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In a Nutshell. . .

COUNTERING CHEMICAL POLLUTION

Green Swans countering chemical pollution by Posthuma et al.

It is hoped that Green Swan solutions can offset the adverse impacts of chemical pollution by inverting identified risks to opportunities in a sustainable economy.

EXPOSOMICS AND EMERGING PUBLIC HEALTH ISSUES

Exposomics in Practice: Multidisciplinary Perspectives on Environmental Health and Risk Assessment by Wood et al.

Areas that can benefit from exposome research and refinement include One Health, factors linking exposure and effects, informing intervention and treatment regarding adverse health outcomes, and environmental regulation.

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Green Swans countering chemical pollution

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If a problem has exponential features, its solution asks for counter-exponential approaches. Chemical pollution appears to be such a problem. Analyses of chemical hazards to human health, biodiversity, and ecosystem services and estimates of the cost of inaction suggest the potential for adverse impacts, and analyses of trends in the chemical economy appear exponential in kind. Here, we argue that we need and can develop an exponential and application-focused mindset in thinking about solutions.

Today, the people of the world speak (via the United Nations [UN]) of a triple planetary crisis, covering interactive effects of climate change, biodiversity loss, and increasing pollution (UN, 2022). The UN writes: "Each of these issues has its own causes and effects and each issue needs to be resolved if we are to have a viable future on this planet." Observations such as the >75% decline in biomass of flying insects in European nature protection areas (Hallmann et al., 2017) make one think of both causes and consequences, if not

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solutions, for example, when thinking of pollination of plant species in nature as well as those used as food. Or that the global mammal biomass is dominated by livestock (≈630 Mt, vis a vis 60 Mt for terrestrial and marine mammals, and 390 Mt for humans, Greenspoon et al. [2023]). In response, it was recognized that a global, regional, or local response requires "[…] explanation that starts with science but translates to the language and praxis of business" (Passarelli et al., 2021). In turn, the scientific community replied by listing some opportunities that need to be employed or developed (such as prospective economy-wide life cycle assessments) to help steer away from the problems (e.g., Hellweg et al., 2023).

As a practical application of our subject—chemical pollution in its diverse forms—we must first recognize the importance of chemicals in our society. Furthermore, we recognize its complexity with >350k substances and mixtures on the market (Wang et al., 2020), diverse usages (diversity and masses in use) and trends therein (Bernhardt et al., 2017), and effects that can unfold in a multitude of diverse pathways and scenarios, including both direct and indirect interactions and outcomes (Sigmund et al., 2023). As an example, on average, 26% of impacts on the ecological status of European surface waters are attributable to exposure to unintended mixtures (Lemm et al., 2021). Along with the results of such specific, large-scale diagnostic studies, there are also global concerns that the planetary boundary for chemical pollution has been transgressed (Persson et al., 2022). How complex can things be?

We are not afraid of complexity. It has drawn us to the question that we ask here, which is: 'How can the science on chemical pollution be best developed and translated towards effective utility?' Given the scale of the triple crisis, we purport that incremental solutions or minor amendments to current 'business-as-usual' models would not be sufficient. To develop truly effective solutions, we need to adopt bold novel paradigms to guide our thinking about them. Any solution would need to be both counter-exponential and practicable. Here, we argue that we should adopt two approaches to develop environmental science for such a disruptive, aspirational practice, as the European Green Deal and with it the ambitions of a zero-pollution and toxicfree environment are seeking to change the course of the European Union and the World.

First, enter Green Swans.

Inspired by the Black Swan metaphor of Taleb (2007), the Green Swan metaphor has been coined by John Elkington—the sustainability expert who also introduced the triple bottom line of "People, Planet, Profit"—to define desirable solutions to unsustainable situations (Elkington, 2020). A Green Swan solution is characterized by an exponential transition pathway toward a final stage that is resilient and regenerative—we provide a potential example for the chemical context below, starting with a vision on the desired status of no impacts, and designing a plan to reach that. Such a solution serves social, environmental, and economic welfare alike, although Elkington recognizes that in realistic transition pathways, each welfare aspect may progress at differing temporal scales. We posit that Green Swan thinking would serve us well in countering the problems brought by chemical pollution.

Second, enter application-oriented approaches to scientific roadmapping.

Evaluating the utility of established risk assessment paradigms by the USEPA, the US National Academy of Sciences proposed to change gears, toward solution-focused risk assessments (known as "the Silver Book") (National Research Council, 2009). That is, while the earlier-generation assessments yielded a "risk-value" to a problem, the Academy concluded that such an answer did not help out sufficiently. Instead, the Academy proposed to generate optional solution strategies (i.e., define the "solution space") upfront in the process, and produce comparative risk assessment outcomes. Thus, the classical "risk-value" of the problem can directly be compared to scenario-outcomes of the optional solutions, and the best can be chosen and implemented. We see that solution-focused risk assessment will create opportunities and drive innovation within the sector. Based on our experiences, for example, in the project SOLUTIONS (www.solutions-project.eu), we posit that the solution-focused paradigm should be further expanded, especially by developing the science toward application-oriented utility—that is, tools for daily decision-making.

Looking at chemical pollution through the lenses of the Green Swan and the application orientation brought us some exciting ideas. At a first glance, one can recognize that chemical pollution is a Black Swan problem, but it actually has some past and, so far, hidden Green Swan feathers. That is, Rachel Carson's book *Silent Spring* (1962) described the disappearance of birds from university campuses in the United States as an effect of the then-use of pesticides (the Black Swan effect), but also co-triggered the establishment of the USEPA in 1970 (a Green Swan egg). The Agency has since served as a key actor, tasked with preventing and limiting adverse effects for a wide array of antropogenic pressures on health and the environment. This can be seen as a Black Swan–Green Swan trajectory. Elkington describes more of such Black Swans, which partly turned Green, in the context of the chemical economy. An opposite development is also possible, as some of the initially thought good ideas can morph into Blacker Swans as well. Chemical pollution and Swans of many colors, thus, have a history.

A second observation is that Green Swans must and likely do have a future when addressing the pollution crisis. We recognize that the European Green Deal is a nest with some Green Swan eggs. Specifically addressing chemical pollution, there is the chemicals strategy for sustainability (European Commission, 2020), with its key component, the concept of *safe and sustainable by design* (SSbD). If fully implemented, true SSbD would be more than exponential in its effect on countering chemical pollution impacts. Safe and sustainable by design is already solution-focused and highly aspirational. But here enters an already proven applicationoriented need. An ongoing test phase of the SSbD framework shows that this Green Swan egg requires many scientific problems to be solved—and not only that but also that the scientific solutions should be formatted in such a way that they can be used by the tens of thousands of actors in the chemical economy. Small- and medium-sized enterprises need to be able to use SSbD science in practice. This asks scientists to consider utility and simple operational formats, even for problems as complex as chemical pollution. It is as simple as that.

At this point, we posit that there is ample latitude to shape the results of the scientific research on chemical pollution problems into valid and operational solutions to the identified problems that currently hinder the implementation of the SSbD vision. Past research has provided us with a plethora of concepts, models, data, and tools that can be transformed and integrated into useful approaches to support SSbD operations. We posit this because roadmapping techniques (Phaal et al., 2011) show us that our collective experience, data, and models, along with our brain power, can deliver innovative and operational solutions for the most pressing problems.

Let us give an example. Past regulations and scientific interests have resulted in the collation of hundreds of thousands of ecotoxicity data, stored in and retrievable from the world's databases. As early as 1995, the concept of quantitative species sensitivity relationships (QSSRs) was coined at RIVM to describe in full how different species react to different chemicals, "trained" on all available data. Lack of computational power limited the practical development of such QSSRs in 1995, but that is no longer the case. Machinelearning studies provide us with interesting insights. Thus, the key problem of "data availability" for safety and sustainability assessments encountered in SSbD practice may be solved (Schür et al., 2023), enabling the operationalization of QSSR modeling to propel the generation of comprehensive *hazard information* on *any* chemical compound. Would the SSbD Green Swan remain grounded due to missing data, or could it fly by means of innovative combinations of science-based data collection and modern modeling efforts? If science would bridge the data gaps here, what would an associated tool look like, ready for use by large and small companies? Systematic planning via roadmapping techniques would be of help here.

In conclusion, we are certain that the collective brain power of today's environmental scientists can and indeed should be brought into play to generate and operationalize Green Swan ideas that can counter the adverse impacts of chemical pollution by inverting identified risks to opportunities in a sustainable economy. As we have done ourselves, we tried to combine the Green Swan idea with our own scientific work, and that of close and distant neighbors—not limited by our own disciplinal habits. We became convinced that there are many more Green Swans hiding in the bushes—waiting to be uncovered and thus providing business opportunities and revenues to the finders in the chemical sector. We therefore invite the broad community of environmental scientists to contribute to developing and operationalizing Green Swan ideas to counter (prevent and limit) chemical pollution, for the benefit of social, environmental, and economic wealth as aspired in the Green Deal.

AUTHOR CONTRIBUTION

Leo Posthuma: Writing—original draft. **Michelle Bloor:** Writing—original draft. **Bruno Campos:** Writing—original draft. **Ksenia Groh:** Writing—original draft. **Annegaaike Leopold:** Writing—original draft. **Hans Sanderson:** Writing—original draft. **Hanna Schreiber:** Writing—original draft. **Christoph Schür:** Writing—original draft. **Paul Thomas:** Writing—original draft.

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Exposomics in practice: Multidisciplinary perspectives on environmental health and risk assessment

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INTRODUCTION AND KEY FINDINGS

In 2005, Chris Wild introduced the idea of the exposome as the study of the sum of all environmental exposures throughout life and their impact on health as it pertains to cancer. He broke down the exposome into the internal (endogenous hormones, gut microflora, etc.), specific external (infectious agents, environmental pollutants, medical interventions, etc.), and general external exposome (psychological, climatic, etc.) (Wild, 2012). As part of an exploratory class on topics in environmental risk assessment, we reviewed exposomic framing and research papers across disciplines such as One Health, zoonoses, mycotoxins, occupational exposure, air pollution, infectious diseases, ecological assessments, and microbiomes. We sought to improve our understanding of the concept and how it might be applied more broadly beyond cancer to environmental toxicology.

There is a growing effort to illustrate the value of exposomic work. An example is shown in Figure 1.

We agree with the many papers that found exposome framing to be useful in holistically capturing and evaluating exposure to complex mixtures of stressors throughout the lifecourse of individuals, organisms, and populations. One way to apply the exposome concept in a challenging multiexposure context is by measuring environmental and biological stressors across lifecourse, for example, starting in pregnancy and early childhood to inform chronic disease outcomes. Several areas where we see benefits to including exposomics are: One Health, factors linking exposure and effects, informing intervention and treatment regarding adverse health outcomes, and environmental regulation. We discuss these briefly and examine exposome application to legionellosis.

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EXAMPLE AREAS THAT COULD OR DO BENEFIT FROM EXPOSOME RESEARCH

The One Health concept

This can be met by including ecosystems and ecological functions alongside human populations. For example, exposome research could be helpful in agriculture to evaluate mycotoxin impacts on humans and animals.

Factors linking exposure and effects

Exposomics has been used to identify emerging trends by generating hypotheses from large databases. For example, the exposome-wide association study (EWAS), using genomewide association studies (GWAS), analyzes thousands of environmental exposures linked with genomic analysis to make health outcome associations (Patel et al., 2010). Unlike GWAS, exposome research requires consideration of modifiers and unidentified potential exposures. These include (1) individual genetic modifiers which can define susceptible populations and the types and dynamics of DNA adducts formed by hazardous chemicals in the environment, leading to mutations and disease-initiation in humans; (2) microbiotic makeup, impacted by the environment and diet; and (3) timing, including specific age group exposures, duration of exposure, and lag times after exposures, which are all factors that define quantitative impacts. At the same time, it is important to recognize uncertainties in measuring exposure and effects. For example, 80% of metabolomic features in blood samples analyzed by high-resolution mass spectrometry are unidentified (Uppal et al., 2016), indicating a large potential profile of chemicals or mixtures affecting responses yet to be identified.

Informing intervention and treatment—Application to individual medicine

Differentiating exposure and hazard through top-down (stressor to effect) or bottom-up (effect to stressor) approaches provides mechanistic insights. Top-down methods analyze individual biomarkers at a population level