THE PUBLISHING HOUSE
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MEDICINE
Health and the Environment

FOOD SYSTEMS AND GLOBAL POLLUTION GENERATE AN INSIDIOUS PLANETARY HEALTH BUBBLE

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Received April 15, 2025

Human societies are integral to the biosphere. Aligning all human activities with nature's regenerative capacity constitutes a civilizational bifurcation. Engaging with this disruptive shift in societal trajectory requires recognizing that planetary boundaries, which define the global physical limits within which humanity can operate safely, are being differentially transgressed. Analyzing the interconnectedness of these boundaries enables their articulation in a higher-order framework centred on two primary components: food systems and global physico-chemical pollution. Both are interacting grand stressors, and have direct and indirect impacts on the health of individuals, societies, and ecosystems. The markets are largely blind to food security and global pollution. Trends through 2050 indicate that global food demand is expected to double. Food systems represent both a problem and a potential solution. At the same time, chemical production has doubled in the last 20 years, shows no sighs of slowing, and no scientific solutions can address the effects of complex mixtures of man-made chemicals on the interconnected health of people and nature. To promote preventive, rather than merely curative, solutions requires the partial to complete phase out of large groups of chemicals, with coordinated action at all institutional levels.

Keywords: agriculture, bundles of planetary boundaries, cocktail effect, food democracy, governance and legal frames, health costs, stranded assets.

INTRODUCTION

The Unavoidable Socioecological Bifurcation

Human societies and their activities are deeply embedded in nature and systemically depend on its multifunctional cycles and functions, translating into nature services and vital resources. The underlying socioecological framework has been neglected for decades (UNEP, 2019), with as result a global crisis with multiple interwinding consequences. We are thus far from fully understanding the depth and breadth of the current downturn. Addressing the situation implies neither more nor less a civilizational bifurcation (Panel 1).

Panel 1. The socio-ecosystemic bifurcation.

Bifurcation is used here to refer to two divergent trajectories in our economic system and way of life. Bifurcation means revising the economy to reduce wealth inequality and ensure that price, taxation, and incentive systems take into account the real costs which consumption patterns impose on the environment (Ripple *et al.*, 2017). For example, more than half of global GDP is estimated to be reliant on natural resources, but its consumption is not amortized (UNEP, 2019). This generates an ecological debt that can not simply be written off. This is why human activities must be part of the functions and cycles of the biosphere, with societies being intimately linked to them.

Bifurcation is likely to better describe the changes our societies have to go through, as compared with transition, transformation, sustainability, or collapse. Bifurcation could consist, for example, in

– Limiting the role of markets and making them subject to societal aims;

– Enforcing limits through regulation, standards and norms, so that measurement of impacts can be made without commoditising land and nature;

– Taking into account the particularities of communities, cultures, lifestyles, work, and employment issues, but also legal requirements in social and economic matters;

– Ensuring that technology serves the vital needs of humans and the regeneration and preservation of nature's cycles and services.

In short, bifurcation is about what and why we measure, namely a balance between managing by numbers and governance by law.

Apart from localized empowerment initiatives (Bennet *et al*., 2016), there is little evidence to suggest whether such a bifurcation might occur in a consensual and coordinated manner (Negrutiu, 2022). Given that many issues and facts remain open, indeterminate, or contested (Hulme, 2020), the question becomes: what mechanisms or leverage points might enable us to overcome structural socio-ecosystemic obstacles and engage effectively with this potential bifurcation?

To address the challenge, the article unfolds according to the following plan:

Chapter 2 describes Planetary Boundaries as a two-component system, namely food systems and global pollution. That changes the way major boundary stressors can be dealt with.

Chapter 3 shows that food systems are a problem and solution at the same time and points out why existing solutions are slow to come.

Chapter 4 dissects the global physical chemical pollution to reveal the extent of the problem and outline the difficulty to target credible solutions.

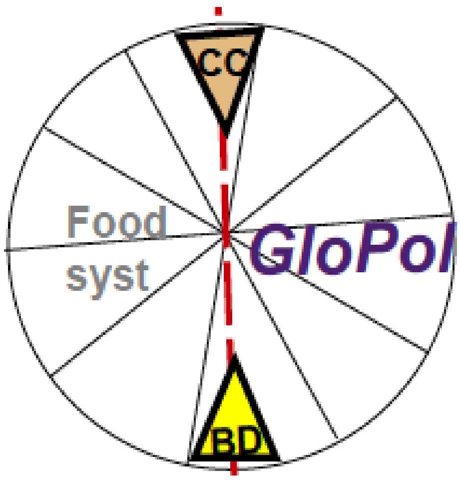
Chapter 5 summarizes how food systems and global pollution act in concert on the integrated health of societies and nature.

The analysis terminates with the plausible consequences of immediate action versus inaction.

AGGREGATING PLANETARY BOUNDARIES PAYS OFF, BY REVEALING TWO GRAND STRESSORS

The Planetary Boundaries approach (Rockstrom *et al*., 2023) has identified biological and geo-physical limits within interconnected functions and cycles of the Earth system. The planetary boundary framework measures variables of biosphere integrity, pollution and waste, water and land use, and ocean, air, and climate changes that eventually translate into thresholds, tipping points, warning signs, and state shifts.

Compiling interactions and connections among boundaries is essential for addressing the current rush for, and inequitable access to, vital resources. Our analysis has shown that individual boundaries can be grouped into two major pressure subsystems within the biosphere: food systems and global physico-chemical pollution (Fig. 1; Arguello and Negrutiu, 2019; Negrutiu *et al*., 2020; see also Campbell *et al*., 2017). Tipping cascades originate within these subsystems and feed into climate destabilization, biodiversity loss, and other impacts.



Global health bubble

Fig. 1 – **The two-system approach to Planetary Boundaries.** Planetary Boundaries categories are according to Steffen et al (2015) and modified by the author. They can be aggregated in two subsets of interacting boundaries: Food Systems (Food Syst) and the physico-chemical (global pollution, including waste, GloPol) disruptions. The aggregation shows that climate change (CC) and biodiversity (BD) variables overlap Food and Global Pollution system boundaries. The framework has profound consequences on people and ecosystem health, i.e., it generates a global health bubble.

Once aggregated, Planetary Boundaries gain traction to science, policy, and business. This clarification could fundamentally alter the approach to resource policies and decision-making on broader challenges, such as poverty, health, economic development, and ecological transitions (Millward-Hopkins *et al*., 2020; Rammelt *et al*., 2022). For instance, there is bias in the energy transition thinking: transition is focusing exclusively on housing and transportation, which are thermic energy issues. It ignores the fact that humans are equally concerned by access to food, a metabolic energy component of that same transition considered holistically. The two dimensions are obviously interconnected: meeting the level of renewable energy production needed to replace fossil fuels involves significant trade-offs, including land allocation for biomass necessary for food versus biofuels, or the construction of large river dams for hydroelectric power and irrigation (Brand *et al*., 2021). In this respect, an important parameter in trending food systems is the ratio of energy output to fossil energy input, *i.e*., food calories produced per unit of energy input. A ratio above one is the marker of a sustainable agriculture (Bonneuil and Fressoz, 2026). With the industrialization and artificialization of agriculture, the ratio is variably declining according to the considered sector (e.g., crop production and livestock) (Pelletier *et al*., 2011).

FOOD SYSTEMS, METABOLIC ENERGY SECURITY, AND SYSTEMIC HEALTH

Food systems are a critical stressor of planetary boundaries. They account for the use of nearly half of the world's vegetated land, 80% of deforestation, and 70% of freshwater use, and 15% of fossil fuel consumption. Globally, agriculture *lato sensu* is responsible for roughly a third of anthropogenic greenhouse gas emissions, and is contributing increasingly to biodiversity loss (UNEP, 2016; WWF, 2020). Agriculture remains humanity's largest consumer of land and biomass, making it central to land use conversions in human history (Verburg et al., 2015; Negrutiu *et al*., 2020). Given population growth projections and societal trends through 2050, global food demand is expected to double, with a persistent rise in animal-based food demand. These developments suggest that greenhouse gas emissions from food systems will likely triple (WRI, 2022). Despite decades of efforts to mitigate these risks (Brundtland, 1987; WRI, 2019; Dixson-Declève *et al*., 2022; Negrutiu, 2022; FAO, 2024), solutions highlight the significant gap between global needs and the resources available, and poorly tackle power dynamics in the global agri-food sector, market concentration, price volatility, and improving livelihoods for small farmers, indigenous communities, and women.

The business centric agri-food world is the mirror of the illogical route from farm to fork, in which agribusiness oligopoly and influence is at the root of, to name just a few, waste, unhealthy diets, the privatization of profit through intellectual-property law, the inability of the market economy to account for the true cost of farming (Lawrence, 2019).

The above highlight the fact that the dominant industrial food system neglects the key bio-geophysical building blocks of the biosphere – soil, water, and biomass—vital interconnected resources that face increasing threats (Negrutiu *et al*., 2020). These primary resources are stranded assets (Caldecott *et al*., 2013) that need protection from environmental and management related risks through policy-decision making on the land-water nexus (Falkenmark and Wang-Erlandsson, 2021; Constantini *et al.*, 2023; Cailloce, 2024; WRI, 2024). This is important because the geopolitics of biomass, water, and land is driving resource scarcity agendas (Mathijs *et al*., 2015; Negrutiu *et al*., 2020; Erb and Gingrich, 2022), causing conflict between national security and international order instruments and mechanisms. Last but not least, we keep underscoring the time pressure to act before socio-ecosystem boundaries hit their limits (Meadows *et al*., 2005; Barnosky *et al*., 2012; Dixson-Declève *et al*., 2022; Negrutiu *et al*., 2023).

The process of addressing food system challenges, while theoretically grounded in common sense solutions, appears to be falling short in practice. Food and food security issues encompass complex geopolitical, human rights, and Sustainable Development Goals (SDGs) concerns, making them high-priority on international agendas. Numerous institutions and organizations have stepped up to address these challenges, including the UN Committee on World Food Security, FAO, the UN Special Rapporteur on the Right to Food, and various groups of intergovernmental experts like iPES Food, IPCC, IPBES, and the CBD. These bodies play significant roles in shaping the global food security landscape, and UN food system summits (such as those held by the FAO) aim to provide solutions and guide policy direction (FAO, 2017).

Can such contrasting or even conflicting aspects be reconciled and squared?

From this perspective, building integrated, fair, and robust food systems implies public policies addressing both needs (food) and means (agriculture), while focusing attention on legal frameworks. Thus, food security is the objective, nature is the issue, agriculture is a means, and public health and the economic model are the result. This means that each person has the right to choose the food they need and want according to culture, taste, tradition, and production territory. Taken collectively, the society has the right to participate in the definition of food policies. This is not what happens at present. “From farm to fork”, as currently promoted by, for example, the EU agenda (*e.g.*, EU, 2020), dictates agro-food policies. Reversing the perspective to “from fork to farm” (Dangour *et al*., 2017; Collart Dutilleul, 2021) completely changes the societal perception. From fork to farm has a great deal to do with democratic participation, inclusive health and well-being.

Finally, the legal frameworks on the governance of food systems and food security are essential to challenging the dominance of industrial agriculture (undergoing a massive process of corporate and financial concentration at all nodes of the food system supply chain; Clapp, 2025) and to supporting diverse, localized farming systems, best adapted to economic, natural, and climatic contexts. Also, there is growing momentum behind establishing a form of food social security. It reflects the recognition that food must be treated as a fundamental human right, not just a commodity. According to FAO, global food security is effective when all human beings have, at all times, physical and economic access to sufficient, safe, and nutritious food to meet their energy needs and food preferences for a healthy and active life (FAO, 2022b; FAO, 2023).

The preceding discussion highlights that food system thinking has evolved to a level where coherent policies and practices can be implemented at local and regional scales. A key component of this evolution is recognizing the role of food in preventive health and its economic impact on individuals.

For example, the food system indicator framework represents a significant contribution from science, offering a structured way to address these challenges. It tracks food system transformation across five themes and baseline indicators (Schneider *et al*., 2023). The chosen food system indicators seek ***legal recognition of the right to food*** (13 indicators such as Access to safe water; Prevalence of undernourishment; Dietary diversity), assesses ***diets, nutrition, and health*** (16 indicators, such as Cropland expansion (% change); Food system emissions; Functional integrity; Pesticide use; Yield), followed by ***governance*** (10 indicators, such as Accountability index; Food safety capacity; Right to food), ***lively hoods, poverty and equity*** (7 indicators, such as Social protection coverage; Rural underemployment), and ***resilience*** (8 indicators, such as Social capital index; Reduced coping strategies).

However, despite these efforts, there is widespread lobbying and confusion that hamper the clarity and coherence needed for long-term strategies. Various stakeholders, including corporations, governments, and international bodies, often have conflicting interests, making it difficult to achieve a unified vision (Clapp *et al*., 2021). This lack of convergence hinders progress, leaving key issues unresolved despite the availability of practical solutions. For example, concerning Europe, it is about time to think the food system in terms of Common Food Policy in order to escape from the schizophrenic drift of the Common Agricultural Policy. Namely, anti-obesity strategies operate alongside agri-trade policies that make junk food cheap and abundant, young farmers are offered premiums while subsidies drive up land prices and undermine access to land, and strict environmental standards are set up while the advisory services farmers need to meet them are defunded (iPES Food, 2019).

In summary, the major problems within food systems have been identified, and there are solutions within reach. To transform the global food system by 2050, it is needed to simultaneously improve food production practices, reduce food loss and waste, and shift diets (Clark *et al*., 2020). Translating this knowledge into action depends on political and economic actors taking responsibility at both local and global levels. The challenge remains in mobilizing will and resources to implement these solutions effectively in real-world contexts.

GLOBAL POLLUTION, SYSTEMIC ENERGY, AND HEALTH ISSUES

Cumulative raw material extraction, consumption, and footprint together with chemical intensification keep rising at alarming rates, causing global pollution, energy overuse, and related health issues (Krausmann *et al*., 2009; Hickel *et al*., 2022).

In the last 100 years, the produced amounts of anthropogenic chemicals has surged 500-fold. Between 2000 and 2017 alone, the industry's production capacity doubled, with no signs of slowing for the next decades (GCO2, 2019). Asia has emerged as the world's largest producer and consumer of chemicals, with China accounting for over a third of global sales.

About 350,000 man-made chemicals have been licensed for manufacturing and global use (Wang *et al*., 2020). The safety profile of these substances is as follows: 60% of anthropogenic chemicals are considered life-threatening (40% being persistent and toxic), and 20% are potential carcinogens.

According to chemical properties of produced compounds (GCO1, 2012; Mcdonald *et al*., 2018; *pubchem.ncbi.nlm.nih.gov.;* www.cancer-environnement.fr), the following families have been inventoried:

– VOC (volatile organic compounds) and VCP (volatile chemical products) – essentially paints, solvents, adhesives, detergents, hygiene and cosmetic products.

– POP (Persistent Organic Products, such as dioxins, PFAS or per- and polyfluoroalkyl substances); PCB (polychlorinated biphenyls); APH (aromatic polycyclic hydrocarbons) – ubiquitous, many cancerogenic.

– Pesticides (herbicides, fungicides, insecticides) – Food chain residues; Alteration of soil and river ecosystems; Cancerogenic and Specific diseases (farmers).

– Synthetic fertilizers – impacts on soil ecosystem and water quality.

– Synthetic hormones – Presence in water and food (such as meat from intensively farmed animals); Endocrine disruptor effects.

– Metallic compounds, heavy metals (mercury, lead, cadmium, nickel, copper, tin, etc.) and rare earths (lanthanides); Aluminium salts (vaccine additives) – known effects on the nervous system and obesogenic.

– Macro-, micro-, and nano-plastics – The ubiquitous “plastisphere”, namely residues in air and water, and food chains; significant shares from micro-beads in detergents and personal care products; Fast fashion and textile industry in general.

– Nanomaterials (*e.g*., nano-needles and nano-spheres) – Wide array of environmental and consumer applications and electronics.

– Food additives – Ultra-processing of food and chronic diseases.

– Asbestos (fibers) – Lung and larynx cancer.

– Chemical weapons (several dozens of compounds) – Incapacitating, lethal (asphyxiants, vesicants, respiratory poisons, nerve agents).

The global physico-chemical pollution system is composed of complex and evolving "cocktails" of the above listed anthropogenic chemicals. They accumulate in the air, water, and soil, and accentuate the climatic issue beyond the strict effects of greenhouse gasses (Fig. 1). The system poses a hidden and pervasive threat, generated through ocean acidification, more general atmospheric, land, and water pollutions, and waste accumulation.

The slow systemic nature of the global pollution (IRGC, 2013), with its insidious long-term exposure, means it often goes unnoticed, while continuously harming the health of people, societies, and ecosystems (Arguello and Negrutiu, 2019). It is the lottery of breathing, drinking, and eating: each individual permanently lives at table, at work, at school, on vacation, and elsewhere in the company of evolving and invisible mixtures of chemicals. This permanent long-term exposure to such mixtures, the effects of which will never be assessed and understood at scale and in due time (coined relic or legacy pollution, Frickel and Elliot, 2018), corresponds to a global unintended experiment on all the living organisms, human populations included. There is no escape in this real time natural selection process with various effects, namely developmental disorders, sterility, immunodeficiencies, cancers, mortality, and more (Fuller *et al*., 2022; see also iPES food, 2017), but also possible (genetic) adaptations. Such effects are already visible, particularly in high-risk regions like India, China, Pakistan, Bangladesh, the Middle East, and agricultural regions in Central and South America. These areas suffer from severe air and water pollution, as well as intense herbicide and pesticide exposure (Negrutiu *et al*., 2019).

From the scientific perspective, this is a process in which limits up to which organisms or ecosystems can safely cope with additive or multiplicative risks posed by the combination of multiple factors have to be estimated with regard to exposure to any single factor. Literature survey of cocktail effects indicates that additive to synergistic effects are observed in mixtures of 2–5 compounds in cultured cells or biomarker and genotoxicity response tests (Graillot *et al.*, 2012; see also Heys *et al*., 2016).

Therefore, science struggles to predict the outcomes of the complex interactions between multiple chemicals, often relying on probability estimates and extrapolations (Brooks *et al*., 2020). For example, the response to all possible combinations of risk factors (in this case chemical cocktails) implies dividing the limit value for an individual threat by the square root of the number of threat dimensions (Fig. 2; Lomborg, 2001). Even though this would be unrealistic in practice, it suggests that the adoption of limit values two or three order of magnitude smaller than those estimated by single factor impact studies is relevant to legislation in developing prevention protocols and regulations (such as the precautionary principle).

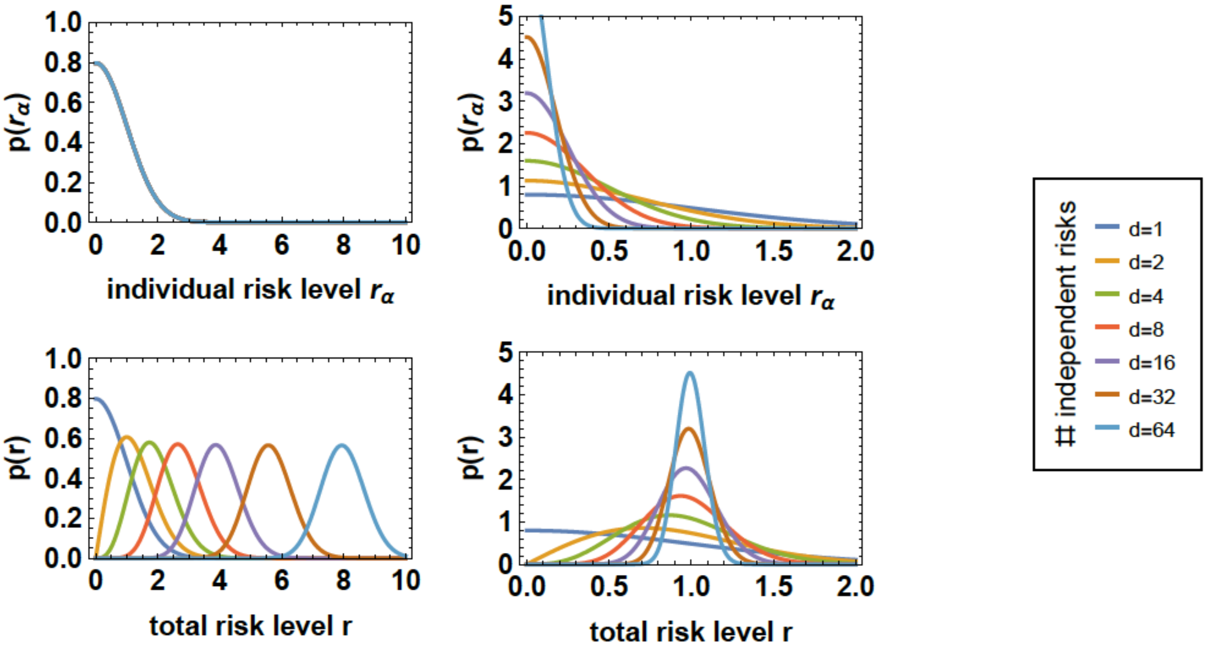


Fig. 2 – Safe operating limits in high-dimensional risk spaces by representation of multidimensional threat levels (courtesy of Ralf Everaers).

Establishing limit values through risk analysis of health harmful effects consists in applying a typical safety factor 100 (Lomborg, 2001). Consider **d** independent stresses, each assessed on a scale where 1 represents a safe boundary in the case where a given risk factor is taken in isolation. Examples could be radiation doses or concentrations of various toxic substances to which organisms or ecosystems are exposed. In this case, risk exposure is characterized by a d dimensional risk vector, \vec r = {r_1, r_2, ... , r_d} enumerating the individual stress levels. The norm |\vec r | = sqrt{\sum_\alpha r_\alpha^2} is a naive, but plausible, estimate for the total stress level in a complex system with a large number of components exposed to independent stresses: exposure to d individually tolerable stresses r_\alpha=1 increases the total risk level to \sqrt{d}. Now assume that all risk factors r_\alpha are managed independently such that their values follow a normal distribution of a width \[Sigma], which is to be chosen for legislation (**top row of panels**). In this case, the Maxwell-Boltzmann distributions of the estimated total stress or risk level (**bottom row of panels**) are straightforward to calculate as a function of the number, d, of independent stresses. The panels in the columns consider two different scenarios. **On the left**, we illustrate how an intolerable total risk level of the order of sqrt(d)=1000 arises from the controlled release of d=106 substances at levels which can, with \sigma=1, be safely supported individually. **On the right**, we show that in order to avoid the accumulation of risk due to a large number of different stresses, individual risk levels need to be managed on levels which are a factor of sqrt(d)=1000 smaller than evaluated by single factor impact studies.

However, there is a significant gap between the current legal frameworks and the magnitude of risks posed by this kind of pollution. In regulatory and normative terms, while far from sufficient, the European Union is one of the most committed political entities to addressing chemical pollution. The REACH regulation (2006) is a key framework designed to systematically monitor and regulate chemical substances in use. In reality, its scope remains limited, the program has recently been frozen, and the polluter-pays principle is still a distant goal.

The uncertainty and unpredictability of the cocktail effects make the situation even more dire. Given the lack of reference norms for these chemical mixtures and the difficulty in monitoring their real-time impact despite improving sensitivity and accuracy, global physico-chemical pollution represents a wicked problem (Baron *et al*., 2024). Taken together, the analysis shows that our societies are confronted with the dilemma of the economic interests at stake and the scale of risks (Appendix 1) that remain largely unpredictable and even inexpressible. The chemical industry is an example of a technological trajectory that is taking off (and even becoming autonomous, the so called technosphere), with society having no control any longer over its direction and amplitude (Bihouix and Perriot, 2024)

Confronted with this dilemma, science has introduced a potential workaround to the cocktail effect through the concept of the exposome (DeBord *et al*., 2016), which seeks to measure and understand the total environmental exposures people face throughout their lives (Panel 2). So here is a titanic instrument requiring complex and very expensive infrastructures and which in itself does not guarantee the protection of public health and of the environment, and the promotion of social justice. In the meantime, the key challenge remains in defining priorities and ensuring that limited resources are efficiently allocated to address them, e.g., promoting substantial advancements in safe-by-design green chemistry (Slootweg, 2024), and coordinating global action to mitigate the risks posed by the ongoing "invisible" pollution.

Panel 2. The exposome – technosolutionism as flight forward.

The concept of "exposome" (DeBord *et al*., 2016) arose from the need to monitor and analyse the set of genetic and environmental determinants that affect people's health throughout life. From toxicology to epidemiology, to ecology and social sciences, the exposome is, from a scientific point of view, an impressive tool. More precisely, it consists of a trio of exposomes: internal exposome (hormones, markers of inflammatory stress, metabolites), specific external exposome (pollutants, radiation, infectious agents, professional life, and lifestyle), and general external exposome (socioeconomic environment, framework of life, social inequalities). Of note, 70% of non-communicable diseases in humans find their source in the socioecological environment. Also, the profile of the exposome would be extremely different when comparing a sustainable agriculture and healthy diet with that corresponding to a polluting agriculture and unhealthy diet.

From a societal point of view, the exposome technology is a trap, *i.e*., the best solution to a wrong question. It means the production of a "passport", the inventory and dynamics of a person's exposures throughout life and the production, large-scale, and permanent storage of personal data thus generated. With family, social, and economic implications that are easy to anticipate. If one wants to be exhaustive and coherent, such a passport must be produced for all the earthlings of today and tomorrow. In this sense, it should be extended to other living beings, certainly to those that feed or heal us.

So here is a titanic instrument requiring complex and very expensive infrastructures and which in itself does not guarantee the protection of public health and of the environment, and the promotion of social justice.

Finally, the market presents a different challenge. It is largely blind to pollution itself but serves as a good proxy for what happens upstream in the economy, particularly in the energy sector (Pincemin and Negrutiu, 2024). The economics of energy resources act as a connector for various extraction, production, and consumption activities across industry, agriculture, and society (Ramirez-Marquez *et al*., 2024). Energy powers technological systems, and minerals, water, and biomass are essential for building and maintaining energy systems (Schulze *et al*., 2024). Furthermore, energy technologies and energy efficiency are critical components of decarbonization efforts in sectors such as industry, building, transportation, waste, and agriculture (IPCC, 2023). Despite the crucial role of the energy market in framing pollution through its link to emissions, the market alone has failed to offer coherent or sustainable solutions to global pollution and environmental degradation (Ezekoye *et al*., 2022). Market forces tend to overlook the full spectrum of environmental costs (*e.g*., returns, investments, subsidies, CO_2 prices, pollution), focusing primarily on profitability and resource extraction.

This analysis demonstrates that global pollution is largely out of control, and science alone can only accompany the partial or complete phase-out of large sets of harmful chemicals (Arguello and Negrutiu, 2019). Achieving this goal requires coordinated institutional action at all levels – local, national, and international – focused on stringent regulation, long-term sustainability, and equitable resource management.

FOOD SYSTEMS AND GLOBAL POLLUTION ARE SYSTEMIC RISKS AND ACT IN SYNERGY

Food systems and global pollution are critical systemic risks (IRGC, 2013) that act in synergy, exacerbating each other's impacts. These risks are tightly linked to the control of physical, informational, and institutional resources, a dynamic that translates these slow-developing pressures into a global health bubble (Fig. 1). For instance, the apparent affordability of low-cost food – often highly processed and nutritionally deficient—has failed to alleviate poverty or food insecurity. In Europe alone, food poverty has been reported to affect nearly a quarter of the population, despite the illusion of accessible food options (De Schutter, 2017).

Determinants of health risks and costs

I argue that the ensemble constitutes the systemic great challenge all societal and political levels must engage with over the next decade: the health bubble. iPES Food, (2017) and Gebreyesus (2018) have estimated at $13 trillion the annual economic costs of health impacts in food systems alone. The distribution of the costs indicated that more than half of the total was due to non-communicable diseases (NCD), followed by malnutrition, obesity, and diabetes. The channels through which food systems impact health are environmental contaminations, occupational hazards (*i.e.*, work under unhealthy conditions), contaminated, unsafe, and altered foods, unhealthy dietary patterns, and food insecurity (no access to adequate, acceptable food at all times). The economic benefits of eating better and the key metrics behind it have been thoroughly investigated: how food is produced, distributed, and consumed is critical for the health and well-being of humans, but also animals, and the environment (Lord *et al.*, 2025).

The Lancet-University of Oslo Commission report (Ottersen *et al*., 2014) identified the political determinants at the origin of the problems of global public health: powerful economic and political interests, institutional, structural, and economic power asymmetries coupled with systems of norms that produce inertia and resistance to change, a lack of transparency and accountability. The main obstacle lies in a frozen political landscape and in an economy dominated by oligopolies in the agri-food and chemical sectors whose global strategy of concentration-consolidation does not make it possible to legally confront the degradation of nature and the insolvency of the world's poor. Market power trumps—and often renders meaningless—the power of human rights standards.

Concerning global pollution, the analysis of plastic pollution alone indicates that the cost of a 50% reduction is estimated at 3500 billion $ a year during 25 years, an amount almost half the cost of inaction (https://www.unep.org/news-and-stories/press-release/pivotal-fourth-session-negotiations-global-plastics-treaty-opens). Under current trends, annual plastics production is expected to triple by 2060, with low recycling capacities in perspective (12%) when considering the entire life cycle of products (namely extraction of fossil sources, production and design, consumption and trade, recycling, waste management, and identification of problematic polymers and chemical additives). The health impacts of the "plastisphere" have not been evaluated so far.

Addressing these issues requires a holistic approach that looks at the intersection of food, pollution, health, primary resources, and equity. It is clear that food systems are not just about production and consumption – they are also deeply connected to social justice and public health.

The double gap of systemic risks governance

The report highlights two critical determinants of human-nature relationship: food systems and global pollution. To address them, the societal bifurcation necessitates focusing on slow-building pressures that are multi-causal, complex, and imperfectly understood (Baron *et al*., 2024), and pose an increasing risk of irreversible changes.

One example of this interconnection is the management of soil and water resources. Caldecott et al. (2013) evaluated the risk levels associated with these stranded assets, showing how high-risk categories include water resources, competition for water rights, greenhouse gas emissions in agriculture, and land-use regulation. Medium-risk factors include soil degradation, decline in ecosystem services, changes in production areas, and climate variability. Additionally, governance risks such as concentration of power on resources, vital needs and the commons, social and ecological dumping, and competition between production areas are emerging as key concerns becoming central to geopolitical conflicts (UNU IWEH, 2021; FAO, 2022a; Cailloce, 2024). Last but not least, integrating climate change into the broader food-pollution-waste challenge (UNEP, 2017; Negrutiu, 2022; Persson *et al*., 2022) should help understand why current political and scientific agendas are not up to the grand challenge reported here.

This requires a comprehensive integration of demographic factors with the relationship between food, soil, water, and health, which underpin the global workforce (Forouzanfar *et al*., 2015; iPES Food, 2017). We already have a range of science, technology, and societal solutions available to inform public policies and regulatory instruments. These can be used to influence production strategies and consumer behavior through incentives, standards, and norms (De Schutter, 2014; IFRPI, 2016; Colart Dutilleul, 2021; Waage *et al*., 2022). The expected result would be enhanced food security and rights-based food sovereignty (Blesh *et al*., 2023).

However, these actions alone may not be enough. To truly transform food systems, we must adopt an "exception" approach that treats agriculture and food products as collectively fundamental goods, rather than as ordinary commodities (Vivero Pol, 2013). A precedent for this approach is the Havana Charter of 1948 (Collart Dutilleul, 2018). It included provisions for food security and the preservation of natural resources, assigning objectives to trade in agricultural, forestry, fishing, and mineral products.

Unlike food systems, science lacks a "silver bullet" to tackle the complex and pervasive issue of global pollution (Wang Z *et al*., 2021; Brooks *et al*., 2020; Tox21, 2021; Fuller *et al*., 2022). These chemicals present a significant burden on human and ecosystem health, and the economy itself. Solutions, therefore, must be political, social, and economic, with a clear focus on the radical chemical simplification in production and consumption processes (The Lancet, 2017; Arguello and Negrutiu, 2019; Fenner and Schringer, 2021).

Is this feasible in a foreseeable future? The task is immense, considering the present and future trends in the sector (Baron *et al*., 2024):

(1) There are approximately 50,000 licensed chemicals currently in use, but only a fraction are adequately monitored and assessed. The vast gap between the number and quantities of chemicals and the ability to monitor and analyze them illustrates the chemical exposure crisis. For example, there are 4,550 unique chemicals in the NORMAN network, with 1470 chemicals acknowledged across all water types in the EU.

(2) The conjunction on the short term of business interests and lobbying, the market, and individual benefits and harms is a constant obstacle to better understand why and how chemicals are consumed by diverse communities.

(3) Cocktail effects from various pollutants and continually changing occurrence and evolving pollutant cocktails across geographies complicate risk assessments further.

(4) Most current attention is focused on immediate threats, like chemical or nuclear accidents, while the slow cumulative risks posed by chemicals in the food-environment-health nexus remain under-addressed.

(5) Detection limits and quality of evidence according to current numbers of scientists and trained citizens, including funding and coordination conditions, is an additional handicap.

(6) Availability of data in real time and transparency on consumption and disposal situations remain a critical challenge.

The adoption in 2019 of the EU's 2030 vision (COM, 2019) aiming at a "zero pollution" and action plan for air, water, and soil (EU, 2021) actually reflects an acknowledgment of the looming crisis. "The measures aim to combat pollution from urban runoff and new or particularly harmful sources of pollution, such as microplastics and chemicals, including pharmaceuticals. There is also a need to address the combined effects of different pollutants" (*i.e*., the cocktail effect). Two issues are sufficient to illustrate the incongruence of the objective: the legal and financial frameworks to be foreseen would constitute an unprecedented *tour de force* facing significant legal and financial barriers (Pistor, 2019).

CONCLUSION

Addressing the interconnected challenges of food systems, pollution, global resource management, and health compels us to adopt a science-informed socioecological bifurcation. This integrative approach emphasizes that human and ecological systems cannot be treated in isolation, and a holistic view is required to ensure both societal well-being and environmental sustainability.

Tackling the agriculture-food-pollution-health nexus over the coming decade will likely mark the turning point of the unavoidable bifurcation (Pincemin and Negrutiu, 2024). This leads to the need of profoundly modifying the macro- and microeconomic concepts, methods, instruments, and organizations that have dominated our societies since the end of the 18th century and generated toxic development (Stigler, 2021). The shift will involve reassessing and restructuring how we understand and manage resources, prioritizing justice, and resilience.

Science is a redoubtable power with political and societal implications. Today, science is expected to define where we stand and how and by what means can societies achieve sustainability and justice for the benefit of all. In other words, science can operate as a clarification instrument of the intrinsic goals of world views, and a methodological guide for action (Lomborg, 2001; NASEM, 2021; Panel 3).

On those grounds the technological progress (or rather progression) needs to be mastered and channeled politically, economically, and culturally (Jensen, 2018; Benayoun and Régnauld, 2020; Negrutiu *et al*., 2020). The expected outcome are coherent choices of technologies that support the common purpose and the commons (see also Randers, 2011; Sarkis, 2019), while pushing the market and investment toward nature-based solutions (Downing *et al.*, 2020).

Panel 3. On science – data and funding policies

Two aspects come into play with respect to public research issues:

(1) The data we generally have on ecological capital and social capital are of mediocre quality and accessibility (Fairbrass *et al*., 2020; Arguello *et al*., 2022). GAFAM, Reuters, Bloomberg, and other private organizations own very important data sets, but they only marginally cover the issues discussed here. An urgent and coherent change in public data policies means focusing on data systems that are findable, accessible, inter-operational, and reusable (Wilkinson *et al*., 2016; Haines *et al*., 2018; NASEM, 2023). Such data systems need to be exhaustive, regular, reliable, transparent, and verifiable, and have precise geographic details in order to enable decision grade information to be explored in policy choices, economic models, investment strategies, etc.

(2) Questioning whether academic and NGO research "should accept funding at all from particular industries that profit from practices and products that cause harm" (Morris and Jacquet, 2024). This illustrates the long term debate that has encompassed tobacco, fossil fuels, various pollutions, beef industry, and climate. It is about influencing the conduct and publication of results and obstructing academic independence to inform on impacts on pollution, health, sustainability, climate understanding and policy (Sass and Rosenberg, 2011; Gaber *et al*., 2023; Morris and Jacquet, 2024). Funding of the sort challenged, among others, the FAO 2006 report, "Livestock's Long Shadow" and the 2019 EAT-Lancet Commission report.

Two primary societal pathways emerge from this analysis on ***Food Systems and Pollution***:

Immediate action. Tackling these issues simultaneously and urgently can create a regenerative feedback loop. By reducing social vulnerabilities and allowing the biosphere time to recover (Negrutiu *et al*., 2020), we could trigger positive changes across multiple sectors. This approach aligns with the notion that addressing the core drivers of ecological and social degradation – such as unsustainable agro-food practices and widespread pollution – will prompt cascading benefits in areas like health, equity, and resource security (Herrero *et al*., 2021; Negrutiu *et al*., 2023). Such a strategy could steer us toward a bifurcation process that initiates large-scale societal transformations.

Inaction and its consequences. Failing to act will likely lead to significant state shifts in socio-ecological systems, with potential cumulative tipping points projected between 2025–2030 (Meadows *et al*., 1972; Randers, 2011; Barnoski *et al*., 2012; Negrutiu *et al*., 2023). Social systems, which are more vulnerable than ecosystems because the time scale for social and ecological systemic risks is not the same, may experience disruptions far earlier and more intensely than environmental systems (Butzer, 2012; Mote *et al*., 2020). Without proactive intervention on social issues, society faces a higher risk of cascading breakdowns.

The bifurcation process, whether driven by deliberate action or inaction and delayed responses, is fraught with challenges. One key obstacle will be integrating risk assessments of cumulative tipping points—which vary across different sociosystems and geographies. This complexity presents a significant threat not only for governments and businesses but also for insurance companies tasked with managing the increasing uncertainty and risks associated with environmental and social tipping points (One Earth, 2023). These risks, particularly in health, are likely to accumulate into what could resemble a black hole, as escalating costs and damages become harder to quantify and mitigate.

Acknowledgements

The author is deeply indebted to François Collart Dutilleul, Marie-Thérèse Charreyre, Ralf Everaers for inspirational conversations and valuable advice. Work supported by the IXXI and RDP laboratories, and the Research Council of the ENS de Lyon.

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Appendix 1.

Society, science, and chemical industry – David against Goliath

Several decades of conventions and programs concerning the sector

* Offshore Mining and Drilling (1982)
* Banned and Severely Restricted Chemicals (1984)
* Marine Pollution from Land-based Sources (1985)

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* Basel, Rotterdam, and Stockholm conventions on chemical and hazardous waste
* MAEs (Chemical-related multilateral environmental agreements)
* REACH 2001 and 2006, Strategy for future policies on chemical substances
* SAICM 2020 (Strategic approach to international chemical management). Johannesburg plan of implementation goals – *chemicals will be produced and used in ways that minimize significant adverse impacts on environment and human health* statement.

http://www.saicm.org/Portals/12/Documents/SAICM_Brochure-2015.pdf

http://www.saicm.org/Implementation/Reporting/tabid/5462/Default.aspx (2013)

http://www.saicm.org/Portals/12/Documents/reporting/k1403579-eowg2-inf4-second-progress-report.pdf

* Global Framework on chemicals – 5th international conference on chemical management (ICCM5, 2023: targets and guidelines for key sectors across the entire lifecycle of chemicals and waste). For ex., phasing out by 2035 of highly hazardous pesticides in agriculture.

https://www.unep.org/news-and-stories/press-release/global-framework-agreed-bonn-sets-targets-address-harm-chemicals-and-waste

Academic and science-informed initiatives (mainly endocrine disruptors)

* Call of Wingspread, 1991
* Washington declaration, 1996
* Barleymont declaration, 2013
* The United Nations Environment Programme reports

Global Chemicals Outlook 1 (GCO 1, 2013). It outlines the following main points:

* Indicators and trends in chemical industries (production, transport, use, disposal) and associated health and environmental impacts
* Costs of inaction and cost benefits of action (economic to public health implications)
* Safer alternatives to use chemicals, for sound management of chemicals
* Encouraging a change from a fragmented sector-by-sector chemical management to a cross-sectoral participative and partnership based proactive approach.

Global Chemicals Outlook 2 (GCO 2, 2019). It offers a global overview with the following main issues:

* The chemical industry continues to grow and hazardous chemicals are more than ever harmful to health and environment.
* The industry accounts for approximately 10% of global energy demand, and almost a third of the total industrial energy demand in the world, *i.e*., the world's largest industrial energy consumer and the third-largest industrial emitter of CO_2 in the world.

The above figures and considerations emphasize the need for an urgent reassessment of how chemicals are produced, managed, and disposed of in order to prevent further damage to environmental systems, human health, and the planet's long-term sustainability..