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# Exploring the planetary boundary for chemical pollution

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ABSTRACT (323 words)

Rockström et al. (2009a, 2009b) have warned that humanity must reduce anthropogenic impacts defined by nine planetary boundaries if “unacceptable global change” is to be avoided. Chemical pollution was identified as one of those boundaries for which continued impacts could erode the resilience of ecosystems and humanity. The central concept of the planetary boundary (or boundaries) for chemical pollution (PBCP or PBCPs) is that the Earth has a finite assimilative capacity for chemical pollution, which includes persistent, as well as readily degradable chemicals released at local to regional scales, which in aggregate threaten ecosystem and human viability. The PBCP allows humanity to explicitly address the increasingly global aspects of chemical pollution throughout a chemical’s life cycle and the need for a global response of internationally coordinated control measures. We submit that sufficient evidence shows stresses on ecosystem and human health at local to global scales, suggesting that conditions are transgressing the safe operating space delimited by a PBCP. As such current local to global pollution control measures are insufficient. However, while the PBCP is an important conceptual step forward, at this point single or multiple PBCPs are challenging to operationalize due to the extremely large number of commercial chemicals or mixtures of chemicals that cause myriad adverse effects to innumerable species and ecosystems, and the complex linkages between emissions, environmental concentrations, exposures and adverse effects. As well, the normative nature of a PBCP presents challenges of negotiating pollution limits amongst societal groups with differing viewpoints. Thus, a combination of approaches is recommended as follows: develop indicators of chemical pollution, for both control and response variables, that will aid in quantifying a PBCP(s) and gauging progress towards reducing chemical pollution, develop new technologies and technical and social approaches to mitigate global chemical pollution that emphasize a preventative approach, coordinate pollution control and sustainability efforts, and facilitate implementation of multiple (and potentially decentralized) control efforts involving scientists, civil society, government, non-governmental organizations and international bodies.

KEYWORDS: planetary boundary, chemical pollution, chemical emissions, Stockholm Convention, tipping point, global threshold, pollution controls, ecosystem health protection, human health protection, chemical management

## 1. INTRODUCTION

Rockström et al. (2009a, 2009b) presented nine anthropogenic impacts of global relevance, including climate change, biodiversity loss, anthropogenic changes of the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, changes in land use, atmospheric aerosol loading, and chemical pollution. The authors proposed that humanity may be moving beyond a “safe operating space” as the magnitude of these impacts approach or exceed certain thresholds that represent tipping points of the global system or a natural limit for processes without clear thresholds (so-called “dangerous levels” in the Rockström et al. articles) (Fig. 1). As discussed in detail below, the authors defined a “safe operating space” as those global conditions that allow for continued human development. Rockström et al. (2009a, 2009b) challenged the global scientific community to determine these “non-negotiable” thresholds or natural limits, which are science-based limits of the Earth’s systems, reflecting conditions that are favorable for human life and cultural development, and then to define human-determined boundaries at an appropriate distance from these limits that allow humanity to “avoid unacceptable global change” (Carpenter and Bennett, 2011). A critical goal of defining the boundaries is to move governance and management away from a piecemeal and sectorial approach, towards an integrated global approach that is necessary to address global phenomena.

For chemical pollution, Rockström et al. (2009a, 2009b) did not define the scope of chemicals considered, natural limits or a planetary boundary, but stated that these remain to be determined. However, they suggested that possible measurable control variables for natural limits could be emissions, concentrations or effects of Persistent Organic Pollutants (POPs), plastics, endocrine disruptors, heavy metals and nuclear wastes. Persson et al. (2013) added to the discussion by suggesting three conditions that must be met simultaneously for chemical pollution to present a global threat. Here we consider a broad range of chemicals including synthetic organic substances and metals, and those intentionally and unintentionally released. We do not consider the nutrients nitrogen and phosphorus that are considered under a separate planetary boundary, or sulfates that can also fall under another planetary boundary (atmospheric aerosol loading).

A large primary literature and numerous reviews document the extent and diversity of chemical pollution and attendant adverse health effects to humans and ecosystems (e.g.,UNEP, 2012; AMAP, 2004, 2009; Letcher et al., 2010; WHO and UNEP, 2013; *inter alia*). Indeed, the number of scientific studies providing such evidence fills environmental journals and conference halls. Examples of widespread effects are diminishing populations of wildlife (e.g., Oaks et al., 2004; Tapparo et al., 2012; EFSA, 2013) and increasing burdens of human clinical and subclinical illness related to environmental toxicants (WHO and UNEP, 2013; Grandjean and Landrigan, 2006; Stillerman et al., 2008). Mounting evidence also indicates that the assessment of individual chemicals is insufficient, as complex mixtures might cause significant toxic effects, even if all individual chemicals are present only at individually non-toxic concentrations, as discussed below. This pattern has been observed repeatedly in a broad range of bioassays at different levels of complexity and for different types of chemicals (see reviews by Kortenkamp et al., 2007, 2009; Kortenkamp, 2008; Backhaus et al., 2010; SCHENIHR et al., 2012). Together, this evidence implies that if emissions of increasing numbers and amounts of chemicals continue at current and anticipated increasing rates (UNEP, 2012), concentrations of such chemicals in many parts of the world, alone or as mixtures, will push the global system beyond the safe operating space. In turn, reaching this point will lead to erosion of vital ecosystems and ecosystem services, and threaten human well-being. Some argue that this point has already been reached (WHO and UNEP, 2013; *inter alia*). Furthermore, the boundary of global chemical pollution cannot be ignored because it is inextricably connected to the other planetary boundaries by the manifold impacts across the life-cycle of chemicals at a global scale, e.g., energy and water use for extraction and manufacturing, land use change that accompanies waste disposal with a potential loss of biodiversity.

This paper explores the definitions and meaning of, and arguments for, a planetary boundary or boundaries for chemical pollution (PBCP). We discuss the many challenges that indicate that defining a boundary or boundaries for chemical pollution is not easily within reach. Our intent here is not to reproduce or re-summarize evidence of widespread adverse effects due to chemical pollution. Rather, we submit that this evidence points to the need for considering a planetary boundary or more likely *boundaries* for chemical pollution to help humanity remain within the Earth's safe operating space. Thus, the paper closes with recommendations for steps that hopefully will move humanity towards a safe operating space with respect to chemical pollution.

We start the discussion by acknowledging that defining natural limits and a PBCP(s) is challenging for many reasons. In the framework presented by Rockström et al. (2009a, 2009b), defining a PBCP is more difficult than for other planetary boundaries (e.g. for global warming), due to the difficulty of identifying a single or a few measurable control variables. A control variable is defined, according to Rockström et al. (2009a, 2009b), as a measureable parameter that can be related to a specific planetary boundary, e.g., atmospheric $CO_2$ or temperature for global warming. However, agreeing on one or more control variables for chemical pollution is challenging because chemical pollution is caused by an enormous number of chemicals emitted from innumerable sources and in extremely different amounts in different regions of the world. In the same way, the response variable is difficult to define and measure in a clear-cut way, since chemicals cause a wide variety of adverse effects in a similarly wide variety of species, including humans. The links to the related boundary of biodiversity are evident (Steffen et al. 2015). The critical point is that the Earth's assimilative capacity, or the number and capacities of the sinks capable of degrading or immobilizing anthropogenically-released chemicals, is limited at the global level, even for readily biodegradable chemicals.

## 2. WHY A PLANETARY BOUNDARY FOR CHEMICAL POLLUTION?

Several policy instruments aimed at controlling chemical pollution have been developed and are in varying degrees of implementation (Table S1). How does a PBCP differ from existing instruments for chemical management and how or why might it be useful rather than redundant? In order to answer these questions we first expand on the concept of planetary boundaries and a "safe operating space" introduced by Rockström et al. (2009a, 2009b) and then move to put a PBCP into the context of existing instruments for chemicals management.

Rockström et al. (2009a, 2009b) identified that several Earth processes and subsystems behave non-linearly, with thresholds that, once crossed, could tip them into new, undesirable states. For these processes, a sharp "tipping point" may exist beyond which the system may transition into a qualitatively different stage, such as much more rapid global warming at $CO_2$ concentrations above a certain value (Fig. 1a). Examples of Earth systems with such global thresholds or tipping points include the global climate and ocean acidification (e.g., Lenton et al., 2008; Doney et al., 2009; 2014). The planetary boundary can then be set at a level somewhere below the tipping point.

Other processes and subsystems may not have sharp thresholds (Fig. 1b), but their continued erosion or depletion at continental to global scales may cause functional collapse in an increasing number of globally interconnected systems. Here, examples are freshwater use, land use change and loss of biodiversity (May, 1977; Gerten et al., 2013; Baronsky et al., 2012; Brook et al., 2013). For these, the planetary boundary can be set at a level where the risk of functional collapse is deemed acceptably low. In aggregate, planetary boundaries may thus be defined as a set of critical values for one or several control variables defined by humans to be at a safe distance from such thresholds or dangerous levels (if no threshold is evident) that, if crossed, could lead to abrupt global environmental change. The domain below the boundary can be considered a "safe operating space".

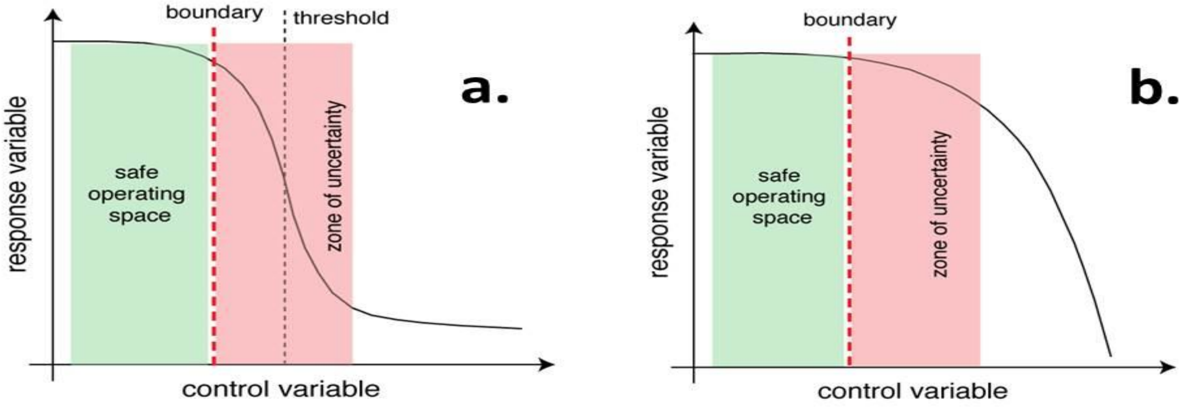

Figure 1. Illustration of the concept of the planetary boundary (a) for phenomena with a clear tipping point or threshold, where the system moves into a new state, such as $CO_2$-driven climate change, and (b) without a tipping point, where the system is constantly eroded (modified figure from Rockström et al. (2009a), reprinted with permission of the Stockholm Resilience Center, Stockholm University, Sweden). We suggest that aggregated chemical pollution is illustrated by (b) where there is no clear tipping point.

Although the intention was to define planetary boundaries for systems or processes affecting the Earth at the global scale, Rockström et al. (2009a, 2009b) recognized that many of the identified boundaries have thresholds that are more evident at local and/or regional scales where disturbance is concentrated or the affected ecosystem is more sensitive. These were identified as "slow processes without known global scale thresholds". As such, they become a global problem when they occur at many sites at the same time, aggregating to a level that undermines the resilience of ecosystems or that adversely affects human health. In turn, these effects would make it more likely that a threshold with global consequences will be crossed. Examples include biodiversity loss, land use change, global nitrogen and phosphorus biogeochemical cycles, and chemical pollution (Erisman et al., 2013; Hooper et al., 2012; Diaz and Rosenberg, 2008). Slow processes without global thresholds may also exert their effects by affecting other planetary boundaries, for example, chemical pollution of ecosystems linked to biodiversity loss (Voeroesmarty et al., 2010; Lenzen et al., 2012; Steffen et al. 2015). For example, chemical pollution can increase the vulnerability of ecosystems to species loss and land-use change, notably deforestation, can increase terrestrial-based chemical loadings to surface waters.

The distance between the planetary boundary and the threshold or natural limit ideally depends on the uncertainty that surrounds the scientific knowledge about the threshold or natural limit (Fig. 2). If the uncertainty is high, a larger distance between the threshold and the boundary is advisable.

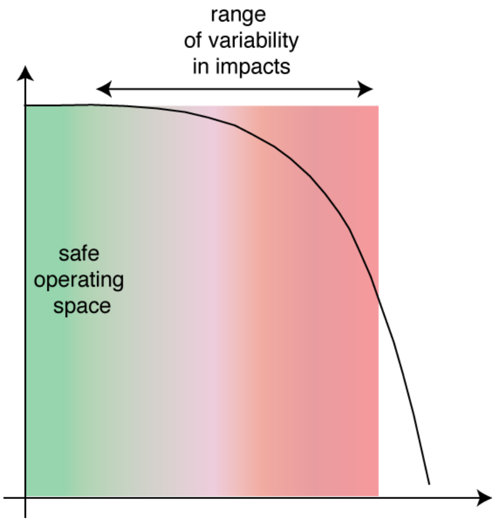

Figure 2. Illustration of where global impacts are located with respect to the safe operating space.

For the planetary boundaries where critical limits were estimated, most of these could be based on one or two specific control variables, such as atmospheric $CO_2$ concentrations and radiative forcing for climate change. Most of the planetary boundaries that were quantified are preliminary, rough estimates with large uncertainties and for which knowledge gaps were acknowledged.

Although some preliminary boundaries have been proposed, Rockström et al. (2009a, 2009b) pointed out the normative quality of a “safe” distance, as it is based on how societies deal with risk and uncertainty. By normative we mean that decisions on what constitutes a “safe operating space” are societal decisions, supported by scientific evidence. This implies that the diversity of viewpoints held by different societal groups have to be heard in order to come to a decision on what constitutes a safe operating space.

What does the PBCP offer that existing pollution control instruments lack? The planetary boundary concept allows us to explicitly address the *global aspects of chemical pollution.* By recognizing the global nature of chemical pollution, including aggregated local effects or where distance separates emissions from effects, we highlight the need for an integrated global response and acknowledge that pollution control activities of local to national entities alone, are insufficient.

Chemical pollution is a global issue. Several groups of chemicals are distributed around the globe by virtue of their persistence and ability to undergo long-range transport, for example chlorofluorocarbons (CFCs) and persistent organic pollutants (POPs). Others, such as high-production-volume metals that are inherently persistent, are used and emitted globally because of their high production volumes, global trade and widespread use in a broad range of applications. Additionally, the global economy is undergoing chemical “intensification”, as described by the UNEP “Global Chemicals Outlook” analysis (UNEP, 2013). Chemical intensification is due to rapidly increasing global production of chemicals (Wilson and Schwarzman, 2009), to the increasing use of synthetic substances to replace natural materials, and to the use of increasingly complex chemicals in more and more applications. Chemical intensification is predicted to lead to increasing per-capita chemical usage amongst a growing global population (UNEP, 2013).

In addition, chemical product chains, which span the life cycle stages from resource extraction to product manufacturing, use and disposal, are increasing in complexity, often covering several continents and decades of time, and offer new challenges to pollution control. For example, chemical production today can result in future emissions, particularly for chemicals in infrastructure and goods with long lifetimes. Brunner and Rechberger (2001) have estimated that whereas ~10% of all chemical stocks is contained in waste deposits from primary production and ~10% is contained in land filled waste, ~80% is contained in in-use and "hibernating" stocks. Most documentation of uncontrolled releases concern the two former sources (i.e., 20%) but not the 80% (e.g., Brunner and Rechberger, 2001; Weber et al., 2013; *inter alia*). Examples of the "20%" include long-term emissions from tailings, waste rock piles, nuclear waste repositories, abandoned industrial sites, and numerous landfills in developing countries (Turk et al., 2007; Torres et al., 2013; Weber et al., 2011). One example of long-term emissions from an in-use chemical stock is that of polychlorinated biphenyls (PCBs, listed as a POP under the Stockholm Convention) from equipment that was still in use in Canada in 2006 despite the ban on PCB production nearly 40 years ago (Diamond et al., 2010; Csiszar et al., 2013). Another example is that of CFCs contained in blown building insulation that is subject to uncontrolled releases as the generation of buildings using that foam undergoes renovation or destruction over the next 30 years (Brunner and Rechberger, 2001)

Similar application patterns of chemical technologies and similar uses of chemical products in almost all regions of the world result in widespread chemical releases. Chemical manufacturing and industrial usage are rapidly shifting from Western industrialized countries to developing countries and countries with economies in transition, including BRICS countries (Brazil, Russia, and especially India and China, and most recently South Africa) (UNEP, 2013). New and increasing resource extraction and chemical manufacturing, usage and waste disposal are leading to increased chemical pollution, particularly in jurisdictions with insufficient control mechanisms (Schmidt, 2006; Gottesfeld and Cherry, 2011). Short-lived chemicals are also being released in many regions at rates that exceed degradation rates and hence environmental assimilative capacities. Examples of such chemicals include pharmaceuticals, high production volume plastics and plasticizers such as bisphenol A and di-ester phthalates, and “D4” and “D5” siloxanes (e.g., WHO and UNEP, 2013; Kolpin et al., 2002; Rosi-Marshall et al., 2013; Peck and Hornbuckle, 2004; Fromme et al., 2002; Fries and Mihajlovic, 2011; Wang et al., 2013).

As pointed out above, the global nature of chemical pollution demands a global response of internationally coordinated control measures, in addition to multiple local, regional and national efforts covering different groups of substances, which are disconnected in time and space. One example of a global governance instrument is the Stockholm Convention on Persistent Organic Pollutants (POPs), which seeks elimination at best, or more broadly, the sound management, of a set of POPs agreed upon through international negotiations (Stockholm Convention, 2008). While achieving many successes (Stockholm Convention, 2012), the Convention is limited to a small number of chemicals or chemical classes (currently 22 are listed, with four more under review), includes numerous exemptions, and has no instrument for sanctions to ensure national implementation. This is not a shortcoming of the Convention because the intention of the Convention is not to address the totality of chemical pollution. As such, the Stockholm Convention is not adequate for challenge presented by developing a PBCP. Similarly, the Montreal Protocol is limited to substances that deplete the stratospheric ozone layer (UNEP 2010-2011) and the Minamata Convention is limited to mercury (UNEP 2015). The Convention on Long-range Transboundary Air Pollution, under the aegis of the United Nations Economic Commission for Europe and to which there are 51 parties, addresses a range of chemical pollutants including metals and POPs (UNECE 2004).

Another example of a global governance tool is the United Nations Framework Convention on Climate Change where global negotiations and agreements have led to reduction goals for greenhouse gases that are intended to be implemented at national levels (UNFCCC, 2013). International climate negotiations have seen the emergence of control instruments of largely two types. The first is an absolute limit for total $CO_2$-equivalent emissions (a “cap”) to assure that total global emissions are on target to prevent the global atmospheric $CO_2$ concentration exceeding an agreed-upon boundary. The second type of control scheme links emissions to activity or intensity such as $CO_2$-equivalent emissions per unit of electricity generated or per kilometre driven, or to an economic cost resulting in reductions of $CO_2$-equivalent emissions/capita (Azar and Rodhe, 1997; Ellerman and Sue Wing, 2003). These intensity or efficiency-based emission controls acknowledge the need to reduce greenhouse gas emissions but cannot ensure that global emissions are within the global safe operating space because of population and economic growth that increase the demand for energy services, most of which are based on fossil fuels (IEA, 2014).

Implicit in the concept of a safe operating space for $CO_2$ and other greenhouse gases, ocean acidification, nitrogen and phosphorus cycles, and “chemical pollution”, is that there is a finite global assimilative capacity. Here we define assimilative capacity as the ability of an ecosystem to render substances harmless, i.e. avoiding adverse effects. By seeing the problem in this light, it leads us towards exploring the need for a globally coordinated cap for emissions, rather than jurisdiction-specific, intensity-based controls, which may be sufficient in some circumstances but fail to account for cumulative, global effects.

## 3. CHALLENGES OF DEFINING A PLANETARY BOUNDARY FOR CHEMICAL POLLUTION

Moving the idea of a PB beyond a conceptual model requires that the impact of anthropogenic stressor(s) on all ecosystems can be described and quantified as a function of a measurable control variable(s) that is (are) related to a measurable response variable(s). For a PBCP, the ultimate effect or response variable (Fig. 1) subject to control is widespread adverse impact(s) to ecological and/or human health caused by exposure to (a) substance(s). Exposure can be identified as the critical control variable since it is the necessary prerequisite for any kind of chemically induced effect or response we want to safeguard against. Ideally, chemical exposure can be used to define a threshold(s) or natural limit(s) that, in turn, can be translated into a global boundary (boundaries) and a safe operating space. As noted above, the boundary (boundaries) is (are) established by humans and is (are) a product of societal demands, needs, value judgments and negotiations. The control variable(s) must also be amenable to translation into possible mitigation or control activities, which in this case would reduce exposure and thus, would maintain human and ecosystem health within the safe operating space, the latter reflected in maintained biodiversity, ecosystem functionality and human health.

Challenges arise at all stages in the definition process that starts with a control variable(s) and ends with “actionable” activities. First, operationalizing “exposure” as the control variable is difficult because of the high and poorly defined number of chemicals that fall under the umbrella of “chemical pollution”. More than 100 000 substances are in commerce (Egeghy et al., 2012), including pesticides, biocides and pharmaceuticals, industrial chemicals, building materials and substances in personal care products and cosmetics (e.g., Howard and Muir, 2010, 2011; ECHA, 2013) and very few of them have undergone adequate risk assessment for adverse effects. A recent screening of 95 000 chemicals for persistence (P), bioaccumulation (B) and toxicity (T) properties (REACH criteria) identified 3% or approximately 3000 chemicals as potential PBT chemicals (uncertainty range of 153-12 500 chemicals) (Strempel et al., 2012). Similarly, 93 000 chemicals were screened for P, B and long range transport potential according to the Stockholm Convention criteria, plus T (REACH criteria) resulting in the identification of 510 potential POPs (uncertainty range of 190-1 200 chemicals) (Scheringer et al., 2012). Unintentionally produced substances, such as the combustion by-products polycyclic aromatic hydrocarbons (PAH) and polychlorinated and polybrominated dibenzo-*p*-dioxins and furans (PCDD/F and PBDDs/Fs), are emitted as a consequence of human activity and many emitted chemicals are transformed to a multitude of other chemicals by biological and physical-chemical processes. Whereas some limits have been placed on a few selected chemicals that are highly persistent, bioaccumulative and toxic such as PCDD/F, those with intermediate PBT properties have received insufficient attention (Muir and Howard, 2006; Howard and Muir, 2010; Scheringer et al., 2012). In addition, an enormous number of organisms in a diversity of ecosystems are exposed to chemical pollution (which is invariably a complex chemical mixture) and they will respond in myriad ways. Moreover, chemicals have specific modes of actions and can show very different toxicological potencies. Humans take a specific place among affected organisms. Any approach to establishing a PBCP(s) must include impacts on human health, even if this is in contrast to the framework of Rockström et al. (2009a, 2009b) or which the objects of protection are biogeochemical systems and ecosystems, e.g., the climate system, the ozone layer, and freshwater.

Second, we acknowledge that boundaries for chemical pollution have been developed at a global scale for selected POPs and mercury, and at local and regional scales for chemicals in foods, water and air (Table S1). However, only a few of these boundaries account for exposure to multiple chemicals simultaneously that can act in an additive fashion. Moving beyond a chemical-by-chemical approach to acknowledge mixture effects is of growing importance if limits are to be protective (e.g., Kortenkamp, 2007; Kortenkamp et al., 2007; Backhaus et al., 2010; Meek et al., 2011; SCHENIHR et al., 2012). An increasing body of evidence suggests that, *de facto*, the existing boundaries are not sufficiently protective for endocrine disrupting chemicals that can cause transgenerational effects (e.g., Baccarelli and Bollati, 2009; Bollati and Baccarelli, 2010; Bouwman et al., 2012; Mani et al., 2012; WHO and UNEP, 2013; *inter alia*). This is not surprising since accepted and validated methods for identifying and testing endocrine disrupting chemicals, particularly after exposure during critical early life stages, are generally lacking or have not yet been implemented in chemicals risk assessment (WHO and UNEP, 2013; *inter alia*).

Third, connecting exposure as the control variable to an “actionable” activity (such as controlling emissions) is difficult because of the diversity of fate and transformation processes at play between an initial emission of a chemical or a chemical mixture and the concentration(s) resulting in exposure and then an adverse effect. Establishing the release-fate-concentration-effect linkage is necessary for other planetary boundaries such as $CO_2$, stratospheric ozone, phosphorus and nitrogen cycles. Establishing this linkage for chemical pollution is also necessary but it is more challenging because of the large number of chemicals of varying persistence and toxicity that are captured by this boundary.

Finally, in addition to the scientific challenges of defining a boundary(s), it must be remembered that most of the world's countries do not have the capacity or resources to measure a control variable such as exposure and to implement effective controls such as those listed in Table S1 (e.g., Klanova et al., 2009; Adu-Kumi et al., 2012). Furthermore, as noted above, a boundary(s) is normative and as such, a diversity of viewpoints will be held on what constitutes an "acceptable' level of pollution.

The combination of numerous substances with different use and emission patterns, affecting a multitude of different endpoints in a plethora of exposed species in the vastly different ecosystems of the world, plus consideration of human health, makes the derivation of a single quantitative PBCP or multiple PBCPs a daunting, if not impossible task. However, the situation of increasing chemical production, emissions and adverse effects cannot be allowed to continue unabated. Thus, we believe that the concept of a planetary boundary or boundaries for chemical pollution is a useful framework for global action, but that it needs to be modified to account for these complexities and challenges.

## 4. STEPS TOWARD GLOBAL CHEMICALS MANAGEMENT

Although it may not be possible to establish a single or even multiple PBCP(s) at this time, an increasing body of evidence strongly suggests that we need more effective global chemicals management. What has been accomplished in global chemicals management? Global cooperation amongst nations has, amongst others, resulted in the Stockholm Convention on POPs, the Montreal Protocol on CFCs, the Basel Convention on Control of Transboundary Movements of Hazardous Wastes, and the Rotterdam Convention on Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade. These Multilateral Environmental Agreements have come together under the aegis of UNEP. The Stockholm and Montreal agreements strive towards zero-emissions of the listed chemicals. In January 2013, UNEP brokered the Minamata Convention on mercury, the language of which has gained support from 94 signatory countries (UNEP, 2015). The Minamata Convention specifies the banning of production, export and import of a range of mercury-containing products, calls for the drafting of strategies to limit the use of mercury in artisanal and small-scale gold mining, and aims to work towards minimizing mercury emissions from combustion sources such as conventional fossil fuel power plants and cement factories. Like the Stockholm Convention, the Minamata Convention includes the provision to develop a compliance mechanism that will be established through negotiation after the official signing of the Convention.

These five agreements address priority chemical pollutants at the global scale, reflect the insight that global dilution is not the solution to local or global pollution, and that environmental safeguards are the right of all countries. Well over 100 countries have adopted them (except for the most recent Minamata Convention), which in itself is a great accomplishment. However, these agreements have limitations due to numerous official exemptions and unofficial "loopholes", they cover only a limited number of chemicals, implementation costs are largely left to individual countries of which many lack such capacity, and sanctions cannot be levied for a lack of compliance. As such, these agreements are not adequate to address the totality of chemical pollution (which was never their intent). Importantly, the fact that these agreements have been enacted is a reflection that humanity has come close to or crossed boundaries for these chemicals. A PBCP provides an overarching conceptual basis to characterize the achievements of these agreements and to accommodate additional necessary controls.

For chemicals listed by the Stockholm and Minamata Conventions and the Montreal Protocol, the planetary boundary is set at a *de minimus* level (ideally zero emissions but exemptions preclude this). In addition to the zero emissions boundary, several other types of boundaries have been defined during the past decades under many jurisdiction-specific regulations and initiatives spanning local to national scales. As summarized in Table S1, the initiatives, which come from international agencies, Europe, Japan, North America, China, India and Nigeria, include limits to levels of pesticides in groundwater and surface water, levels of priority pollutants in surface waters, and acceptable daily intakes (ADIs) for a wide range of food contaminants. However, as noted above, not all of these agencies are able to monitor for, and enforce compliance.

Another major global initiative is the Strategic Approach to International Chemicals Management (SAICM), which is also under the aegis of UNEP. The ultimate goal of SAICM is to facilitate activities to ensure that "…chemicals will be produced and used in ways that minimize significant adverse impacts on the environment and human health" (SAICM, 2006). The role of SAICM is advisory by acting as a source of information to governmental and extra-governmental bodies regarding safe chemical management and funding projects to fulfill the aim of the initiative. SAICM is a non-binding agreement with broad participation of countries and other stakeholders such as the chemical industry. In comparison to the five chemical agreements, SAICM is much broader in scope by addressing all agricultural and industrial chemicals from cradle to grave, aiming at overall sound chemicals management. However, SAICM does not have a compliance mechanism.

To move towards a truly global approach encompassing the aggregated impacts from all anthropogenic chemical pollution, we need to learn from experience and build on successes (and failures). What are the key lessons learned? One lesson learned is that implementation of stringent controls by specific jurisdictions has led to improved local conditions in those jurisdictions. However, increased global trade and the fluidity of global finance have moved more chemical and goods production and waste disposal to locations without stringent controls (e.g., Skelton et al., 2011; Breivik et al., 2011; Sindiku et al.., 2014). Thus, one intention of a global boundary is avoiding "pollution free" jurisdictions at the expense of creating "pollution havens" in developing nations (e.g. Gottesfeld, 2013). Examples of developed nations achieving their pollution control goals by shipping waste and waste products to developing nations have been described elsewhere (Schmidt, 2006; Breivik et al., 2011, 2014; Gioia et al., 2011; Abdullah et al., 2013).

A second lesson learned is that despite the challenges, as scientists we need to avoid calling for more scientific certainty before action is taken as this delays adoption of control measures, which in this case translates to measures that will help stem widespread chemical pollution. Gee and others (Gee, 2006; Gee et al., 2013; Harremoës et al., 2001) have documented examples of where the call for more research to improve risk assessments of chemicals often led to delays in action of up to several decades although early warnings of adverse effects were already apparent (e.g. tobacco smoking and asbestos). Persson et al. (2013) provide a persuasive argument in this regard.

As a result of these considerations, we submit that the PBCP is a useful aspirational framework that allows natural and social scientists, policy makers, industry and civil society to visualize the idea of a safe operating space, see the limited assimilative capacity of the Earth, recognize chemical pollution at a global scale, and see the inadequacy of current control measures to deal with the totality of global chemical pollution. Having said that, we recognize that defining a single or multiple quantitative PBCP(s), or even a single approach for its definition, is not now within reach. Rather, we recommend advancing in multiple directions that involve globally coordinated action in scientific, technical and political domains (e.g., Conklin, 2005; Horn and Weber, 2007). For the scientific domain we propose the following:

1. Explore advancing the concept of, and methods for quantifying a PBCP(s). We advocate making stepwise progress using a few well-known chemicals such as POPs, intermediate PBT chemicals (demonstrated toxicity but not highly persistent), and a few high production volume chemicals with demonstrated toxicity.

2. Continue to identify and develop indicators of global chemical pollution, initially based on proxies for chemical exposure and potency. Information on indicator status should then be used to gauge progress towards staying within the safe operating space for chemical pollution. Useful information to guide this task can be taken from the Drivers, Pressures, States, Impacts, Responses (DPSIR) approach (OECD, 1991; Harremoës, 1998), and suggestions of how this could be accomplished are given in the Supporting information. This proposal builds on the global monitoring networks that have achieved considerable success such as those under the Stockholm Convention (e.g., the Global Atmospheric Passive Sampling network or GAPS (Gawor et al., 2014) and Human milk survey (UNEP et al., 2013)).
3. Conduct research into new technologies and methods that will aid in implementing the goals of the six global chemical agreements (Montreal Protocol; Stockholm, Minamata, Rotterdam, Basel and UNECE LRTAP Conventions) and in lowering production and emissions of non-POP priority chemicals. This research includes methods for identifying and characterizing stocks of chemicals scheduled for elimination, developing technologies for efficient and effective destruction of stockpiles, research into societal and cultural considerations that will maximize the likelihood of policy implementation, etc.
4. Connect activities aimed at chemical pollution control in the context of PBCP to efforts aimed at moving towards sustainable resource use. This should include investigating ways to

chemically “de-intensify” economies, to use “green chemistry” substitutes and non-chemical solutions, and to implement social solutions aimed at reducing resource consumption. Efforts are underway in this regard, such as the U.S. EPA’s Design for the Environment Program (U.S.EPA, 2014) and the GreenScreen© for Safer Chemicals (Clean Production Action, 2015). These two issues, PBCP and sustainable resource use, are intertwined such that chemical pollution is a manifestation of unsustainable and inefficient resource use. Thus, efforts directed towards achieving both goals would benefit from coordinated action.

Progressing towards a PBCP(s) will require scientific, political, social and economic strategies. In the political domain, it will be important to raise more awareness for chemical pollution problems in all parts of the world, and to aid individual countries in implementing existing local and regional boundaries and international agreements. The shift of chemical production from OECD countries primarily to the BRICS countries needs to be complemented by a process that helps to develop chemical regulation and enforcement in these regions to a level comparable or better than that of OECD countries.

To address these needs, organizations at the global level such as WHO and UNEP can be drivers for effective exchange and collaboration amongst the public, environmental NGOs, industry and national government institutions to enable significant pollution control. Civil society and local jurisdictions also have and continue to implement effective pollution controls using a variety of tools. Examples here include the activities of the International POPs Elimination Network

(IPEN), the Pesticides Action Network (PAN), and C40 Cities for “Global Leadership on Climate Change” (C40 Cities, 2013).

In closing, 50 years ago Rachel Carson pointed out for the first time that the extensive use of pesticides is dangerous not only to wildlife, but also to humans. This is still an ongoing concern, emphasized by the recent finding that neonicotinoid pesticides are contributing to the massive collapse of bee populations (Tapparo et al., 2012; Henry et al., 2012; Whitehorn et al., 2012). Now we need to go beyond Rachel Carson’s clarion call about pesticides. Today’s phenomenon of locally to globally distributed chemicals that are causing adverse effects, demands that a wide range of chemical products and uses be restrained and many chemicals in commerce need to be used with much more prudence and precaution. It is time to harness the knowledge, capacity and commitment held by many to see Rachel Carson’s vision moved to a truly global scale.

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# Supplementary information

# Exploring the planetary boundary for chemical pollution

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Table S1. Examples of regulations addressing the occurrence of chemicals in the environment or the human body that establish boundaries for chemical pollution. Regulations are listed according to the type of boundary used: risk-based, concentration-based, emissions-based, technology-driven.

| **4** | **Issuing organization and year of entry into force** | **Chemicals covered** | **Boundary type** | **Spatial scale** | **Protection goal** |
|---|---|---|---|---|---|
| Acceptable Daily Intake (ADI), | World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO), 1961 | food additives, veterinary pharmaceuticals and pesticide residues in food | *risk-based*<br>a lifelong daily uptake below the ADI is considered safe | global human population | human health |
| Tolerable Daily Intake (TDI) | WHO and Joint FAO/WHO Expert Committee on Food Additives (JECFA), 1961 | non-intentionally used xenobiotics in food | *risk-based*<br>a lifelong daily uptake below the TDI is considered safe | global human population | human health |
| Provisional Tolerable Weekly Intake (PTWI) | JECFA | non-intentionally used xenobiotics in food that may accumulate in the human body | *risk-based*<br>a lifelong weekly uptake below the PTWI is considered safe | global human population | human health |
| Reference Dose (RfD) | US Environmental Protection Agency | toxic chemicals in general | *risk based*<br>the RfD provides an estimate of the lifelong daily oral exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime. | US population | human health |

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| Maximum Residue Levels (MRL) | Regulation (EC) 396/2005,<br>2008 | pesticides in food | *risk based, technology based*<br>the upper legal level of a concentration for a pesticide residue in or on food or feed set in accordance with this Regulation, based on good agricultural practice and the lowest consumer exposure necessary to protect vulnerable consumers | European population | human health |
| Critical loads and levels | United Nations Economic Commission for Europe (UN ECE) Convention on Long-range Transboundary Air Pollution (LRTAP), 1981 | major air pollutants (e.g. SOx, NOx) | *risk-based*<br>a maximum permissible load of a chemical below which no harmful effects occur in an exposed ecosystem | ecosystem (local, regional) | environment |
| Toxicity Exposure Ratio (TER) | Council Directive 91/414/EEC, which has just been repealed by Regulation (EC) No 1107/2009 (21.10.2009) | pesticides (active ingredients and formulated products) | *risk-based*<br>a TER above a pre-define threshold is considered safe | ecosystem (local, regional) | environment |
| Environmental Quality Standards (EQS) and Maximum allowable concentrations (MAC) | Water Framework Directive (WFD), Directive 2000/60/EC, Directive 2008/105/EC on Environmental Quality Standards, Directive on priority substances (2008/105/EC)<br>Oct. 2000 | priority pollutants detected in water bodies | *risk-based*<br>EQS: a level providing protection against long-term exposure, and MAC: protection against short-term exposure | ecosystem (local, regional ) | environment (water bodies only) |
| Environmental quality standards (EQS) | Ministry of the Environment, Government of Japan, for water pollution under basic Environment Law of Japan (Established in 1968, last amendment in 2014)<br>http://www.env.go.jp/en/water/wq/wp.pdf | Substances relating to human health and living environment | *risk-based*<br>EQS: a level providing protection against long-term exposure, and MAC: protection against short-term exposure | Japanese population and ecosystem (local, regional ) | h~~H~~uman health and environment (water bodies only) |
| Predicted No Effect Concentrations (PNEC) | Regulation EC 1907/2006 (REACH)<br>1.6. 2007. | industrial chemicals in water, air, soil, sediment | *risk-based:*<br>a concentration below the PNEC is considered safe | local, regional | environment |
| Derived No Effect Level (DNEL) | Regulation EC 1907/2006 (REACH)<br>1.6. 2007. | industrial chemicals | *risk-based:*<br>a concentration below the DNEL is considered safe | European human population | human health |

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| Zero discharges, emissions and losses of hazardous substances | The Convention for the Protection of the marine Environment of the North-East Atlantic (OSPAR Convention), 1998 | hazardous chemicals | *concentration-based:* concentration of zero for artificial chemicals and concentration at natural background levels for naturally occurring chemicals | regional (north-east Atlantic) | environment (marine ecosystems only) |
| Emission Limit Values (ELVs) | Ministry of the Environment, Government of Japan, Regulatory Measures against Air Pollutants Emitted from Factories and Business Sites and the Outline of Regulation (last amended in 1998), http://www.env.go.jp/en/air/aq/air.html | Air pollutants that may affect human health and environment | *risk-based*<br>ELVs and other regulatory measures for factories and business sites are adopted to achieve EQSs to protect human health and environment | local | human health and environment |
| Action limits | Guideline of the European Medicines Agency (EMA) on the environmental risk assessment of medicinal products for human use (EMEA/CHMP/SWP/4447/00) | human pharmaceuticals | *concentration-based*<br>concentration below 0.01 µg/l in surface waters are considered inherently safe, unless specific reasons for concern are given (e.g. endocrine activity). | local, regional | environment |
| Threshold of toxicological concern (TTC) Threshold of Regulation | EMA Guideline on the limits of genotoxic impurities (EMEA/CHMP/QWP/251344/2006), 2006 | genotoxic impurities in pharmaceuticals food contact materials | *concentration-based*<br>the TTC defines a common exposure level (1.5µg/day) for an unstudied chemical that will not pose a risk of "significant carcinogenicity or other toxic effects". | European human population | human health |
| Threshold of Regulation (TOR) | US Food and Drug Adminstration (FDA), Code of Federal Regulation (CFR), 21, § 170.39 | food contact materials | *concentration-based*<br>Concentrations of ≤ 0.5 ppb (corresponding to dietary exposure levels ≤ 1.5 µg/(person*day)) are considered safe. | US human population | human health |
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| Maximum Contaminant Level (MCL), maximum contaminant level goals (MCLGs) and | Safe Drinking Water Act (SDWA), enforced by US EPA | contaminants in drinking water | *concentration, risk and technology based*<br>MCLG: The level of a contaminant in drinking water below which there is no known or | US human population | human health |

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| Practical Quantitation Limit (PQL) | | | expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals. MCL describe the highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.<br>For non-carcinogens, MCLGs levels for drinking water are established based on the RfD, average drinking water consumption, etc. For carcinogens the MCLG is set to zero, which is practically ensued by checking whether a contaminant is present above the PQL. | | |
| Canadian Environmental Quality Guidelines | Canadian Council of Ministers of the Environment | VOCs, SVOCs and metals | *Concentration-based:* chemical specific goals (non-enforceable) for protection of aquatic life, protection of soil quality, protection of groundwater at contaminated sites, protection of environmental and human health. | national | human health and environment |
| Canadian “tolerances” and “standards” for various chemical contaminants in food | Health Canada Food Directorate | specified chemicals | *Concentration-based*: Maximum concentrations expressed as tolerances (through regulation) and standards (not regulated) for listed chemicals. | national | human health |
| Environmental Standards for ambient air and | Ministry of Environment, Forest and climate change, Government of India Reference: | specified chemicals and parameters | *Concentration based:* chemical or parameter specific goals for protection of environmental and | national | human health and environment |

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| water quality criteria | http://envfor.nic.in/environmental_standards | | human health, protection of aquatic life and water resources. | | |
| | Montreal Protocol, 1989 | CFCs | *emission-based*: production has to reach zero. | global | ozone layer; human health and~~&~~ environment |
| | Stockholm Convention, 2004 | POPs | *emission-based*: production and use have to reach zero. | global | human health and~~&~~ environment |
| Schedule 1 Compounds | Canadian Environmental Protection Act (CEPA) 1999 | chemicals deemed "CEPA toxic" | *emission-based*: limits on production, use and importation of chemicals listed in Schedule 1 | national | human health and/or environment |
| Emission Limit Values (ELVs) | Directive 2008/1/EC concerning integrated pollution prevention and control (IPPC directive), 2008 | chemicals produced at a given site | *technology-based*: ELVs are part of the permit an installation needs to acquire, based on the best available techniques (BAT), as defined in the Directive, and also taking specific local conditions into account. ELVs "should lay down provisions on minimising long-distance or transfrontier pollution and ensure a high level of protection for the environment as a whole". Emissions are regarded in an integrated manner in order to avoid switching from one compartment to another. | local | human health and~~&~~ environment |
| National Environmental Regulations | National Environmental Standards and Regulations Enforcement Agency (NESREA) Nigeria<br>Federal Republic of Nigeria Official Gazette No. 92. Vol. 94 of 31st July, 2007. | specified chemicals and parameters | *concentration, emission and risk based:* Enforceable maximum concentrations, emission limits and tolerance limits for specified chemicals | national | human health and environment |
| Environmental Protection Law of the People's | Ministry of Environmental Protection | general environmental protection issues | *Concentrations and emission-based:* prevention and control of water and air pollution; | national | h~~H~~uman health and environment |

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| Republic of China<br>(Regulations, and laws) | | | management in solid waste, marine environment, hazardous chemicals;<br>pollution discharge and levying; environmental standards and monitoring. | | |
| Environmental Protection Law of the People's Republic of China<br>(Environmental Standards) | Ministry of Environmental Protection | specified chemicals and parameters | *c~~C~~oncentration and/technology based:* protection of water, air, soil, and eco-environment. | national | h~~H~~uman health and environment |

PEC: predicted environmental concentration
PNEC: predicted no-effect concentration
DNEL: derived no-effect concentration
BAT: best available technology

## Indicators

Environmental management schemes employ indicators as metrics that allow evaluation of the status of an environmental system that is influenced by human activities (OECD, 1991a; Gallopín, 1996; Harremoës, 1998). In the context of a planetary boundary (PB), the "control variable" is a type of indicator, linking human activities (that hopefully can change under a governance scheme) to a specific threshold – a tipping point - for some of the categories (like global warming) or, for other categories (like biodiversity), to a derived limit. Considering the challenges of establishing one or more planetary boundary/boundaries for chemical pollution (PBCP), precaution, warranted by uncertainties and/or knowledge gaps, can be integrated into the PB analysis by introducing an uncertainty range on the safe side of its defined limit.

Rather than defining a single indicator that can be directly related to a control variable, defining an "interim" indicator may be necessary. An example within the PB context is biodiversity that is addressed at a continental to global scale, since biodiversity loss depends on many factors rather than a single control variable and a single threshold may not exist (Schellnhuber, 2002; Rockström et al., 2009). Here, the present extinction rate is an "interim indicator" of the ultimate mean of long-term maintained biodiversity. A PB can then be obtained by relating the present extinction rate to the long-term mean extinction rate (Rockström et al., 2009).

The construction of indicators of planetary chemical pollution is a formidable task given the large set of difficulties in this particular case. As discussed in the text, one difficulty is the *very large number of specific chemical structures identified* and of potential concern - about 100 000 are expected to be on the market following the definitions used by European REACH-legislation. A second difficulty is the *widespread production, and inclusion of chemicals in manufacturing* of a very wide set of products, which are used and wasted in many different ways wherever humans are found. Globalized production chains and increasing human consumption underline the importance of this aspect. A third difficulty is that the *release of chemical substances* occurs along complex product chains during the life-cycles of the products. The emissions are influenced by a number of factors, including material composition, fragmentation of the product increasing the effective surface for release, and environmental factors like temperature, making only the determination of *emissions* a daunting task. A further difficulty is the *environmental distribution, transformation and transportation*, that all are complicated processes, continue after emission. These processes are influenced by many environmental factors spanning from temperature and light intensity to pH and the ability of (micro)organisms to transform, transport and degrade the substances.

Furthermore the *very large numbers of organisms, exposed under an overwhelming number of conditions, express a wide number of responses to chemicals.* (Eco)toxicologists have identified a huge number of such responses, on different levels of biological complexity, and are employing a large number of test species and measurement endpoints in order to cover the potential effects of chemicals on human health and the environment. Reconnecting to the huge number of chemicals, as mentioned above, these chemicals differ tremendously in their *potency* to exert a particular effect in a particular species.

It is on the combination of these aspects that indicators of planetary chemical pollution must act, giving a simplified, but still meaningful representation of the actual pollution situation. Furthermore, the indicators must meet practical requirements: they must be unambiguously defined, their values must be measurable and data must be available or possible to gather, the method for acquisition, processing and presenting of values must be clear, transparent and standardized, and the means to do this must be available. Meeting these requirements would bring into focus the benefits and costs of indicators, and therefore their political acceptability and the process to establish them (Gallopín, 1996).

The perception of a simplified cause-effect-chain, along which environmental indicators can be identified, has dominated the development of such indicators since the first OECD State of the Environment report (OECD, 1991a). The DPSIR framework (*D*riving forces-*P*ressures-*S*tates-*I*mpacts-*R*esponses) was adopted for the European environmental indicators by the European Environmental Agency (Harremoës, 1998; Smeets and Weterings, 1999). A similar approach was also taken within life-cycle impact assessment methods (Udo de Haes et al., 1999), and considerable effort has been expended to developing sustainability indicators more or less along these lines (Meados, 199; OECD, 1998; Bossel, 1999; Lundin et al., 1999; Parris and Kates, 2003; Palme et al., 2005; OECD, 1991b). Here we have adapted the DPSIR framework for the PBCP, placing currently existing indicators of chemical pollution within the DPSIR framework in order to illustrate possible indicators and further required development.

Table S2 suggests a framework for indicators of chemical pollution at different stages in a simplified cause-effect chain, inspired by the DPSIR-approach and applying proxy indicators reflecting *exposure* and *potency* as the key aspects. The indicators suggested in Table S2 offer the possibility of moving from distant or indirect drivers of chemical pollution (like production or emissions) to more direct indicators of adverse effects. Another explanation of Table S2 begins with indicators that are proxies of exposure (production and emissions), to indicators of the control variable (exposure), to “interim indicators” where effects, which are connected to chemical potency, are identified. It is also possible to develop spatially dependent indicators (e.g. derived from indicators listed in Table S2) related to, for example, the proportion of land (or sea) area impacted by a certain degree of chemical pollution. Such an approach opens the application of GIS-based emission, fate and exposure modeling that is under development (Pistocchi et al., 2010).

Several existing global monitoring efforts of concentrations form an important step towards developing indicators that can be used to define a PBCP. These include monitoring efforts coordinated under the umbrella of the Stockholm Convention, such as the Global Atmospheric Sampling network or GAPS, the Arctic Monitoring and Assessment Programme or AMAP, the East Asia Air Monitoring Program, ~~(Stockholm Convention and UNEP, 2008; Gawor et al., 2014)~~ and the Human Milk Survey (Stockholm Convention and UNEP, 2008; Gawor et al., 2014; UNEP et al., 2013).

Defining a PBCP related to one or several of the suggested indicators is the next step. Here we suggest some possible indicators for control variables and some starting points for further scientific elaboration.

**Table S2.** Examples of indicators for chemical pollution at different stages along a generalized cause-effect chain for chemicals that can be further elaborated aiming for one or more indicator of PBCP. ADI is the Acceptable daily intake according to the IPCS~~WHO~~ (1987) and Renwick (1998). Toxic unit is the quotient of an actual concentration or intake of a substances and a determined effect measure (e.g. the EC50 or LC50) (Peterson, 1994). A critical volume is the volume of a medium (often water) needed to dilute an emitted mass of a substance to a concentration lower than the no-effect concentration of a representative species or group of species. Disability adjusted life-years (DALY) is an indicator of disease burden that can be connected to human chemical exposure (Murray and Lopez, 1996).

| | **Drivers** | | | **Pressures** | **States** | | **Impacts** | |
|---|---|---|---|---|---|---|---|---|
| **Indicator target** | **Innovation** | **Production** | **Societal stock** | **Emission** | **Environmental concentration** | **Exposure** | **Effects** | **Damage** |
| **Single chemicals OR groups of chemicals OR all chemicals** | Number of commercially available chemicals [dimensionless] | Annual production of single, groups of, or all chemicals [ton/year] | Current stock of single, groups of, or all chemicals [ton] | Annual emissions of single, groups of, or all chemicals [ton/year] | Environmental concentrations of single, groups of, or all chemicals [mol/l or $kg/m^3$] | (Potential) Daily intake (PDI) of single, groups of, or all chemicals [mg/kg bw/day]<br>Concentration in tissue of single, groups of, or all chemicals [mg/kg] | PDI/ADI of single, groups of, or all chemicals [dimensionless]<br>Toxic units [dimensionless]<br>Critical volumes [$m^3$]<br>Potentially Damaged Fraction of species (PDF) [$PDF \cdot m^2 \cdot yr$]<br>Loss of population(s) or species [dimensionless] | An explicit and relative valuation of effect indicator(s) e.g.<br>DALY [years] |

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