

1 **Why is High Persistence Alone a Major Cause of Concern?**

2

3 Ian T. Cousins¹, Carla A. Ng², Zhanyun Wang³, Martin Scheringer^{4*}

4

5 1 Department of Environmental Science and Analytical Chemistry (ACES),
6 Stockholm University, SE-10691 Stockholm, Sweden, ORCID 0000-0002-7035-8660

7 2 Department of Civil & Environmental Engineering, University of Pittsburgh, 3700
8 O'Hara St, Pittsburgh, PA 15261, USA, ORCID: 0000-0001-5521-7862

9 3 Chair of Ecological Systems Design, Institute of Environmental Engineering, ETH
10 Zürich, 8093 Zürich, Switzerland, ORCID: 0000-0001-9914-7659

11 4 Institute of Biogeochemistry and Pollutant Dynamics, ETH Zürich, 8092 Zürich,
12 Switzerland, ORCID: 0000-0002-0809-7826

13

14 * To whom correspondence may be addressed:

15 Martin Scheringer, ETH Zürich, Universitätstr. 16, 8092 Zürich, Switzerland, e-mail:
16 scheringer@usys.ethz.ch

17 **Abstract**

18 Persistence is a hazard criterion for chemicals enshrined in chemical regulation
19 worldwide. In this paper, we argue that the higher the persistence of a chemical, the
20 greater the emphasis that it should be given in chemicals assessment and decision
21 making. We provide case studies for three classes of highly persistent chemicals
22 (chlorofluorocarbons, polychlorinated biphenyls, and per- and polyfluoroalkyl
23 substances) to exemplify problems unique to highly persistent chemicals, despite their
24 otherwise diverse properties. Many well-known historical chemical pollution
25 problems were the result of the release of highly persistent chemicals. Using
26 evaluative modeling calculations, we demonstrate that if a chemical is highly
27 persistent, its continuous release will lead to continuously increasing contamination
28 irrespective of the chemical's physical-chemical properties. We argue that these
29 increasing concentrations will result in increasing probabilities of the occurrence of
30 known and unknown effects and that, once adverse effects are identified, it will take
31 decades, centuries or even longer to reverse contamination and therefore effects.
32 Based on our findings we propose that high persistence alone should be established as
33 a sufficient basis for regulation of a chemical, which we term the "P-sufficient
34 approach". We argue that regulation on high persistence alone is not over-
35 precautionary given the historical and ongoing problems that persistent chemicals
36 have caused. Regulation of highly persistent chemicals, for example by restriction of
37 emissions, would not only be precautionary, but would serve to prevent poorly
38 reversible future impacts.

39 **1 Introduction**

40 The persistence of organic chemicals has been an important element of chemical
41 hazard assessment for over 40 years¹⁻⁴. High persistence indicates the potential for
42 long-lasting environmental and human exposure to a chemical that is difficult to
43 control and reverse⁵⁻⁷. The importance of persistence is reflected by the persistence
44 (P) criterion in the PBT (persistence, bioaccumulation potential, toxicity) assessment
45 schemes used under the Stockholm Convention on Persistent Organic Pollutants and
46 in an increasing number of jurisdictions such as Australia, Canada, the EU, Japan,
47 South Korea and the US, and by the “very persistent” (vP) criterion under the EU
48 chemicals regulation, REACH. A review of the historical development of
49 international persistence criteria is provided by Matthies and Beulke (2017)⁸. Here we
50 suggest that the higher the persistence of a chemical, the greater the emphasis that it
51 should be given in chemicals assessment and decision-making. Specifically, the aim
52 of this work is to provide a transparent and conclusive reasoning why, from a certain
53 point on, the persistence of a chemical indicates such a high level of concern that it
54 should be given strong priority in the assessment and management of such a chemical.

55 The focus of this work is on the persistence of organic chemicals⁹, which is
56 generally quantified in terms of degradation half-lives in individual environmental
57 media (“single-media half-lives”)^{8,10}. Not covered are synthetic polymers; stable
58 (“persistent”) inorganic substances such as water, nitrogen (N₂), salts, mineral
59 substances (e.g. concrete and sand), and metals such as anthropogenically mobilized
60 mercury, cadmium and lead. Although synthetic polymers are not explicitly included,
61 some challenges associated with synthetic polymers, which are poorly degradable by
62 their very nature, are addressed in the Discussion section.

63 By “high persistence” we mean that a chemical has at least one degradation
64 half-life exceeding, for example, 6 months. Importantly, this value is just indicative
65 and not meant as a proposal for a regulatory cutoff value (regulatory implementation
66 of the approach proposed here will be a separate step).

67 The particular importance of the persistence of chemicals was already pointed
68 out by Stephenson (1977)¹ more than 40 years ago:

69 “On the face of it there appears little reason to be concerned about a material
70 which, even though present in the environment, it not causing any detectable
71 damage. On the other hand, persistent materials, because of this property, will
72 accumulate in the environment for as long as they are released. Since the

73 environment is not effective at cleansing itself of these materials, they will remain
74 for indefinite periods which were not recognized at the time of their original
75 release. The problem could become entirely out of control and it would be
76 extremely difficult if not impossible to do anything about it. Materials which are
77 strongly persistent can accumulate to rather high levels in the environment and
78 effects which would not otherwise be important could become so.”
79 Since then, this point has been reiterated by several authors every 5–10
80 years^{2,3,5,7,10,10–14}. Our final conclusion from all of these analyses is that there may be
81 chemicals whose persistence is so high that it is sufficient alone as a basis for the
82 regulation of these chemicals.

83 Here we first present conceptual arguments that highlight the meaning of the
84 persistence of chemicals for the occurrence of exposure and, importantly, also risks.
85 We then use results from a multi-compartment environmental fate model to further
86 illustrate these arguments, and finally draw conclusions for the assessment and
87 management of highly persistent chemicals and discuss, also in the context of the
88 precautionary principle, the “P-sufficient” approach that we introduce here.

89 The P-sufficient approach is intended to complement established methods of
90 chemical risk assessment. It starts from the well-established insight that for PBT
91 chemicals a risk assessment would be fraught with too high uncertainty and that,
92 therefore, these chemicals should be assessed and managed on the basis of their PBT
93 properties^{15,16}. Here we maintain that of these three properties P is of particular
94 importance and that all chemicals that show a high persistence should be assessed and
95 managed on the basis of their high persistence alone, irrespective of their B and T
96 properties. This approach applies only to a small subset of organic chemicals on the
97 market and does not have any implications for the majority of chemicals, which are
98 not highly persistent and can be managed on the basis of chemical risk assessment.
99

100 **2 Why persistence matters and what it means**

101 Persistent chemicals are at the center of many of the most serious cases of
102 environmental contamination in the last 50 years. Examples are polychlorinated
103 biphenyls (PCBs)^{13,17}, chlorofluorocarbons (CFCs)^{18,19}, and per- and polyfluoroalkyl
104 substances (PFASs)²⁰. These cases have been investigated in much detail; Table 1
105 provides an overview of the chemicals’ persistence, production history and the major
106 issues that follow from their persistence. Importantly, the adverse effects caused by

107 persistent chemicals are not limited to health effects in humans and wildlife, but also
 108 include physical and chemicals effects such as ozone depletion and global warming.

109

110 *Table 1: Overview of the persistence, production history, and major issues associated*
 111 *with three well-known classes of persistent chemicals. CFCs = chlorofluorocarbons;*
 112 *PCBs = polychlorinated biphenyls; PFASs = per- and polyfluoroalkyl substances;*
 113 *PFAAs = perfluoroalkyl acids; PFOA = perfluorooctanoic acid.*

	CFCs	PCBs	PFASs
persistence	many decades to a century or more in the stratosphere ²¹	years to decades ²² in terrestrial and aquatic environments	all PFASs are, or ultimately transform into stable substances, often PFAAs. PFAAs degrade slowly in the air ²³ and negligibly in other media ²⁴⁻²⁶
production history	since the late 1930s ²⁷	since 1929 ²⁸	since the late 1940s ²⁹
first report(s) of presence	mid-1960s early 1970s after invention of the electron capture detector ³⁰⁻³²	late 1960s ^{33,34}	organofluorine fraction discovered in human blood in 1968 ³⁵ and in 1976 ³⁶ PFOA tentatively identified using NMR
start of large-scale investigation	1970s following the discovery of their depletion of stratospheric ozone ³⁷	1970s following the first reports of their presence	2000s after discovery of widespread presence of PFAAs in wildlife ³⁸ and human blood ³⁹ .
Major issues associated with the persistence of the chemicals			
long-range transport / previously unexpected exposure	the atmospheric lifetime of CFCs is long enough to reach, and be persistent in, the stratosphere ³² .	PCBs are globally transported ⁴⁰ and present everywhere in the global environment, even in regions far away from sources (e.g. Antarctica, ⁴¹ deep oceans ⁴² and Arctic biota ⁴³).	PFASs are globally distributed (e.g. in oceans ⁴⁴ and soils ⁴⁵ , wildlife ⁴⁶ and human blood ⁴⁷) including at poles (e.g. Antarctic ⁴⁸). Short-chain PFAAs are very mobile and can easily pass through drinking water treatment facilities ⁴⁹ .

114

	CFCs	PCBs	PFASs
delayed identification of unexpected effects	More than 40 years after their large-scale production began, CFCs were shown to be depleters of stratospheric ozone ³⁷ and later also found to be potent greenhouse gases ⁵⁰ .	In the late 1960s, it was shown that PCBs bioaccumulate in Baltic food webs ⁴² and later reproductive effects on seals ⁵¹ and white-tailed eagles ⁵² were observed. In the 1980s, it emerged that PCBs could affect unborn children. ⁵³⁻⁵⁵	Exposure to low doses of PFAAs at an early stage of life produces effects not captured by current regulatory testing guidelines (e.g., developmental and Immuno-toxicity, endocrine disruption, etc. ⁵⁶). Consideration of immunotoxicity in health guidelines has reduced the assumed safe levels by orders of magnitude. ⁵⁷
effectiveness of risk assessments	In 1973, J. Lovelock concluded “that the presence of these compounds constitutes no conceivable hazard”. ³² Stratospheric ozone depletion was an unknown effect at that time.	Risk assessments have been continually refined (health guideline values revised downwards) from the 1920s to the present day as new information on effects emerged ⁵ .	Risk assessments do not reflect the long-term and irreversible exposure to PFASs ^{7,20} Many PFASs are not considered in risk assessment, and mixture toxicity and non-standard toxicity tests are often neglected. One can therefore expect continual refinement of risk assessments ²⁰ .
effectiveness of regulatory actions	International agreement was reached under the Montreal Protocol, which entered into force in 1987. The Montreal Protocol only called for a reduction in emissions of certain damaging CFCs, with later amendments agreeing to their phase-out by 2000. Despite this phase-out, it takes decades for the ozone layer to recover ⁵⁸ .	Regulatory action began in the late 1970s in some western countries when there was a high level of proof of effects associated with PCBs, but manufacture and use continued elsewhere. ³⁹ Despite their eventual global phase-out, PCBs are still present in many applications and will continue to be major contaminants for decades to come. Levels in soils ⁵⁹ , sediments ⁶⁰ and biota ⁶¹ decline especially slowly.	Regulatory action can eliminate point source emissions. However, it has no influence on what has already been emitted. Environmental redistribution of PFASs will continue for decades, and background levels will keep increasing ⁶² . For example, PFOS levels in humans started to decrease after actions by 3M in 2000-2002, but there are no clear trends for environmental and wildlife levels yet ⁶³ .

115

116

	CFCs	PCBs	PFASs
technical implications for remediation	Stopping emissions was the only way to reduce levels in the troposphere and thus stratosphere, and this was achieved through international treaties.	PCBs can be found in contaminated soils and sediments. The most frequent remediation solutions adopted have been “dig and dump” and “dig and incinerate”, but there are currently new methods emerging ⁶⁴ .	It is energy-intensive to break the C-F bond to mineralize PFASs. The most effective method for large-scale treatment is through incineration at high temperatures and new advanced mineralization methods are being developed ⁶⁵ . Short-chain PFASs are too mobile to be concentrated, causing additional challenges in remediation ⁶⁵ .
financial implications for remediation	CFC replacements were quickly identified (but often have high global warming potential), but some economies were less able to cover the costs of switching to these alternatives ⁵⁸ . Average destruction costs are estimated to range from \$4 to over \$6 per kg (for concentrated refrigerant or blowing agent) ⁶⁶ .	The costs of legacy PCB contamination in the European Union have been estimated to be as high as 75.3 billion Euros between 1971 and 2018 ^{13,20} .	High energy demand means it is very costly to safely dispose of contaminated products and remediate contaminated sites even if technically feasible. Costs of remediation are currently uncertain. The U.S. Air Force estimates that it will cost them \$2 billion to clean up PFAS-contaminated water ⁶⁶ .

117
118 The cases in Table 1 and others (e.g. PCDD/Fs⁶⁷⁻⁶⁹, brominated flame retardants⁷⁰⁻⁷²,
119 organochlorine pesticides⁷³) show that, *empirically*, the particular concerns caused by
120 highly persistent chemicals have been documented in much detail. *Conceptually*, the
121 essence of why high persistence is of outstanding importance in chemicals assessment
122 is perhaps less obvious and worth clarifying here. The concern about a chemical in the
123 environment is, of course, related to unwanted effects (of any kind, e.g. toxic effects
124 on wildlife or humans, global warming, ozone depletion, see Table 1) that the
125 chemical may cause. However, as has been learned from many cases in chemical risk
126 assessment (e.g. immunotoxicity of PFASs⁵⁷, endocrine disrupting effects⁷⁴, effects of
127 neonicotinoid pesticides⁷⁵), adverse effects are difficult to predict and the scientific
128 knowledge about effects will always remain uncertain and, importantly, *incomplete*.
129 This is because the number of possible effects is infinite and it is epistemologically
130 impossible to identify them all. This means that unexpected effects may always occur.

131 If unexpected effects are caused by a short-lived chemical, it is possible to
132 rapidly cease environmental contamination by restricting or banning its use, which
133 then also means that no additional effects will be caused by that chemical. This is why
134 short-lived chemicals that are released to the environment at high rates should not be
135 called “pseudo-persistent” or “semi-persistent”. In such a case, high levels in the
136 environment are observed, but they are solely caused by continuous and high
137 emissions, not by any type of persistence of the chemical.

138 In contrast, in the case of highly persistent chemicals, it is not possible to
139 cease environmental contamination within a reasonable time frame by simply
140 restricting or banning their use. Environmental contamination by highly persistent
141 chemicals –and the effects related to this contamination– will continue for years to
142 decades. This poor reversibility of contamination is because highly persistent
143 chemicals are, by definition, difficult to degrade. This implies that highly persistent
144 chemicals will require high inputs of energy to remove them from the environment,
145 either directly for the destruction of their stable chemical bonds (e.g. incineration) or
146 through methods to remove them from the environment that require substantial energy
147 inputs to drive their separation from contaminated media (e.g. pump and treat:
148 pumping water out of groundwater aquifers and subsequent treatment). Examples of
149 the high costs associated with remediation of highly persistent chemicals are provided
150 in Table 1. Importantly, removal or remediation is only feasible for contamination
151 hotspots, but not for the majority of the environment such as the world’s oceans.

152 It is *logically incorrect* to say that persistence merely indicates the presence of
153 a chemical in the environment. Persistence indicates an impactful causal relationship
154 that extends into the future: persistent chemicals that are present now will also be
155 present to a certain extent after a considerable number of years (e.g., 25% after 10
156 years if the degradation half-life is 5 years), and this fact is known already now with
157 certainty. They have the potential to undergo long-range transport in the environment,
158 and then an increasing number of organisms in many ecosystems as well as humans
159 will be exposed, including ones for which this was unexpected such as the Mariana
160 Trench in the case of PCBs⁴². This includes not only chemicals that are volatile and
161 soluble in water, but also low-volatility chemicals with very high octanol-water
162 partition coefficients (K_{OW}) and octanol-air partition coefficients (K_{OA}), such as deca-
163 BDE and heavy PCBs.

164 Furthermore, high persistence indicates that certain thresholds for causing
165 (often unexpected) effects will be exceeded, and this can also be predicted with high
166 reliability. If a substance is persistent, and if emissions continue at a constant rate or
167 increase (because the substance is of technical and economic interest), the substance
168 will attain higher and higher concentrations in the environment. In this case, the risk
169 quotient (i.e. PEC/PNEC ratio) also increases continuously up to the point that the
170 concentration may exceed no-effect thresholds (see examples given in Section 3,
171 below). And even if persistent chemicals are present at low concentrations and do not
172 (yet) exceed effect thresholds, they will still be present when, in the future, other
173 chemicals will be emitted so that there will be co-exposure that may cause mixture
174 effects.

175

176 In summary, the main concerns with highly persistent chemicals are:

- 177 1. The continuous release of highly persistent chemicals will lead to widespread,
178 long-lasting, and increasing contamination.
- 179 2. Increasing concentrations will result in increasing probabilities that known and
180 unknown effects occur, be it by a single chemical and/or in a mixture with other
181 substances.
- 182 3. Once adverse effects are identified, it will be technically challenging, energy
183 intensive, and thus costly, to reverse the chemical contamination and therefore the
184 effects. These measures are limited to contamination hotspots, whereas, for most
185 of the environment, no remediation or clean-up will be possible.

186 Therefore, it is not an unsubstantiated concern about the mere *presence* of a chemical,
187 but it is the much higher likelihood for particularly serious (widespread, long-lasting)
188 *adverse effects* associated with highly persistent chemicals – effects that have become
189 manifest many times as the historical examples show – that would confer particular
190 importance to persistence as a hazard indicator for triggering management actions. In
191 conclusion, concerns about a chemical are always related to effects, but for highly
192 persistent chemicals, it should not be required that these effects are represented
193 explicitly in the hazard assessment scheme. The hazard assessment of these chemicals
194 should be based solely on their high persistence as a placeholder or proxy for effects.

195

196

197 **3 Mass-balance modeling**

198 Here we illustrate the implications of high persistence for the levels and time trends of
199 chemicals in the environment using a simple multimedia environmental fate model for
200 four example chemicals. The purpose of the modeling work is to illustrate and
201 compare the environmental behavior of highly persistent vs. short-lived chemicals,
202 but not to reflect any particular setting. No modeling of this type is needed in the
203 evaluation of chemicals for persistence. The model is a so-called unit-world model⁷⁶
204 with three compartments: the global troposphere (height 6000 m, volume $3.06 \cdot 10^{18}$
205 m^3), the global surface ocean water (depth 100 m, volume $3.62 \cdot 10^{16} \text{m}^3$), and the
206 global surface soil (depth 0.1 m, volume $1.48 \cdot 10^{13} \text{m}^3$). In each compartment, a first-
207 order degradation process takes place; in addition, there are three non-degradative
208 losses: diffusion to the stratosphere, settling to deep ocean water, and burial in deep
209 soil. These non-degradative losses from the model system are not true sinks, but
210 reflect transfer of chemical to parts of the environment not included in this particular
211 model.

212 The model parameters for transfer processes between different compartments,
213 such as the rain rate or soil runoff rate, are the same as in many other environmental
214 fate models and are listed in Table 7.2 of the book by Mackay (2001)⁷⁷.

215 In total, we modeled four hypothetical chemicals that differ in their
216 degradation half-lives and K_{OW} values, see Table 2. Here we use the K_{OW} to describe
217 the phase partitioning of the example chemicals. Although PFAAs, as one important
218 class of highly persistent chemicals, are dissociated, i.e. present as anions, at
219 environmental pH, they partition to organic matter similar to hydrophobic organic
220 substances with a $\log K_{OW}$ of around two⁷⁸. For all three compartments, the same
221 degradation half-lives of 2 d (chemicals A and C) and 2000 d (chemicals B and D)
222 were assumed. A half-life of 2000 d or 5.5 years is long, but not excessively high.
223 PFASs, for example most PFAAs, can have much longer half-lives. If PFAAs
224 degrade, they do it so slowly that it is not observable and their half-lives could be on
225 the order of decades, centuries or even greater⁷⁹.

226

227

228

229

230

231 *Table 2: Chemical property data of the four example chemicals.*

Property	chemical A	chemical B	chemical C	chemical D
$\log K_{Aw}$	-1	-1	-1	-1
$\log K_{Ow}$	2	2	8	8
$t_{1/2}$ (d)	2	2000	2	2000

232

233 In a first emission scenario, we assumed the same constant emission rate to air (100
 234 mol/h) for each chemical and calculated the concentrations in air, water and soil at
 235 steady-state and in a dynamic scenario where the initial concentrations in all media
 236 are equal to zero. The absolute value of the emission rate is not relevant here because
 237 we compare results of the chemicals relative to one another. The results would be the
 238 same with any emission rate.

239 In reality, emissions may be constant or even increasing as long as a chemical is
 240 extensively used in open applications, often over many years or decades, and then
 241 decrease in a later stage⁶². To capture this situation, we ran a second emission
 242 scenario with emissions increasing linearly for 10 years and then decreasing linearly
 243 for another 10 years. This is still an idealized scenario; for an example of a realistic
 244 emission history and the ensuing environmental distribution of a chemical, see, for
 245 example, Boucher et al. (2019)⁸⁰. In this second scenario, we compare chemicals C
 246 and D.

247

248 The main model results are summarized in Table 3; several features of the
 249 concentration-time curves of the different chemicals are illustrated in Figures 1 and 2.
 250 For each chemical, the results in Table 3 include the total amount present in the model
 251 system; concentrations and fractions in air, water and soil; the overall persistence; the
 252 degradation losses in comparison to non-degradation losses, and the time-to-steady-
 253 state, defined as the time at which the total amount of chemical in the system has
 254 reached 99.9% of the amount at steady-state. The overall persistence, τ , is calculated
 255 as the total amount of chemical at steady-state (in mol) divided by the degradation
 256 losses (in mol/h). It is related to the single-media half-lives, $t_{1/2,i}$, by equation 1:

$$257 \quad \tau = \left(\sum_i f_i \cdot \frac{\ln 2}{t_{1/2,i}} \right)^{-1}, \quad i = \text{air, water, soil};$$

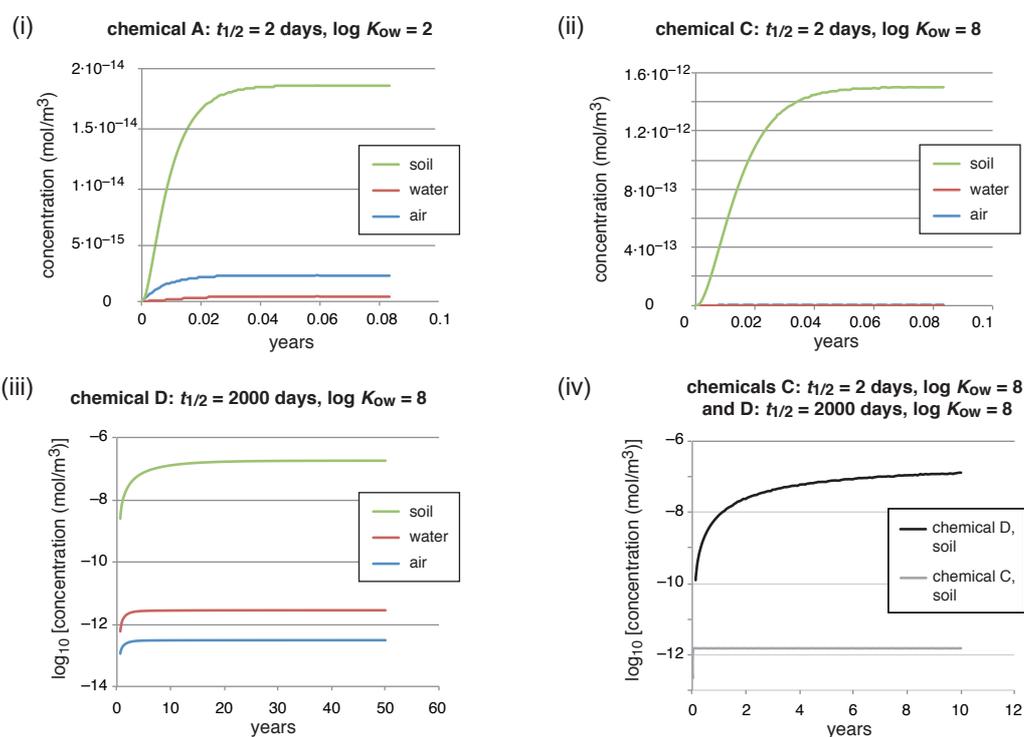
258

259 where the f_i are the fractions of the chemical in the different media. If the single-
 260 media half-lives are the same (the case here), τ is equal to $t_{1/2}/\ln 2$.

261 *Table 3: Main model results for the scenario with constant emissions. Regular font:*
 262 *results from steady-state model. Bold: results from dynamic model.*

Quantity	chemical A	chemical B	chemical C	chemical D
total inventory (mol)	$6.92 \cdot 10^3$	$4.14 \cdot 10^6$	$6.94 \cdot 10^3$	$3.69 \cdot 10^6$
c_A (mol/m ³)	$2.26 \cdot 10^{-15}$	$1.22 \cdot 10^{-12}$	$2.25 \cdot 10^{-15}$	$3.06 \cdot 10^{-13}$
c_W (mol/m ³)	$4.56 \cdot 10^{-16}$	$1.16 \cdot 10^{-11}$	$5.70 \cdot 10^{-16}$	$2.80 \cdot 10^{-12}$
c_S (mol/m ³)	$1.86 \cdot 10^{-14}$	$1.43 \cdot 10^{-11}$	$1.50 \cdot 10^{-12}$	$1.79 \cdot 10^{-7}$
fraction in air, f_a	1.0	0.9	0.99	0.25
fraction in water, f_w	0	0.1	0.00	0.03
fraction in soil, f_s	0	0	0.01	0.72
overall persistence, τ (d)	2.88	$2.89 \cdot 10^3$	2.88	$2.89 \cdot 10^3$
sum degradation losses (mol/h)	99.9	59.8	99.9	53.2
sum non-degradation losses (mol/h)	0.1	40.2	0.1	46.8
time to steady-state (d)	20 d	33 yr	20 d	48.5 yr

263



264

265 *Figure 1: Concentrations of different model chemicals as a function of time in the*
 266 *scenario with constant emissions (chemical B not shown). (i) Chemical A with a $t_{1/2} =$*
 267 *2 days and $\log K_{ow} = 2$ is present in all three media in appreciable amounts and*

268 reaches its steady-state after approximately 0.05 yr. (ii) Chemical C with $t_{1/2} = 2$ days,
269 but a log K_{OW} of 8, reaches its steady-state also after less than 0.1 yr, but is mostly
270 present in the soil. (iii) Chemical D with $t_{1/2} = 2000$ days and log $K_{OW} = 8$ reaches its
271 steady-state after approximately 33 years and is mostly present in the soil. (iv)
272 Comparison of the concentrations in soil of chemicals C (short half-life) and D (long
273 half-life). After 10 years, the concentration of chemical D is 84,000 times greater than
274 that of chemical C and is still building up, see panel (iii); their emission rates are the
275 same.

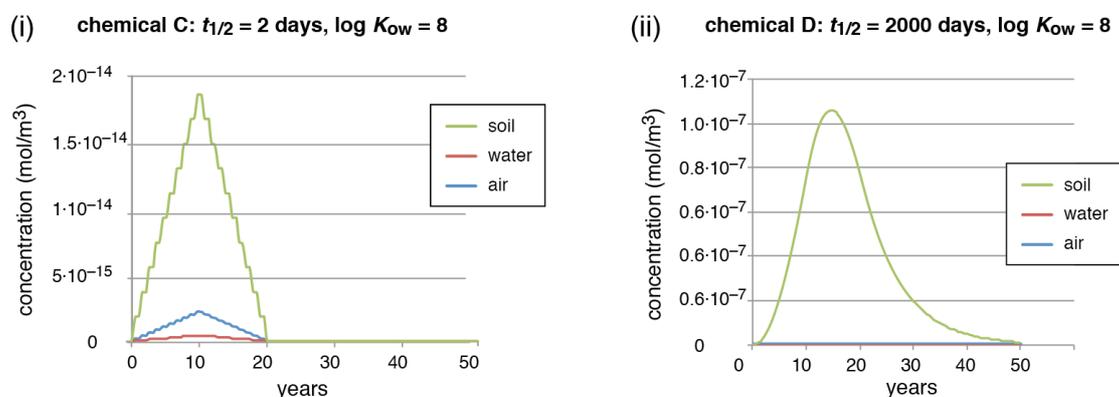
276

277 Important observations from the scenario with constant emissions are as follows:

278 An increase in the degradation half-life by a factor of 1000 (from 2 d to 2000
279 d, chemicals A vs. B, see Table 1, and chemicals C vs. D, see Figure 1, panel (iv))
280 leads to an increase in the time to steady-state by a factor of 600-880 (from 20 d to
281 33-48.5 yr). This increase is lower than a factor of 1000 because of the advective
282 losses. These do not scale with the degradation half-lives and, therefore, become
283 increasingly important if the degradation half-life is longer (see Table 3, degradation
284 losses vs. non-degradation losses). Similarly, the increase in the total inventory of
285 chemical in the model system is only around a factor of 550 to 600 because of the
286 increasing effect of the non-degradation losses. Next, the steady-state concentrations
287 in air, water and soil of the highly persistent chemicals, B and D (half-life 2000 d), are
288 higher by factors of 136 to $1.19 \cdot 10^5$, compared to the short-lived chemicals. Here it is
289 the influence of the non-degradation losses in combination with different partitioning
290 because of different K_{OW} values that explains why they differ from 1000. Chemical D,
291 for example, is rapidly deposited from the air to soil and water with settling particles
292 and accumulates in the soil, which is caused by its high K_{OW} in combination with the
293 high half-life. Accordingly, the concentration in air of chemical D increases only by a
294 factor of 136 compared to chemical C, but its concentration in soil increases by a
295 factor of $1.19 \cdot 10^5$, which is much more than the 1000-fold increase in the half-lives.

296 An increase in log K_{OW} by 6 log units leads to a shift of the chemical from air
297 and water to soil (see panels (i) and (ii) in Figure 1). However, this does not change
298 the overall persistence because in the examples presented here each chemical has the
299 same degradation half-life in all environmental media. For short-lived chemicals the
300 half-lives often vary markedly between environmental media, but in the case of highly
301 persistent chemicals such as PFASs the half-lives are long in all media and

302 degradation is slower than all phase-partitioning processes. Therefore, in the case of
303 highly persistent chemicals, the partitioning properties (e.g. K_{OW}) are not important
304 for controlling the overall persistence of a chemical in the environment.
305



306
307 *Figure 2:* Concentrations of chemicals C and D as function of time in the scenario
308 with dynamic emissions. For both chemicals, emissions start in year 0, increase by 10
309 mol/h every year, peak in year 10 at a value of 100 mol/h, then decrease by 10 mol/h
310 every year, and end in year 20. Note the much higher levels of chemical D compared
311 to chemical C.

312
313 In the scenario with dynamic emissions, the concentrations of the short-lived chemical
314 (chemical C) directly follow the time course of the emissions (Figure 2, left). This
315 illustrates that it is easily possible to quickly reduce even high concentrations of a
316 short-lived chemical by reducing the emissions. The long-lived chemical (chemical
317 D), in contrast, shows a marked overshoot with increasing concentrations for more
318 than 4 years after the emission peak in year 10 (concentration peak in year 14.5).
319 Moreover, the decreasing concentrations form a long tail that extends for many years
320 after the stop of the emissions in year 20. This type of behavior is also visible in
321 reality for PCBs and other highly persistent chemicals after the stop of major
322 emissions, see overview and references in Table 1.

323 PFAs are a class of chemicals with extremely long degradation half-lives in
324 all media and it is therefore interesting to compare their environmental behavior with
325 our modeling results. A steady-state condition was never reached for PFAs because
326 production continually increased between 1950 and 2000 until action to reduce
327 emissions was taken. Even if emissions had levelled off at their production peak in the
328 late 1990s, our modeling results imply that environmental levels would have

329 continued to increase for many decades afterwards. Since action to reduce emissions
330 of PFAAs commenced, starting in 2000–2002, there has been no evidence of
331 consistent declines of any PFAA in the environment or biota⁶³. Perfluoroalkyl
332 carboxylic acids with nine or more carbons continue to increase in human blood even
333 after measures to reduce their emissions were introduced⁶³.

334

335 **4 Discussion and recommendations**

336 **Model-derived findings.** The model results presented above illustrate the important
337 general implications of high persistence: the higher the persistence of a chemical, the
338 longer the time-to-steady state, the higher the steady-state concentrations, and the
339 greater the overshoot and long-lasting contamination tail after the end of the
340 emissions. Another important finding from the model results is that the K_{OW} does not
341 modify these general implications of high persistence. The K_{OW} does modify the
342 specific properties and environmental distribution of a chemical, but if the
343 degradation half-lives are long in all media, the persistence-related concerns (high
344 time-to-steady state, overshoot, etc.) are present irrespective of the values of the
345 partition coefficients. This has an important implication: a high K_{OW} is generally
346 related to a high bioaccumulation factor⁸¹, and a high bioaccumulation factor is an
347 additional source of concern, but the fundamental concerns related to high persistence
348 are independent of any bioaccumulation (“B”) properties of a chemical. B is not a
349 useful criterion for protecting against poorly reversible effects because the residence
350 time of highly persistent chemicals in the environment is often much greater than their
351 residence time in humans and biota, which means that levels in organisms will be
352 poorly reversible regardless of the magnitude of B⁷. The irrelevance of environmental
353 partitioning with regard to regulation of highly persistent chemicals is reflected on the
354 regulatory side by two regulatory schemes that both focus on persistent chemicals, in
355 one case with high K_{OW} (Stockholm Convention on POPs, K_{OW} cutoff of $\log K_{OW} >$
356 5)⁸², and in one case with low K_{OW} (the proposed scheme for persistent, mobile and
357 toxic (PMT) chemicals with a cutoff of $\log K_{OW} < 4$)^{9,83,84}.

358

359 **Policy implications of the findings.** Based on the findings presented above, our
360 general proposal is that, in addition to existing chemical assessment schemes, *high*
361 *persistence should be established as a sufficient basis for regulation of a chemical.*
362 We call this the “P-sufficient” approach (a similar reasoning supporting the P-

363 sufficient approach has been presented by Goldenman et al.¹⁰). Current chemical
364 assessment schemes place special emphasis on persistent chemicals only if other
365 hazardous properties, such as bioaccumulation potential and toxicity, are also present,
366 whereas high persistence as such is not relevant in chemicals assessment. For
367 example, under REACH the identification of a substance as PBT or vPvB (very
368 persistent and very bioaccumulative) automatically requires the registrant to carry out
369 an estimate of emissions, to identify and implement measures to minimize emissions,
370 to indicate in the safety data sheet (SDS) that the substance is PBT/vPvB, and to
371 communicate measures for minimizing emissions to downstream users via the SDS.
372 However, if a chemical is identified as P or vP, but neither PBT nor vPvB, there is no
373 requirement to estimate and mitigate emissions nor any requirement to consider future
374 continuing emissions in the risk assessment. This is a gap in the current European
375 chemical assessment and management schemes, given that concentrations in the
376 environment and, thereby, also PEC/PNEC ratios keep increasing for a long time for
377 highly persistent chemicals if emissions continue. As far as we know, these
378 deficiencies exist in all international chemical regulation schemes because high
379 persistence in itself is not used as a trigger for regulation in any jurisdiction.

380 The P-sufficient approach, in contrast, means that high persistence is sufficient
381 for a chemical to be flagged for subsequent management actions. For example, under
382 REACH, the vP criteria could be used for this purpose¹⁰. If a chemical exceeds the vP
383 criteria, the P-sufficient approach would imply that this is sufficient to require
384 estimation (and minimization) of emissions as occurs currently for PBT and vPvB
385 chemicals. Furthermore, the implication of vP properties could be that the chemical is
386 listed as a Substance of Very High Concern (SVHC) without any consideration of its
387 other properties (i.e. B and T in the case of PBT, or vB in the case of vPvB). Here the
388 reference to the vP criteria under REACH is merely a suggestion for how the P-
389 sufficient approach may be implemented. The actual cutoff value(s) for identifying
390 highly persistent chemicals remain to be defined in a subsequent step.

391 When high persistence is identified for a chemical, the uses of this chemical
392 should be grouped into essential and non-essential uses as a basis for determining
393 management actions⁸⁵. Essential uses are uses that are indispensable for the health
394 and/or safety of a certain population of workers, of patients under certain medical
395 treatments, or of other groups, and for which there are no technically and
396 economically feasible alternatives. Non-essential uses, on the other hand, are uses for

397 which there are alternatives or where a substance has no essential technical function
398 in a product and the use is driven only by convenience or market opportunity. These
399 non-essential uses of a substance with high persistence could then be phased out with
400 highest priority, whereas for essential uses measures should be taken that help avoid
401 emissions (no wide-dispersive applications, collection and recycling, etc.). In the
402 longer term, also for these uses alternatives should be developed.

403

404 **Empirical basis for the proposed “P sufficient” approach.** Technically, the P-
405 sufficient approach could be based on the same type of evidence that is currently used
406 for, e.g., the vP assessment under REACH. The substances currently classified as
407 vPvB substances in the EU include, a.o., dechlorane plus, short-chain chlorinated
408 paraffins, UV absorbers, long-chain perfluorocarboxylic acids, PFHxS, musk xylene,
409 and the cyclic volatile methylsiloxanes D4, D5, and D6. A review of the SVHC
410 dossiers of these substances shows that a range of different data have been used for
411 the determination of vP properties. In several cases, simulation tests and field
412 dissipation studies were available (UV absorbers, anthracene oils, short-chain
413 chlorinated paraffins, some of the long-chain perfluorocarboxylic acids). These were
414 often complemented by negative results from tests for ready or inherent
415 biodegradability. In other cases (PFHxS, long-chain PFCAs, D6), read-across from
416 similar chemicals with results from simulation tests for degradation was applied. In
417 one case (deca-BDE), the formation of highly persistent transformation products was
418 used as a reason why the substance was classified as vP. In the same way as for the
419 current vPvB determinations, all these types of data can be used under the P-sufficient
420 approach. If read-across is not possible, simulation tests or field dissipation studies
421 may have to be performed, but this can be done under existing test guidelines. The
422 formation of highly persistent transformation products will also be an important type
423 of evidence, in particular for many PFASs that have reactive endgroups and will form
424 – highly persistent – PFAAs in the environment.

425 On the one hand, it is advantageous that different types of data can be used for
426 persistence determinations, as outlined above. On the other hand, there is a great need
427 for one particular type of data, namely empirical degradation test results from a large,
428 diverse set of chemicals with intermediate to high persistence. A broader empirical
429 basis of degradation test results will help identify the types and number of highly

430 persistent chemicals and will provide a basis for the development of improved
431 methods for estimating degradation half-lives from the chemical structure.

432

433 **The P-sufficient approach and the precautionary principle.** As pointed out in
434 section 2, the concern underlying any chemical hazard assessment is about adverse
435 effects. In the context of persistence assessments, this is often expressed in such a way
436 that P seemingly only matters in addition to B and T. This is enshrined in the current
437 PBT assessment schemes, see above, part 2 of this discussion section, but was already
438 clearly reflected, for example, in the following quote from an internal 3M document
439 from the 1980s⁸⁶,

440 “Perhaps the most important conclusion from previous studies is the stability of
441 fluorochemicals. Although stability is one of the most desirable properties
442 fluorochemicals possess for many applications, from an environmental
443 perspective, "stability" connotes "persistence" which can be the cause of
444 concern especially when coupled with other properties. For example, some
445 fluorochemicals have a tendency to accumulate in biological tissues. Moreover,
446 some fluorochemicals have biological activity. This is most seriously
447 demonstrated by the use of some fluorochemicals as pesticides. This is not to
448 say that all fluorochemicals accumulate or that all have biological activity. But
449 taken together, stability, the tendency to bioaccumulate, and biological activity
450 are a potentially troublesome combination.”

451

452 In contrast to this approach, the key point of the P-sufficient approach is that this
453 evidence of some type of effect should *not* be required to be demonstrated explicitly:
454 because the possible effects cannot be predicted with sufficient reliability and remain
455 incompletely known or entirely unknown, high persistence alone should be used as a
456 sufficient indicator that serves as a proxy for adverse effects (see the reasoning
457 provided in section 2). Often, using a proxy of actual impacts as a basis for decision-
458 making is considered an application of the precautionary principle^{5,87,88}. The
459 precautionary principle states that, “where there are threats of serious or irreversible
460 damage, lack of full scientific certainty shall not be used as a reason for postponing
461 cost-effective measures to prevent environmental degradation”⁸⁹.

462 A problem with the implementation of the precautionary principle has been
463 that the call for action based on limited evidence is often considered over-cautious.

464 However, the empirical evidence that has accumulated over the last decades shows
465 that it would not be over-cautious to restrict or regulate the use of highly persistent
466 chemicals. When the known cases of highly persistent chemicals are considered, it
467 shows that many of them have caused serious environmental impacts. Accordingly,
468 there is a very high likelihood that additional highly persistent chemicals will also
469 cause some kind of relevant environmental impact. Therefore, regulating highly
470 persistent chemicals on the basis of their persistence alone may well be called an act
471 of *prevention*, not just of precaution. In other words, it is entirely rational and
472 empirically well founded to take high persistence seriously as a proxy of unwanted
473 environmental impacts and to base preventive action on it.

474 There are also persistent chemicals that exert relatively low toxicity according
475 to current knowledge, such as trifluoroacetic acid (TFA)⁹⁰. The point of the P-
476 sufficient approach is exactly that also highly persistent chemicals for which the
477 currently known toxicity is rather low should be flagged and considered for
478 regulation. As outlined above, it is well possible that unwanted effects occur at a large
479 scale if such a chemical enters the environment, is distributed widely, and leads to
480 continuously increasing environmental and human exposure. The evidence available
481 from the last 50 years shows that this is not just a hypothetical possibility, but a highly
482 likely outcome.

483 Similarly, the P-sufficient approach is also potentially suitable for synthetic
484 polymers, which are (very) poorly degradable by their very nature. Jurisdictions
485 around the world have various ways of defining when a substance is a synthetic
486 polymer based on, for example, molecular weight, number of monomers, percentage
487 impurities etc. We therefore do not provide a specific definition of a synthetic
488 polymer here. Many high-molecular-weight synthetic polymers have traditionally
489 been treated as of low concern under chemical assessment and management schemes
490 due to their low bioavailability. However, as elaborated above, once released,
491 (unexpected) adverse effects by highly persistent chemicals may not only be
492 biological effects, but also be physical or chemical effects. In the case of a subclass of
493 high-molecular-weight synthetic polymers, namely plastics, an increasing number of
494 wildlife mortality by entanglement or ingestion of marine plastic debris has been
495 observed (e.g., Wilcox et al., 2015⁹¹). In addition, plastics may break down into many
496 smaller pieces (i.e., microplastics), which is another issue of emerging concern^{92,93}.

497 The P-sufficient approach is also in line with the recent call of classifying plastic
498 waste as hazardous⁹⁴ as well as it being flagged as a planetary boundary threat^{95,96}.

499

500 **Conflicts of Interest**

501 There are no conflicts of interest to declare.

502

503 **Acknowledgment**

504 We thank the Global PFAS Science Panel for travel support and helpful discussions.

505

506 **References**

- 507 1 M. E. Stephenson, An approach to the identification of organic compounds
508 hazardous to the environment and human health, *Ecotoxicol. Environ. Saf.*, 1977, **1**,
509 39–48.
- 510 2 W. Klöpffer, Environmental Hazard- Assessment of chemicals and products,
511 *Environ. Sci. Pollut. Res.*, 1994, **1**, 108.
- 512 3 E. Webster, D. Mackay and F. Wania, Evaluating environmental persistence,
513 *Environ. Toxicol. Chem.*, 1998, **17**, 2148–2158.
- 514 4 D. Mackay, D. M. Hughes, M. L. Romano and M. Bonnell, The role of persistence
515 in chemical evaluations, *Integr. Environ. Assess. Manag.*, 2014, **10**, 588–594.
- 516 5 EEA, *Late Lessons from Early Warnings: The Precautionary Principle 1896-2000*,
517 European Environment Agency, Copenhagen, 2001.
- 518 6 L. M. Persson, M. Breitholtz, I. T. Cousins, C. A. de Wit, M. MacLeod and M. S.
519 McLachlan, Confronting Unknown Planetary Boundary Threats from Chemical
520 Pollution, *Environ. Sci. Technol.*, 2013, **47**, 12619–12622.
- 521 7 I. T. Cousins, R. Vestergren, Z. Wang, M. Scheringer and M. S. McLachlan, The
522 precautionary principle and chemicals management: The example of perfluoroalkyl
523 acids in groundwater, *Environ. Int.*, 2016, **94**, 331–340.
- 524 8 M. Matthies and S. Beulke, Considerations of temperature in the context of the
525 persistence classification in the EU, *Environ. Sci. Eur.*, 2017, **29**, 15.
- 526 9 H. P. H. Arp, T. N. Brown, U. Berger and S. E. Hale, Ranking REACH registered
527 neutral, ionizable and ionic organic chemicals based on their aquatic persistency
528 and mobility, *Environ. Sci. Process. Impacts*, 2017, **19**, 939–955.
- 529 10 G. Goldenman, R. Pedersen, H. Bradley, M. Fernandez, R. Weber, M. Scheringer
530 and P. Fantke, *Study for the strategy for a non-toxic environment of the 7th EAP.*
531 *Sub-study d: Very Persistent Chemicals*, Milieu, Ltd, Brussels, 2017.
- 532 11 R. Frische, G. Esser, W. Schönborn and W. Klöpffer, Criteria for assessing the
533 environmental behavior of chemicals: Selection and preliminary quantification,
534 *Ecotoxicol. Environ. Saf.*, 1982, **6**, 283–293.
- 535 12 M. Scheringer and M. Berg, Spatial and temporal range as measures of
536 environmental threat, *Fresenius Environ. Bull.*, 1994, **3**, 493–498.
- 537 13 EEA, *EEA, Late lessons from early warnings II: Science, precaution, innovation.*,
538 European Environment Agency, 2013.
- 539 14 R. A. Hites, *Elements of Environmental Chemistry*, Wiley-Blackwell, Hoboken,
540 N.J, 1 edition., 2007.

- 541 15 European Chemicals Agency, *Guidance on Information Requirements and*
542 *Chemical Safety Assessment, Chapter R.11: PBT/vPvB Assessment, Version 3.0.*,
543 European Chemicals Agency, Helsinki, Finland, 2017.
- 544 16 European Chemicals Bureau, *Technical Guidance Document on Risk Assessment.*
545 *Part II: Environmental Risk Assessment*, European Commission Joint Research
546 Centre, Ispra, Italy, 2003.
- 547 17 P. D. Jepson and R. J. Law, Persistent pollutants, persistent threats, *Science*, 2016,
548 **352**, 1388–1389.
- 549 18 H. Duan, T. R. Miller, G. Liu, X. Zeng, K. Yu, Q. Huang, J. Zuo, Y. Qin and J. Li,
550 Chilling Prospect: Climate Change Effects of Mismanaged Refrigerants in China,
551 *Environ. Sci. Technol.*, 2018, **52**, 6350–6356.
- 552 19 S. A. Montzka, G. S. Dutton, P. Yu, E. Ray, R. W. Portmann, J. S. Daniel, L.
553 Kuijpers, B. D. Hall, D. Mondeel, C. Siso, J. D. Nance, M. Rigby, A. J. Manning,
554 L. Hu, F. Moore, B. R. Miller and J. W. Elkins, An unexpected and persistent
555 increase in global emissions of ozone-depleting CFC-11, *Nature*, 2018, **557**, 413–
556 417.
- 557 20 Z. Wang, J. C. DeWitt, C. P. Higgins and I. T. Cousins, A Never-Ending Story of
558 Per- and Polyfluoroalkyl Substances (PFASs)?, *Environ. Sci. Technol.*, 2017, **51**,
559 2508–2518.
- 560 21 F. S. Rowland, Stratospheric Ozone Depletion by Chlorofluorocarbons (Nobel
561 Lecture), *Angew. Chem. Int. Ed. Engl.*, **35**, 1786–1798.
- 562 22 J. Borja, D. M. Taleon, J. Auresenia and S. Gallardo, Polychlorinated biphenyls
563 and their biodegradation, *Process Biochem.*, 2005, **40**, 1999–2013.
- 564 23 M. D. Hurley, M. P. Sulbaek Andersen, T. J. Wallington, D. A. Ellis, J. W. Martin
565 and S. A. Mabury, Atmospheric Chemistry of Perfluorinated Carboxylic Acids:
566 Reaction with OH Radicals and Atmospheric Lifetimes, *J. Phys. Chem. A*, 2004,
567 **108**, 615–620.
- 568 24 J. S.-C. Liou, B. Szostek, C. M. DeRito and E. L. Madsen, Investigating the
569 biodegradability of perfluorooctanoic acid, *Chemosphere*, 2010, **80**, 176–183.
- 570 25 S. Vaalgamaa, A. V. Vähätalo, N. Perkola and S. Huhtala, Photochemical reactivity
571 of perfluorooctanoic acid (PFOA) in conditions representing surface water, *Sci.*
572 *Total Environ.*, 2011, **409**, 3043–3048.
- 573 26 D. Liu, Z. Xiu, F. Liu, G. Wu, D. Adamson, C. Newell, P. Vikesland, A.-L. Tsai
574 and P. J. Alvarez, Perfluorooctanoic acid degradation in the presence of Fe(III)
575 under natural sunlight, *J. Hazard. Mater.*, 2013, **262**, 456–463.
- 576 27 M. McFarland and J. Kaye, Chlorofluorocarbons and Ozone, *Photochem.*
577 *Photobiol.*, 1992, **55**, 911–929.
- 578 28 P. De voogt and U. A. T. Brinkman, in *Halogenated Biphenyls, Terphenyls,*
579 *Naphthalenes, Dibenzodioxins and Related Products (Second Edition)*, eds. R. D.
580 Kimbrough and A. A. Jensen, Elsevier, Amsterdam, 1989, pp. 3–45.
- 581 29 E. Kissa, Ed., *Fluorinated Surfactants and Repellents, Second Edition*, CRC Press,
582 New York, 2 edition., 2001.
- 583 30 J. E. Lovelock, A sensitive detector for gas chromatography, *J. Chromatogr. A*,
584 1958, **1**, 35–46.
- 585 31 J. E. Lovelock, Atmospheric Fluorine Compounds as Indicators of Air Movements,
586 *Nature*, 1971, **230**, 379.
- 587 32 J. E. Lovelock, R. J. Maggs and R. J. Wade, Halogenated Hydrocarbons in and
588 over the Atlantic, *Nature*, 1973, **241**, 194–196.
- 589 33 S. Jensen, Report of a new chemical hazard, *New Sci.*, 1966, **32**, 612.

- 590 34S. Jensen, A. G. Johnels, M. Olsson and G. Otterlind, DDT and PCB in Marine
591 Animals from Swedish Waters, *Nature*, 1969, **224**, 247–250.
- 592 35D. R. Taves, Evidence that there are Two Forms of Fluoride in Human Serum,
593 *Nature*, 1968, **217**, 1050–1051.
- 594 36W. S. GUY, D. R. TAVES and W. S. BREY, in *Biochemistry Involving Carbon-*
595 *Fluorine Bonds*, AMERICAN CHEMICAL SOCIETY, 1976, vol. 28, pp. 117–
596 134.
- 597 37M. J. Molina and F. S. Rowland, Stratospheric sink for chlorofluoromethanes:
598 chlorine atom-catalysed destruction of ozone, *Nature*, 1974, **249**, 810–812.
- 599 38J. P. Giesy and K. Kannan, Global distribution of perfluorooctane sulfonate in
600 wildlife, *Env. Sci Technol*, 2001, **35**, 1339–1342.
- 601 39K. J. Hansen, L. A. Clemen, M. E. Ellefson and H. O. Johnson, Compound-
602 Specific, Quantitative Characterization of Organic Fluorochemicals in Biological
603 Matrices, *Environ. Sci. Technol.*, 2001, **35**, 766–770.
- 604 40F. Wania and D. MacKay, Peer Reviewed: Tracking the Distribution of Persistent
605 Organic Pollutants, *Environ. Sci. Technol.*, 1996, **30**, 390A-396A.
- 606 41R. W. Risebrough, W. Walker II, T. T. Schmidt, B. W. De Lappe and C. W.
607 Connors, Transfer of chlorinated biphenyls to Antarctica, *Nature*, 1976, **264**, 738–
608 739.
- 609 42S. Dasgupta, X. Peng, S. Chen, J. Li, M. Du, Y.-H. Zhou, G. Zhong, H. Xu and K.
610 Ta, Toxic anthropogenic pollutants reach the deepest ocean on Earth, *Geochem.*
611 *Perspect. Lett.*, 2018, **7**, 22–26.
- 612 43D. C. Muir, R. Wagemann, B. T. Hargrave, D. J. Thomas, D. B. Peakall and R. J.
613 Norstrom, Arctic marine ecosystem contamination, *Sci. Total Environ.*, 1992, **122**,
614 75–134.
- 615 44N. Yamashita, K. Kannan, S. Taniyasu, Y. Horii, G. Petrick and T. Gamo, A global
616 survey of perfluorinated acids in oceans, *Mar. Pollut. Bull.*, 2005, **51**, 658–668.
- 617 45K. Rankin, S. A. Mabury, T. M. Jenkins and J. W. Washington, A North American
618 and global survey of perfluoroalkyl substances in surface soils: Distribution
619 patterns and mode of occurrence, *Chemosphere*, 2016, **161**, 333–341.
- 620 46M. Houde, J. W. Martin, R. J. Letcher, K. R. Solomon and D. C. G. Muir,
621 Biological monitoring of polyfluoroalkyl substances: A review, *Env. Sci Technol*,
622 2006, **40**, 3463–3473.
- 623 47R. Vestergren and I. T. Cousins, Tracking the pathways of human exposure to
624 perfluorocarboxylates, *Env. Sci Technol*, 2009, **43**, 5565–5575.
- 625 48P. Casal, Y. Zhang, J. W. Martin, M. Pizarro, B. Jiménez and J. Dachs, Role of
626 Snow Deposition of Perfluoroalkylated Substances at Coastal Livingston Island
627 (Maritime Antarctica), *Environ. Sci. Technol.*, 2017, **51**, 8460–8470.
- 628 49C. Eschauzier, E. Beerendonk, P. Scholte-Veenendaal and P. De Voogt, Impact of
629 treatment processes on the removal of perfluoroalkyl acids from the drinking water
630 production chain, *Environ. Sci. Technol.*, 2012, **46**, 1708–1715.
- 631 50D. A. Fisher, C. H. Hales, W.-C. Wang, M. K. W. Ko and N. D. Sze, Model
632 calculations of the relative effects of CFCs and their replacements on global
633 warming, *Nature*, 1990, **344**, 513–516.
- 634 51S. Jensen, B. Jansson and M. Olsson, Number and identity of anthropogenic
635 substances known to be present in Baltic seals and their possible effects on
636 reproduction, *Ann. N. Y. Acad. Sci.*, 1979, **320**, 436–448.
- 637 52J. Koivusaari, I. Nuuja, R. Palokangas and M. Finnlund, Relationships between
638 productivity, eggshell thickness and pollutant contents of addled eggs in the

- 639 population of white-tailed eagles *Haliaeetus albicilla* L. in Finland during 1969–
640 1978, *Environ. Pollut. Ser. Ecol. Biol.*, 1980, **23**, 41–52.
- 641 53 G. G. Fein, J. L. Jacobson, S. W. Jacobson, P. M. Schwartz and J. K. Dowler,
642 Prenatal exposure to polychlorinated biphenyls: effects on birth size and gestational
643 age, *J. Pediatr.*, 1984, **105**, 315–320.
- 644 54 W. J. Rogan, B. C. Gladen, J. D. McKinney, N. Carreras, P. Hardy, J. Thullen, J.
645 Tinglestad and M. Tully, Neonatal effects of transplacental exposure to PCBs and
646 DDE, *J. Pediatr.*, 1986, **109**, 335–341.
- 647 55 B. C. Gladen, W. J. Rogan, P. Hardy, J. Thullen, J. Tinglestad and M. Tully,
648 Development after exposure to polychlorinated biphenyls and dichlorodiphenyl
649 dichloroethene transplacentally and through human milk, *J. Pediatr.*, 1988, **113**,
650 991–995.
- 651 56 J. C. DeWitt, *Toxicological Effects of Perfluoroalkyl and Polyfluoroalkyl*
652 *Substances*, Humana Press, 2015.
- 653 57 P. Grandjean, Delayed discovery, dissemination, and decisions on intervention in
654 environmental health: a case study on immunotoxicity of perfluorinated alkylate
655 substances, *Environ. Health*, 2018, **17**, 62.
- 656 58 M. P. Chipperfield, S. S. Dhomse, W. Feng, R. L. McKenzie, G. J. M. Velders and
657 J. A. Pyle, Quantifying the ozone and ultraviolet benefits already achieved by the
658 Montreal Protocol, *Nat. Commun.*, 2015, **6**, 7233.
- 659 59 C. Bogdal, N. Niggeler, J. Glüge, P. S. Diefenbacher, D. Wächter and K.
660 Hungerbühler, Temporal trends of chlorinated paraffins and polychlorinated
661 biphenyls in Swiss soils, *Environ. Pollut. Barking Essex 1987*, 2017, **220**, 891–899.
- 662 60 M. Desmet, B. Mourier, B. J. Mahler, P. C. Van Metre, G. Roux, H. Persat, I.
663 Lefèvre, A. Peretti, E. Chapron, A. Simonneau, C. Miège and M. Babut, Spatial
664 and temporal trends in PCBs in sediment along the lower Rhône River, France, *Sci.*
665 *Total Environ.*, 2012, **433**, 189–197.
- 666 61 S. P. Bhavsar, D. A. Jackson, A. Hayton, E. J. Reiner, T. Chen and J. Bodnar, Are
667 PCB Levels in Fish from the Canadian Great Lakes Still Declining?, *J. Gt. Lakes*
668 *Res.*, 2007, **33**, 592–605.
- 669 62 Z. Wang, I. T. Cousins, M. Scheringer, R. C. Buck and K. Hungerbühler, Global
670 emission inventories for C4-C14 perfluoroalkyl carboxylic acid (PFCA)
671 homologues from 1951 to 2030, Part I: production and emissions from quantifiable
672 sources, *Environ. Int.*, 2014, **70**, 62–75.
- 673 63 M. Land, C. A. de Wit, A. Bignert, I. T. Cousins, D. Herzke, J. H. Johansson and J.
674 W. Martin, What is the effect of phasing out long-chain per- and polyfluoroalkyl
675 substances on the concentrations of perfluoroalkyl acids and their precursors in the
676 environment? A systematic review, *Environ. Evid.*, 2018, **7**, 4.
- 677 64 H. I. Gomes, C. Dias-Ferreira and A. B. Ribeiro, Overview of in situ and ex situ
678 remediation technologies for PCB-contaminated soils and sediments and obstacles
679 for full-scale application, *Sci. Total Environ.*, 2013, **445–446**, 237–260.
- 680 65 N. Merino, Y. Qu, R. A. Deeb, E. L. Hawley, M. R. Hoffmann and S. Mahendra,
681 Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl
682 Substances in Water, *Environ. Eng. Sci.*, 2016, **33**, 615–649.
- 683 66 U.S. Air Force Civil Engineer Center, U.S. Air Force Civil Engineer Center >
684 What We Do > Environment > Perfluorinated-Compounds >
685 FAQs>Investigation/Mitigation Cost, [https://www.afcec.af.mil/What-We-Do/Environment/Perfluorinated-](https://www.afcec.af.mil/What-We-Do/Environment/Perfluorinated-Compounds/FAQs/#Investigation/Mitigation%20Cost)
686 [Compounds/FAQs/#Investigation/Mitigation%20Cost](https://www.afcec.af.mil/What-We-Do/Environment/Perfluorinated-Compounds/FAQs/#Investigation/Mitigation%20Cost), (accessed 4 November
687 2018).
688

689 67J. L. Pirkle, W. H. Wolfe, D. G. Patterson, L. L. Needham, J. E. Michalek, J. C.
690 Miner, M. R. Peterson and D. L. Phillips, Estimates of the half-life of 2,3,7,8-
691 tetrachlorodibenzo-p-dioxin in Vietnam veterans of operation ranch hand, *J.*
692 *Toxicol. Environ. Health*, 1989, **27**, 165–171.

693 68K. M. Yeager, P. H. Santschi, H. S. Rifai, M. P. Suarez, R. Brinkmeyer, C.-C.
694 Hung, K. J. Schindler, M. J. Andres and E. A. Weaver, Dioxin Chronology and
695 Fluxes in Sediments of the Houston Ship Channel, Texas: Influences of Non-
696 Steady-State Sediment Transport and Total Organic Carbon, *Environ. Sci.*
697 *Technol.*, 2007, **41**, 5291–5298.

698 69J. M. Armitage, M. S. McLachlan, K. Wiberg and P. Jonsson, A model assessment
699 of polychlorinated dibenzo-p-dioxin and dibenzofuran sources and fate in the
700 Baltic Sea, *Sci. Total Environ.*, 2009, **407**, 3784–3792.

701 70P. Schmid, M. Kohler, A. C. Gerecke, E. Gujer, M. Zennegg and M.
702 Wolfensberger, Old Sins Throw Long Shadows; Old and Emerging Persistent
703 Organic Pollutants in the Swiss Environment, *Chimia*, 2003, **57**, 509–513.

704 71R. J. Law, A. Covaci, S. Harrad, D. Herzke, M. A.-E. Abdallah, K. Fernie, L.-M. L.
705 Toms and H. Takigami, Levels and trends of PBDEs and HBCDs in the global
706 environment: status at the end of 2012, *Environ. Int.*, 2014, **65**, 147–158.

707 72M. Venier, A. Salamova and R. A. Hites, Halogenated Flame Retardants in the
708 Great Lakes Environment, *Acc. Chem. Res.*, 2015, **48**, 1853–1861.

709 73L. Camenzuli, M. Scheringer and K. Hungerbühler, Local organochlorine pesticide
710 concentrations in soil put into a global perspective, *Environ. Pollut. Barking Essex*
711 *1987*, 2016, **217**, 11–18.

712 74D. Fagin, Toxicology: The learning curve, *Nat. News*, 2012, **490**, 462.

713 75B. A. Woodcock, J. M. Bullock, R. F. Shore, M. S. Heard, M. G. Pereira, J.
714 Redhead, L. Ridding, H. Dean, D. Sleep, P. Henrys, J. Peyton, S. Hulmes, L.
715 Hulmes, M. Sárospataki, C. Saure, M. Edwards, E. Genersch, S. Knäbe and R. F.
716 Pywell, Country-specific effects of neonicotinoid pesticides on honey bees and
717 wild bees, *Science*, 2017, **356**, 1393–1395.

718 76D. Mackay, Finding fugacity feasible, *Environ. Sci. Technol.*, 1979, **13**, 1218–
719 1223.

720 77D. Mackay, *Multimedia Environmental Models: The Fugacity Approach, Second*
721 *Edition*, CRC Press, 2001.

722 78J. Armitage, I. T. Cousins, R. C. Buck, K. Prevedouros, M. H. Russell, M.
723 MacLeod and S. H. Korzeniowski, Modeling global-scale fate and transport of
724 perfluorooctanoate emitted from direct sources, *Environ. Sci. Technol.*, 2006, **40**,
725 6969–6975.

726 79J. R. Parsons, M. Sáez, J. Dolfing and P. de Voogt, Biodegradation of
727 perfluorinated compounds, *Rev. Environ. Contam. Toxicol.*, 2008, **196**, 53–71.

728 80J. M. Boucher, I. T. Cousins, M. Scheringer, K. Hungerbühler and Z. Wang,
729 Toward a Comprehensive Global Emission Inventory of C4–C10
730 Perfluoroalkanesulfonic Acids (PFSAs) and Related Precursors: Focus on the Life
731 Cycle of C6- and C10-Based Products, *Environ. Sci. Technol. Lett.*, 2019, **6**, 1–7.

732 81F. A. Gobas, W. de Wolf, L. P. Burkhard, E. Verbruggen and K. Plotzke,
733 Revisiting Bioaccumulation Criteria for POPs and PBT Assessments, *Integr.*
734 *Environ. Assess. Manag.*, 2009, **5**, 624–637.

735 82UNEP, Stockholm Convention on Persistent Organic Pollutants,
736 [http://www.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/D](http://www.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx)
737 [efault.aspx](http://www.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx), (accessed 4 November 2018).

- 738 83 German Environment Agency, *Protecting the sources of our drinking water.*,
739 German Environment Agency, 06813 Dessau-Roßlau.
- 740 84 T. Reemtsma, U. Berger, H. P. H. Arp, H. Gallard, T. P. Knepper, M. Neumann, J.
741 B. Quintana and P. de Voogt, Mind the Gap: Persistent and Mobile Organic
742 Compounds—Water Contaminants That Slip Through, *Environ. Sci. Technol.*,
743 2016, **50**, 10308–10315.
- 744 85 A. Ritscher, Z. Wang, M. Scheringer, J. M. Boucher, L. Ahrens, U. Berger, S.
745 Bintein, S. K. Bopp, D. Borg, A. M. Buser, I. Cousins, J. DeWitt, T. Fletcher, C.
746 Green, D. Herzke, C. Higgins, J. Huang, H. Hung, T. Knepper, C. S. Lau, E.
747 Leinala, A. B. Lindstrom, J. Liu, M. Miller, K. Ohno, N. Perkola, Y. Shi, L.
748 Småstuen Haug, X. Trier, S. Valsecchi, K. van der Jagt and L. Vierke, Zürich
749 Statement on Future Actions on Per- and Polyfluoroalkyl Substances (PFASs),
750 *Environ. Health Perspect.*, 2018, **126**, 84502.
- 751 86 3M Internal Correspondence. Letter to Olson CW. Subject: Fluorochemicals in the
752 Environment., 1992.
- 753 87 M. Berg and M. Scheringer, Problems in environmental risk assessment and the
754 need for proxy measures, *Fresenius Environ. Bull.*, 1994, **3**, 487–492.
- 755 88 EEA, *Chemicals in the European environment: low doses, high stakes?*, European
756 Environment Agency, Copenhagen, 1998.
- 757 89 UN, *Report of the United Nations conference on environment and development,*
758 *Annex I: Rio Declaration on environment and development*, United Nations, 1992.
- 759 90 K. R. Solomon, G. J. M. Velders, S. R. Wilson, S. Madronich, J. Longstreth, P. J.
760 Aucamp and J. F. Bornman, Sources, fates, toxicity, and risks of trifluoroacetic
761 acid and its salts: Relevance to substances regulated under the Montreal and Kyoto
762 Protocols, *J. Toxicol. Environ. Health B Crit. Rev.*, 2016, **19**, 289–304.
- 763 91 C. Wilcox, E. V. Seville and B. D. Hardesty, Threat of plastic pollution to seabirds
764 is global, pervasive, and increasing, *Proc. Natl. Acad. Sci.*, 2015, **112**, 11899–
765 11904.
- 766 92 GESAMP, *Sources, Fate and Effects of Microplastics in the Marine Environment*
767 *(Part 2)*, IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP Joint
768 Group of Experts on the Scientific Aspects of Marine Environmental Protection,
769 2016.
- 770 93 GESAMP, *Sources, fate and effects of microplastics in the marine environment*
771 *(Part 1) | GESAMP*, IMO/FAO/UNESCO-
772 IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the
773 Scientific Aspects of Marine Environmental Protection, 2015.
- 774 94 C. M. Rochman, M. A. Browne, B. S. Halpern, B. T. Hentschel, E. Hoh, H. K.
775 Karapanagioti, L. M. Rios-Mendoza, H. Takada, S. Teh and R. C. Thompson,
776 Policy: Classify plastic waste as hazardous, *Nature*, 2013, **494**, 169–171.
- 777 95 P. Villarrubia-Gómez, S. E. Cornell and J. Fabres, Marine plastic pollution as a
778 planetary boundary threat – The drifting piece in the sustainability puzzle, *Mar.*
779 *Policy*, 2018, **96**, 213–220.
- 780 96 A. Jahnke, H. P. H. Arp, B. I. Escher, B. Gewert, E. Gorokhova, D. Kühnel, M.
781 Ogonowski, A. Potthoff, C. Rummel, M. Schmitt-Jansen, E. Toorman and M.
782 MacLeod, Reducing Uncertainty and Confronting Ignorance about the Possible
783 Impacts of Weathering Plastic in the Marine Environment, *Environ. Sci. Technol.*
784 *Let.*, 2017, **4**, 85–90.
785