fuels for cooking. [70] Between 1980 and 2012 there was a reduction in the use of solid fuels for cooking from 60 to 42%. [72] In 2017, anywhere from 22% of people in Yemen to 65% in Nepal to almost all people in South Sudan—total of 35.4 million—were still using solid cooking fuels. [70] Despite a decline in overall rates of usage globally, because of population growth, the absolute number of people exposed may remain stable or even increase. [70]

Planetary Health Impacts

Pollutants from transportation and electricity generation include those produced from the combustion of fossil fuels—air pollution and greenhouse gas emissions; mining—fossil fuel wastewater and soil pollution. All of these have significant impacts on ecosystems and planetary health, which ultimately impacts human health.

Air Pollution Particulate matter pollutants (PM) and its constituents (e.g., heavy metals and poly-aromatic hydrocarbons) have a significant impact on the structure and function of plants. These impacts include structural attributes such as leaf area and number as well as functional components such as pigment and enzyme levels and relative water content. [73] These deviations from expected structure and function are indicative of altered epigenetic expression.

This has significance for food security and climate change mitigation as air pollution impacts the ability of vegetation to pull CO_2 from the air for photosynthesis and impacts crop yield. Nitrogen oxides and volatile organic compounds, which are precursors to ozone, react to form ground-level ozone (O_3). [74]

This is of concern for global food security as published experiments have shown that, compared to ozone-free air, ambient ozone concentrations with an average of 40 ppb have reduced the yields of major food crops such as wheat, rice, soybean, and potato by about 10%. [75] A study performed in China revealed that current ground-level O_3 pollution resulted in wheat yield loss of 6.4–14.9% and future (predicted) ground-level O_3 pollution levels would subsequently reduce yields by 14.8–23.0%. [75]

Wheat and soybeans are particularly sensitive to O3 while potato, rice, and maize are moderately sensitive. Barley has been found to be O_3 resistant. This is concerning given that the most sensitive crops are staple foods for a majority of the global population. [74]

Soil Pollution Soil pollution attributed to transportation and electricity generation can result from oil spills, mining of fossil fuels and minerals used in the renewable energy sector, corrosion of underground storage tanks and pipelines, acid rain, road debris and runoff, oil and fuel dumping, and coal ash. Petroleum hydrocarbons, solvents, pesticides, lead, and other heavy metals including mercury, lead, chromium, and cadmium are most the most often implicated chemicals. Of these, lead contamination of soil is the most well studied.

The human health risks of lead exposure, even at very low blood concentrations, are well documented [4] and will not be reviewed here. Rather, the planetary health impacts of lead contamination will be highlighted.

Lead in the soil can be retained for up to 2000 years. As lead moves into and throughout ecosystems, adverse effects can occur. Lead concentrations of 10,000–40,000 ppm dry weight, levels not uncommonly found at roadsides, can destroy soil populations of bacteria and fungi, negatively impacting decomposition and the food web. Plants, microorganisms, and invertebrates exposed to lead concentrations of 500 to 1000 ppm can reduce their population numbers, allowing more lead-tolerant populations of the same or different species to take their place, which alters ecosystem type. Lead is also neurotoxic to non-human animals. Lead blood concentrations of above 40 μg/dl can result in clinical symptoms in domestic animals. Predators can also be exposed to toxic levels of lead that accumulates in their prey. [76]

As is the case with air pollution, lead and other heavy metal contaminants in soil negatively impact crop yields and contaminate food, rendering it inedible, which impacts food security. It has been estimated that grain yields in China have decreased by 10 million and 12 million tons due to soil contamination and food containing high residues of pollutants, respectively. Examination of the safety of rice in the Chinese market found that lead and cadmium are found at levels over maximum residue concentrations of 28.4% and 10.3%, respectively. [77]

Water Pollution Fossil fuel and nuclear power plants utilize as much water as all farms and more than four times as much as all US residences. Most of this cooling water (80%) comes from nearby lakes and rivers, which impacts local ecosystems and contributes to water stress [78].

Thermal pollution from return water degrades water quality as a result of changes in water temperature, disrupting aquatic ecosystems. Symptoms of stress such as tachycardia in fish and reduced fish fertility result, in part, from the warmer water itself and, in part, from the relative hypoxia of the warmer water. Temperature gradations can be quite significant. For a typical system, as many as 180 billion gallons of water is cycled through the power plant. The water that is then released can have temperatures as much as 25 °F warmer than when initially withdrawn from its source. [78]

Oil and gas extraction, as well as the preparation of coal for combustion, are also sources of chemical water pollution related to transportation and electricity generation. Coal slurry, a watery waste byproduct from washing coal prior to combustion, contains arsenic, mercury, chromium, cadmium, and other heavy metals. [79]. Of US coal combustion waste ponds and landfills, 42% lack protective linings, leading to leaching of these compounds into surface and groundwater supplies. [80–82].

During the extraction of oil and gas, groundwater carrying dissolved solids, heavy metals, hydrocarbons, and naturally occurring radioactive materials is brought to the surface. [79] These contaminated wastewaters, as well as spilled hydrocarbons, can leak into water ecosystems adhering to fish and waterfowl, destroying algae and plankton disrupting the primary food sources of aquatic organisms. Even in low concentrations, the heavy metals in wastewater can be toxic to fish, and once again, bioaccumulate, adversely affecting humans and larger animals that may consume them. [79]

Greenhouse Gases Carbon dioxide (CO_2) and other greenhouse gases (nitrous oxide and methane) are now considered pollutants as they are the cause of anthropogenic global warming and climate change.

The Annual Greenhouse Gas Index is used by the National Oceanic and Atmospheric Administration (NOAA) to track the influence of persistent greenhouse gases on warming and the climate. Between 1990 and 2016, the index increased by 40% mostly as a result of rising CO_2 levels [83]. Greenhouse gases are considered stock pollutants given that they impact the climate long after being emitted due to their persistence in the atmosphere for decades or even centuries. In order to prevent atmospheric accumulations of a stock pollutant, major reductions in emissions are required. [84]

CO_2 levels in the atmosphere are at their highest level in 800,000 years [85], rising from 320 ppm in 1965 to over 400 ppm in 2016. [84] Global warming and a changing climate have the potential to impact human health via sea-level rise; extreme weather events such as floods, droughts, storms, and heatwaves; and disrupted hydrological systems that can impact crop growth and food security. [86]

Each year, around 35 billion metric tons of carbon dioxide is released into the atmosphere. [87] In 2014, the transportation and electricity/heat production sectors were responsible for approximately 70% of CO_2 emissions. [86] Of this, approximately 42% was from liquid fuels, 32% from coal, and 27% from natural gas [88]. While the combustion of natural gas emits less CO_2 than other fossil fuels, [89] its production (drilling, extraction, and transportation) results in methane leakage, reducing its advantage. [90]

Consumerism-Related Pollution (Plastics)

Plastics have become central to our lives. Since their invention 65 years ago, they have been used and produced in abundance with annual production increasing from 15 million tons to 381 million tons between 1964 and 2015. [91] For context, this is roughly equivalent to the mass of two-thirds of the world population. [92] We have entered an age of consumerism with a global consumer class comprised of 3.6 billion individuals today which is expected to increase to 5.6 billion by 2030. As such, plastic production is expected to increase by 200% over the next 20 years. [93]

Single-use plastics are found in nearly everything including grocery bags, food packaging, drink bottles, straws, containers, cups, lids, cutlery, cigarette butts, and foam take-way containers. As of 2018, only 0.5% of all plastic is recycled worldwide. [94] As a result, there is now a "Great Pacific Garbage Patch" with more than 1.8 trillion pieces of plastic, covering nearly 1.6 million square kilometers, which is equivalent to an area twice the size of Texas or three times the size of France. [95]

Plastic is cheap and durable. These qualities contribute to both its ubiquity and its current and projected harm to the environment.

Planetary Health Impacts

In 2018, single-use plastics accounted for 43% of total marine litter on Europe's beaches and [93] by 2050 marine plastic pieces will outnumber fish in the ocean. [91] Plastic refuse in the oceans can become ensnared on coral reefs, stressing them through light deprivation, toxin release, and anoxia, increasing the likelihood of disease by 20-fold. [95]

Plastics contribute to climate change as they have significant, carbon-intense life cycles. Most plastics are derived from petrochemicals. Extraction and distillation of petroleum, product manufacture, and transport to market all emit greenhouse gases, as do disposal, incineration, and recycling. It is estimated that, in 2015, the life-cycle emissions from plastics produced that year were nearly 1.8 billion metric tons of CO_2, which is approximately 5% of total global emissions for 2015. [94]

While it is relatively well known that pulverized plastic waste (microplastics) used on land pollute the surface layer of the oceans, a recent study found that microplastics have been identified at depths ranging from 5 to 1000 m with the highest concentrations present at depths between 200 and 600 m. [96] As a result, plastic has been found in species spanning all levels of marine food webs.

Microplastics from automobile tire wear, household and laundry dust, industrial processes, and deterioration of plastic-coated surfaces occur in both urban and residential areas, entering municipal wastewater treatment plants. This contaminated water and sludge retains up to 90% of the microplastics and is often applied to agricultural soils, particularly in developing nations. This has unknown consequences for sustainability and food security but arguably could impact soil ecosystems, crops, and livestock via toxic and endocrine-disrupting substances in plastics. [97]

Human Health Impacts

Great ocean garbage patches threaten both marine and human life. As these materials are degraded, xenobiotics and other metabolites of decomposition are released creating an acute threat to human health. [98]

Cox et al. recently estimated Americans consume, on average, 39,000 to 52,000 microplastic particles annually. This estimate increases to 74,000 and 121,000 when considering inhaled microplastics. Consuming water from bottled sources can add another 90,000 microplastics annually, compared to an additional 4000 microplastics for tap water–only consumption. [99]

There is now evidence that constituent compounds of plastic are now ubiquitous in human blood and cells. [98] These substances include short/medium-chain-chlorinated paraffin, endocrinologically active alkylphenols, such as bisphenols, and flame retardants. Additionally, plastic polymers accumulate other harmful pollutants from the surrounding environment, including PCBs, dioxins, DDTs, and PAHs, which are known carcinogens. As such, these plastics particles can act as a vector, transferring these "persistent, bioaccumulative and toxic substances" from the water to humans. [97]

Even without additional accumulated toxins, micro- and nano-plastic particles can cross the placental and blood-brain barriers inducing immunotoxicological responses, altering gene expression, and causing cell death or apoptosis. These particles can also cause harm as they are taken up into the gastrointestinal tract and lungs. [100]

Agriculture-Related Pollution

According to Jared Diamond [101] "... the adoption of agriculture, supposedly our most decisive step toward a better life, was in many ways a catastrophe from which we have never recovered." Diamond argues that, "with agriculture came the gross social and sexual inequality, the disease and despotism, that curse our existence." [101] While his statements are open for debate, it could be argued that one of the ways that agriculture has been a catastrophe is from the perspective of pollution.

Global synthetic fertilizer application began in earnest around 1960. Since then, it has increased from approximately 930 kg/ha of arable land to over 1770 kg/ha in 2014, with a peak in 1999 at 2244 kg/ha. [102] Similarly, pesticide use by the largest consumers (China, Brazil, Argentina, and the US) is 2.8 million tons annually. [102] This is compared to 1.2 million pounds applied in those same countries in 1990, when tracking of pesticide application began. [103] Nearly all the growth in pesticide use is attributed to China.

While use of these agrochemicals has doubled crop production, on average, crop yield has stagnated or even declined in some regions. While fertilizer and pesticide use has increased for 35–40% of countries between 1960 and 2010, cereal production in 38% of countries and yields in 47% of countries have not kept pace or have even declined, mainly in Africa, South America, and West Asia. This is largely due to an imbalance of application. In wealthier, more developed nations, there has been a continuous increase in application and yield to the point of over-application leading to the runoff of excess nutrients that cannot be taken up by the crop. This, in conjunction with the destruction of the microbial soil web from pesticide use and soil erosion, is leading to a peak in yields for countries reliant upon industrial agriculture. Conversely, in poor and developing nations, yield has stagnated or decreased due to lack of access to these agrochemicals in conjunction with depletion of soil nutrients from annual agriculture. [104]

However, population growth and higher living standards have led to increased food demand. The increased demand and environmental pressures created by agrochemical use is predicted by some to be leading to a global food crisis. [104]

Planetary Health Impacts

Soil and Water Pollution No two nutrients have had such an impact on natural and agricultural ecosystems in terms of both degradation and production as nitrogen and phosphorus. Both are used to a significant extent in agriculture and, as a result, are having complex, harmful effects on ecosystems due to the excess loads that have been added to the biosphere. [105]

Only about 42–47% of the nitrogen added to agricultural lands globally is taken up by crops. Most of the rest is lost to the environment, [98] moving into fresh and groundwater systems, increasing groundwater pollution and nitrate levels in drinking water. These excess nutrients also lead to eutrophication which increases the frequency and severity of algal blooms, hypoxia and fish kills, and "dead zones" in aquatic ecosystems [106] where it poses threats to human and ecosystem health on local to global scales. In the US alone, 65 % of estuaries and coastal water bodies are at risk of eutrophication due to excessive nutrient inputs (nitrogen and phosphorus) that can lead to eutrophication. [107]

Certain pesticides impact biodiversity by impacting bystander organisms such as birds, amphibians, fish, and beneficial insects, pollinators primarily. [108] Pollinators have been in rapid decline, threatening global food security. Seventy-five percent of crops require insect pollination which is performed mostly by bees. [108] It is theorized that sublethal pesticide exposure on a routine basis can hamper the health of individual bees leading to collapse of already-weakened colonies. [108]

Neonicotinoids have been used in agriculture since the early 1990s, and are suspected to be partially responsible for Colony Collapse disorder and bee population decline more generally. As such, the European Union banned three neonicotinoids in 2013 in attempts to support pollinators. In 2018, the ban was extended [109]. Debate remains which of these insecticides contribute to pollinator collapse, and to what extent. Evidence reveals that other fungicides and insecticides are also associated with compromised health in colonies. [110]

A complete loss of pollinators would not likely impact overall food production. Global caloric supply would likely only be reduced by about 5–8%. However, it would result in a global deficit of fruits, vegetables, and stimulants like coffee, tea, and cacao. This is problematic as these foods provide most of the polyphenols and antioxidants in the diet. [108]

Soils that have been exposed to conventional methods of agriculture and chemical application sequester less water and less carbon. [111] This is particularly important because, with global warming, higher temperatures will increase demand for water but will also increase variability of rainfall, increasing risk of drought and flood. [112]

Air Pollution Once again, greenhouse gas emissions are the most significant form of agriculture-related air pollution given the implications of climate change as agriculture is responsible for 30–35% of global greenhouse gas emissions. Deforestation, methane from livestock and rice cultivation, and nitrous oxide emissions from fertilized soils are the primary emissions sources. [113] Global population growth and increased food demand will lead continued rising emissions due to the expansion and intensification of agriculture. [113]

Agricultural expansion is a prime driver of deforestation, responsible for up to 80% of forest loss. [114] Deforestation and conversion to agricultural land lead to decreased CO_2 sequestration and release of CO_2 from soils during tilling. This land use change is responsible for around 11% of all annual GHG emissions. The magnitude of land use change and its impact on biodiversity is stunning. Globally, “70% of grasslands, 50% of the savanna, 45% of temperate deciduous forests, and 27% of tropical forests have been cleared or converted for agricultural use.” [113] A prime example of this is the continued deforestation of the Amazon. Nearly 20% of the Amazon has been deforested and it is estimated that reaching 40% deforestation would trigger a “tipping point” that could cause climate impacts leading to further forest loss. [115]

One gallon (3.79 l) of gasoline can do the work of 100 humans, each working for 1 h. This fact explains why fossil fuels have replaced human and animal labor to such a degree and allowed for intensified agricultural systems. Fossil fuels have also allowed for land use changes that increased field sizes and allowed for monocropping, through the use of heavy machinery and petroleum-based agrochemicals, while reducing biodiversity. Fossil fuels supply 99.95% of the energy calories required to grow an acre of corn in the US today and often, the food contains only one-fourth of the fossil fuel calories expended in growing it. [116]

Lifecycle emissions of various foods depend on both the type of food and the way in which it was raised or grown. However, whether the GHG emissions are determined on a per kilocalorie, per gram of protein, or per serving basis, animal foods have the highest greenhouse gas emissions with the highest emissions resulting from ruminant meat, recirculating aquaculture, and trawling fishery. [117].

Additionally, the growing middle class described earlier has led to significant increases in meat consumption. The average per capita global annual meat consumption for 2013 was 43 kg and for dairy, it may 85 kg. This is compared to an average annual global consumption per capita of 28 kg of meat and an approximate 79 kg of dairy in 1970. According to a 2018 report by Greenpeace, in order to avoid dangerous warming, consumption rates must fall to 22 kg by 2030, and then to 16 kg by 2050 for meat and to 57 kg by 2030 and to 33 kg by 2050 for dairy to avoid dangerous warming. For reference, the average annual per capita meat and dairy consumption currently reside at 115 kg and 255 kg for meat and dairy in the US and at 85 kg and 260 kg for meat and dairy in Western Europe. [118]

Research findings from the Institute for Agriculture and Trade Policy suggested that “together, the world’s top five meat and dairy corporations are now responsible for more annual greenhouse gas emissions than Exxon, Shell or BP”. By 2050, in order to limit global warming to 1.5 °C, global GHG emissions must be reduced by 38 billion tons. If emissions reductions in all other sectors meet those reduction goals but the predicted growth of the meat and dairy industries is realized, the livestock sector would consume 80% of the allowable GHG budget. [119]

Similarly, project findings from the Johns Hopkins Center for a Livable Future showed that “if global trends in meat and dairy intake continue, global mean temperature rise will more than likely exceed 2 °C, even with dramatic emissions reductions across non-agricultural sectors. Immediate and substantial reductions in wasted food and meat and dairy intake, particularly ruminant meat (e.g., beef and lamb) are imperative to mitigating catastrophic climate change.” [120]

As discussed previously, global food security is threatened by O_3 pollution. It is estimated that O_3 causes global crop losses of 6–16% for soy, 7–12% for wheat, and 3–5% for corn (maize). [74]

Human Health Impacts

Clearly, the concern over a global food crisis has wide-ranging implications for human health. More specifically, however, pollinator-dependent crops provide many micronutrients, including vitamins A and C, calcium, fluoride, and folic acid. Pollinators, thus, supply important components required for human diets and pollinator losses could increase the global rates of preventable diseases. One group of researchers quantified the nutrient composition of pollinator-dependent foods and estimated that a complete loss of pollinators could result in a 1.42 million increase in global, annual deaths from non-communicable diseases while simultaneously increasing disability-adjusted life years (DALYs) by 27.0 million. A 50% loss of pollination services could lead to an additional 700,000 deaths and 13.2 million DALYs annually. [121]

Pesticides are also of concern due to their exposure-related links to multiple cancers (breast, colon, lung, ovarian, pancreatic, kidney, testicular, and stomach) and their neurotoxicity. Currently, there are more than 17,000 pesticide products in use. [122] The most commonly used pesticide, glyphosate, has already been discussed.

Atrazine, the second most commonly used pesticide in the US, is the most commonly detected pesticide contaminating surface water in the US. [123] Atrazine levels often exceed the maximum contaminant level (3 μg/L) set by the EPA for drinking water. Concentrations that exceed 0.1 parts per billion have been shown to produce deformities in frogs due to its endocrine-disrupting nature. Additionally, exposure to atrazine in drinking water, particularly in pregnancy, has toxic fetal effects and is associated with lower birth weights among term infants. [123]

Via a similar mechanism to antibiotic resistance, agricultural fungicide use has been implicated in the rise of resistance to anti-fungal medications having serious consequences for immune-suppressed individuals, in particular. [124]

Antibiotic resistance has become a health threat on a global level and is often linked with non-judicious use in clinical settings however routine use in veterinary settings at sub-therapeutic doses is the primary culprit. In order to meet rising demand for meat, production has shifted from pasture-based systems to confined systems (CAFOs (Concentrated Animal Feeding Operations)) that utilize several veterinary pharmaceuticals, especially antibiotics, to speed and augment animal growth, reducing time to market. The livestock waste, containing both antibiotics and antibiotic-resistant organisms, is not adequately managed in these feeding operations leading to water contamination and causing a growing public health concern over antibiotic-resistant infections. [125]

Nitrate contamination of drinking water has been associated with birth defects when consumed by pregnant women [126], including blue baby syndrome, and with certain types of cancer among adults, including stomach, colorectal, non-Hodgkin lymphoma, thyroid, and ovarian. [127] Lastly, corn (maize) production is associated with 4300 premature deaths annually in the US due to reduced air quality from fine particulate matter, PM2.5, due to ammonia emissions from nitrogen fertilizer use. [128]

Chemical Pollution as a Planetary Boundary and the Implications for Human Health

In order to characterize complex, global environmental change and its links to human health, utilizing the construct of planetary boundaries as a systems approach is helpful.

In 2009, Rockström et al. proposed a set of planetary boundaries that delineate a "safe operating space for humanity". [129] The International Geosphere-Biosphere Programme (IGBP) further expanded this definition as: "Earth's interacting physical, chemical and biological processes including the land, oceans, atmosphere and poles, the planet's natural cycles such as the carbon, water, nitrogen, phosphorus, sulfur, and other cycles, deep Earth processes and life". [130]

Nine planetary boundaries were identified.

1. Climate change
2. Ocean acidification
3. Stratospheric ozone
4. Global phosphorus and nitrogen cycles
5. Atmospheric aerosol loading
6. Freshwater use
7. Land use change
8. Biodiversity loss
9. Chemical pollution and the release of novel entities

For the boundary described as "chemical pollution and release of novel entities", no clear definition was provided as the group was unable to quantify a boundary for chemical pollution. However, it was determined that "the risk of crossing Earth system thresholds is sufficiently well-defined for it to be included in the list as a priority." [131]

Persson et al. proposed that there is "no single chemical pollution planetary boundary, but rather that many planetary boundary issues are governed by chemical pollution." This is demonstrated by the fact that five of the nine planetary boundaries are governed by chemical agents: ozone depletion (halocarbons), climate change (CO2, CH4, and other climate-forcing agents), ocean acidification (CO_2), the nitrogen and phosphorus cycles, and chemical pollution. [132]

Currently, of the seven boundaries that have defined thresholds, four have been breached (climate change, loss of biosphere integrity, land-system change, altered biogeochemical cycles (phosphorus and nitrogen)). [133] However, lack of a defined threshold for two of the boundaries (chemical pollution and atmospheric aerosol loading), has the potential to lull society into a sense of complacency regarding those boundaries. Rather, it should be recognized that "...the relatively stable, 11,700-year-long Holocene epoch is the only state of the Earth Systems (ES) that we know for certain can support contemporary human societies." And that, "There is increasing evidence that human activities are affecting ES functioning to a degree that threatens the resilience of the ES—its ability to persist in a Holocene-like state in the face of increasing human pressures and shocks." [133]

The various types of pollution driven by anthropogenic activities that have been reviewed here (food pollution, transportation and electricity production-related pollution, consumerism-related pollution, and agriculture-related pollution) are driving those five boundaries governed by chemical agents. However, these activities are also driving the other four planetary boundaries (freshwater use, land use change, biodiversity loss, and aerosol loading).

This exemplifies the many interactions among the boundaries. As such, it has been suggested that climate change and biosphere integrity are core planetary boundaries determining how the other boundaries operate. These two boundaries "operate at the level of the whole Earth system and provide the planetary-level overarching systems for the other boundaries" while also being regulated by them. Large changes in the climate or in biosphere integrity have the profound possibility of pushing the Earth system out its current state. However, crossing of one or more of the other boundaries alone would not necessarily lead to a new Earth system state but could still seriously impact human wellbeing. [133]

In conclusion, because pollution from the primary anthropogenic activities is driving at least eight of the nine planetary boundaries, it has been suggested that pollution control will help achieve the goal of global sustainable development by sustaining ecosystems services while still meeting societal and economic development goals for humanity. [4] However, given that the two core planetary boundaries, climate change and biodiversity loss, have been crossed, and that the IPCC 2018 report calls for emissions reductions of 45% from 2010 levels by 2030, reaching net zero around 2050 to limit global warming to 1.5 °C, [112] it would seem that avoiding catastrophe and meeting the basic needs of the global populace will require nothing less than a rapid reduction of fossil hydrocarbon use in addition to a drastic reduction in ruminant meat consumption.

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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