ce-manifesto-ch1-0425.docx

ce-ch2-risk-land-intro-0324-part1

ce-ch3-eco-overshoot-0324-part1

ce-ch4-hum-syst-0324-part1

latest-ce-ch5-nat-disaster-0525-part1

Chapter 6: Advanced Tech_ZAK_DRAFT

near-final-ce-ch7-violent-conflict-0324-part1

ce-ch8-two-attrct-threshold-0324-part1

Ch 3: Ecological Overshoot

The emergence of large scale civilizations depended upon a unique state of the biosphere. The favorable climate, the life supporting environment, and the relative abundance of resources were needed for the permanent settlement and agriculture required for a growing population. These essential conditions, necessary for humans and countless other species, are now being undermined. The cumulative effects of an exponentially growing global economy powered by industrial technology operating at a planetary-scale have critically degenerated the biosphere which has sustained all of life up to this point.

The current world system's rates of resource depletion, pollution, and waste accumulation are occurring much faster than the ecology can tolerate in order to remain stable. This relationship between the two systems of the biosphere and global civilization is coming to an end as it will no longer be able to support billions of people, and if continued, will result in a radically less habitable planet. For there to be a desirable future for humanity, civilization will need to become ecologically regenerative and long-term compatible with the biosphere[1].

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[1] See, for example, Richardson, Katherine, Steffen, Will, and Lucht, Wolfgang et al. "Earth beyond six of nine planetary boundaries." *Science Advances* 9, aadh2458 (2023). doi:10.1126/sciadv.adh2458

Some examples of environmental crises that reflect the current trend of ecological overshoot include: biodiversity loss[2], loss of keystone species and extinction cascades[3], overfishing[4],

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It is worth noting that there are environmentalists who will not support the idea of ecological overshoot due to the belief that technological advancements reduce humanity's dependence on nature (e.g. industrial agriculture). Therefore any physical boundaries to human consumption are "so theoretical as to be functionally irrelevant". Technological advancements such as nuclear fusion and genetically engineered crops will guarantee the survival of civilization and promise to decouple economic growth from environmental impacts.

It will become clear throughout this chapter and the following why we are less optimistic about technology's ability to save us from ecological overshoot. Decades of environmental research continues to support the notion of ecological overshoot and limits to growth, with little evidence to support any progress on "absolute decoupling" – i.e., that technological advancement and economic growth can occur independently of ecological extraction.

Asafu-Adjaye, John, Blomqvist, Linus, and Brand, Stewart et al. *An Ecomodernist Manifesto.* 2015. https://www.ecomodernism.org/

Haberl, H., Weidenhofer, Dominik, and Virag, Doris et al. "A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights." *Environ. Res. Lett.* 15, (2020): 065003. doi:10.1088/1748-9326/ab842a

Parrique, Timothee, Barth, Jonathan, and Briens, Francois et al. *Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability.* The European Environmental Bureau, 2019. https://eeb.org/wp-content/uploads/2019/07/Decoupling-Debunked-FULL-for-ONLINE.pdf

[2] Jaureguiberry, Pedro, Titeux, Nicolas, and Weimers, Martin et al. "The direct drivers of recent global anthropogenic biodiversity loss." *Sci. Adv.* 8. (2022): https://doi.org/10.1126/sciadv.abm9982

[3] Extinction cascades are the domino effect of coextinctions, where the loss of one species leads to the demise of others connected in a food web. This tends to magnify the rate of biodiversity loss and extinction risk. One modeling study found that in average climate scenarios, coextinctions will increase the biodiversity impact of primary extinctions by 184%, leading to an average of nearly 18% of loss in local vertebrate biodiversity by the end of this century. Such cascades are even more pronounced in cases where top predators and keystone species are lost, which can lead to the unraveling of entire food webs.

See: Strona, Giovanna, and Bradshaw, Corey, J. A. "Coextinctions dominate future vertebrate losses from climate and land use change." *Science Advances* 8, (2022): eabn4345. https://doi.org/10.1126/sciadv.abn4345

Terborgh, John, and Estes, James, A., eds. *Trophic Cascades: Predators, Prey, and the Changing Dynamics of Nature.* United States: Island Press

Petchey, Owen, L., Eklöf, Anna, Borrvall, Charlotte, and Ebenman Bo. "Trophically Unique Species Are Vulnerable to Cascading Extinction." *The American Naturalist* (2008): 171:5, 568-579. doi:10.1086/587068

Donohue, Ian, Petchey, Owen, L, Kefi, Sonia et al. "Loss of predator species, not intermediate consumers, triggers rapid and dramatic extinction cascades." *Global Change Biology* 23, (2017): 2962–2972. doi:10.1111/gcb.13703

[4] Kroodsma, David, A., Mayorga, Juan, Hochberg, Timothy et al. "Tracking the global footprint of fisheries." *Science* 359, (2018):904-908. doi:10.1126/science.aao5646

Watson, Reg, A. and Tidd, A. "Mapping nearly a century and a half of global marine fishing: 1869–2015." *Marine Policy* 93, (2018):171–177. https://doi.org/10.1016/j.marpol.2018.04.023

Pacoureau, Nathan, Rigby, Cassandra, and Kyne, Peter et al. "Half a century of global decline in oceanic sharks and rays." *Nature* 589, (2021):567–571. https://doi.org/10.1038/s41586-020-03173-9 climate change[5], deforestation,[6] Earth system changes such as slowing ocean currents[7] and disrupted hydrological cycles[8], various kinds of ecosystem collapse[9], coral bleaching[10] and damage to ocean ecosystems including oceanic dead zones[11], overloading nitrogen and

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[5] IPCC. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)].* IPCC, Geneva, Switzerland, (2023):pp. 35-115. https://doi.org/10.59327/IPCC/AR6-9789291691647

[6] Bologna, Mauro, and Aquino, Gerardo. "Deforestation and world population sustainability: A quantitative analysis." *Scientific Reports*, 10(1), (2020):7631. https://doi.org/10.1038/s41598-020-63657-6
Hoang, Nguyen Tien, & Kanemoto, Keiichiro. "Mapping the deforestation footprint of nations reveals growing threat to tropical forests." *Nature Ecology & Evolution*, 5(6), (2021):845–853. https://doi.org/10.1038/s41559-021-01417-z
Lawrence, Deborah, Coe, Michael, Walker, Wayne, Verchot, Louis, and Vandecar, Karen. "The Unseen Effects of Deforestation: Biophysical Effects on Climate." *Frontiers in Forests and Global Change*, 5, (2022): https://doi.org/10.3389/ffgc.2022.756115
West, Chris, Rabeschini, Gabriela, and Singh, Chandrakant et al. "The global deforestation footprint of agriculture and forestry." *Nature Reviews Earth & Environment*, 6(5), (2025):325–341. https://doi.org/10.1038/s43017-025-00660-3
Wolf, Christopher, Levi, Taal, Ripple, William, J., Zárrate-Charry, Diego, A. and Betts, Matthew, G. "A forest loss report card for the world's protected areas." *Nat Ecol Evol* 5, (2021): 520–529. https://doi.org/10.1038/s41559-021-01389-0
Hoang, Nguyen, T. and Kanemoto, Keiichiro. "Mapping the deforestation footprint of nations reveals growing threat to tropical forests." *Nat Ecol Evol* 5, (2021):845–853. https://doi.org/10.1038/s41559-021-01417-z

[7] Li, Guancheng, Cheng, Lijing, Zhu, Jiang, Trenberth, Kevin, E., Mann, Michael, E., and Abraham, John, P. "Increasing ocean stratification over the past half-century." *Nat. Clim. Chang.* 10, (2020):1116–1123 https://doi.org/10.1038/s41558-020-00918-2
Ditlevsen, Peter, and Ditlevsen, Susanne. "Warning of a forthcoming collapse of the Atlantic meridional overturning circulation." *Nat Commun* 14, (2023):4254. https://doi.org/10.1038/s41467-023-39810-w

[8] Fowler, Kiernan, Peel, Murray, and Saft, Margarita et al. (2022). "Hydrological Shifts Threaten Water Resources." *Water Resources Research* 58(8) (2022): doi:10.1029/2021WR031210
Raimi, Morufu Olalekan, Abiola, Ilesanmi, Alima, Ogah and Omini, Dodeye Eno. "Exploring How Human Activities Disturb the Balance of Biogeochemical Cycles: Evidence from the Carbon, Nitrogen and Hydrologic Cycles." *Research on World Agriculture Economy* 2, (2021): http://dx.doi.org/10.2139/ssrn.3896054
Yang, Dawen, Yang, Yuting, and Xia, Jun. "Hydrological cycle and water resources in a changing world: A review." *Geography and Sustainability* 2, (2021):115–122. https://doi.org/10.1016/j.geosus.2021.05.003

[9] There is some disagreement on definitions for ecosystem collapse. One working definition being used here is : "A degraded ecosystem state that results from the abrupt decline and loss of biodiversity, ecosystem functions and/or services, where these losses are both substantial and persistent, such that they cannot fully recover unaided within decadal timescales." Examples include eutrophication of freshwater lakes, fragmentation of food webs in grasslands, and overfishing leading to trophic collapse in coral reefs. This definition is from Newton, Adrian, C., Britton, Bob, and Davies, Kimberly, L. et al. "Operationalising the concept of ecosystem collapse for conservation practice." *Biological Conservation* 264, (2021):109366. doi:10.1016/j.biocon2021.109366
Jackson, Robert, B., and Canadell, Josep, G., eds. *Ecosystem Collapse and Climate Change.* vol. 241. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-71330-0

[10] van Woesik, Robert, Shlesinger, Tom, and Grottoli, Andrea, G., et al. "Coral-bleaching responses to climate change across biological scales." *Global Change Biology* 28, (2022):4229–4250. https://doi.org/10.1111/gcb.16192

[11] Altieri, Andrew, H., Harrison, Seamus, B., Seemann, Janina, and Knowlton, Nancy. "Tropical dead zones and mass mortalities on coral reefs." *Proceedings of the National Academy of Sciences* 114, (2017):3660–3665. https://doi.org/10.1073/pnas.1621517114

phosphorus cycles[12], and passing critical limits on various types of chemical pollution[13] and waste accumulation[14].

Ecological overshoot is already an existential threat to the countless complex life forms facing extinction. 70% of the individuals of all vertebrate species have disappeared since 1970[15]. Human activity has increased the current rate of species extinction at least 100 times greater than the average rate over the past 65 million years. We are perpetuating a mass extinction event – the sixth in Earth's 4.5 billion year history – destroying the web of life upon which we fundamentally depend[16].

The mass destruction of sentient life and billions of years of biological evolution is unethical and unacceptable on its own terms. It is like an ***ecological genocide***[17], where the violence is not

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Diaz, Robert, J. and Rosenberg, Rutger. "Spreading Dead Zones and Consequences for Marine Ecosystems." *Science* 321, (2008):926–929 https://doi.org/10.1126/science.1156401

[12] Filippelli, Gabriel, M. "The Global Phosphorus Cycle: Past, Present, and Future." *Elements* 4, (2008):89–95. https://doi.org/10.2113/GSELEMENTS.4.2.89

Fowler, David, Coyle, Mhairi, and Skiba, Ute et al. "The global nitrogen cycle in the twenty-first century." *Philosophical Transactions of the Royal Society B: Biological Sciences* 368, (2013):20130164. https://doi.org/10.1098/rstb.2013.0164

Beusen, A. H. W., Doelman, J.C., and Van Beek L.P.H., et al. "Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways." *Global Environmental Change* 72, (2022):102426 https://doi.org/10.1016/j.gloenvcha.2021.102426

[13] Naidu, Ravi, Biswas, Bhabananda, and Willet, Ian, R., et al. "Chemical pollution: A growing peril and potential catastrophic risk to humanity." *Environment International* 156, (2021):106616 https://doi.org/10.1016/j.envint.2021.106616

Cousins, Ian, T., Johansson, Jana, H., Salter, Matthew, E., Sha, Bo, and Scheringer, Martin. "Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS)." *Environ. Sci. Technol* 56, (2022):11172–11179. https://doi.org/10.1021/acs.est.2c02765

[14] Chen, David, M.-C., Bodirsky, Benjamin, L., Krueger, Tobias, Mishra, Abhijeet, and Popp, Alexander. "The world's growing municipal solid waste: trends and impacts." *Environ. Res. Lett.* 15, (2020):074021 https://doi.org/10.1088/1748-9326/ab8659

[15] Almond, R.E.A., Grooten M. and Petersen, T., eds. *Living Planet Report 2020 - Bending the curve of biodiversity loss.* WWF, Gland, Switzerland, 2020. https://www.worldwildlife.org/publications/living-planet-report-2020

[16] Background extinction rates are measured in extinctions per million-species years (E/MSY). Ceballos et al. (2015) considered a (conservative) background extinction rate based on empirical fossil records of 2 E/MSY, equivalent to 2 extinctions for every 10,000 vertebrate species per 100 years. Current extinction rates are accelerated to at least 100 times this, which means species that have gone extinct in the last century would have otherwise taken 10,000 years to disappear. Even if we do not know how many species have been lost exactly, we can determine the rate of modern extinction is exceptionally high, indicative of a Sixth Mass Extinction.

Ceballos, Gerardo, Ehrlich, Paul, Barnosky, Anthony, D., Garcia, Andres, Pringle, Robert, M., and Palmer, Todd, M. et al. "Accelerated modern human–induced species losses: Entering the sixth mass extinction." *Sci. Adv.* 1, (2015):e1400253. https://doi.org/10.1126/sciadv.1400253

[17] Ceballos, Gerardo, and Ehrlich, Paul, R. "Mutilation of the tree of life via mass extinction of animal genera." *Proceedings of the National Academy of Sciences* 120, (2023):e2306987120. https://doi.org/10.1073/pnas.2306987120

motivated by hatred of a specific group, but is directed towards nature writ large as a continuous, cumulative consequence of our civilization's basic modes of operating. The killing and torture of other species is accepted as a somewhat unfortunate reality but ultimately necessary to maintain our current comforts and expected standards of living. However, ***this is also an act of civilizational suicide***. In addition to the harms experienced by other species and ecosystems, the various environmental crises also cause or accelerate many types of catastrophic risks to humans, such as from food and water shortages, natural disasters, public health crises, and even violent conflict.

Planetary Boundaries and Ecological Tipping Points

Humanity is now approaching, and in some cases already surpassing, several planetary boundaries[18]. These are the "safe operating limits" of the Earth system which, once crossed, may have devastating and potentially irreversible consequences. Moving beyond certain boundaries risks triggering ecological tipping points: self-reinforcing feedback loops where critical Earth systems are suddenly brought from a prior safe state to a potentially catastrophic one[19].

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[18] The Planetary Boundaries framework was developed by an international group of environmental scientists at the Stockholm Resilience Centre in 2009, and quantifies nine interrelated boundary processes within the biophysical Earth System which have been heavily perturbed by human activity. These include Climate change, Novel Entities, Biosphere Integrity, Land System Change, Freshwater Change, Biogeochemical Flows, Ocean Acidification, Atmospheric Aerosol Loading, Stratospheric Ozone Depletion.
Staying within Planetary Boundaries allows the Earth to remain in a habitable, "Holocene-like" state similar to the last 10,000 years in which agriculture and modern civilization arose. Crossing boundaries increases the risk of large-scale, abrupt or irreversible disruption to the Earth System - endangering stability and life support systems critical for human welfare. As of 2023, the first full quantification of these boundaries revealed six out of nine boundaries have been transgressed.
Richardson, Katherine, Steffen, Will, and Lucht, Wolfgang et al. "Earth beyond six of nine planetary boundaries." *Sci. Adv.* 9, (2023):eadh2458. doi:10.1126/sciadv.adh2458
Rockström, Johan, Steffe, Will, and Noone, Kevin et al. "A safe operating space for humanity." *Nature* 461, (2009):472–475. https://doi.org/10.1038/461472a
[19] In the Earth Systems literature, there are subtle distinctions between the concept of a "planetary boundary" and that of a "tipping point." Planetary boundaries were defined for the purposes of assessing safe levels of human impact on the earth and to avoid the worst long-term impacts. They neither rule out nor assume the existence of tipping points. They are points of acceptable risk to stay within a "safe operating zone" for processes at the scale of the whole Earth system.
Tipping points, on the other hand, are nonlinear thresholds between a driver and the state of a system (e.g. nutrients added to a freshwater lake until it switches to having no oxygen and mostly algae). They occur when a change in a dynamical system becomes self-perpetuating beyond a certain threshold as a result of asymmetries between balancing and destabilizing feedback loops. Tipping points are ubiquitous

One example of an ecological tipping point is the disruption of the Amazon rainforest's *hydrological cycle*. A common cause of deforestation is clear cutting or burning rainforest, often to create space for animal agriculture or crop production (such as cattle, soy and palm oil). Alongside a hotter and drier climate, this has significant effects on the region's hydrological cycle in which water moves from the land to the atmosphere by evaporation from soil and transpiration from plants and then back to land by means of rainfall. Deforestation leads to less rainfall because the atmosphere is no longer "taking up" water transpired from the trees. Water was also being held in the root systems and bodies of the trees, so less water from rainfall can be "taken in" and stored by the forest ecosystem. In turn, these drier conditions make it easier to burn larger amounts of the forest, and also increase the occurrence and severity of forest fires[20].

Leading Earth system scientists argue that, beyond a critical point, a runaway feedback loop is triggered: drier conditions from burning, deforestation, and climate change lead to more severe burning and greater tree loss in an accelerating fashion, ultimately resulting in a rainforest

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across systems of all scales, from lakes and forests to ice sheets and ecosystems.
Crossing a planetary boundary entails higher risks of passing tipping points for related subsystems, for example, the collapse of ocean currents, ice sheets and coral reefs for climate change; or trophic cascades and ecosystem collapse for biodiversity integrity. Planetary boundaries themselves are not necessarily "global tipping points." Most known tipping points are at local, regional or continental scales - though tipping points themselves can have planetary-scale ramifications.
Hughes, Terry, P., Carpenter, Stephen, Rockström, Johan, Scheffer, Marten, and Walker, Brian. "Multiscale regime shifts and planetary boundaries." *Trends in Ecology & Evolution* 28, (2013):389–395. doi:10.1016/j.tree.2013.05.019
Rocha, Juan, C., Peterson, Garry, Bodin, Örjan, and Levin, Simon. "Cascading regime shifts within and across scales." *Science* 362, (2018):1379–1383. doi:10.1126/science.aat7850
Steffen, Will, Richardson, Katherine, and Rockstrom, Johan et al. "Planetary boundaries: Guiding human development on a changing planet." *Science* 347, (2015):doi:10.1126/science.1259855
Stockholm Resilience Center. *A Fundamental Misrepresentation of the Planetary Boundaries Framework.* 2017.
https://www.stockholmresilience.org/research/research-news/2017-11-20-a-fundamental-misrepresentation-of-the-planetary-boundaries-framework.html

[20] The Global Tipping Points report describes two amplifying feedback mechanisms for tropical forest tipping behavior. At regional scales, the dominant mechanism stabilizing tropical forests like the Amazon is the forest-rainfall feedback, where the forest increases annual rainfall by recycling water through evapotranspiration, and reducing seasonal-interannual variability. Deforestation causes this feedback to become destabilizing, inducing further tree mortality. At local scales, fire-vegetation feedback can maintain an ecosystem in an open vegetation state; less tree cover lets fire spread more easily across drier, more flammable grasses, which prevents trees from growing back.
Moreover, the forest-rainfall and fire-vegetation feedbacks amplify each other. Both of these make it possible for the Amazon rainforest to tip into a degraded forest or open savannah as a result of climate change and deforestation.
Global Tipping Points. *The Global Tipping Points Report 2023.* University of Exeter, Exeter, UK, 2023. https://global-tipping-points.org/

ecosystem no longer able to sustain itself.[21] The Amazon is the largest contiguous forest in the world, therefore a disruption of its hydrological cycle would have significant effects on global rainfall patterns. For example, winds move the water transpired from trees in the Amazon to other regions of the world, contributing to rainfall in areas such as South America. One of the consequences of passing this tipping point—"breaking" the hydrological cycle of the Amazon—would be a catastrophic disruption of rainfall in South America, likely leading to food and water insecurity and associated public health, national security, and economic crises[22].

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[21] A significant body of scientific research has documented evidence for the Amazon tipping point due to deforestation and climate change:
Sterling, Shannon, M., Ducharne, Agnes, and Polcher, Jan. "The impact of global land-cover change on the terrestrial water cycle." *Nature Clim Change* 3, (2013):385–390. https://doi.org/10.1038/nclimate1690
Zemp, D. C., Schleussner, C. -F., Barbosa, H. M. J. & Rammig, A. (2017). *Deforestation effects on Amazon forest resilience.* Geophysical Research Letters 44, 6182–6190. https://doi.org/10.1002/2017GL072955 ;
Shukla, J., Nobre, C. & Sellers, P. (1990). "Amazon Deforestation and Climate Change." *Science* 247, (1990):1322–1325. https://doi.org/10.1126/science.247.4948.1322
Boulton, Chris, A., Lenton, Timothy, M. and Boers, Niklas. "Pronounced loss of Amazon rainforest resilience since the early 2000s." *Nat. Clim. Chang.* 12, (2022):271–278. https://doi.org/10.1038/s41558-022-01287-8
Zemp, Delphine Clara, Schleussner, Carl-Friedreich, Barbosa, and Henrique, M. J., et al. "Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks." *Nat Commun* 8, (2017):14681. https://doi.org/10.1038/ncomms14681
Staal, Arie, Tuinenburg, Obbe, A., and Bosmans, Joyce, H.C., et al. "Forest-rainfall cascades buffer against drought across the Amazon." *Nature Clim Change* 8, (2018):539–543. https://doi.org/10.1038/s41558-018-0177-y
Flores, Bernardo, M., Montoya, Encarni, and Sakschewski, Boris et al. "Critical transitions in the Amazon forest system." *Nature* 626, (2024):555–564. https://doi.org/10.1038/s41586-023-06970-0
[22] The most significant impacts from a dieback of the Amazon would be felt across South America, including possibly disrupting monsoon circulation over the continent. One estimate suggests that Amazon dieback would lead to economic damages of up to $US 3,589 billion, an order of magnitude greater than the GDP of the Amazon area.
Boers, Niklas, Marwan, Norbert, Barbosa, Henrique, M. J., and Kurths, Jurgen et al. (2017). "A deforestation-induced tipping point for the South American monsoon system." *Sci Rep* 7, (2017):41489. https://doi.org/10.1038/srep41489
Lapola, David, M., Pinho, Patricia, Quesada, Carlos, A., and Nobre, Carlos, A., et al. "Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action." *Proceedings of the National Academy of Sciences* 115, (2018):11671–11679. https://doi.org/10.1073/pnas.1721770115

It is extremely difficult to predict exactly when tipping points will be crossed[23]. However, even given conservative estimates placing certain tipping points decades (rather than mere years) away, without significant structural changes, their likelihood increases to near certainty over time[24].

There are several critical planetary boundaries that are suspected to have already been crossed. For example, toxic "forever chemicals," such as those used in plastic products, non-stick cookware, water-repellent materials, and stain-resistant fabrics (PFAS)[25], were recently found in freshwater, rainwater samples and soils all around the world, far exceeding safe levels set by the EPA and EU[26]. These as well as hundreds of other toxic categories of

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[23] There is a large body of work on early warning signals for tipping points across climate, ecological and socio-environmental systems, however operationalizing these to work with real data remains an active area of research.
Lenton, T. M., Livina, V. N., Dakos, V., van Nes, E. H. and Scheffer, M. "Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, (2012):1185–1204. https://doi.org/10.1098/rsta.2011.0304
Swingedouw, Didier, Ifejika Speranza, Chinwe, and Bartsch Annett et al. "Early Warning from Space for a Few Key Tipping Points in Physical, Biological, and Social-Ecological Systems." *Surv Geophys* 41, (2020):1237–1284. https://doi.org/10.1007/s10712-020-09604-6
Dylewsky, Daniel, Lenton, Timothy, M., and Scheffer, Marten et al. "Universal early warning signals of phase transitions in climate systems." *Journal of The Royal Society Interface* 20, (2023):20220562. https://doi.org/10.1098/rsif.2022.0562

[24] Armstrong McKay, David I., Staal, Arie, and Abrams, Jessie, F., et al. "Exceeding 1.5°C global warming could trigger multiple climate tipping points." *Science* 377, (2022):eabn7950. https://doi.org/10.1126/science.abn7950

[25] As mentioned in footnote 19 above, the planetary boundary for novel entities (such as PFAS) is not technically a tipping point. Surpassing it does not imply an abrupt shift in the dynamics of an ecological or Earth system. However, Persson et al. (2022) concluded we are outside the safe operating zone for novel entities because annual production of these outstrips the pace of global capacity for assessment and monitoring. Establishing a physically quantitative boundary for all novel entities, however, is an intractable problem, as there are over 350,000 novel chemicals and mixtures, of which one third are confidential or ambiguously described.
Persson, Linn, Carney Almroth, Bethanie, M., and Collins, Christopher, D., et al. "Outside the Safe Operating Space of the Planetary Boundary for Novel Entities." Environ. Sci. Technol. 56, (2022):1510–1521. https://doi.org/10.1021/acs.est.1c04158 ;
Kunnas, Jan, G. "Comment on "Outside the Safe Operating Space of the Planetary Boundary for Novel Entities."" *Environ. Sci. Technol.* 56, (2022):6786–6787. https://doi.org/10.1021/acs.est.2c00524
Persson, Linn, Carney Almroth, Bethanie, M., and Collins, Christopher, D., et al. "Response to Comment on "Outside the Safe Operating Space of the Planetary Boundary for Novel Entities."" *Environ. Sci. Technol.* 56, (2022):6788–6789. https://doi.org/10.1021/acs.est.2c02265
There are over 200 use categories for more than 1400 individual PFAS compounds, including textiles, fire-fighting foam, electronics, artificial turf, musical instruments and ammunition. Glüge, Juliane, Scheringer, Martin, and Cousins, Ian, T., et al. "An overview of the uses of per- and polyfluoroalkyl substances (PFAS)." *Environ. Sci.: Processes Impacts* 22, (202):2345–2373. https://doi.org/10.1039/D0EM00291G

[26] Cousins et al. (2022) conclude that an identifiable planetary boundary for PFAS have been exceeded, as diffuse PFAS pollution is global in scale, with PFAS related substances exceeds safe guideline levels in rainwater, surface water and soils based on US EPA, EU Environmental Quality Standards and Dutch

chemicals have been found in human blood samples and breast milk[27]. They have been shown to cause numerous negative health effects such as increasing cancer, kidney and neurotoxicity, and developmental defects in fetuses and infants[28]. They also affect soil, microorganisms, and other critical ecosystems with unknown long-term consequences on biosphere health and integrity[29].

Over 350,000 novel chemicals and mixtures are registered globally.[30] Each year there is roughly an exponential increase in toxic chemical pollution (see figure 1 below[31]) – added on top of the already existing waste accumulated over several hundred years of industrial activity[32]. Toxic

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guidelines for soils. PFAS levels exceed safe levels even in remote areas such as the Tibetan plateau and Antarctica, by up to 14x. Moreover, atmospheric cycling and enriched concentration in sea spray aerosols means these levels are so far seen to be practically irreversible.
Cousins, Ian, T., Johansson, Jana, H., Salter, Matthew, E., Sha, Bo, and Scheringer, Martin. "Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS)." *Environ. Sci. Technol.* 56, (2022):11172–11179. https://doi.org/10.1021/acs.est.2c02765

[27] Monroy, Rocio, Morrison, Katherine, and Teo, Koon et al. "Serum levels of perfluoroalkyl compounds in human maternal and umbilical cord blood samples." *Environmental Research* 108, (2008):56–62. https://doi.org/10.1016/j.envres.2008.06.001
LaKind, Judy, S., Naiman, Josh, Verner, Marc-Andre, Lévêque, Laura, and Fenton, Suzanne. "Per- and polyfluoroalkyl substances (PFAS) in breast milk and infant formula: A global issue." *Environmental Research* 219, (2023):115042. https://doi.org/10.1016/j.envres.2022.115042

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Mamsen, Linn, S., Bjorvang, Richelle, D., and Mucs, Daniel et al. "Concentrations of perfluoroalkyl substances (PFASs) in human embryonic and fetal organs from first, second, and third trimester pregnancies." *Environment International* 124, (2019):482–492. https://doi.org/10.1016/j.envint.2019.01.010

[29]Xu, Baile, Yang, Gaowen, Lehmann, Anika, Riedel, Sebastian, and Rillig, Matthias, C. "Effects of perfluoroalkyl and polyfluoroalkyl substances (PFAS) on soil structure and function." *Soil Ecol. Lett.* 5, (2023):108–117. https://doi.org/10.1007/s42832-022-0143-5
Brendel, Stephan, Fetter, Éva, Staude, Claudia, Vierke, Lena, and Biegel-Engler, Annegret. "Short-chain perfluoroalkyl acids: environmental concerns and a regulatory strategy under REACH." *Environ Sci Eur* 30, (2018):9. https://doi.org/10.1186/s12302-018-0134-4

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[31] Cousins, Ian, T., Johansson, Jana, H., Salter, Matthew, E., Sha, Bo, and Scheringer, Martin. "Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS)." *Environ. Sci. Technol.* 56, (2022):11172–11179. https://doi.org/10.1021/acs.est.2c02765

[32] Global production of novel entities by the chemical industry has increased 50-fold since 1950. Out of the 350,000 chemicals registered globally, 70,000 have been registered in the past decade, with nearly half of these in emerging economies where management and disposal capacity is limited. Many synthetic chemicals, pesticides, pharmaceuticals are persistent or "pseudo-persistent" taking a long time to degrade, or having environmental release that exceeds degradation rates. With an increasing rate of production of existing and new persistent chemicals, a substantial fraction of which do not degrade in the environment, the rate of accumulation in the environment is plausibly exponential.
Bernhardt, Emily, S., Rosi, Emma, J., and Gessner, Mark, O. "Synthetic chemicals as agents of global change." *Frontiers in Ecology and the Environment* 15, (2017):84–90. https://doi.org/10.1002/fee.1450

chemicals are distributed everywhere (often invisible): sitting on the surface of water, evaporating into the atmosphere, and raining down upon all of humanity and the biosphere as a whole. Occasionally some of these chemicals are banned, but too often, they are simply replaced with others which are potentially equally as harmful and whose long-term safety is largely unknown[33].

In the United States in 2019 there were approximately 3.4 billion pounds of toxic chemicals released into the environment[34]. The link between synthetic chemical exposure and cancer is fairly well-established: environmental toxins may be responsible for between 1% and 19% of human cancers, and 5% of childhood cancers[35]. ***Our assault on the biosphere is also a war waged against our own bodies***. 99% of the global population breathes air exceeding safe limits of pollution.[36] Air pollution is responsible for around seven million premature deaths every

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[33] ChemTrust. *From BPA to BPZ: a toxic soup?* 2018.
https://www.chemtrust.org/wp-content/uploads/chemtrust-toxicsoup-mar-18.pdf ;
Li, Fan, Duan, Jun, and Tian, Shuting et al. "Short-chain per- and polyfluoroalkyl substances in aquatic systems: Occurrence, Impacts and treatment." *Chemical Engineering Journal* 380, (2020):122506.
https://doi.org/10.1016/j.cej.2019.122506
[34] The Toxic Release Inventory (TRI) by the EPA, which covers only the United States, reported that approximately 3.3 billion pounds of toxic chemicals were released into the environment or managed through disposal or other methods in 2022 alone.
EPA. *Releases of Chemicals*. Accessed June 11th, 2025.
https://www.epa.gov/trinationalanalysis/releases-chemicals
This, however, only represents a fraction of the total global production and does not account for all toxic chemicals. According to the European Chemicals Agency (ECHA), the REACH database includes information on over 120,000 chemical substances registered for use in the European Union.
AIHA. *European Chemicals Agency Launches New Chemicals Database.* Accessed June 11th, 2025.
https://www.aiha.org/news/240222-european-chemicals-agency-launches-new-chemicals-database
Globally, the number of chemicals commercially used is estimated to be in the hundreds of millions, with several millions of these being toxic to varying degrees.
Schymanski, Emma, L., Zhang, Jian, Thiessen, Paul, A., Chirsir, Parviel, Kondic, Todor, and Bolton, Evan, E. "Per- and Polyfluoroalkyl Substances (PFAS) in PubChem: 7 Million and Growing." *Environmental Science & Technology*, 57(44), (2023):16918–16928. https://doi.org/10.1021/acs.est.3c04855
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https://doi.org/10.1016/j.envint.2019.04.067
Straif, K. "The burden of occupational cancer." *Occup Environ Med* 65, (2008):787–788.
https://doi.org/10.1136/oem.2007.038224
World Health Organization. *Global health risks : mortality and burden of disease attributable to selected major risks.* 2009. https://iris.who.int/handle/10665/44203
[36] The WHO daily limit for exposure to particulate matter (PM) less than 2.5 micrometers in diameter is 15 μg/m3. One recent study also found that globally across 175 countries, the mean annual population-weighted $PM_{2.5}$ concentration from 2000-2019 was 32.8 μg/m3 - more than double the WHO daily limit.
Yu, Wenhua, Ye, Tingting, and Zhang, Yiwen et al. "Global estimates of daily ambient fine particulate matter concentrations and unequal spatiotemporal distribution of population exposure: a machine learning modelling study." *The Lancet Planetary Health* 7, (2023):e209–e218.
https://doi.org/10.1016/S2542-5196(23)00008-6
World Health Organization. *Billions of people still breathe unhealthy air: new WHO data.* 2022.

year around the world, contributing to pulmonary and heart diseases, lung cancer and respiratory infection[37]. Over 1800 chemicals like PFAS, metals, plastic additives and certain pesticides are endocrine-disrupting chemicals (EDCs) which mimic, block, or interfere with the body's hormonal systems[38]. They bind to hormone receptors, disrupt hormone synthesis, or alter hormone transport across the body, and are associated with intellectual disability, obesity, diabetes, and cancer[39]. Exposure to certain chemicals, such as phthalates (used in plastics), and other EDCs are associated with reduced sperm count in men, contributing to decreased male fertility rates[40]. Between 1973 and 2011, sperm counts in North America, Europe, Australia, and New Zealand have declined 52.4%[41]. Polycystic ovary syndrome affects up to 26% of women worldwide, and is strongly linked with environmental exposure to EDCs like PFAS, Bisphenol A and phthalates[42]. ***A toxic Earth is hostile to human reproduction, health, and well-being.***

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https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data
World Health Organization. *The top 10 causes of death.* 2020.
https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death

[37]One review by Roser (2024) of five major recent published estimates of mortality from air pollution (both indoor and outdoor) found between 6.7 million to 8.8 million premature deaths every year, however a much broader review by Pozzer et al. (2023) finds a much wider range across 31 studies published since 2005 for mortality attributable to PM2.5 - between 0.8 million/year for the lowest published estimate to 10.2 million/year for the highest.
Roser, Max. *Data review: how many people die from air pollution.* OurWorldInData.org. 2021.
https://ourworldindata.org/data-review-air-pollution-deaths
Pozzer, A., Ananberg, S.C., Haines, A., Lelieveld, J., and Chowdhury, S. "Mortality Attributable to Ambient Air Pollution: A Review of Global Estimates." *Geohealth* 7, (2023):e2022GH000711.
https://doi.org/10.1029/2022GH000711

[38] Yilmaz, Bayram, Terekeci, Hakan, Sandal, Suleyman and Kelestimur, Fahrettin. "Endocrine disrupting chemicals: exposure, effects on human health, mechanism of action, models for testing and strategies for prevention." *Rev Endocr Metab Disord* 21, (2020):127–147. https://doi.org/10.1007/s11154-019-09521-z

[39] Kahn, Linda, G., Philippat, Claire, Nakayama, Shoji, F., Slama, Remy, and Trasande, Leonardo. "Endocrine-disrupting chemicals: implications for human health." *The Lancet Diabetes & Endocrinology* 8, (2020):703–718. https://doi.org/10.1016/S2213-8587(20)30129-7

[40] Rehman, Saba, Usman, Zeenat, and Rehman, Sabeen et al. "Endocrine disrupting chemicals and impact on male reproductive health." *Translational andrology and urology* vol. 7,3 (2018): 490-503
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6043754/

[41] The lack of statistically significant sperm count decline in non-Western countries may be due to relatively fewer studies, but is also consistent with there being less EDC exposure in those regions.
Levine, Hagai, Jorgensen, Niels, and Martino-Andrade, Anderson et al. "Temporal trends in sperm count: a systematic review and meta-regression analysis." *Human reproduction update* vol. 23, (2017):6:646-659
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6455044/

[42]Silva, Ana Beatriz, P., Carreiró, Filipa, Ramos, Fernando, and Sanches-Silva, Ana. "The role of endocrine disruptors in female infertility." *Mol Biol Rep* 50, (2023):7069–7088.
https://doi.org/10.1007/s11033-023-08583-2
Jozkowiak, Malgorzata, Piotrowska-Kempisty, Hanna, and Kobylarek, Dominik et al. "Endocrine Disrupting Chemicals in Polycystic Ovary Syndrome: The Relevant Role of the Theca and Granulosa Cells in the Pathogenesis of the Ovarian Dysfunction." *Cells* 12, (2022):174.
https://doi.org/10.3390/cells12010174

Figure 2

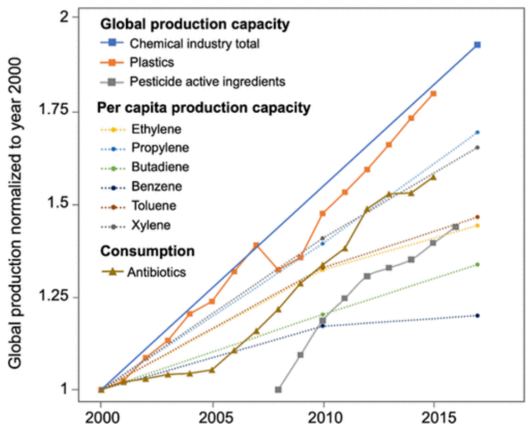

Figure 2. Current rising global trends of chemical industry production, expressed as the relative growth in some novel entities between 2000 and 2017 (for when comparable data are available): 1. Global production capacity for the chemical industry as a whole, plastics production and pesticide active ingredients (for which earliest data are from 2008); 2. Per capita production capacity in weight for key monomers and solvents: benzene, butadiene, ethylene, propylene, toluene, and xylene, 3: Global consumption of antibiotics. Data from the Global Chemicals Outlook II, (1) Geyer et al. 2017, (37) and Søgaard Jørgensen et al. (38)

The consequences of passing critical ecological limits may exhibit *delayed causation*. This means there can be catastrophic risks from certain environmental harms that effectively become inevitable even if the situation appears safe and stable at the moment the boundary is crossed. Coordinated effort will be required to mitigate such damages from those limits which we have already exceeded and to avoid those which humanity is rapidly approaching.

Furthermore, the various identifiable planetary boundaries – such as those involved in deforestation, chemical pollution, or climate change – must be thought of as more than isolated environmental problems to be solved. Rather, they each reflect a general increase in cumulative stress to the biosphere from increasing depletion and toxicity. The various subsystems within the biosphere are deeply interconnected, and environmental harms interact, accumulate, and compound.[43]

For example, global forest loss exacerbates countless other environmental crises. Burning and deforestation emits massive amounts of CO_2, methane, black carbon and particulate matter – worsening climate change while simultaneously destroying the trees best equipped to sequester

[43] Lade, Stephen, J., Steffan, Will, and de Vries, Wim et al. “Human impacts on planetary boundaries amplified by Earth system interactions.” *Nat Sustain* 3, (2020):119–128. https://doi.org/10.1038/s41893-019-0454-4

excess carbon[44]. Higher intensity megafires, such as Australia's "Black Summer" in 2020 erode the ozone layer[45] and decrease global rainfall and precipitation patterns.[46] The loss of vegetation and changes to soil increase the likelihood of flooding[47]. Wildfires disrupt the migration of birds, threatening species extinctions and the destabilization of critical ecosystem functions [48]. Sediment and ash runoff dramatically change the chemistry in freshwater lakes and rivers, resulting in massive die-offs of the species who live there there[49].

One environmental issue can worsen several others. The other direction is also true: a single earth system can be degraded from multiple directions. The ocean[50], for example, is getting warmer and more acidic from increased CO_2 in the atmosphere[51]. Rivers and waste streams pour millions of tonnes of toxic chemical pollution into it regularly, including industrial fertilizer

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[44] Liu, Yongqiang, Goodrick, Scott, and Heilman, Warren. "Wildland fire emissions, carbon, and climate: Wildfire–climate interactions." *Forest Ecology and Management* 317, (2014):80–96. https://doi.org/10.1016/j.foreco.2013.02.020

[45] Bernath, Peter, Boone, Chris and Crouse, Jeff. "Wildfire smoke destroys stratospheric ozone." *Science* 375, (2022):1292–1295. https://doi.org/10.1126/science.abm5611

[46] Jiang, Yiquan, Yang Xiu-Qun, and Liu, Xiaohong et al. "Impacts of Wildfire Aerosols on Global Energy Budget and Climate: The Role of Climate Feedbacks." *Journal of Climate* 33, (2020):3351–3366. https://doi.org/10.1175/JCLI-D-19-0572.1

[47] Sankey, Joel, B., Kreitler, Jason, and Hawbaker, Todd, J., et al. "Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds." *Geophysical Research Letters* 44, (2017):8884–8892. https://doi.org/10.1002/2017GL073979

Moody, John, A., Shakesby, Richard, A., Robichaud, Peter, R., Cannon, Susan, H. and Martin, Deborah, A. "Current research issues related to post-wildfire runoff and erosion processes." *Earth-Science Reviews* 122, (2013):10–37. https://doi.org/10.1016/j.earscirev.2013.03.004

[48] Overton, Cody, T., Lorenz, Austin, A., and James, Eric, P., et al. "Megafires and thick smoke portend big problems for migratory birds." *Ecology* 103, (2022):e03552. https://doi.org/10.1002/ecy.3552

[49] Gomez Isaza, Daniel, F., Cramp, Rebecca, L., and Franklin, Craig, E. "Fire and rain: A systematic review of the impacts of wildfire and associated runoff on aquatic fauna." *Global Change Biology* 28, (2022):2578–2595. https://doi.org/10.1111/gcb.16088

[50] Georgian, Samuel, Hameed, Sarah, and Morgan, Lance et al. "Scientists' warning of an imperiled ocean." *Biological Conservation* 272, (2022):109595. https://doi.org/10.1016/j.biocon.2022.109595

[51] Jiang, Li-Qing, Dunne, John, and Carter, Brendan, R., et al. "Global Surface Ocean Acidification Indicators From 1750 to 2100." *Journal of Advances in Modeling Earth Systems* 15, (2023):e2022MS003563. https://doi.org/10.1029/2022MS003563

Cheng, Lijing, Trenberth, Kevin, Fasullo, John, Boyer, Tim, Abraham, John, and Zhu, Jiang. "Improved estimates of ocean heat content from 1960 to 2015." *Science Advances* 3, (2017):e1601545. https://doi.org/10.1126/sciadv.1601545

IPCC. *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 2019. doi:10.1017/9781009157964 runoff[52], antibiotics[53], forever chemicals like PFAS[54], and between 8 - 11 million tonnes of plastic every year[55]. The ocean ecosystems aren't even safe from the rain, which brings with it microplastics, heavy metals and toxic trace elements of arsenic, lead, copper and zinc – changing ocean chemistry and threatening organisms as large as whales and as small as phytoplankton[56]. Concentration of microplastics exceed safe levels even in deep-sea ecosystems[57]. The open ocean has lost 2% of its oxygen (77 billion tons) over the last 50 years.[58] Roughly 30% of the world's fish are overexploited, threatening one-third of all sharks and rays with extinction.[59] [60].

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[52] Malone, Thomas, C., and Newton, Alice. "The Globalization of Cultural Eutrophication in the Coastal Ocean: Causes and Consequences." *Front. Mar. Sci.* 7. (2020) https://doi.org/10.3389/fmars.2020.00670

[53] Traces of commonly used antibiotics such as sulfamethoxazole, azithromycin, and ciprofloxacin have been found throughout riverine and marine waters globally. Many of these are chronically toxic to algae, invertebrates and fish, with further impacts on human health. One study found 53,800 tons of antibiotics released into the environment from China alone.

Maghsodian, Zeinab, Mohammad Sanati, Ali, and Mashifana, Tebogo et al. "Occurrence and Distribution of Antibiotics in the Water, Sediment, and Biota of Freshwater and Marine Environments: A Review." *Antibiotics* 11, (2022):1461. https://doi.org/10.3390/antibiotics11111461

Liu, Lili, Wu, Wei, Zhang, Jaiyu, Lv, Peng, Xu, Lie, and Yan, Yanchun. "Progress of research on the toxicology of antibiotic pollution in aquatic organisms." *Acta Ecologica Sinica* 38, (2018):36–41. https://doi.org/10.1016/j.chnaes.2018.01.006

Chen, Hui, Liu, Shan, and Xu, Xiang-Rong et al. "Antibiotics in typical marine aquaculture farms surrounding Hailing Island, South China: Occurrence, bioaccumulation and human dietary exposure." *Marine Pollution Bulletin* 90, (2015):181–187. https://doi.org/10.1016/j.marpolbul.2014.10.053

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[55] Williams, Allan, T., and Rangel-Buitrago, Nelson. "The past, present, and future of plastic pollution." *Marine Pollution Bulletin* 176, (2022):113429. https://doi.org/10.1016/j.marpolbul.2022.113429

[56] Ventura, Andreia, Simoes, Eliana, F. C., and Almieda, Antoine, S., et al. "Deposition of Aerosols onto Upper Ocean and Their Impacts on Marine Biota." *Atmosphere* 12, (2021):684. https://doi.org/10.3390/atmos12060684

Ryan, Anna, C., Allen, Deonie, and Allen, Steve et al. "Transport and deposition of ocean-sourced microplastic particles by a North Atlantic hurricane." Commun Earth Environ 4, (2023):1–10. https://doi.org/10.1038/s43247-023-01115-7

Hamilton, Douglas, S., Perron, Morgane, M.G., and Bond, Tami, C.m et al. "Earth, Wind, Fire, and Pollution: Aerosol Nutrient Sources and Impacts on Ocean Biogeochemistry." *Annual Review of Marine Science* 14, (2022):303–330. https://doi.org/10.1146/annurev-marine-031921-013612

[57] Harris, Peter, T., Maes, Thomas, Raubenheimer, Karen, and Walsh, J. P. "A marine plastic cloud - Global mass balance assessment of oceanic plastic pollution." *Continental Shelf Research* 255, (2023):104947. https://doi.org/10.1016/j.csr.2023.104947

[58] Breitburg, Denise, Levin, Lisa, A., and Oschlies, Andreas et al. "Declining oxygen in the global ocean and coastal waters." *Science* 359, (208):aam7240. https://doi.org/10.1126/science.aam7240

[59] Dulvy, Nicholas, K., Pacoureau, Nathan, and Rigby, Cassandra, L., et al. "Overfishing drives over one-third of all sharks and rays toward a global extinction crisis." *Current Biology* 31, (2021):4773-4787.e8. https://doi.org/10.1016/j.cub.2021.08.062

[60] Möllmann, Christian, and Diekmann, Rabea. "Marine Ecosystem Regime Shifts Induced by Climate and Overfishing." *Advances in Ecological Research* vol. 47 (2012):303–347 Elsevier. https://doi.org/10.1016/B978-0-12-398315-2.00004-1

Human activity pushes multiple planetary boundaries in parallel, and there may be many environmental risks that are unexpected and difficult to identify in advance. It only takes crossing one critical planetary boundary to threaten substantial and irreversible impacts to the biosphere. Even if greenhouse gas emissions were somehow reversed, for example, passing safe limits on biodiversity or chemical pollution could still massively damage humanity's prospects. Therefore, it is the broader threat of ecological overshoot – and the structures of civilization which give rise to it – which must become the object of shared focus and international collaboration.

Misalignment in the Biosphere-Civilization Relationship

Navigating the metacrisis requires an epochal shift in the biosphere-civilization relationship in which underlying causes of ecological overshoot must be addressed. This entails resolving fundamental structural misalignments between the two planetary-scale processes of economic production and consumption on the one hand and ecological regeneration and renewal on the other. The emergence of a truly sustainable civilization depends on, among other things, a deep redesign of global supply chains, the world's financial system, and associated planetary governance.

Intrinsic to historical industrial supply chains are the processes of resource acquisition, manufacturing, and distribution. This includes the energy required throughout the process and the pollution and waste generated as a byproduct. In economics this is referred to as a *linear materials economy*: the economic process beginning at the point of resource extraction and ending at the point of waste disposal. In natural systems, there are analogous processes occurring between other species, such as herbivores consuming plants, carnivores consuming other species, plants consuming resources from the soil, and so on. However, these ecological processes are not linear. They are circular: the waste of one organism becomes the resource of another in turn.

For the majority of history, human extraction and waste were also able to be metabolized by the environment just like those of any other organism. However, this phase gradually ended as industrial scale human activity could extract more resources and produce more toxic chemicals and waste than the biosphere evolved to process[61]. No other species, or even era of our species, can synthesize millions of new chemicals per year that are unfamiliar to the biosphere and take multiple thousands of years to break down, or clear cut a football field of forest every few seconds[62] and create floating patches of garbage three times the size of France.

Humans ability to degrade the oceans is particularly striking. The surface of the Earth is largely composed of water (covering a little less than ¾ of the planet). Half of the Earth's photosynthesis occurs in the ocean, and produces as much as 70% of the oxygen in the atmosphere. It is even possible that complex life evolved out of the ocean[63]. However, since the industrial revolution, humans have put enough waste into the ocean that microplastics and pharmaceutical remnants can be found in every cubic inch of the ocean. There are now multiple heaps of trash floating in the ocean, the smallest of which is roughly twice the size of Germany[64]. As a result of agricultural runoff there are over 400 *dead zones* in the ocean where most forms of ocean life can no longer exist[65]. Human activity has also warmed, acidified, and

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[61] Bernhardt, Emily, S., Rosi, Eemma, J. and Gessner, Mark O. “Synthetic chemicals as agents of global change.” *Frontiers in Ecology and the Environment* 15, (2017):84–90. https://doi.org/10.1002/fee.1450 ; Naidu, R. et al. (2021). *Chemical pollution: A growing peril and potential catastrophic risk to humanity*. Environment International 156, 106616. https://doi.org/10.1016/j.envint.2021.106616

[62] Global Deforestation rates from Global Forest Watch is 22.7 Mha in 2022. This is equivalent to 7206m^2 of forest loss per second. The standard size of a football pitch is 105x68m = 7140m^2, hence roughly a football pitch every second.
Note, however, that the total annual forest loss from Global Forest Watch is broken down by driver of loss, and not all of this is clear cutting (e.g. forestry). If we just include **permanent** forest loss according to their breakdown, this becomes 4.77 Mha for commodity driven deforestation + 136 Kha urbanization, which is about1557 m^2 per second. This turns the above estimate closer to a soccer/football field of permanent deforestation every 4.5 seconds.

[63] Boag, Thomas, H., Stockey, Richard, G., Elder, Leanne, E., Hull, Pincelli M. and Sperling, Erik, A. “Oxygen, temperature and the deep-marine stenothermal cradle of Ediacaran evolution.” *Proc. R. Soc. B.* 285, (2018):20181724. https://doi.org/10.1098/rspb.2018.1724

[64] There are about five total subtropical oceanic garbage patches. Based on direct aerial surveys, the Great Pacific Garbage Patch was found to be 1.6 million km^2, between 4 - 16 times higher than previous estimates and almost 3x the size of France (549,000 km^2). The other four garbage patches are in the North Atlantic, South Atlantic, Indian Ocean and South Pacific, with size estimates ranging from 0.7 million km^2 (Germany is about 357,000 km^2, hence the smallest is almost double this area) to upwards of 5 million km^2.
Lebreton, Laurent. “The status and fate of oceanic garbage patches.” *Nature Reviews Earth & Environment*, 3(11), (2022):730–732. https://doi.org/10.1038/s43017-022-00363-z
Leal Filho, Walter, Hunt, Julian, and Kovaleva, Marina “Garbage Patches and Their Environmental Implications in a Plastisphere.” *Journal of Marine Science and Engineering*, 9(11), (2021):Article 11. https://doi.org/10.3390/jmse9111289
Lebreton, L., Slat, B., and Ferrari, F., et al. “Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic.” *Scientific Reports*, 8(1), (2018):4666. https://doi.org/10.1038/s41598-018-22939-w

[65] The term "dead zones" is technically a misnomer. These are oxygen minimum zones which are hypoxic (less than 2 ml O_2 per litre), and can lead to mass mortality of aquatic life, but algae proliferates. In about half of oceanic dead zones, eutrophication (accumulation of nutrients) kicks off rapid microbial growth which uses up oxygen, killing off other life and maintaining high nutrient but low oxygen levels. In its worst

polluted the entire ocean to the point where countless species (including coral reefs) are threatened or dying off at massive scales.

Throughout biological evolution the relative power of each organism was small when compared to the environment as a whole. The lion may be an apex predator, but it could do nothing to destroy the broader ecosystem, let alone the entire biosphere. This is not true of a technologically advanced civilization capable of geoengineering at planetary scale.

Externalities and Embedded Growth Obligations

Other life forms also don't rely on financial systems that externalize costs to the commons or require exponential growth of goods and services to function[66]. The phrase "negative externality" in economics is used to describe a cost that is not reflected in the balance sheet of a company. For example, in 2024, it was estimated that, at the current rate it is being produced, the cost of removing and destroying PFAS from the environment would likely exceed the GDP of the entire world at 106 trillion USD[67]. This means that the profitability of companies producing and using

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form, oxygen falls further to anoxia (near zero O_2) and microbes begin generating poisonous hydrogen sulfide.

Recent studies have found a large increase in open ocean oxygen minimum zones. Altieri et al. (2017) notes at least 497 dead zones are currently listed, with at least 370 more yet to be described, about half of which impact tropical reefs. Stramma et al. (2010) found open ocean oxygen minimum zones increased by 4.5 million km^2 (about the size of the European Union) over 50 years from 1960–1974 to 1990–2008. The volume of water that has gone completely anoxic has quadrupled in that same time period.

Stramma, Lothar, Schmidtko, Sunke, Levin, Lisa, A., and Johnson, Gregory, C. "Ocean oxygen minima expansions and their biological impacts." *Deep Sea Research Part I: Oceanographic Research Papers* 57, (2010):587–595. https://doi.org/10.1016/j.dsr.2010.01.005

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Diaz, Robert, J., and Rosenberg, Rutger. "Spreading Dead Zones and Consequences for Marine Ecosystems." *Science*, 321(5891), (2008):926–929. https://doi.org/10.1126/science.1156401

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PFAS depends upon them not paying the costs for its remediation (or the healthcare costs of those who are getting cancer from it). Those costs are “external” to the “internal” accounting of the company. Until the industries are forced to pay those costs, the burden of the externalities is being borne by the public. This is true for many industries, whose profitability is predicated upon externalized harm to the biosphere or to the social-sphere. Those who benefit do not pay the true costs, which fall outside of their accounting systems.

In addition to externalized costs, obligations for economic growth are embedded in the most basic structures underpinning the global financial system, such as debt and interest. Banks, for example, must offer consistent annual returns to clients with ongoing accounts. Corporations or nation-states receiving loans, as is commonplace in venture capital and international development, must return the original cost of the loan plus accrued interest. Financial systems employing interest require the total amount of currency in circulation to increase every year (equal to the sum of the monetary supply from the previous year plus the interest)[68]. When this is applied to the original cost plus accrued interest, it creates a compounding, exponential curve, driving exponential growth in the monetary supply. This is an engine of economic growth. Influxes of debt and the creation of currency create risks such as insolvency (the inability to pay back debts) and inflation (the debasement of currency value). To avoid financial system failure, there must be a continuous – and exponential – increase in economic returns with corresponding increases in the availability of goods and services. For any system subject to debt and interest, growth is required for survival. The economy is not simply growing because there is increasing demand on the part of consumers. Rather, it is growing, in large part, because the increases in debt and currency must be met with economic growth to prevent financial system collapse.

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Increases in economic activity ultimately ground out in increasing resource extraction, energy use, and commercial manufacturing. It has been shown that economic growth – for example, as measured by global gross domestic product (GDP) – is around 99% correlated with growth in the use of energy (e.g., fossil fuels). To create 5 trillion USD of additional wealth (globally) requires the equivalent of 174 million barrels of oil.[69] Increasing wealth is also tightly coupled with increasing use of raw materials such as sand, minerals, and lumber – with roughly every dollar of GDP corresponding to 1.2 kilograms of raw materials[70]. More production, more purchases, and more profits all depend on powering buildings and transporting products. Economic growth is therefore inextricably linked to increasing resource depletion, pollution, waste, and toxicity[71]. (In part two of this book, we explore why engineering solutions that increase the efficiency of renewable energy sources will not necessarily resolve this dilemma due to a well-established – yet paradoxical – trend where increases in energy efficiency actually lead to us using more energy rather than less[72]).

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[69] Garrett (2011) found based on thermodynamic principles and available statistics from 1980 to 2017 there is a constant scaling between the rate of primary energy consumption and the sum total of past global economic production. Further work by Garret et al. (2020, 2022) confirmed this relation, finding that just *maintaining* existing levels of economic production requires sustained growth in energy consumption.
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[70] Wiedmann et al. (2015) also found that for every 10% increase in GDP, the average national material footprint increases by 6%. The global average material footprint was 10.5 tonnes per capita in 2008.
Our World in Data. *Material footprint per unit of GDP, 2009 to 2019*. Our World in Data.
https://ourworldindata.org/grapher/material-footprint-per-unit-of-gdp ;
Wiedmann, Thomas, O., Schandl, Heinz, and Lenzen, Mandred et al. "The material footprint of nations." *Proceedings of the National Academy of Sciences* 112, (2015):6271–6276.
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[71] There is significant evidence that advances in digital technology will not decouple economic growth from ecological impact. See this conversation
https://www.thegreatsimplification.com/episode/132-daniel-schmachtenberger T

[72] The Jevons Paradox states that eventually an increase in efficiency in resource use will generate an increase in resource consumption rather than a decrease. This correlation (sometimes termed the "rebound effect") has been well documented across a variety of sectors and scales.
York, Richard, and McGee, Julius, A. "Understanding the Jevons paradox." *Environmental Sociology* 2, (2016):77–87. https://doi.org/10.1080/23251042.2015.1106060
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Responding to the Risk of an Uninhabitable Earth

Obligatory exponential economic growth with externalized harms, operating on a linear materials economy, employing increasingly powerful technology is fundamentally incompatible with the natural pace of ecological regeneration and biospheric stability.

There are many positive and necessary efforts to combat these trends, including non-profit, governmental, IGO, and impact investment projects in the commercial sector focused on conservation, renewable energies, 'closed loop' economies, and general sustainability. However, the totality of all of these activities taken together has not even slowed the rate of overshoot. The situation continues to worsen year by year. There are still fundamental economic incentives for extraction, waste, and pollution, and our success at international environmental agreements has been disappointing at best.

All of these dynamics (discussed further in part two) drive exponential increases in production and consumption that have run up against real physical and ecological limits. The biosphere-civilization relationship is intrinsically (and appropriately) asymmetric. ***Civilization is inherently dependent upon the biosphere – not the other way around. Yet civilization continues to destroy that which it depends upon for its very existence.*** Absent efforts to resolve these structural misalignments, ecological overshoot will continue mostly unabated, leading to increasing global catastrophes and possibly the uninhabitability of the Earth.