

Exploring the planetary boundary for chemical pollution

Diamond, Miriam L.; de Wit, Cynthia A.; Molander, Sverker; Scheringer, Martin; Backhaus, Thomas; Lohmann, Rainer; Arvidsson, Rickard; Bergman, Åke; Hauschild, Michael Zwicky; Holoubek, Ivan *Total number of authors:*

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1	Exploring the planetary boundary for chemical pollution
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4	Miriam L. Diamond [†] *, Cynthia A. de Wit [‡] , Sverker Molander, [§] Martin Scheringer, [%] Thomas
5	Backhaus, [∥] Rainer Lohmann, [√] Rickard Arvidsson, [§] Åke Bergman, [⊥] Michael Hauschild, [#] Ivan
6	Holoubek, [¶] Linn Persson, ^{&} Noriyuki Suzuki, [@] Marco Vighi, [¤] Cornelius Zetzsch ^{Δ}
7	
8	[†] Department of Earth Sciences, University of Toronto, 22 Russell Street, Toronto, M5S 3B1
9	Ontario, Canada
10	[‡] Department of Environmental Science and Analytical Chemistry (ACES), Stockholm
11	University, SE-106 91 Stockholm, Sweden
12	[§] Environmental Systems Analysis, Department of Energy and Environment, Chalmers
13	University of Technology, SE-412 96 Gothenburg, Sweden
14	[%] Institute for Chemical and Bioengineering, ETH Zürich, Wolfgang-Pauli-Str. 10, 8093 Zürich,
15	CH-8093, Switzerland, and Leuphana University Lüneburg, D-21335 Lüneburg, Germany
16	$\ $ Department of Biological and Environmental Sciences, University of Gothenburg, Box 100,
17	SE-405 30 Gothenburg, Sweden
18	Graduate School of Oceanography, University of Rhode Island, South Ferry Road,
19	Narragansett, Rhode Island, 02882, United States
20	[⊥] Department of Materials and Environmental Chemistry, Stockholm University, SE-106 91
21	Stockholm, Sweden
22	[#] Department of Management Engineering, Technical University of Denmark (DTU), Nils
23	Koppels Allé, Building 426 D, DK-2800 Kgs. Lyngby, Denmark

- 24 Research Centre for Toxic Compounds in the Environment (RECETOX), Faculty of Science,
- 25 Masaryk University, Kamenice 753/5, 625 00 Brno, Czech Republic
- ²⁶ Stockholm Environment Institute, Linnégatan 87D, Box 24218, Stockholm, Sweden
- ²⁷ [@]Strategic Risk Management Research Section, Center for Environmental Risk Research,
- 28 National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
- ²⁹ ^aDepartment of Earth and Environmental Sciences, University of Milano Bicocca, Piazza della
- 30 Scienza 1, Milan, 20126 Italy
- ^AForschungsstelle für Atmosphärische Chemie, Dr. Hans-Frisch-Str. 1-3, Universität Bayreuth,
- 32 D-954 48 Bayreuth, Germany
- 33
- 34
- 35

36 ABSTRACT (323 words)

Rockström et al. (2009a, 2009b) have warned that humanity must reduce anthropogenic impacts 37 defined by nine planetary boundaries if "unacceptable global change" is to be avoided. 38 39 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 40 (or boundaries) for chemical pollution (PBCP or PBCPs) is that the Earth has a finite 41 assimilative capacity for chemical pollution, which includes persistent, as well as readily 42 degradable chemicals released at local to regional scales, which in aggregate threaten ecosystem 43 and human viability. The PBCP allows humanity to explicitly address the increasingly global 44 aspects of chemical pollution throughout a chemical's life cycle and the need for a global 45 response of internationally coordinated control measures. We submit that sufficient evidence 46 47 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 48 to global pollution control measures are insufficient. However, while the PBCP is an important 49 50 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 51 myriad adverse effects to innumerable species and ecosystems, and the complex linkages 52 between emissions, environmental concentrations, exposures and adverse effects. As well, the 53 normative nature of a PBCP presents challenges of negotiating pollution limits amongst societal 54 groups with differing viewpoints. Thus, a combination of approaches is recommended as 55 follows: develop indicators of chemical pollution, for both control and response variables, that 56 will aid in quantifying a PBCP(s) and gauging progress towards reducing chemical pollution, 57 58 develop new technologies and technical and social approaches to mitigate global chemical

59 pollution that emphasize a preventative approach, coordinate pollution control and sustainability

60 efforts, and facilitate implementation of multiple (and potentially decentralized) control efforts

61 involving scientists, civil society, government, non-governmental organizations and international62 bodies.

63 KEYWORDS: planetary boundary, chemical pollution, chemical emissions, Stockholm

64 Convention, tipping point, global threshold, pollution controls, ecosystem health protection,

65 human health protection, chemical management

66

1. INTRODUCTION

Rockström et al. (2009a, 2009b) presented nine anthropogenic impacts of global relevance, 67 including climate change, biodiversity loss, anthropogenic changes of the nitrogen and 68 phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, 69 changes in land use, atmospheric aerosol loading, and chemical pollution. The authors proposed 70 that humanity may be moving beyond a "safe operating space" as the magnitude of these impacts 71 approach or exceed certain thresholds that represent tipping points of the global system or a 72 natural limit for processes without clear thresholds (so-called "dangerous levels" in the 73 Rockström et al. articles) (Fig. 1). As discussed in detail below, the authors defined a "safe 74 operating space" as those global conditions that allow for continued human development. 75 76 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 77 systems, reflecting conditions that are favorable for human life and cultural development, and 78 79 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 80

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.

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For chemical pollution, Rockström et al. (2009a, 2009b) did not define the scope of chemicals 85 considered, natural limits or a planetary boundary, but stated that these remain to be determined. 86 87 However, they suggested that possible measurable control variables for natural limits could be emissions, concentrations or effects of Persistent Organic Pollutants (POPs), plastics, endocrine 88 disruptors, heavy metals and nuclear wastes. Persson et al. (2013) added to the discussion by 89 90 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 91 substances and metals, and those intentionally and unintentionally released. We do not consider 92 the nutrients nitrogen and phosphorus that are considered under a separate planetary boundary, or 93 sulfates that can also fall under another planetary boundary (atmospheric aerosol loading). 94

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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 102 103 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, 104 even if all individual chemicals are present only at individually non-toxic concentrations, as 105 106 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 107 108 et al., 2007, 2009; Kortenkamp, 2008; Backhaus et al., 2010; SCHENIHR et al., 2012). 109 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 110 such chemicals in many parts of the world, alone or as mixtures, will push the global system 111 112 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 113 has already been reached (WHO and UNEP, 2013; inter alia). Furthermore, the boundary of 114 115 global chemical pollution cannot be ignored because it is inextricably connected to the other 116 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 117 waste disposal with a potential loss of biodiversity. 118

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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.

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We start the discussion by acknowledging that defining natural limits and a PBCP(s) is 129 challenging for many reasons. In the framework presented by Rockström et al. (2009a, 2009b), 130 defining a PBCP is more difficult than for other planetary boundaries (e.g. for global warming), 131 due to the difficulty of identifying a single or a few measurable control variables. A control 132 133 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 CO₂ or temperature for 134 global warming. However, agreeing on one or more control variables for chemical pollution is 135 challenging because chemical pollution is caused by an enormous number of chemicals emitted 136 from innumerable sources and in extremely different amounts in different regions of the world. 137 In the same way, the response variable is difficult to define and measure in a clear-cut way, since 138 chemicals cause a wide variety of adverse effects in a similarly wide variety of species, including 139 humans. The links to the related boundary of biodiversity are evident (Steffen et al. 2015). The 140 critical point is that the Earth's assimilative capacity, or the number and capacities of the sinks 141 142 capable of degrading or immobilizing anthropogenically-released chemicals, is limited at the global level, even for readily biodegradable chemicals. 143

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2. WHY A PLANETARY BOUNDARY FOR CHEMICAL POLLUTION?

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Several policy instruments aimed at controlling chemical pollution have been developed and are 146 147 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? 148 In order to answer these questions we first expand on the concept of planetary boundaries and a 149 "safe operating space" introduced by Rockström et al. (2009a, 2009b) and then move to put a 150 151 PBCP into the context of existing instruments for chemicals management. 152 Rockström et al. (2009a, 2009b) identified that several Earth processes and subsystems behave 153 non-linearly, with thresholds that, once crossed, could tip them into new, undesirable states. For 154 155 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.

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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., 166 2013). For these, the planetary boundary can be set at a level where the risk of functional
167 collapse is deemed acceptably low. In aggregate, planetary boundaries may thus be defined as a
168 set of critical values for one or several control variables defined by humans to be at a safe
169 distance from such thresholds or dangerous levels (if no threshold is evident) that, if crossed,
170 could lead to abrupt global environmental change. The domain below the boundary can be
171 considered a "safe operating space".



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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 CO₂-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.

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181 Although the intention was to define planetary boundaries for systems or processes affecting the

182 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 183 disturbance is concentrated or the affected ecosystem is more sensitive. These were identified as 184 "slow processes without known global scale thresholds". As such, they become a global 185 problem when they occur at many sites at the same time, aggregating to a level that undermines 186 187 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 188 189 biodiversity loss, land use change, global nitrogen and phosphorus biogeochemical cycles, and 190 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 191 192 boundaries, for example, chemical pollution of ecosystems linked to biodiversity loss 193 (Voeroesmarty et al., 2010; Lenzen et al., 2012; Steffen et al. 2015). For example, chemical 194 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. 195 196 197 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.

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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.

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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.

224

225 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 226 227 chlorofluorocarbons (CFCs) and persistent organic pollutants (POPs). Others, such as high-228 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. 229 Additionally, the global economy is undergoing chemical "intensification", as described by the 230 231 UNEP "Global Chemicals Outlook" analysis (UNEP, 2013). Chemical intensification is due to 232 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 233 complex chemicals in more and more applications. Chemical intensification is predicted to lead 234 235 to increasing per-capita chemical usage amongst a growing global population (UNEP, 2013).

236

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 241 whereas ~10% of all chemical stocks is contained in waste deposits from primary production and 242 ~10% is contained in land filled waste, ~80% is contained in in-use and "hibernating" stocks. 243 Most documentation of uncontrolled releases concern the two former sources (i.e., 20%) but not 244 245 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, 246 247 abandoned industrial sites, and numerous landfills in developing countries (Turk et al., 2007; 248 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 249 250 Convention) from equipment that was still in use in Canada in 2006 despite the ban on PCB 251 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 252 generation of buildings using that foam undergoes renovation or destruction over the next 30 253 254 years (Brunner and Rechberger, 2001)

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Similar application patterns of chemical technologies and similar uses of chemical products in 256 257 almost all regions of the world result in widespread chemical releases. Chemical manufacturing 258 and industrial usage are rapidly shifting from Western industrialized countries to developing countries and countries with economies in transition, including BRICS countries (Brazil, Russia, 259 and especially India and China, and most recently South Africa) (UNEP, 2013). New and 260 increasing resource extraction and chemical manufacturing, usage and waste disposal are leading 261 262 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 263

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).

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270 As pointed out above, the global nature of chemical pollution demands a global response of 271 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 272 273 example of a global governance instrument is the Stockholm Convention on Persistent Organic 274 Pollutants (POPs), which seeks elimination at best, or more broadly, the sound management, of a 275 set of POPs agreed upon through international negotiations (Stockholm Convention, 2008). While achieving many successes (Stockholm Convention, 2012), the Convention is limited to a 276 277 small number of chemicals or chemical classes (currently 22 are listed, with four more under 278 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 279 Convention is not to address the totality of chemical pollution. As such, the Stockholm 280 281 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 282 2010-2011) and the Minamata Convention is limited to mercury (UNEP 2015). The Convention 283 on Long-range Transboundary Air Pollution, under the aegis of the United Nations Economic 284 285 Commission for Europe and to which there are 51 parties, addresses a range of chemical pollutants including metals and POPs (UNECE 2004). 286

Another example of a global governance tool is the United Nations Framework Convention on 288 Climate Change where global negotiations and agreements have led to reduction goals for 289 greenhouse gases that are intended to be implemented at national levels (UNFCCC, 2013). 290 291 International climate negotiations have seen the emergence of control instruments of largely two types. The first is an absolute limit for total CO₂-equivalent emissions (a "cap") to assure that 292 total global emissions are on target to prevent the global atmospheric CO₂ concentration 293 294 exceeding an agreed-upon boundary. The second type of control scheme links emissions to activity or intensity such as CO₂-equivalent emissions per unit of electricity generated or per 295 296 kilometre driven, or to an economic cost resulting in reductions of CO₂-equivalent 297 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 298 but cannot ensure that global emissions are within the global safe operating space because of 299 300 population and economic growth that increase the demand for energy services, most of which are based on fossil fuels (IEA, 2014). 301

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Implicit in the concept of a safe operating space for CO₂ 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. 310

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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 313 stressor(s) on all ecosystems can be described and quantified as a function of a measurable 314 control variable(s) that is (are) related to a measurable response variable(s). For a PBCP, the 315 ultimate effect or response variable (Fig. 1) subject to control is widespread adverse impact(s) to 316 ecological and/or human health caused by exposure to (a) substance(s). Exposure can be 317 identified as the critical control variable since it is the necessary prerequisite for any kind of 318 319 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 320 321 boundary (boundaries) and a safe operating space. As noted above, the boundary (boundaries) is 322 (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 323 mitigation or control activities, which in this case would reduce exposure and thus, would 324 maintain human and ecosystem health within the safe operating space, the latter reflected in 325 maintained biodiversity, ecosystem functionality and human health. 326

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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 332 333 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 334 recent screening of 95 000 chemicals for persistence (P), bioaccumulation (B) and toxicity (T) 335 336 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, 93 000 337 338 chemicals were screened for P, B and long range transport potential according to the Stockholm 339 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 340 produced substances, such as the combustion by-products polycyclic aromatic hydrocarbons 341 342 (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 343 transformed to a multitude of other chemicals by biological and physical-chemical processes. 344 345 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 346 received insufficient attention (Muir and Howard, 2006; Howard and Muir, 2010; Scheringer et 347 al., 2012). In addition, an enormous number of organisms in a diversity of ecosystems are 348 349 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 350 very different toxicological potencies. Humans take a specific place among affected organisms. 351 Any approach to establishing a PBCP(s) must include impacts on human health, even if this is in 352 353 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.

356

Second, we acknowledge that boundaries for chemical pollution have been developed at a global 357 scale for selected POPs and mercury, and at local and regional scales for chemicals in foods, 358 water and air (Table S1). However, only a few of these boundaries account for exposure to 359 multiple chemicals simultaneously that can act in an additive fashion. Moving beyond a 360 chemical-by-chemical approach to acknowledge mixture effects is of growing importance if 361 limits are to be protective (e.g., Kortenkamp, 2007; Kortenkamp et al., 2007; Backhaus et al., 362 363 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 364 chemicals that can cause transgenerational effects (e.g., Baccarelli and Bollati, 2009; Bollati and 365 Baccarelli, 2010; Bouwman et al., 2012; Mani et al., 2012; WHO and UNEP, 2013; inter alia). 366 This is not surprising since accepted and validated methods for identifying and testing endocrine 367 disrupting chemicals, particularly after exposure during critical early life stages, are generally 368 lacking or have not yet been implemented in chemicals risk assessment (WHO and UNEP, 2013; 369 370 inter alia).

371

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-concentrationeffect linkage is necessary for other planetary boundaries such as CO₂, 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.

380

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.

387

The combination of numerous substances with different use and emission patterns, affecting a 388 multitude of different endpoints in a plethora of exposed species in the vastly different 389 ecosystems of the world, plus consideration of human health, makes the derivation of a single 390 quantitative PBCP or multiple PBCPs a daunting, if not impossible task. However, the situation 391 of increasing chemical production, emissions and adverse effects cannot be allowed to continue 392 unabated. Thus, we believe that the concept of a planetary boundary or boundaries for chemical 393 394 pollution is a useful framework for global action, but that it needs to be modified to account for these complexities and challenges. 395

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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 399 increasing body of evidence strongly suggests that we need more effective global chemicals 400 management. What has been accomplished in global chemicals management? Global 401 402 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 403 Movements of Hazardous Wastes, and the Rotterdam Convention on Prior Informed Consent 404 405 Procedure for Certain Hazardous Chemicals and Pesticides in International Trade. These Multilateral Environmental Agreements have come together under the aegis of UNEP. The 406 407 Stockholm and Montreal agreements strive towards zero-emissions of the listed chemicals. In 408 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 409 the banning of production, export and import of a range of mercury-containing products, calls for 410 the drafting of strategies to limit the use of mercury in artisanal and small-scale gold mining, and 411 aims to work towards minimizing mercury emissions from combustion sources such as 412 413 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 414 415 established through negotiation after the official signing of the Convention.

416

These five agreements address priority chemical pollutants at the global scale, reflect the insight 417 418 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 419 the most recent Minamata Convention), which in itself is a great accomplishment. However, 420 421 these agreements have limitations due to numerous official exemptions and unofficial "loopholes", they cover only a limited number of chemicals, implementation costs are largely 422 423 left to individual countries of which many lack such capacity, and sanctions cannot be levied for 424 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 425 426 have been enacted is a reflection that humanity has come close to or crossed boundaries for these 427 chemicals. A PBCP provides an overarching conceptual basis to characterize the achievements of these agreements and to accommodate additional necessary controls. 428

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430 For chemicals listed by the Stockholm and Minamata Conventions and the Montreal Protocol, 431 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 432 have been defined during the past decades under many jurisdiction-specific regulations and 433 434 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, 435 include limits to levels of pesticides in groundwater and surface water, levels of priority 436 pollutants in surface waters, and acceptable daily intakes (ADIs) for a wide range of food 437 438 contaminants. However, as noted above, not all of these agencies are able to monitor for, and 439 enforce compliance.

440

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

452

453 To move towards a truly global approach encompassing the aggregated impacts from all 454 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 455 456 stringent controls by specific jurisdictions has led to improved local conditions in those 457 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 458 (e.g., Skelton et al., 2011; Breivik et al., 2011; Sindiku et al., 2014). Thus, one intention of a 459 global boundary is avoiding "pollution free" jurisdictions at the expense of creating "pollution 460 havens" in developing nations (e.g. Gottesfeld, 2013). Examples of developed nations achieving 461 their pollution control goals by shipping waste and waste products to developing nations have 462

463 been described elsewhere (Schmidt, 2006; Breivik et al., 2011, 2014; Gioia et al., 2011;
464 Abdullah et al., 2013).

465

466 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 467 in this case translates to measures that will help stem widespread chemical pollution. Gee and 468 469 others (Gee, 2006; Gee et al., 2013; Harremoës et al., 2001) have documented examples of where 470 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. 471 472 tobacco smoking and asbestos). Persson et al. (2013) provide a persuasive argument in this regard. 473

474

As a result of these considerations, we submit that the PBCP is a useful aspirational framework 475 476 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 477 chemical pollution at a global scale, and see the inadequacy of current control measures to deal 478 with the totality of global chemical pollution. Having said that, we recognize that defining a 479 480 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 481 coordinated action in scientific, technical and political domains (e.g., Conklin, 2005; Horn and 482 Weber, 2007). For the scientific domain we propose the following: 483

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 488 proxies for chemical exposure and potency. Information on indicator status should then be 489 used to gauge progress towards staying within the safe operating space for chemical 490 pollution. Useful information to guide this task can be taken from the Drivers, Pressures, 491 492 States, Impacts, Responses (DPSIR) approach (OECD, 1991; Harremoës, 1998), and suggestions of how this could be accomplished are given in the Supporting information. This 493 proposal builds on the global monitoring networks that have achieved considerable success 494 such as those under the Stockholm Convention (e.g., the Global Atmospheric Passive 495 Sampling network or GAPS (Gawor et al., 2014) and Human milk survey (UNEP et al., 496 497 2013)).

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

507	chemically "de-intensify" economies, to use "green chemistry" substitutes and non-chemical
508	solutions, and to implement social solutions aimed at reducing resource consumption.
509	Efforts are underway in this regard, such as the U.S. EPA's Design for the Environment
510	Program (U.S.EPA, 2014) and the GreenScreen [®] for Safer Chemicals (Clean Production
511	Action, 2015). These two issues, PBCP and sustainable resource use, are intertwined such
512	that chemical pollution is a manifestation of unsustainable and inefficient resource use.
513	Thus, efforts directed towards achieving both goals would benefit from coordinated action.
514	
515	Progressing towards a PBCP(s) will require scientific, political, social and economic strategies.
516	In the political domain, it will be important to raise more awareness for chemical pollution
517	problems in all parts of the world, and to aid individual countries in implementing existing local
518	and regional boundaries and international agreements. The shift of chemical production from
519	OECD countries primarily to the BRICS countries needs to be complemented by a process that
520	helps to develop chemical regulation and enforcement in these regions to a level comparable or
521	better than that of OECD countries.
522	

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 onClimate Change" (C40 Cities, 2013).

530

In closing, 50 years ago Rachel Carson pointed out for the first time that the extensive use of 531 532 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 533 534 collapse of bee populations (Tapparo et al., 2012; Henry et al., 2012; Whitehorn et al., 2012). 535 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 536 537 range of chemical products and uses be restrained and many chemicals in commerce need to be 538 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. 539 540 ACKNOWLEDGEMENTS 541 542 543 544 The authors gratefully acknowledge financial support by the Swedish Research Council FORMAS and the International Panel on Chemical Pollution, which funded a workshop on this 545 topic. 546 547 548 549 550 REFERENCES 551

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842	Miriam L. Diamond [†] *, Cynthia A. de Wit [‡] , Sverker Molander, [§] Martin Scheringer, [%] Thomas
843	Backhaus, [∥] Rainer Lohmann, ^{$Rickard Arvidsson,§ Åke Bergman,⊥ Michael Hauschild,# Ivan$}
844	Holoubek, [¶] Linn Persson, ^{&} Noriyuki Suzuki, [@] Marco Vighi, [¤] Cornelius Zetzsch ^{Δ}
845	
846	[†] Department of Earth Sciences, University of Toronto, 22 Russell Street, Toronto, M5S 3B1
847	Ontario, Canada
848	[‡] Department of Applied Environmental Science and Analytical Chemistry (ITMACES),
849	Stockholm University, SE-106 91 Stockholm, Sweden
850	[§] DEnvironmental Systems Analysis, Department of Energy and Environment, Chalmers
851	University of Technology, SE-412 96 Gothenburg, Sweden
852	[%] Institute for Chemical and Bioengineering, ETH Zürich, Wolfgang-Pauli-Str. 10, 8093 Zürich,
853	CH-8093, Switzerland, and Leuphana University Lüneburg, D-21335 Lüneburg, Germany
854	Department of Biological and Environmental Sciences, University of Gothenburg, Box 100,
855	SE-405 30 Gothenburg, Sweden
856	\sqrt{G} Graduate School of Oceanography, University of Rhode Island, South Ferry Road,
857	Narragansett, Rhode Island, 02882, United States

	Diamond et al. Chemical Planetary Boundary	
858	^L Department of Materials and Environmental Chemistry, Stockholm University, SE-106 91	
859	Stockholm, Sweden	
860	[#] Department of Management Engineering, Technical University of Denmark (DTU), Nils	
861	Koppels Allé, Building 426 D, DK-2800 Kgs. Lyngby, Denmark	
862	[¶] Research Centre for Toxic Compounds in the Environment (RECETOX), Faculty of Science,	
863	Masaryk University, Kamenice 753/5, 625 00 Brno, Czech Republic	Formatted: Font color: Auto
864	^{&} Stockholm Environment Institute, Linnégatan 87D, Box 24218, Stockholm, Sweden	
865	[@] Strategic Risk Management Research Section, Center for Environmental Risk Research,	
866	National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan	
867	[¤] Department of Earth and Environmental Sciences, University of Milano Bicocca, Piazza della	
868	Scienza 1, Milan, 20126 Italy	
869	$^{\Delta}$ Forschungsstelle für Atmosphärische Chemie, Dr. Hans-Frisch-Str. 1-3, Universität Bayreuth,	
870	D-954 48 Bayreuth, Germany	
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Diamond et al.

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

Maximum Residue Levels (MRL)	Regulation (EC) 396/2005, 2008	pesticides in food	risk based, technology based 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)	<i>risk-based</i> 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)	<i>risk-based</i> 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) Oct. 2000	priority pollutants detected in water bodies	<i>risk-based</i> 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) http://www.env.go.jp/en/water/wg/wp.pdf	Substances relating to human health and living environment	<u>risk-based</u> <u>EQS: a level providing</u> protection against long-term exposure, and MAC: protection against short-term exposure	Japanese population and ecosystem (local, regional)	hHuman health and environment (water bodies only)
Predicted No Effect Concentrations (PNEC)	Regulation EC 1907/2006 (REACH) 1.6. 2007.	industrial chemicals in water, air, soil, sediment	<i>risk-based:</i> a concentration below the PNEC is considered safe	local, regional	environment
Derived No Effect Level (DNEL)	Regulation EC 1907/2006 (REACH) 1.6. 2007.	industrial chemicals	<i>risk-based:</i> a concentration below the DNEL is considered safe	European human population	human health

Zero discharges, emissions and losses	The Convention for the Protection of the marine Environment of the North-East	hazardous chemicals	<i>concentration-based:</i> concentration of zero for artificial	regional (north- east Atlantic)	environment (marine
of hazardous substances	Atlantic (OSPAR Convention), 1998		chemicals and concentration at natural background levels for		ecosystems only)
			naturally occurring chemicals		
Emission Limit	Ministry of the Environment, Government	Air pollutants that	risk-based	local	human health and
Values (ELVs)	of Japan, Regulatory Measures against Air Pollutants Emitted from Eactories and	may affect human	ELVs and other regulatory		environment
	Business Sites and the Outline of	environment	business sites are adopted to		
	Regulation (last amended in 1998),	<u>•••••••••</u>	achieve EQSs to protect human		
	http://www.env.go.jp/en/air/aq/air.html		health and environment		
Action limits	Guideline of the European Medicines	human	concentration-based	local, regional	environment
	Agency (EMA) on the environmental risk	pharmaceuticals	concentration below 0.01 μ g/l in		
	assessment of medicinal products for human		surface waters are considered		
	use (EMEA/CHMP/S wP/4447/00)		inherently safe, unless specific		
			endocrine activity).		
Threshold of	EMA Guideline on the limits of genotoxic	genotoxic	concentration-based	European human	human health
toxicological	impurities	impurities in	the TTC defines a common	population	
concern (TTC)	(EMEA/CHMP/QWP/251344/2006), 2006	pharmaceuticals	exposure level $(1.5\mu g/day)$ for an		
Regulation		materials	nose a risk of "significant		
Regulation		materials	carcinogenicity or other toxic		
			effects".		
Threshold of	US Food and Drug Adminstration (FDA),	food contact	concentration-based	US human	human health
Regulation (TOR)	Code of Federal Regulation (CFR), 21, §	materials	Concentrations of ≤ 0.5 ppb	population	
	170.39		$ evels < 1.5 \mu g/(person*day))$ are		
			considered safe.		
Maximum	Safe Drinking Water Act (SDWA),	contaminants in	concentration, risk and technology	US human	human health
(MCL) maximum	enforced by US EPA	drinking water	Dasea MCLG: The level of a	population	
contaminant level			contaminant in drinking water		
goals (MCLGs) and			below which there is no known or		

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Practical			expected risk to health. MCLGs			
Quantitation Limit			allow for a margin of safety and			
(PQL)			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.			
			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 POI			
Canadian	Canadian Council of Ministers of the	VOCs SVOCs and	Concentration-based: chemical	national	human health and	
Environmental	Environment	metals	specific goals (non-enforceable)	Introntal	environment	
Quality Guidelines		metals	for protection of aquatic life		chvironnent	
Quanty Outdennes			protection of soil quality			
			protection of groundwater at			
			contaminated sites, protection of			
			containinated sites, protection of			
Consider	Health Canada Eagd Directorists	anonified chamicals	<u>environmental and numan head</u>	notional	For	matted: Font: Not Italic
<u>Canadian</u> "toloropoos" and	Health Callada Food Difectorale	specified chemicals	<u>Concentrations expressed as</u>	national	<u>numan neatur</u>	
"standarde" for			tolerances (through regulation)			
stalluarus 101			and standards (not regulated) for			
various chemical			listed shamicals			and the second second second
<u>contaminants in</u>			insteu chemicais.		For	matted: Font: Not Italic
<u>1000</u>	Minister of English many transformed and			and an effective	1	
Environmental	Ministry of Environment, Forest and	specified chemicals	Concentration based: chemical or	national	numan health and	
Standards for	climate change, Government of India	and parameters	parameter specific goals for		environment	
ambient air and	Reference:		protection of environmental and			

and a second state of the second state of the			have a local descent of the off			
water quality criteria	<u>nup://envior.mc.in/environmental_standards</u>		numan nearth, protection of			
			aquatic life and water resources.			
	Montreal Protocol, 1989	CFCs	<i>emission-based</i> : production has to	global	ozone layer; For	matted: Font: Italic, No underline,
			reach zero.		human health Fon	t color: Auto
					and &	
					environment	
	Stockholm Convention, 2004	POPs	<i>emission-based</i> : production and	global	human health For	matted: Font: Italic, No underline,
			use have to reach zero.		and & Fon	t color: Auto
					environment	
Schedule 1	Canadian Environmental Protection Act	chemicals deemed	emission-based: limits on	national	human health	
Compounds	(CEPA) 1999	"CEPA toxic"	production, use and importation of		and/or	
Compounds		CERTIFICATIO	chemicals listed in Schedule 1		environment - For	matted: Font: Not Italic
Emission Limit	Directive 2008/1/EC concerning integrated	chamicals produced	technology based:	10001	human health	matted. Fond. Not Italic
Volues (ELVs)	pollution prevention and control (IDDC	et a given gite	ELVe are part of the permit on	Iocal	and b	
values (EL vs)	limition prevention and control (IFFC	at a given site	ELVS are part of the permit an		anue	
	difective), 2008		installation needs to acquire, based		environment	
			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			
			avoid switching from one			
National	National Environmental Standards and	specified chemicals	compartment to another.	national	human health and	
Environmentel	Pagulations Enforcement A geney	and perometers	based: Enforceable maximum	<u>IIau0IIai</u>	anvironment	
Degulations	(NESDEA) Nicovia	and parameters	appartentions, amission limits		environment	
Regulations	(INEOREA) INIGERIA Federal Depublic of Migania Official		concentrations, emission inmits			
	Federal Republic of Nigeria Official		and tolerance limits for specified			
	Gazette No. 92. Vol. 94 of 31st July, 2007.		chemicals			
Environmental	Ministry of Environmental Protection	general	Concentrations and emission-	national	<u>h</u> Human health	
Protection Law of		environmental	based: prevention and control of		and environment	
the People's		protection issues	water and air pollution;			

Chemical Planetary Boundary

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

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

Chemical Planetary Boundary

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.

Chemical Planetary Boundary

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 (*Driving forces-Pressures-States-Impacts-Responses*) 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

Chemical Planetary Boundary

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, ⁷(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.

Diamond et al.

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 <u>the IPCSWHO</u> (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] Concentration in tissue of single, groups of, or all chemicals [mg/kg]	PDI/ADI of single, groups of, or all chemicals [dimensionless] Toxic units [dimensionless] Critical volumes [m ³] Potentially Damaged Fraction of species (PDF) [PDF·m ² ·yr] Loss of population(s) or species [dimensionless]	An explicit and relative valuation of effect indicator(s) e.g. DALY [years]

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