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FIVE URGENT QUESTIONS ON ECOLOGICAL SECURITY

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SUMMARY

● **The increasing pressure of ecological disruption on people and on security means that ideas and policy on peace and security must increasingly address the need for ecological security. This paper poses five research questions concerning: (*a*) amplification of antimicrobial resistance (pathogens that are increasingly drug-resistant); (*b*) the physiological consequences of pollution; (*c*) the loss of nature's contribution to people's well-being; (*d*) local and regional ecological tipping points; and (*e*) detrimental organisms and processes that thrive in the rapidly changing planet.**

Each question has a human health dimension, with likely socio-economic impacts and effects on behaviour, as well as potential effects on security and political stability. Understanding these issues is essential if appropriate responses are to be developed.

More research is needed in both the natural and the social sciences, with interdisciplinary work that is in close contact with the policy world. The situation is urgent and policy responses cannot wait until all the answers are known and uncertainty has been fully eliminated.

Introduction

Today's and tomorrow's challenges for peace and security are unprecedented because one of their main drivers is an unfolding ecological crisis. Crafting responses to this challenge starts with thinking about the contemporaneous weakening of the natural foundations on which all social life is built. Just as it is impossible to imagine an economy without a society in which it functions, it is impossible to imagine a society without the biosphere to feed it, land on which to live, the hydrosphere and the atmosphere for water and air for life, and the climate sphere to regulate food production. All these spheres—taken together, the ecosphere—now face pressure as a result of human activities, especially over the last 200 years, and with even greater intensity in the last 70, and consequently the ecosphere is changing. The effects of these changes propagate as drivers of instability and disruption, with the potential to weaken social cohesion and resilience, exacerbate disputes and grievances and, as a result, contribute to intense conflicts and, at the same time, a diminished capacity to manage conflict peacefully. All this is by way of saying that ideas and policy about peace and security must increasingly address the challenge of ecological disruption that leads to insecurity.

This discussion uses the term *ecological disruption*, rather than the more common vocabulary of 'nature loss', 'biodiversity loss' or 'environmental degradation'. Though species are being lost at an unprecedented rate and the environment is becoming less supportive for many organisms, others are thriving and, in some cases, their emergence is unwelcome. This paper treats *ecological disruption* as a supra-concept that embodies climate change, biodiversity loss, pollution, plastics and other planetary stresses. *Ecological security* can then be seen as an approach in policy and action aimed at mitigating the human and societal vulnerability that does and will result both directly and indirectly from this disruption.

Perturbations to the ecosphere carry significant—and probably harrowing—consequences for people and societies; however, risk pathways from there to human, national and global insecurity need elucidation. This paper poses five research questions that, if successfully addressed, would generate a deeper understanding of the ecological security risks ahead. They concern:

1. Amplification of antimicrobial resistance (pathogens that are increasingly drug-resistant),
2. The physiological consequences of pollution,
3. The loss of nature's contribution to people's well-being,

4. Local and regional ecological tipping points, and
5. Detrimental organisms and processes that thrive in the rapidly changing planet.

The five questions are not a comprehensive list of problems presented by ecological disruption. They leave to one side some that are already being addressed by a steadily maturing literature. There is plentiful discussion centred on the effects of overloaded and depleted soils, toxified and acidified oceans and stressed freshwater systems, as well as the impact of each on food security.[1] The knock-on consequences of rising food insecurity in terms of social grievance and instability, political upheaval and risks of violent conflict are likewise receiving increasing attention.[2] The impact of climate change on insecurity is also the focus of growing attention, not least due to the work produced by SIPRI itself.[3] The focus here, in an attempt to initiate a discussion that should eventually be on at least a similar scale to the climate security discussion, is on the biosphere, which is in a state of rapid destabilization due to loss of biodiversity and biomass, biotic homogenization, redistribution of species and supercharged biological invasions.

The security implications of these issues have not been much discussed; addressing them properly requires a coming together of different communities of knowledge and practice, just as the discussion on climate change and security has done. This paper identifies key issues and poses questions about them. Few of the answers are currently available and the point is that those answers must be developed.

In each case, a three-sided process of exploration is required. First, all five questions reveal gaps and uncertainties in basic scientific knowledge that need to be filled. Second, as the natural scientific base begins to be a little more established, it will be possible to start addressing knowledge needs about the social and economic consequences of each of these challenges. Third, as an understanding of social consequences—and thus of the degree of risk entailed—takes shape, policy responses need to be formulated, funded and implemented. It is essential to understand that these steps are not sequential. As relevant to security as it is to environmental policy, the precautionary principle holds that decision makers should not wait until scientific uncertainty is eliminated before acting. Thus, it is inadvisable to wait for the natural scientific research to mature before beginning to explore the socio-economic and security implications, and similarly misguided to wait for that research to be finalized before initiating a policy response.

[1] On soil pollution see United Nations Environment Programme (UNEP), 'Soil pollution a risk to our health and food security', 4 Dec. 2020; and Food and Agriculture Organization (FAO) of the United Nations, *Soil Pollution: A Hidden Reality* (FAO: Rome, 2018). On ocean acidification see: UNEP, UNEP Emerging Issues, *Environmental Consequences of Ocean Acidification: A Threat to Food Security*, 2010. On water stress see Kookana, R. S. et al., 'Urbanisation and emerging economies: Issues and potential solutions for water and food security', *Science of the Total Environment*, vol. 732, 25 Aug. 2020; Mekonnen, M. M. and Hoekstra, A. Y., 'Four billion people facing severe water scarcity', *Science Advances*, vol. 2, no. 2 (Feb. 2016); and UN Water, *Summary Progress Update 2021: SDG 6, Water and Sanitation for All* (UN Water: Geneva, Mar. 2021).

[2] International Committee of the Red Cross (ICRC), *Food security and Armed Conflict* (ICRC: Geneva, Oct. 2022); and Delgado, C. and Smith, D., 'Hunger and food systems in conflict settings', *2021 Global Hunger Index: Hunger and Food Systems in Conflict Settings* (Concern Worldwide and Welthungerhilfe: Bonn and Dublin, 2021).

[3] Black, R. et al., *Environment of Peace: Security in a New Era of Risk* (SIPRI: Stockholm, 2022).

Ecological disruption is moving fast, its consequences have appeared in our rear-view mirror and we risk being soon overtaken. This paper sets out the case for beginning the process of exploring the issues, which must, in short order, lead to a policy response that will need to be adjusted as research continues and unearths further dimensions of the overall problem.

Each of the questions has an immediate human health dimension. The biosphere is responding biotically to disruption, which means that there are more novel encounters with pathogens, pests and microbial entities. In consequence, on the basis of the economic disruption caused by the Covid-19 pandemic—characterized by the World Bank as 'the largest global economic crisis in more than a century', leading to 'a dramatic increase in inequality within and across countries'[4]—this paper posits that all these questions also have an economic dimension. In many countries, national health systems are already over-stretched.[5] If poor health increases, this inevitably leads to greater economic risks; recently, the President of the Royal Society of Arts in the United Kingdom warned that the worsening health of the British people is now constraining economic growth, reversing a 200-year trend.[6] The current condition of other components of the social commons is equally worrisome in many countries—fraying infrastructure, rising debt, cost-of-living crises, eroded confidence in political leaders and public institutions—weakening the economic and social foundations of collective life.

In addition, partly arising from economic disturbance and partly as a direct effect without intermediary stages, it is likely that the five issues addressed here will also have implications for social behaviour, in ways outlined below. Negative modes of adaptation to changing pressures are among the possible outcomes.

Starting from the aspects of ecological disruption discussed below, potential pathways via health consequences to adverse socio-economic impacts seem reasonably clear. Travelling along these pathways is not inevitable; we are not trapped in a deterministic model so a variety of outcomes is possible. Nonetheless, the risk seems clear. The further pathway to political instability within and perhaps between states, and thence potentially to violent conflict, is less clear, partly because remedial action along the way is possible in social policy, policing, politics and diplomacy. Even so, the security implications of this discussion are ominous, especially in the light of both the disruption caused by the Covid-19 pandemic and the clear pathways from climate change to violent conflict.[7]

[4] World Bank, *World Development Report 2022: Finance for an Equitable Recovery* (World Bank: Washington, DC, 2022), p. 25.

[5] *The Economist*, 'Excess deaths are soaring as health-care systems wobble', 21 Jan. 2023.

[6] Inman, P. and Partington, R., 'Worsening health of Britons is holding back UK economy, Andy Haldane warns', *The Guardian*, 10 Nov. 2022.

[7] Mobjörk, K. F. and Tarif, K., *Pathways of Climate Insecurity: Guidance for Policymakers* (SIPRI: Stockholm, 2020); Tarif, K., *Climate Change and Violent Conflict in West Africa: Assessing the Evidence* (SIPRI: Stockholm, 2022); and Smith, E., *Gender Dimensions of Climate Insecurity* (SIPRI: Stockholm, 2022).

1. How will antimicrobial resistance be affected by ecological disruption, and with what societal consequences?

In 2021, a team of Nigerian microbiologists reported on a study examining the presence of drug-resistant bacteria in regional ponds used for aquaculture.[8] Antibiotic resistance (ABR) arises in aquacultural settings primarily by being subjected to antibiotics used to prevent or treat infections and promote growth in farmed fish and other seafood. What intrigued the Nigerian scientists is that they also detected antibiotic-resistant genes in bacterial samples that had no known antibiotic exposure. Instead, these samples had high concentrations of metal contaminations, namely copper, zinc, lead, nickel and chromium, which themselves pose many risks to aquatic organisms and the predators that eat them.

The Nigerian study thus contributes to a growing recognition that ABR can and often does arise in the environment without it being subjected to natural and synthetic drugs. ABR is a sub-set of the broader category, antimicrobial resistance (AMR), which includes antifungal, antiviral and antiparasitic resistance. Like ABR, these other forms of AMR can and often do emerge where neither natural nor synthetic drugs are prevalent. This should not be surprising since bacteria, fungi, viruses and other pathogens have been in a microbial competition since long before more complex organisms, including humans, appeared on the scene. AMR is typically discussed as a consequence of improper use of medicines in domestic, clinical and food production settings, but it is also something that may emerge on its own.

Getting the facts about AMR right is crucial because of the grave danger it poses to society. The annual death toll was estimated in 2016 to be about 500 000 rising to 10 million by 2050, making AMR a leading cause of death.[9] However, the effect of AMR will be felt not only in terms of increased mortality from currently treatable diseases and their associated economic costs, but also from slower, weaker and less complete recovery from diseases. After penicillin, discovered by Alexander Fleming in the 1920s, became available for use, it was welcomed as a miracle drug because the speed of recovery from infections and serious ailments was so rapid. AMR may well return societies to a 'pre-miracle' state.

What effects do increased temperatures have on ABR emergence?

There is some evidence that increased temperatures will cause ABR to emerge more rapidly in the environment.[10] In the case of vertical gene trans-

[8] Adekanmbi, A. O., Olawuni, O. G. and Olaposi, A. V., 'Metal contamination and coexistence of metal and antibiotic resistance in Vibrio species recovered from aquaculture ponds with and without history of antibiotic usage in Southwest Nigeria', *Bulletin of the National Research Centre*, vol. 45, no. 1 (2021), pp. 1–10.

[9] Review on Antimicrobial Resistance, Chaired by Jim O'Neill, *Tackling Drug-resistant Infections Globally: Final Report and Recommendations*, May 2016.

[10] See e.g. MacFadden, D. R. et al., 'Antibiotic resistance increases with local temperature', *Nature Climate Change*, vol. 8 (2018), pp. 510–14; McGough, S. F. et al., 'Rates of increase of antibiotic resistance and ambient temperature in Europe: A cross-national analysis of 28 countries between 2000 and 2016', *Eurosurveillance*, vol. 25, no. 45 (2020); and Li, W. et al., 'Association between antibiotic resistance and increasing ambient temperature in China: An ecological study with nationwide panel data', *The Lancet Regional Health-Western Pacific*, vol. 30 (Jan. 2023).

fer—the process by which genetic material is passed from parent to offspring, the most common form of gene transfer in complex organisms—the evidence is unclear. Higher temperatures increase the rates of metabolism, reproduction, development and mutation, which might increase the likelihood of ABR emergence; however, they can also impede the survival and reproduction of bacteria, thus slowing the rate of transfer. However, in horizontal gene transfer, when genes hop between organisms, higher temperatures generally facilitate interactions between bacteria, weaken cell membranes, destabilize DNA and increase the efficiency of DNA uptake, all making it more likely that an organism incorporates novel genetic material. Further research is needed to move beyond generalities into more specificity about where the most serious problems lie and whether some bacteria species are of particular concern.

What effects does ecological disruption have on other forms of AMR as well as ABR?

Climate change, nutrient overabundance and other forms of ecological disruption may also facilitate the emergence of resistance in viruses, fungi, protozoa and parasites. All forms of AMR can evolve in the wild and are affected by environmental factors. Unfortunately for human and animal health, these factors are all increasing worldwide.

Nitrogen and phosphorus overabundance is increasing worldwide, largely due to use of fertilizers; growing food for a projected world population of 9.7 billion by 2050 makes reversing this trend very difficult. This overabundance has two consequences worth highlighting here. First, it increases the growth of many kinds of fungal pathogens.[11] This is particularly significant because fungal infections are often complicated to treat. While mammals have historically been plagued by relatively few fungal diseases compared to other organisms, a proliferation of fungal infections would present a new therapeutic challenge. It appears some fungal pathogens are evolving the ability to inhabit (i.e., infect) mammals because of warmer environmental temperatures.[12]

Furthermore, nitrogen and phosphorus compounds promote the rapid growth of aquatic biofilms—groups of bacteria that form layers on the surface of ponds and lakes. This provides an ideal reservoir for exchanging genetic material so that biofilms become hotspots for the development of ABR. Bacteria present in biofilms can be up to 1000 times more resistant to antibiotics than those in free-swimming environments.[13]

In addition, some studies suggest that environmental microplastics may provide a breeding ground for ABR.[14] The scale of the problem and the influence of microplastics on other forms of AMR need more research.

[11] Lekberg, Y. et al., 'Nitrogen and phosphorus fertilization consistently favor pathogenic over mutualistic fungi in grassland soils', *Nature Communications*, vol. 12, no. 1 (2021), p. 3484.

[12] Nnadi, N. E. and Carter, D. A., 'Climate change and the emergence of fungal pathogens', *PLOS Pathogens*, vol. 17, no.4 (2021).

[13] Uruén, C. et al., 'Biofilms as promoters of bacterial antibiotic resistance and tolerance', *Antibiotics*, vol. 10, no. 1 (2020).

[14] Gaur, V. K. et al., 'A review on the effect of micro-and nano-plastics pollution on the emergence of antimicrobial resistance', *Chemosphere*, e-pub 15 Oct. 2022.

What is the timescale for AMR emergence?

Many analyses describe AMR as a future problem, with 2050 as a familiar benchmark. However, it is possible, if not probable, that the compound effects of climate change, plastics, pollution (which is addressed in the Nigerian study referenced above), nutrient overabundances and other ecological stresses will usher in a pre-antimicrobial—pre-miracle—phase much earlier.

What are the implications of increased AMR for political stability and security?

The economic burdens posed by AMR include increased healthcare costs, reduced productivity due to illness and decreased production of goods from AMR-affected livestock, aquaculture and agriculture. The cumulative global economic burden of AMR to 2050 could climb to $11 trillion, according to the World Bank.[15] Resilience, dynamism, entrepreneurialism, and cultural and scientific innovation may all deteriorate in AMR's wake.

Concerns about security seem likely to be articulated in two forms—one narrow, one broad. The narrower form concerns how military operations and readiness may be affected if field-borne wounds and injuries become increasingly untreatable. In the final year of World War II, when penicillin was available in a large enough volume to be available throughout the US Army, 'the mortality rate was reduced 12 to 15 per cent through the use of penicillin alone'.[16] Reversion to a pre-penicillin age could have a significant effect on tactics and strategy among some militaries, and probably on the willingness even to consider various kinds of roles and missions.

The broader form concerns underlying political and social stability. The prospect is that routine surgeries and some pregnancies may return to previous levels of danger. Health levels may fall and health crises recur. The experience of the Covid-19 pandemic offers some warnings on this score, not least in its impact on increasing violence against women and children,[17] and its depressing economic effects and aftermath.[18] The pandemic, however, was of relatively short duration; it is the impact of a long-term change in the effectiveness of treatments and in expectations that is of concern here. Overall, AMR could turn out to be a key vector of disruption—a sort of waist in the hourglass between nature and humanity, where the effects are concentrated and channelled onward.

[15] World Bank Group, *Drug Resistant Infections: A Threat to Our Economic Future* (World Bank: Washington, DC, Mar. 2017).

[16] Goyette, D., 'The surgical legacy of World War II: Part 2, the Age of Antibiotics', *The Surgical Technologist*, June 2017, pp. 256–65.

[17] UN Women, *Measuring the Shadow Pandemic: Violence Against Women during Covid-19* (UN Women: Geneva, 2021); and Fogstad, H., Langlois, E. V. and Dey, T., 'Covid-19 and violence against women and children: Time to mitigate the shadow pandemic', *British Medical Journal*, 24 Nov. 2021.

[18] World Bank (note 4).

2. Do (or will) the physiological effects of pollution have sociological effects and, if so, with what security dimensions?

Two decades ago, Mexican researchers collected post-mortem samples from dogs in Mexico City, a city with exceptionally high levels of air pollution, and compared them with samples from similar dogs in the less polluted city of Tlaxaca.[19] The dogs in the study had been kept indoors, although residential windows were typically kept open in both locales for better ventilation. The samples reflected a wide range of ages. Dogs and other household pets are affected, as humans are, by air pollution, so it was no surprise to find cellular damage in the dogs' respiratory and olfactory systems, and at a significantly higher level in the dogs from Mexico City than from Tlaxaca.

The researchers were surprised, however, by what they found in samples taken from canine brain tissue. There was clear evidence that air pollutants had triggered a cellular stress response similar to that observed when exposed to heavy metals, pathogens and other harmful agents. Furthermore, several dangerous anatomical changes were found in the dogs' brains. Beyond the immediate harm to brain tissue, the study suggested damage to the dogs' immune systems, leaving them vulnerable to many maladies, such as autoimmune disease, viral susceptibility and septic shock.

The study's authors warned that the degree of brain damage observed in the dog samples was 'of sufficient magnitude to warrant concerns that similar histopathology may occur in humans residing in large polluted metropolitan areas'. Such damage can threaten the brain's ability to control, coordinate and regulate the body's various systems, and interfere with its ability to sense and respond to external and internal stimuli.

What is the magnitude of air pollution and its physiological effects?

The simple act of breathing in environments such as Mexico City, whether indoors or outdoors, introduces a complex mixture of gases, particulate matter and chemicals into the lungs. The nose and throat are particularly vulnerable to damage, including cancer, because they are the body's entry points for air pollution.

A 2017 UN report rated poor air quality as the greatest global environmental risk to health.[20] Some 90 to 95 per cent of the world's population breathes outdoor air that is polluted beyond acceptable standards set by the World Health Organization (WHO).[21] Among other problems, air pollution causes asthma, bronchitis, lung cancer and other human respiratory diseases, increases the risk of premature births,[22] is associated with reduced

[19] Calderón-Garcidueñas, L. et al., 'Air pollution and brain damage', *Toxicologic Pathology*, vol. 30, no. 3 (2002), pp. 373–89.

[20] United Nations Environment Programme (UNEP), *Towards a Pollution-free Planet: Background Report* (UNEP: Nairobi, 2017).

[21] Health Effects Institute, *State of Global Air 2020: A Special Report on Global Exposure to Air Pollution and its Health Impacts* (Health Effects Institute: Boston, MA, 2020).

[22] Bekkar, B. et al., 'Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: A systematic review', *JAMA Network Open*, vol. 3, no. 6 (June 2020).

fertility and,[23] on the basis of strongly suggestive evidence, may also increase the risk and incidence of dementia among those aged from 50 to 79.[24]

Outdoor air pollution caused 4.5 million deaths in 2019 (a 57 per cent increase in annual mortality from this cause this century).[25] Unless there is decisive action that prioritizes higher air quality worldwide—especially but not exclusively in the urban environments where 70 per cent of us will be living in a couple of decades—the trend of increasing mortality will continue. In terms of the knock-on effects on insecurity and instability, an initial hypothesis would anticipate similar outcomes to those likely to result from intensifying AMR. In addition, and possibly more destabilizing, are the behavioural effects.

What are the possible behavioural effects of air pollution?

The brain plays a crucial role in human behaviour and research shows that air pollution affects it. Air pollution is known to cause mental ill-health and disorders including depression.[26] Looking at other animals, one study has shown that monkeys living in polluted air are more aggressive, although the study could not discriminate between physiological and psychological pathways.[27] Other studies have shown that air pollution can cause behavioural changes in mice, such as increased anxiety and impaired learning,[28] and that pigeons home significantly faster when flying through polluted conditions.[29]

Recent studies have shown that air pollution can cause significant behavioural changes in people. One study showed exposure to high levels of air pollution increased aggression among children,[30] while another revealed increased depressive symptoms among adults.[31] Another study connected air pollution with decreased grey matter in regions of the brain involved in regulating emotion.[32] This suggests that long-term exposure to air pollution may impair an individual's ability to regulate their emotions, possibly leading to increased aggression or depression over time.

There are also correlations between air pollution and some types of crime. A 2019 study of air pollution in the United States showed a robust

[23] Wesselink, A. and Wellenius, G. A., 'Impacts of climate change on reproductive, perinatal and paediatric health', *Pediatric and Perinatal Epidemiology*, vol. 36, no. 1 (Jan. 2022).

[24] Carey, I. M. et al., 'Are noise and air pollution related to the incidence of dementia? A cohort study in London, England', *British Medical Journal Open*, vol. 8, no. 9 (Sep. 2018).

[25] Institute for Health Metrics and Evaluation (IHME), University of Washington, GBD Compare, Data as of 2019.

[26] Newbury, J. B. et al., 'Association between air pollution exposure and mental health service use among individuals with first presentations of psychotic and mood disorders: Retrospective cohort study', *British Journal of Psychiatry*. vol. 219, no. 6 (2021).

[27] Xu, A. et al., 'Monkeys fight more in polluted air', *Scientific Reports*, vol. 11 (2021).

[28] Davis, D. A. et al. 'Prenatal exposure to urban air nanoparticles in mice causes altered neuronal differentiation and depression-like responses', *PLOS One*, vol. 8, no. 5 (2013).

[29] Li, Z., Courchamp, F. and Blumstein, D., 'Pigeons home faster through polluted air', *Scientific Reports*, no. 6 (5 Jan. 2016).

[30] Reuben, A. et al. 'Association of air pollution exposure in childhood and adolescence with psychopathology at the transition to adulthood', *JAMA Network Open*, vol. 4, no. 4 (2021).

[31] Borroni, E. et al., 'Air pollution exposure and depression: A comprehensive updated systematic review and meta-analysis', *Environmental Pollution*, vol. 292 (1 Jan. 2022).

[32] Beckwith, T. et al., 'Reduced gray matter volume and cortical thickness associated with traffic-related air pollution in a longitudinally studied pediatric cohort', *PLOS One*, vol. 15, no. 1 (2020).

relationship with violent crime, specifically assault, but no relationship with property crime.[33] In 2020, researchers found that poor air quality in London was correlated with spontaneous crimes, such as interpersonal violence and property damage, but not premeditated crimes.[34] While more research is needed to establish mechanistic pathways between air pollution and crime, these studies suggest a robust neurophysiological influence.

What are the possible consequences of the physiological effects of chemical pollution?

According to the WHO, there are 40 000–60 000 chemicals in use commercially.[35] Humans encounter them in our food and water intake, through workplace exposure, as by-products of industry, transport and energy production, through agriculture, and from ingredients and materials used in some detergents, textiles, cosmetics, construction materials and furniture. Among them are thousands of a class of pollutants known informally as 'forever chemicals', because they break down over centuries, if ever.[36] Recent reports reveal their global spread,[37] as well as the intensity of their presence in Europe.[38] Chemicals spread both through their intended use and through accidents; in the USA, accidental releases of chemicals average one every two days, according to an analysis of data collected by the Environmental Protection Agency and civil society groups.[39]

A UN report published in 2017 pointed out that relatively few chemicals have been thoroughly analysed for their behaviour and effects when released into the environment.[40] A US Centers for Disease Control and Prevention platform currently lists just 199 chemical compounds and minerals, the toxicology of which has been assessed.[41] Even those that have been thus analysed have been studied as individual novel entities, leaving their potential interactions and compound effects unexplored.[42] The 2017 UN report also states that, among the known effects, more than 100 000 people die annually from exposure to asbestos, while lead in paint is known to affect the IQ of children.[43] Further effects from different pollutants include

[33] Burkhardt, J. et al., 'The effect of pollution on crime: Evidence from data on particulate matter and ozone', *Journal of Environmental Economics and Management*, vol. 98 (2019).

[34] Bondy, M. et al., 'Crime is in the air: The contemporaneous relationship between air pollution and crime', *Journal of the Association of Environmental and Resource Economists*, vol. 7, no. 3 (2020), pp. 555–85.

[35] World Health Organization (WHO), Compendium of WHO and other UN guidance on chemicals and health.

[36] Or more formally as Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS), see Dictionary.com, 22 Aug. 2022.

[37] Environmental Working Group (EWG), 'Wildlife warning: More than 330 species contaminated with "forever chemicals"', 22 Feb. 2023; and EWG, 'Global danger: Wildlife at risk from PFAS exposure', Environmental Working Group, [n.d.].

[38] Salvidge, R. and Hosea, L., 'Revealed: Scale of "forever chemical" pollution across UK and Europe', *The Guardian*, 23 Feb. 2023.

[39] Gillam, C., 'Revealed: The US is averaging one chemical accident every two days', *The Guardian*, 25 Feb. 2023.

[40] United Nations Environment Programme (note 20), pp. 27–28.

[41] Agency for Toxic Substances and Disease Registry, 'Toxicological Profiles', 10 Feb. 2023.

[42] United Nations Environment Programme (note 20), p. 28.

[43] United Nations Environment Programme (note 20), p. 27.

neurological damage and cell mutation, weakened immune systems, and digestive and pulmonary disorders.

In short, even though chemical pollution has widespread effects on air, water and soil quality, and on the physiologies of human beings and animals, these effects are under-researched and their social consequences and knock-on effects have received little attention.

What are the possible consequences of the physiological effects of water and soil pollution?

As with the atmosphere, water and soil can also suffer from pollution, although the character of their pollutants is markedly different. While air pollutants are typically gases and aerosolized particulate matter, pollutants found in water and soil are typically more complex, with substantial potential for chemical, biological or radiological activity. They include metals and other inorganic compounds, as well as organic compounds, nutrients, pathogens, sediment, waste and radioactive materials. Exposure to water and soil pollution, usually through ingestion, can affect many physiological systems, including the digestive, immune, nervous, musculoskeletal and neurological systems.[44]

Some pollutants are endocrine disruptors, which interfere with a body's hormone-secreting glands or the receptors that detect and respond to them, and particularly affect reproductive and development physiology. Exposure to endocrine inhibitors has been linked to reduced fertility, pre-term birth, miscarriage, low sperm count and motility, and changes in sexual development, including early onset of puberty in females.[45] Since hormones typically operate at very small doses, trace amounts of these pollutants risk triggering negative outcomes, even when they occur below established toxicity levels. These dangers are not isolated to humans but permeate the animal kingdom.

The consequence of possible reductions in fertility or birth rates among both animal and human populations may include challenges for food security and long-term economic development. However, geographical differences in pollution levels mean that such effects are unlikely to be consistent across all regions of the world. While rich, middle-income and poor countries alike may all be vulnerable, countries in each category are likely to fare differently, with potential consequences for relations between them.

How much is known about the effects of exposure to plastics?

In 2017, a study estimated that total world production of plastics since 1950 amounted to 8.3 billion tonnes and was increasing by an estimated 400 million tonnes annually.[46] On that basis, total production has probably now surpassed 10 billion tonnes. Plastics have found their way into every

[44] Schwarzenbach, R. P. et al., 'Global water pollution and human health', *Annual Review of Environment and Resources*, vol. 35 (2010), pp. 109–36.

[45] Kabir, E. R., Sharfin, M. R. and Rahman, I., 'A review on endocrine disruptors and their possible impacts on human health', *Environmental Toxicology and Pharmacology*, vol. 40, no. 1 (2015), pp. 241–58.

[46] Geyer, R., Jambeck, J. R. and Lavender Law, K., 'Production, use, and fate of all plastics ever made', *Science Advances*, vol. 3, no. 7 (July 2017).

type of ecosystem, reconfiguring the natural world into one injected with synthetic components that are widely agreed to be long-lived, although there is little clarity about how long.[47] Primarily passed into the environment through waste, plastic has accumulated in oceans, rivers, ice and soil. Microplastics—the specks of plastic found in facial scrubs, toothpaste, clothing and other materials—have been detected in every type of organism and in every physiological system of afflicted organisms.

The adverse effects of plastics in the environment are well described at the macroscopic level, where plastic masse can entangle and strangle organisms or choke off entire ecosystems.[48] However, the effects of microplastics—and the chemicals they decompose into—are poorly understood. Plastics pollution is found in every physiological system in the human body,[49] and even in mothers' milk,[50] raising concerns about possible cascading effects on health.

There is, however, a debate about the nexus between microplastics and human health—another area in which considerably more research needs to be done to establish whether any risks are being run and how serious they might be.[51] Assessment of socio-economic impacts would start to be feasible as the underlying natural science begins to provide preliminary answers about the health impacts of plastics.

What effects might arise from non-material pollutants?

There is a growing recognition that non-material forms of pollution, such as noise, light and thermal pollution, can also adversely impact people and animal life. It has been clear for well over a decade that exposure to noise pollution can contribute to high blood pressure, increased stress, heart ailments, hearing loss, sleep disturbances and impaired cognitive performance; long-term exposure can also lead to mental health issues, such as depression and anxiety.[52]

Light pollution is far more significant than generally realized, given that 69 per cent of mammals are nocturnal.[53] It is increasing at dizzying speed, even though the number of people without access to electricity is still high and is estimated to have increased from 755 to 775 million in 2022.[54] Globally,

[47] Chamas, A. et al., 'Degradation rates of plastics in the environment', *ACS Sustainable Chemical Engineering*, vol. 8, no. 9 (Feb. 2020).

[48] Bucci, K., Tulio, M. and Rochman. C. M., 'What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review', *Ecological Applications*, vol. 30, no. 2 (Mar. 2020).

[49] Campanale, C. et al., 'A detailed review study on potential effects of microplastics and additives of concern on human health', *International Journal of Environmental Research and Public Health*, vol. 17, no. 4 (Feb. 2020).

[50] Ragusa, A. et al., 'Raman Microspectroscopy detection and characterisation of microplastics in human breastmilk', *Polymers*, vol. 14, no. 13 (July 2022).

[51] Lim, X., 'Microplastics are everywhere: But are they harmful?', *Nature*, 4 May 2021.

[52] Passchier-Vermeer, W. and Passchier, W. F., 'Noise exposure and public health', *Environmental Health Perspective*, vol. 108, suppl. 1 (2000), pp. 123–31; and World Health Organization (WHO) and Joint Research Centre, European Commission, *Burden of Disease from Environmental Noise* (WHO: Copenhagen, 2011).

[53] Bennie, J. J. et al., 'Biogeography of time partitioning in mammals', *Proceedings of the National Academy of Sciences of the USA*, vol. 111, no. 38 (Sep. 2014).

[54] Cozzi, L. et al., 'For the first time in decades, the number of people without access to electricity is set to increase in 2022', *IAEA Commentary*, 3 Nov. 2022.

the loss of night sky visibility is about 10 per cent a year.[55] Too much exposure to light can disrupt the body's circadian rhythm, leading to a host of physical and mental disorders; these effects occur in other animals as well.[56] On the one hand, such issues can seem to be mere irritants, the side-effects of urban living with neon lighting, building sites and sirens all around. On the other hand, while we adapt to live with these irritants, just as we adapt to live while breathing polluted air, we do not know what price we are paying. Arguably, a combination of the effects of air pollution on behaviour with the effects of noise and light pollution on emotions and cognition may be stirring up a compound effect that is both toxic and hard to identify in individuals. Further research could deepen the assessment of how behaviour is affected by these kinds of pollution and consider the social consequences, including the impact on human security.

What are the implications of pollution for political stability and security?

The potential impact of pollution on both health and behaviour is among the most worrying issues here. The health impact is already serious. Some of the effects are well-researched, some not. Without a change of course in industry, urban planning, transport and agriculture, the problem is likely to get worse. Adding this dimension of generally weakening health worldwide to the concerns about the treatment of disease as AMR becomes increasingly widespread suggests profound health problems to come.

In addition, the brief scan of the issues above shows there is enough evidence about the effects of air, chemical, noise and light pollution on the brain to allow a preliminary conclusion that there are and will be consequences for human behaviour. Getting a fuller sense of what these consequences may be is a priority topic for research. The possibility of a greater prevalence of depression and anxiety is obviously of concern, as is the possibility that tendencies to violent crime might be exacerbated. Against a backdrop of slowing economies and declining health, grievances may be pursued with a greater proclivity to violence. While speculative, this line of enquiry suggests that there are lurking challenges to human security, and social and political stability. At the same time, the paucity of evidence means that much has to be conjectured rather than known. It is past time to fill the knowledge gaps. The questions are concerning and it would be better to know the answers than not.

3. What are the social consequences as nature's contribution to people's well-being diminishes?

In May 2008, Cyclone Nargis struck Myanmar's Irrawaddy Delta. With winds of up to 200 kph and heavy rains, compounded by a 3.6-metre storm

[55] Kyba, C. C. M. et al., 'Citizen scientists report global rapid reductions in the visibility of stars from 2011 to 2022', *Science*, 19 Jan. 2023, pp. 265–68.

[56] Chepesiuk, R., 'Missing the dark: Health effects of light pollution', *Environmental Health Perspectives*, vol. 117, no. 1 (Jan. 2009), pp. A20–A27.

surge, the cyclone caused widespread destruction and loss of life. More than 140 000 people were killed and over one million made homeless.

Several studies have since demonstrated that the clearing of mangrove forests almost certainly amplified the power of Nargis.[57] Deforested regions absorbed less of the incoming wave energy, so there was extensive flooding and infrastructure damage, and the storm surge pushed inland, leading to widespread destruction in low-lying areas that might otherwise have been less hard hit. However, where the mangrove forests were intact, many people in coastal villages sought refuge in them. The trees provided food, fuel, shelter and an elevated platform for safety from flooding during the storm surge. Some people tied themselves or their boats to deep-rooted mangrove trees, enabling them to survive rough waters and preventing themselves from being washed out to sea.

This is just one example of nature's contribution to people (NCP). Another example is the reliance of an estimated 4 billion people on natural medicines for healthcare, while about 70 per cent of the drugs used to treat cancer are either natural products or, if synthetic, were first identified because of the effects of natural products and inspired by them.[58] A further example is pollination: about 75 per cent of crop types grown by humans require pollination by insects.[59] In these ways, the loss of biodiversity and biomass is a clear, direct hazard to health and well-being worldwide.

The IPBES Global Assessment of Biodiversity identified 18 categories of NCP in 2019 (see figure 1).

What are the implications of declines in pollination and seed dispersal by animals?

Pollination is crucial to every terrestrial ecosystem and is critical to food security through the provision of fruits, vegetables and many non-grain crops. Animal pollination, particularly by wild honeybees, is at risk as their populations decline, and through changing animal-plant interactions ushered in by habitat degradation and climate change.[60] Researchers have documented declines in wild insect pollinators in Europe and North America, although trends have yet to be established globally and across species.[61]

In addition to heightened stresses on global and regional food availability, pollination deficits would add to economic, labour and health pressures on political stability. For nations with economies especially dependent on pollination, through their agricultural production or commodity exports,

[57] See e.g. Mohamed, N., *Learning from Cyclone Nargis: Investing in the Environment for Livelihoods and Disaster Risk Reduction* (United Nations Environment Programme: Nairobi, 2009); and Sandilyan, S. and Kathiresan, K., 'Mangroves as bioshield: An undisputable fact', *Ocean & Coastal Management*, no. 103 (Jan. 2015), pp. 94–96.

[58] Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services (IPBES), *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES Secretariat: Bonn, Germany, 2019).

[59] Noriega, J. A. et al., 'Research trends in ecosystem services provided by insects', *Basic and Applied Ecology*, vol. 26 (Feb. 2018), pp. 8–23.

[60] Settele, J., Bishop, J. and Potts, S. G., 'Climate change impacts on pollination', *Nature Plants*, vol. 2, no. 7 (2016), pp. 1–3.

[61] LeBuhn, G. and Luna, J. V., 'Pollinator decline: What do we know about the drivers of solitary bee declines?', *Current Opinion in Insect Science*, vol. 46 (Aug. 2021), pp 106–11.

Figure 1. Nature’s contributions to people

Source: Adapted from Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES Secretariat: Bonn, Germany, 2019).

the negative effects are likely to be enormous, if not catastrophic, and could arrive well before global repercussions are felt.[62]

Disruption of the biosphere is also affecting animal-mediated seed dispersal of plants—notably, trees and forests. Biodiversity loss of key seed dispersers, such as mammals and birds, is probably accelerating due to loss of habitat and overexploitation of organisms.[63] Unfortunately, little is currently known about the status of most seed dispersers, and few studies have explored the downstream effects on societies that would accompany seed dispersal decline.

What are the implications of soil decline?

Global soil resources are declining from the intensive use of fertilizers and pesticides, overgrazing, deforestation, habitat change, pollution and, increasingly, climate change.[64] As much as a quarter of all animal species live below ground. In addition to providing nutrients that underpin food security, soil also stores carbon, helps regulate the climate and acts as a water purifier. Breakdowns in the provisioning of soil, which takes thousands of years to form, have far-reaching implications for society. As indicated above, the consequences of this decline for food security are being investigated, and the full social dimensions of the issues are yet to be fully explored.[65]

Are some NCPs more critical to human well-being than others?

Significant research has been done on the societal implications of a handful of material NCPs—food, energy, water and some materials, such as timber. Much less is known about the consequences of breakdowns of other NCPs listed in figure 1. It is also unclear whether and in what ways some NCPs are more critical than others to well-being and social stability, and a further degree of murkiness is added by the strong likelihood that the importance of a particular NCP will differ from one location to another.

This question is therefore one of several in this paper that cannot yet be answered; indeed, it is not clear that the basis in science yet exists to pose the question with appropriate precision. Nonetheless, for practical policy to manage the consequences of ecological disruption and limit the malign effects on people, some greater clarity on this issue is important.

What are the implications of erosion of NCPs for political stability and security?

Returning to the Nargis example, before deforestation, the mangroves protected people from extreme weather events. The removal of those natural defences against disaster implies that either the state steps in to construct alternative defences, or people are left to suffer and manage as best they

[62] Schoonover, R., *Societal and Security Implications of Ecosystem Services Declines: Part 1, Pollination and Seed Dispersal* (Council on Strategic Risks: Washington, DC, 2022).

[63] Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services (note 58).

[64] Food and Agriculture Organization (FAO) of the United Nations et al., *State of Knowledge of Soil Biodiversity: Status, Challenges and Potentialities*, Summary for policymakers (FAO: Rome, 2020).

[65] Wall, D. H. and Six, J., 'Give soils their due', *Science*, 13 Feb. 2015, pp. 695–95.

can. When the state is uncaring, incompetent, corrupt or simply lacks the necessary resources to protect its citizens hit by extreme weather events, the frequency of which is increasing under the impact of climate change,[66] as well as by other disasters such as earthquakes or tsunamis, grievances may be quick to surface. If these are mobilized politically, especially in a context where there are already grievances, evidence suggests an increasing risk of instability and insecurity.[67]

Thus, in addition to the broader weakening of society through contributing, for example, to malnutrition and ill-health, the erosion of NCPs offers specific security-related concerns. Their implications, while ill-defined and poorly researched (with some exceptions) to date, are grounds for serious concern.

4. Is there a relationship between ecological tipping points and social change, political instability and consequent insecurity?

Purple sea urchin populations exploded along the Pacific coasts of the United States and Canada in 2014 due to a wasting disease in sea stars, a keystone predator. Many commercially important fisheries in the region have collapsed due to the destruction of kelp forests and marine ecosystems that provide food and habitat for thousands of fish, invertebrates and marine mammals. Since 2015, 95 per cent of the canopies of the kelp forests off Northern California's coast have been lost to urchin barrens—areas where sea urchins are growing rampantly.

This is an example of an *ecological regime shift*—a large, sudden and persistent change in the function and structure of an ecosystem, often known more informally as a tipping point. Regime shifts can be triggered by external shocks such as heatwaves and disease outbreaks or from changes in underlying system properties such as acidifying waters. A few regime shifts are mostly reversible, primarily those in small-scale ecosystems such as ponds and lakes. However, many if not most are irreversible or what is known as hysteretic, which is when the pathway for an ecosystem's recovery differs from its decline, rendering the original regime inaccessible.

In recent decades, scientists have identified numerous classes of ecological regime shifts (see figure 2). They are often grouped by their relevant domain, such as aquatic, terrestrial or land-water interface ecosystems.[68]

In addition, regime shifts are under way in the climate system, such as the collapse of the West Antarctic ice sheet or destabilization of the summer Indian Monsoon. Unless checked by radical decarbonization, these regime shifts will have impacts on a vast scale. Equally important in many ways are the more localized regime shifts exemplified by the change from kelp canopies to urchin barrens.

[66] World Meteorological Organization, 'Climate change and extreme weather', 2022.

[67] Pfaff, K., 'Assessing the risk of pre-existing grievances in non-democracies: The conditional effect of natural disasters on repression', *International Journal of Disaster Risk Reduction*, vol. 42 (Jan. 2020).

[68] Biggs, R. O., Peterson, G. and Rocha, J. C., 'The Regime Shifts Database: A framework for analyzing regime shifts in social-ecological systems', *bioRxiv* (2015).

Some ecological regime shifts will almost certainly have a substantial negative impact on people and societies. For example, hypoxia—the depletion of dissolved oxygen in water—often triggers mass die-offs in marine life, including commercially important fish, and creates dead zones in freshwater and oceans. This has evident, direct impacts on livelihoods, employment and food security.

What are the social implications of savannization of tropical forests?

Tropical forest systems provide essential local and global benefits to humanity. They provide food, fuel, shelter and materials for people to use and contribute to clean air, reliable water and a stable climate. In addition, some of the world's most vulnerable populations, including indigenous people, depend on tropical forests for livelihoods, shade, sustenance and health, and draw important aspects of culture and belief from them.

Scientists have warned that some tropical rainforests, notably the Amazon, are in the early stages of savannization,[69] the conversion of a forest to a savanna (see figure 2). As trees are lost, the open space allows more sunlight and air to circulate, encouraging grasses and other non-woody plants to take root and spread. While savannization slowly occurs naturally over centuries and more, deforestation, overgrazing and other human activities can dramatically reduce the transition time to a few decades or less. Moreover, fires play a central role in the process by rapidly reducing tree cover. This makes for a self-reproducing downward spiral as deforestation contributes to climate change, which makes wildfires more intense and more frequent,[70] pushing savannization still further.

Since forests are so intricately connected to people, the savannization of the Amazon would be highly likely to trigger myriad adverse human impacts. Food and water stress, loss of residence and shelter, and health risks would probably result from the regime shift.

Rainforest systems in Central Africa, Southeast Asia, the Caribbean and Madagascar are also at risk and merit deeper analysis, including of the social consequences of forest loss, than they have received thus far.

What are the effects of ecological tipping points on other ecological tipping points?

The biosphere is a network of interactions. Many of them seem strange at first sight and difficult to grasp, such as the connections between trees and the Earth's rotation, or between the behaviour of wolves and the course of a river.[71] A list of regime shifts, such as those in figure 2, therefore naturally raises questions about their interconnectedness. For some tipping points, the relationship is clear; for example, eutrophication (see figure 2) often leads to hypoxia, which, in turn, can spur the collapse of fisheries or bivalve stocks. A recent study found that roughly half of regime shift couplings

[69] Lovejoy, T. E. and Nobre, C., 'Amazon tipping point', *Science Advances*, vol. 4, no. 2 (Feb. 2018).
[70] Jones, M. W. et al., 'Climate change increases the risk of wildfires', Science Brief, Jan. 2020.
[71] Wohlleben, P., *The Secret Network of Nature* (Vintage: London, 2018).

Regime shift	From regime 1	To regime 2
Aquatic		
Freshwater eutrophication[a]	Clear water	Murky water
Coastal marine eutrophication	Normal nutrient abundance	Nutrient overabundance
Submerged plants transition	Submerged plants-dominant	Floating plants-dominant
Hypoxia transition	Normoxia (normal O_2)	Hypoxia (depleted O_2)
Fisheries collapse	High abundance of fish	Low abundance of fish
Bivalves collapse[b]	High abundance of bivalves	Low abundance of bivalves
Marine foodweb recomposition	Predator-dominanted	Lower trophic group-dominated
Coral transition	Coral-dominated reefs	Algae/sponge-dominated reefs
Kelp transition	Canopy-forming algae	Turf-forming algae/urchins
Seagrass transition	Seagrass	Algae, sediments
Terrestrial		
Soil salinization	Low salinity soil	High salinity soil
Savannization[c]	Forest	Savanna
Bush encroachment	Grass-dominated savanna	Shrub/tree-dominant terrain
Coniferous forest transition	Coniferous forest	Deciduous forest
Tundra transition	Tundra	Boreal forest
Steppe transition	Steppe grassland	Tundra
Land/water		
Thermokarst lake transition[d]	Thermokarst lake	Terrestrial ecosystem
River channel position transition	Old channel course	New channel course
Peatland transition	Low productivity, high carbon	High productivity, low carbon
Salt marsh transition	Salt marsh	Tidal or subtidal flat
Mangrove transition	Mangrove forest	Ponds, marshes, coasts

Figure 2. Classes of ecological regime shifts

Source: Regime Shifts Database, Stockholm Resilience Centre, Stockholm University, <https://regimeshifts.org>.

[a] Eutrophication is the excessive richness of nutrients in water systems.

[b] Bivalves are molluscs with a two-part hinged shell, such as clams and oysters.

[c] Savannization is the conversion of a forest to a grassy plain (savanna).

[d] Thermokarst lakes are those formed when permafrost thaws, creating surface depressions filled with meltwater.

share some kind of structural interdependence.[72] Nonetheless, scientists know little about the fine-scale inter-dynamics between most regime shifts. Interconnectedness is a fundamental characteristic of the Earth, which makes the system as a whole relatively robust. Once disrupted, however, the consequences may unfold in cascades. This question is exceedingly important because it relates to the severity and rapidity of events that might transpire once a single threshold is passed. Nature has proved to be a lot more durable than a house of cards but, if and when parts of it are fatally damaged, that may well be how collapses happen.

Can some ecological tipping points be predicted, and possibly dampened, in advance?

While science has made substantial strides in understanding, describing and categorizing regime shifts, this knowledge is not particularly useful to decision makers unless science can also provide possible points of intervention. Regime shifts often come as surprises; however, in some laboratory settings and models, early warning signals can be detected.[73] So far, it remains unclear whether complex real-world systems will exhibit the theoretically predicted early-warning signals. Detecting them requires robust statistical indicators derived from field monitoring, which remains a low priority for most nations.[74] Beyond that, some tipping points are probably unforecastable, in the sense that it is simply not known what they will be. Forecasting events of a kind of which there is experience is hard enough; attempting to forecast events of a kind that has not been defined or identified adds further layers of complexity. The underlying mechanisms are poorly understood and under-researched while their interconnections are hidden altogether. This reinforces the importance of addressing the drivers of disruption in addition to preparing for its effects.[75]

What are the implications of ecological regime shifts for political stability and security?

Among the second-order effects if particular tipping points are passed are risks of political instability, increased migration and threats to critical economic sectors. To understand how this might play out as a security issue, it is only necessary to refer to the increase in piracy off the coast of Somalia as fishing communities there found their normal fishing grounds exhausted, largely thanks to massive-scale factory fishing.[76] Whatever the causes, disruptive changes are unsettling, can include profound psychological and

[72] Rocha, J. C. et al., 'Cascading regime shifts within and across scales', *Science*, 21 Dec. 2018, pp. 1379–83.

[73] Scheffer, M. et al., 'Early-warning signals for critical transitions', *Nature*, 3 Sep. 2009, pp. 53–59.

[74] Dakos, V. et al., 'Resilience indicators: Prospects and limitations for early warnings of regime shifts', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 5 Jan. 2015.

[75] Hastings, A. and Wysham, D. B., 'Regime shifts in ecological systems can occur with no warning', *Ecology Letters*, vol. 13, no. 4 (2010), pp. 464–72.

[76] Flückiger, M. and Ludwig, M., 'Economic shocks in the fisheries sector and maritime piracy', *Journal of Development Economics*, vol. 114 (May 2015), pp. 107–25.

psycho-social effects,[77] and can overthrow previous social norms if survival becomes the paramount goal for a community.

Despite its growing prominence in scientific research, the concept of ecological regime shifts has barely surfaced in security policies and discussions. Even among experts in environmental and climate security, there is little discussion of regime shifts. Embracing the regime shift concept embeds aspects of discontinuous change in the ground floor of analysis. This represents the real world much better than a model that deals only with linear change, which unfolds gradually and at an even pace. That is not how things work in the natural environment, in human societies or in politics. Policy initiatives and approaches based on a smooth, linear model are convenient for our general ways of thinking but do not prepare governments well for the challenges that are sure to surface. Considerable further research and discussion are needed in order to identify, understand and prepare responses to non-linear shifts in nature and human society, and to their consequences.

5. What consequences arise from detrimental organisms and ecological processes that are strengthened as the ecosphere changes?

Numerous species of the brown macroalgae, *Sargassum*, are distributed throughout the temperate and tropical oceans of the world. In the open ocean, thick mats of the seaweed often provide the biological infrastructure necessary for other organisms to feed, shelter and reproduce; in coastal ecosystems, they provide nutrients and protect against erosion. *Sargassum* typically washes ashore in small and sporadic amounts.

However, since the late 2000s, *Sargassum* biomass has increased exponentially in the Atlantic Ocean. Sometimes dubbed the Great Atlantic Sargassum Belt, it acutely affects many Caribbean, Latin American and West African nations. Vast quantities hamper fishing activities offshore by snagging lines, breaking nets, clogging motors and obstructing boats. Onshore, it accumulates in mounds that damage local biodiversity and must be removed daily, often by bulldozers. Recreational activities become precarious or undesirable. When the seaweed decomposes, it releases hydrogen sulfide gas that is noxious and dangerous in high concentrations or close proximity. The impact of *Sargassum* on tourism- and fisheries-dependent economies has been severe. On Mexico's Caribbean coast, the navy leads the *Sargussum* response—in a perennial effort that often has minimal effect.

Scientific consensus is lacking as yet,[78] but the cause of the *Sargassum* boom is almost certainly linked to some facet of recent ecological disruption—probably nutrient discharges into marine waters. However, looking past the question of causation, the phenomenon is representative of a wider problem. A process is unfolding in which organisms that used to be mere nuisances have become substantial and sometimes severe economic and health security issues for many nations in under a decade. That *Sargassum* is thriving while

[77] Makweana, M., 'Disaster and its impact on mental health: A narrative review', *Journal of Family Medicine and Primary Care*, vol. 8, no. 10 (Oct. 2019).

[78] Djakouré, S. et al., 'On the potential causes of the recent Pelagic Sargassum blooms events in the tropical North Atlantic Ocean', *Biogeosciences Discussions*, 20 Sep. 2017.

much of the natural world's biodiversity is plummeting is a stark reminder that rapid changes in the ecosphere do not pose commensurate dangers across the living world.

How are harmful algal blooms and jellyfish responding to ecological disruption and what are their effects?

Seaweed evolved on Earth around 500 million years ago and has thus survived and adapted to a wide array of changing planetary conditions, including all five major extinction events. *Sargassum* is a relatively recent arrival, believed to have evolved some 65 million years ago. There are other algal forms, including harmful algal blooms that thrive in both freshwater and marine systems and secrete powerful biotoxins, many of which target the nervous systems of higher-order organisms, including humans. They are naturally occurring phenomena but their prevalence has been amplified by human activities, especially nutrient overabundance and climate change. The melting Arctic is beginning to suffer population explosions of *Alexandrium*, which causes paralytic shellfish poisoning.[79] Marine heatwaves have been known to spur major blooms of *Pseudonitzchia*, which causes amnesic shellfish poisoning. When they decompose, harmful algal blooms also contribute significantly to oceanic dead zones, often triggering mass die-offs of marine life.

Many regions of the world are also observing increases in jellyfish abundance (despite decreases in other regions).[80] This can reduce fish populations and damage or impede fishing activities. Stings can be dangerous or even lethal to humans and animals. Moreover, large jellyfish blooms have caused infrastructure damage, such as interfering with desalination and power plants, and can clog ships' cooling systems, leading to engine failure. Some experts worry about a possible 'jellification' of the oceans,[81] although sparse data has impeded scientific efforts to nail down the scope of the problem. Nonetheless, the phenomenon warrants closer scrutiny in an era of rapid global change, and its sociological impacts could be far-reaching.

Does ecological disruption amplify populations of disruptive insects and other arthropods, and what are their consequences?

The 2019–2022 transcontinental desert locust plague was one of the worst in modern history, causing catastrophic crop losses, food shortages and widespread socio-economic distress. The swarms affected over 25 countries in East Africa, the Middle East and South Asia, where locust control efforts were often hampered by pre-existing instability, conflict and the Covid-19 pandemic. Several countries in South America were afflicted by a separate

[79] Anderson, D. M. et al., 'Evidence for massive and recurrent toxic blooms of *Alexandrium catenella* in the Alaskan Arctic', *Proceedings of the National Academy of Sciences*, 12 Oct. 2021.

[80] Lee, S.-H. et al., 'The global spread of jellyfish hazards mirrors the pace of human imprint in the marine environment', *Environment International*, no. 171 (Jan. 2023); and Lee, S.-H. et al., 'Jellyfish blooms challenge the provisioning of ecosystem services in the Korean coastal waters', *Hydrobiologia*, 29 Nov. 2022.

[81] Havermans, C. et al., 'Exploring the role of gelatinous zooplankton in tomorrow's Arctic Ocean', 16th Deep-Sea Biology Symposium, Brest, France, 12–17 Sep. 2021; and Gershwin, L.-A. *Stung! On Jellyfish Blooms and the Future of the Ocean* (University of Chicago Press: Chicago, 2013).

swarm, marking the first locust outbreaks there in many decades.[82] The plague was fuelled by a combination of factors, notably unusual tropical storm patterns, high temperatures and agricultural expansion.[83] It remains unclear whether this particular event signals a new phase in locust activity in a changing ecosphere or is just one more in a millennia-long line of infestations. Clearly, even this narrow question has great relevance for ecological security.

The locust plague illustrates that, like aquatic systems, the terrestrial domain harbours classes of organisms positioned to take advantage of rapid change. The broader group of insects, which compromise 80 per cent of all animal life, are the most successful life form in the 450 million years of terrestrial evolution.[84] Some subset is likely to thrive during rapid change even as global insect populations are probably on the decline, facing a different set of ecological security risks.[85] Insects, especially mosquitos, and other arthropods, such as ticks and mites, are significant carriers of a large number of diseases; beetles, aphids, flies, larval moths and other insects are devastating agricultural pests.[86] Climate change, habitat change, invasive species and nutrient abundance are all known drivers of change for insects in general,[87] but their effects on disease, agriculture and larger social dimensions need greater attention.

What are the effects of ecological disruption on zoonotic spillover?

Concern about climate change tends to focus on a set of familiar abiotic factors, such as heat, extreme weather events, sea-level rise and melting ice sheets. These are all important but are not the whole story. Climate change is precipitating shifts in species' range throughout the living world. Organisms—and the pathogens they harbour—are tending to move poleward in latitude and upward in altitude in response to rising global temperatures, if they are able. At local scales, however, their rates of movement are context-specific, leading to novel types of biotic mixing. New opportunities for contact are advantageous for pathogens with pre-existing capacities to infect susceptible but unexposed hosts.[88] With time, it may be that the most impactful stress to societies from climate change arises from the amplified zoonotic spillover of animal pathogens to humans resulting in new, emerging and re-emerging infectious diseases. The spillover of pathogens to livestock and other animals could also cause socio-economic disruption, such as that

[82] Lecoq, M. and Cease, A., 'What have we learned after millennia of locust invasions?', *Agronomy*, vol. 12, no. 2 (Jan. 2022).

[83] Salih, A. A. M. et al., 'Climate change and locust outbreak in East Africa', *Nature Climate Change*, vol. 10 (2020), pp. 584–85.

[84] Bradley, T. J. et al. 'Episodes in insect evolution', *Integrative and Comparative Biology*, vol. 49, no.5 (2009), pp. 590–606.

[85] Donkersley, P. et al., 'Global insect decline is the result of wilful political failure: A battle plan for entomology', *Ecology and Evolution*, vol. 12, no. 10 (2022).

[86] Dent, D. and Binks, R. H., *Insect Pest Management* (Cabi: Wallingford, Oxfordshire, 2020).

[87] Gibert, P., Debat, V. and Ghalambor, C. K., 'Phenotypic plasticity, global change, and the speed of adaptive evolution', *Current Opinion in Insect Science*, vol. 35 (2019), pp. 34–40.

[88] Brooks, D. R., Hoberg, E. P. and Boeger, W. A., *The Stockholm Paradigm* (University of Chicago Press: Chicago, 2019).

seen in the 2018–20 African swine fever epidemic which wiped out roughly a quarter of the world's pork production.[89]

What are the implications of supercharged biological invasions?

Invasive species are a growing problem in the 21st century due to the increasing number of global connections and transportation networks, which enable species to move between regions with ease. Habitat change and global warming are likely to accelerate the movement of non-native species into new environments. There, they can outcompete native species, leading to displacement and potential extinction, while also introducing tagalong parasites and pathogens to new ecosystems. Even before the heavier press of ecological disruption sets in, invasive species are already causing immense damage to a variety of sectors, including agriculture, aquaculture, fisheries, livestock, forestry, shipping and tourism. As a major contributor to biodiversity loss, supercharged biological invasions could amplify the potential damage in unexpected ways.

What are the implications of detrimental organisms and processes for political stability and security?

This discussion should encourage researchers and policymakers to think beyond the problem of organisms that are at risk (or that pose risks) to consider the challenge of disruptive ecological *processes* that are fuelled by rapid ecosphere change. This question first focused on organisms—taking algal blooms, jellyfish, and insects and other arthropods as examples; it then looked at the processes of zoonotic spillover and biological invasion. The discussion of AMR in question 1 above raises the same question, as its emergence can be considered, in part, a naturally occurring ecological process amplified by ecological disruption.

The security implications of these changes are seldom considered. For example, harmful algal blooms are typically framed by ecologists as an issue of water quality management, but they can cause significant political and socio-economic stress, even instability.[90] A notable case was the catastrophic series of harmful algal bloom events in the Chiloé Archipelago in Chile in 2016, which killed many millions of commercially important fish over a few weeks, devastating livelihoods and fuelling civil unrest and citizen blockades in its aftermath.[91] Similar discord arrived in the wake of the 2019–22 transcontinental locust swarm and the 2017–21 fall armyworm plague in southern Africa.[92] Even though the disruptive effects of Covid-19

[89] Mackenzie, D., 'A quarter of all pigs have died this year due to African swine fever', *New Scientist*, 8 Nov. 2019.

[90] See e.g., Mardones, J. I. et al., 'Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016', *Science of the Total Environment*, 20 Apr. 2021; Brooks, B. W. et al., 'Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems?', *Environmental Toxicology and Chemistry*, vol. 35, no. 1 (2016), pp. 6–13; and Weir, M. J., Kourantidou, M. and Jin, D., 'Economic impacts of harmful algal blooms on fishery-dependent communities', *Harmful Algae*, no. 118 (Oct. 2022).

[91] Mascareño, A. et al., 'A Twitter-lived red tide crisis on Chiloé Island, Chile: What can be obtained for social-ecological research through social media analysis?', *Sustainability*, vol. 12, no. 20 (2020).

[92] Guarino, B., 'Armyworm pests invade southern Africa "like one of the 10 plagues of the Bible"', *Washington Post*, 14 Feb. 2017.

remain fresh in the collective memory, zoonotic spillover is more likely to be discussed primarily as a public health concern than an input to instability.

Conclusions and recommendations

This paper is intended to initiate a discussion of the potential security implications of five areas of challenges arising from ecological disruption:

1. Amplification of antimicrobial resistance;
2. The physiological consequences of pollution;
3. The decline of nature's contribution to people's well-being;
4. Local and regional ecological tipping points; and
5. Detrimental organisms and processes that thrive in the rapidly changing planet.

This paper does not, of course, claim to have fully answered the five questions; indeed, it has not even posed them fully. It is not yet clear which aspects of the answers to the five questions, once fully posed, will reveal risks of social disruption, political upheaval, insecurity and conflict. Overall, however, it should be clear that human well-being is better served by answering them as well as possible than by ignoring or even hiding from them.

The first conclusion of this exercise, then, is that these are issues that need to be understood better, so that assessments can be made whether policies are required among governments, intergovernmental organizations and others to meet these challenges—and, if so, what policies would offer most promise. When researchers first began to make the link between climate change and insecurity, there was considerable pushback in the scholarly community. Some scholars looked for proof of the link, found none and thus concluded that there is none. To find proof, they had to look to the past: large-n studies of the previous 60 years showed no climate signal. It should perhaps be added that many of the studies confused climate with weather and insecurity with just one of its forms—armed conflict. This paper is not concerned with proof, the search for which is a distraction. For proof, one looks back but this discussion is about looking ahead, and that means not the fruitless hunt for proof but the urgent assessment of risk. If risk can be identified, is it really a good idea to wait until proof consolidates in the shape of disaster before attempting to prevent, mitigate, adapt and/or limit the damage?

Each of the five areas covers multiple interlinked questions. Because the ecosphere as a whole is a network of linked sub-spheres—and thus what happens in the climate affects the air, the land, organisms and both fresh- and seawater—the questions in each area are linked with questions in other areas. The emphasis on interconnectedness means that, as well as thinking more clearly and systematically about risk, there is an urgent need to develop deeper understanding of what happens when, for example, one ecological regime shift triggers other changes. At that point, the interactions within the ecosphere might spur disruptive discontinuities. Thus, thinking systematically about interconnected risk means there is a need to absorb non-linear thinking into the framework of assessment.

The second conclusion, accordingly, is that while each component of the problems outlined above needs to be studied with care and in detail—and probably more components as yet unseen—this must be done in such a way that the different research efforts constantly build on each other. An interdisciplinary open-mindedness is required to take forward this research, which will be best served if its institutional settings are themselves experienced in communication between the disciplines.

As this overview of the issues indicates, some basic scientific knowledge already exists but there are also some significant gaps. As knowledge grows, awareness of the risks entailed will become clearer. There will be more understanding of which risks need to be addressed, with what priority and with how much urgency. Over time, however, as further research is pursued, the picture will change. Nonetheless, even as the picture changes, action must be taken to minimize and manage the risks.

The third conclusion is that the hard science research must be accompanied from the outset by social and political science research, while **the fourth conclusion** is that this research effort as a whole must be persistently oriented towards the policy world, which in turn must support the research effort and be open to the assessment and discussion of its findings.

How this should be done—what the best institutional settings are for research and policy development—is the next item on the agenda of this discussion. For now, the point is simply to establish that there is an agenda, and that it is urgent to start work on it.

Abbreviations

ABR	Antibiotic resistance
AMR	Antimicrobial resistance
NCP	Nature's contribution to people
WHO	World Health Organization

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