Identifying chemicals that are planetary boundary threats

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The development of human society was made possible by the stable conditions of the planet known as the Holocene.

The planetary boundary concept
(Rockström et al., Nature 461, Sept 2009)
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• The development of human society was made possible by the stable conditions of the planet known as the Holocene
• Human activities threaten to destabilize the Holocene by impacting vital earth system processes
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“biophysical processes of the Earth System that determine the self-regulating capacity of the planet”

The planetary boundary concept
(Rockström et al., Nature 461, Sept 2009)
A safe operating space for humanity

- 5 of the 9 planetary boundaries are governed by chemical agents
  - Climate change (CO$_2$, CH$_4$ & others)
  - Ocean acidification (CO$_2$)
  - Stratospheric ozone depletion (halocarbons)
  - Nitrogen & phosphorus cycles
  - Chemical pollution

Rockstrom et al, Nature 461, Sept 2009
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• Our challenge is to confront our ignorance.

• What are the conditions that must be fulfilled for chemical pollution to pose a planetary boundary threat?
Planetary boundary threats

• We assume that society will react to manage known planetary boundary concerns
Planetary boundary threats

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• A planetary boundary threat exists when:
  – We are ignorant of the existence of a boundary
  – We cannot easily “un-cross” the boundary
The Three Conditions
for chemical pollution to pose a planetary boundary threat
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2. The disruptive effect is not discovered until it is, or inevitably will become, a problem at a planetary scale.
The Three Conditions for chemical pollution to pose a planetary boundary threat

1. The chemical or mixture of chemicals has a disruptive effect on a vital earth system process.

2. The disruptive effect is not discovered until it is, or inevitably will become, a problem at a planetary scale.

3. The effect of the pollutant cannot be readily reversed.
How can we manage unknown planetary boundary threats from chemicals?
How can we manage unknown planetary boundary threats from chemicals?

Are existing hazard indicators useful to tell us if a chemical satisfies the three conditions to be a planetary boundary threat?
Hazard Indicators for Planetary Boundary Threats

**Persistence**

- Useless
- Partly Useful
- Useful

C1. Effect on a vital earth system process

C2. Effect not discovered until it is a problem at a planetary scale.

C3. Effect cannot be readily reversed.
Hazard Indicators for Planetary Boundary Threats

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Toxicity

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Hazard Management Cannot Fully Mitigate Planetary Boundary Threats

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Can we identify **scenarios** that satisfy each of the three conditions?

and

Can we define **profiles** of chemicals that could fulfill each scenario?
Reference scenario for managing chemical pollution
Reference scenario for a persistent organic pollutant
Planetary Boundary Threat Scenario 1.

Rapid global distribution of exposure + poorly reversible exposure
We should be looking for alternatives to chemicals that fit the (incomplete) profiles of PB threats

**Exposure-related profiles**

- **Profile C2-1:** Rapid development of near homogeneous pollution levels at the global scale
  - Emissions dispersed globally + moderate mobility
  - Volatile & persistent chemicals dispersed in the global atmosphere

- **Profile C3-1:** Poor reversibility of exposure
  - Chemicals that are persistent in the exposure environment
  - Emissions from vital technologies, or from many sources that are costly to eliminate
Planetary Boundary Threat Scenario 2.

Rapid global distribution of a poorly reversible effect
We should be looking for alternatives to chemicals that fit the (incomplete) profiles of PB threats

**Effect-related profiles**

- Profile C2-2: Rapid global distribution of effects
  - Unknown, but an example would be genetic changes in organisms that are distributed and proliferate

- Profile C3-2: Poor reversibility of effects
  - Permanent damage, or a regime shift to a new stable state
Planetary Boundary Threat Scenario 3.

Delayed manifestation of effect + poorly reversible exposure or poorly reversible effect
Planetary Boundary Threat Scenario 4.

Effect that only manifests at the global scale + poorly reversible exposure or poorly reversible effect
We should be looking for alternatives to chemicals that fit the (incomplete) profiles of PB threats

Joint exposure & effect-related profiles

• Profile C2-3: Time delay between exposure & effect
  • Unknown, but an example could be a trans-generational effect

• Profile C2-4: Effect only observable on the global scale
  • Unknown, but could arise from global exposure to persistent chemicals distributed relatively slowly in oceans or by air/surface exchange
We should be looking for alternatives to chemicals that fit the (incomplete) profiles of PB threats

Effect-related profiles

• Profile C1-1: Unknown effect on a vital Earth system process
  • Unknown, but less likely for chemicals that have been used/emitted for many years if emissions are not increasing
Table 1. Three Conditions That Must Be Simultaneously Fulfilled for Chemical Pollution to Pose a Planetary Boundary Threat, Scenarios for Chemicals to Fulfill Each Condition, And Profiles of Chemicals That Fulfill Each Scenario

<table>
<thead>
<tr>
<th>condition</th>
<th>scenario</th>
<th>chemical profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 unknown disruptive effect on a vital Earth system process</td>
<td>C1-1 unknown disruptive effect on a vital Earth system process</td>
<td>C1-1 unknown, but less likely for chemicals that have been used and emitted for many years if production/emissions and environmental concentrations are not increasing.</td>
</tr>
<tr>
<td>C2 disruptive effect is not discovered until it is, or inevitably will become, a problem at a planetary scale</td>
<td>C2-1 rapid development of nearly homogeneous pollution levels at the global scale(^\text{a})</td>
<td>C2-1 emissions dispersed globally combined with moderate mobility, or volatile and persistent chemicals that are rapidly distributed in the atmosphere.</td>
</tr>
<tr>
<td></td>
<td>C2-2 rapid global distribution of effects (independent of exposure)</td>
<td>C2-2 unknown, but an example would be a chemical that causes genetic changes in organisms followed by distribution and proliferation of the affected organisms.</td>
</tr>
<tr>
<td></td>
<td>C2-3 time delay between exposure and effects</td>
<td>C2-3 unknown, but an example would be a subtle effect on long-lived organisms, or a transgenerational epigenetic effect.</td>
</tr>
<tr>
<td></td>
<td>C2-4 effects only observable on a global scale</td>
<td>C2-4 unknown, but could arise as a result of global exposure to persistent chemicals distributed in the oceans or persistent and semivolatile chemicals distributed by a combination of atmospheric and oceanic transport.</td>
</tr>
<tr>
<td>C3 disruptive effect is poorly reversible</td>
<td>C3-1 poor reversibility of exposure(^\text{a})</td>
<td>C3-1 emissions from a technology that society is highly dependent on or from multiple sources that are costly to eliminate, or the chemical is persistent in the exposure environment.</td>
</tr>
<tr>
<td></td>
<td>C3-2 poor reversibility of effects</td>
<td>C3-2 effects that are permanent or cause a regime shift to a new stable state.</td>
</tr>
</tbody>
</table>

\(^\text{a}\)The chemical agent causing disruptive effects may be a persistent, immobile compound formed from the transformation of a mobile compound, which in turn could be the transformation product of an immobile compound. Therefore, transformation products must be considered when chemicals are evaluated against these chemical profiles.
We should be looking for alternatives to chemicals that fit the profile of PB threats

• Prioritizing chemicals against exposure-related profiles of potential planetary boundary threats is feasible
• Prioritizing against effect-related profiles is more complicated, but also possible to a certain extent
• Monitoring and study of vital Earth system processes is a vital complement
• Addressing the planetary boundary threat issue is an important challenge for modern society!
Confronting Unknown Planetary Boundary Threats from Chemical Pollution

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Rockström et al. proposed a set of planetary boundaries that delimit a “safe operating space for humanity”. One of the planetary boundaries is determined by “chemical pollution”, however no clear definition was provided. Here, we propose that there is no single chemical pollution planetary boundary, but rather that many planetary boundary issues governed by chemical pollution exist. We identify three conditions that must be simultaneously met for chemical pollution to pose a planetary boundary threat. We then discuss approaches to identify chemicals that could fulfill those conditions, and outline a proactive hazard identification strategy that considers long-range transport and the reversibility of chemical pollution.

ABSTRACT: Rockström et al. proposed a set of planetary boundaries that delimit a “safe operating space for humanity”. Many of the planetary boundaries that have so far been identified are determined by chemical agents. Other chemical pollution-related planetary boundaries likely exist, but are currently unknown. A chemical poses an unknown planetary boundary threat if it simultaneously fulfills three conditions: (1) it has an unknown disruptive effect on a vital Earth system process; (2) the disruptive effect is not discovered until it is a problem at the global scale, and (3) the effect is not readily reversible. In this paper, we outline scenarios in which chemicals could fulfill each of the three conditions, then use the scenarios as the basis to define chemical profiles that fit