Plastics Pollution and the Planetary Boundaries framework

Patricia Villarrubia-Gómez,*[a] Bethanie Carney Almroth,[b] Marcus Eriksen,[c] Morten Ryberg,[d,e] and Sarah E. Cornell,[a]

[a] *Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden.*

[b] *Department of Biological and Environmental Sciences, University of Gothenburg, Box 463, SE-405 30 Göteborg, Sweden.*

[c] *5Gyres Institute. Five Gyres Institute, Los Angeles, California, United States of America CA, 90016, USA*

[d] *Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark*

[e] *Sweco Denmark, Copenhagen S, Denmark*

*Corresponding author: patricia.villarrubia@su.se

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ABSTRACT

Plastics are novel entities that have exceeded the planetary safe operating space due to extensive and resource-intensive production, uncontrolled environmental releases, and failure to control the chemicals within the materials. This paper examines evidence and discusses how plastics pollution affects Earth-system processes along the impact pathway from production, to release, to environmental fate and impacts of plastics and their additives. Multiple lines of evidence are necessary to capture the complex reality of these substances and attempts to quantify a singular boundary would be detrimental to the global governance of plastics. We demonstrate causal links between plastics and other major environmental problems at the global scale, exacerbating the consequences of breaching other planetary boundaries, especially climate change and biodiversity loss. We propose ways to translate these assessments into control variables for the globally and biophysically defined planetary boundaries framework that can be utilized to tackle plastics pollution. Efforts should be oriented towards further developing and monitoring a set of control variables that describe the actual state of the system along the impact pathway. We call for experts and policymakers to take urgent action, considering plastics pollution not only as a waste management problem but as an integrative part of climate change, biodiversity and natural resource use policy.

Key Words: *planetary boundaries framework; plastics pollution; climate change, microplastics, Earth system processes*

INTRODUCTION

For over half a century, plastics were considered a safe, chemically inert material (Renfrew and Lewis 1946) that would help solve environmental problems and revolutionize people's lives (Freinkel 2011). Plastics would democratize access to daily goods, technologies, safer drinking water and food, and improve health care. However, plastics have become a growing social and ecological challenge. The globalized emergence of convenience lifestyles ignited the exponential production, consumption and disposal of plastics, which simultaneously is decoupled from an appropriate global sound waste management system (Geyer 2020). Plastic leakage to the environment is estimated to almost triple by 2060 unless drastic measures are taken (OECD 2022). The growth of plastics waste worldwide vastly outpaces efforts to mitigate plastic pollution (Borrelle et al. 2020), production is widely unregulated (Dauvergne 2018) and impacts are disrupting Earth system processes (Arp et al. 2021, MacLeod et al. 2021), indicating that the safe operating space for these novel entities has been exceeded (Persson et al. 2022). With the globalized economy's reliance on fossil fuel feedstocks, the world has to deal with a legacy of carbon lock-in (Bauer and Fontenit 2021), while the plastics industry's drive to maneuver around tightening regulations and create new markets moves problems from one place to another (Blumenthal et al. 2022). Plastics pollution threatens the environment, food security and human health (WHO et al. 2013, UNEP 2021), which presents serious consequences for inequality and environmental justice (Chisholm Hatfield 2019, Abrahms-Kavunenko 2021), and environmental racism (Castellon 2021).

Even though impacts of plastics pollution were recorded soon after mass production started, it took several decades to attract scientific and policy interest. Dauvergne (2018) describes a status quo of "fragmented authority, weak international institutions, uneven regulations, uncoordinated policies, and business-oriented solutions." Plastics are currently an ungovernable challenge, reflecting a failure of common pool resource management on the global scale, for which collective action is required (Jagers et al. 2020). Researchers emphasize the need to systemically account for the global resource extraction, production, use, and waste management of plastics (Persson et al. 2022, Bauer et al. 2022). This paper aims to comprehensively explore early evidence of how plastics pollution impacts Earth system processes. We use the planetary boundaries framework (Rockström et al. 2009) to help structure a better understanding of how plastics (including their chemical additives) relate to Earth system processes throughout their entire life cycle.

Box 1: Defining terms.

Historically, post-consumer plastics have been referred to interchangeably as “litter”, “debris”, “waste” or “pollution” by scientists and policymakers. Litter refers to the intentional or unintentional disposal of waste products, while pollution refers to introducing harmful materials into the environment. The implication of this semantic difference for policy is significant. Treating plastics as pollutants rather than just litter implies the need for more profound change, a broader view of contaminants and their toxic impacts, and broader politics extending to topics such as waste colonialism and environmental justice (Liboiron 2021).

Plastic pollution is often divided into size categories: macroplastic (>5 mm in size), microplastic (<5 mm), and more recently nanoplastic (<1 nm) are sizes commonly referenced in scientific literature and policy. The size of plastic can have very different ecological and social impacts, ranging from macroplastic entanglement of megafauna to nanoplastics passing the gut barrier into the human circulatory system. GESAMP (2020) highlights current limitations of data and evidence about nanoplastics in the environment, arguing that there are many more “unknowns” about the potential impacts of nanoplastic from a risk assessment perspective. Our discussion therefore refers to the two main categories (macro and micro).

Plastics pollution within the planetary boundaries framework. The planetary boundaries framework highlights human-caused perturbations of the Earth system against a baseline of Holocene conditions (Rockström et al. 2009, Steffen et al. 2015). The world has now shifted into what many term the Anthropocene: rapid changes in ecological, biogeochemical and physical climate processes (here collectively termed biophysical processes), largely driven by industrialized societies, bring new and poorly predictable Earth system conditions, raising the risks of “business as usual”. Although planetary boundaries are not operational targets, its long-term, large-scale perspective has been taken up by sustainability governance (Häyhä et al. 2016) and business (SBTN 2020), aiming for translation to target-based strategies to mitigate environmental risks and deal with multiple environmental pressures simultaneously. Recent developments in the framework status (Wang-Erlandsson et al. 2022, Persson et al. 2022) show that the world is now outside the safe operating space for humanity for at least six of the nine planetary boundaries.

Plastics, like other novel entities, are human-made materials with no precedent in the Holocene. However, taking a zero baseline for the planetary boundary makes no connection between anthropogenic pressures and Earth system perturbations nor can it be readily translated to operational measures for policy and practice. Planetary boundaries are features of an interconnected Earth system. Profound biophysical changes, especially to the two core boundaries of climate change and biodiversity loss, can push the Earth system to irreversible regime shifts (Steffen et al. 2018, Armstrong McKay et al. 2022). Systemic analyses are needed to develop socially relevant operational control variables for this global sustainability framework. Persson et al. (2022) proposed an Impact Pathway approach that considers impacts along the life cycle of novel entities, arguing for pluralism in control variables, and using a weight of evidence approach, concluding that the Novel Entities boundary has been overstepped.

Plastics are a "poster child" novel entity – as the combination of thousand chemicals and monomers, a visible and tangible example of human-driven environmental change. Capturing the complexity of plastics pollution in a planetary boundaries assessment is useful as an indicator for a wide range of Earth system effects (Persson et al. 2013, Villarrubia-Gómez et al. 2018). The 2022 UN Environmental Assembly called for improved understanding of the global impact of plastic pollution along with action at all levels up to the global (UNEP/EA.5/L.23/Rev.1 2022), making plastics an international governance priority. In this paper, we therefore outline the global impacts of plastics pollution and illuminate these in terms of Earth system processes.

METHODS AND MATERIALS

Conceptual framing

Following Persson et al. (2022), we apply the *Impact Pathway* approach to identifying potential control variables for the planetary boundaries framework. The impact pathway considers the entire life cycle of plastics, from raw material extraction to production, consumption, disposal and environmental release as a pollutant – with ecological and societal impacts at each step (see Figure 1). We consider effects from local to global scales to identify plastics pollution impacts on the Earth system.

We also adopt the criteria for assessing control variables from Persson et al. (2022): **i) Feasibility:** Can it be measured? Are data available that permit quantification at relevant spatial and temporal scales and comparison with other biophysical monitoring data**;** **ii) Relevance**: Can it be robustly linked to effects? It must be possible to establish a cause-effect link to a change in biophysical functioning**; iii) Comprehensiveness**: Does it capture the planetary scale of the problem? This can be either through cause-effect thresholds affecting a specific Earth system process or through effects on other planetary boundaries processes.

We propose more than one control variable, spanning the operational contexts of plastics production and use, and environmental policy and Earth system analysis to demonstrate the value of our globally systemic approach. The control variables in the planetary boundaries framework (Rockström et al. 2009, Steffen et al. 2015) reflect metrics and data used in Earth system analysis. This means they generally need to be translated for use in different scientific, sectoral and geographic contexts (Häyhä et al. 2016). For instance, climate action target-setting uses carbon emission budgets rather than metrics of atmospheric CO_2 concentration and radiative forcing. Uncertainties and assumptions are introduced in the translation process (e.g., between greenhouse gas emissions, concentrations and global heating; (Lorenz et al. 2015). We consider that it would be good to use more than one control variable: different actors encounter impacts differently and have different scopes of influence.

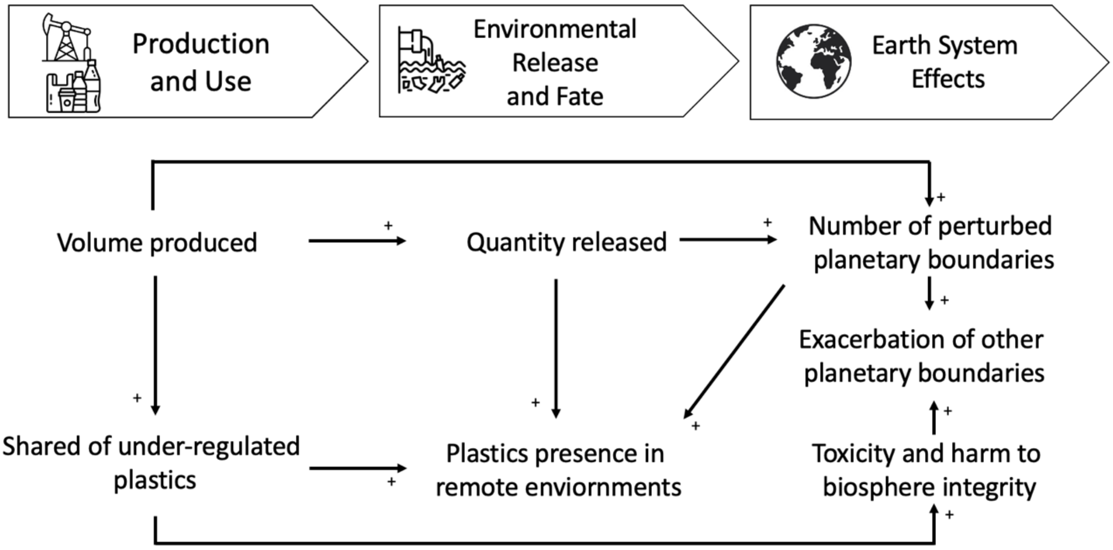

Figure 1: The impact pathway of plastic pollution – explanation of overall rationale for control variables at stages of production and use volumes, Environmental mass concentrations, and Earth system effects, including ecological impacts that aggregate or cascade.

Exploratory literature review

We have gathered the early evidence of how plastics pollution impacts Earth system processes and how it may enhance the severity of major environmental problems such as climate change and biodiversity loss. We used the Web of Science engine (WoS) and Google Scholar to comprehensively explore the scientific literature on biophysical impacts of plastics pollution in line with the planetary boundaries framework, searching with keywords relating to plastics pollution (i.e., plastic*, plastic* pollution, microplastic*, nanoplastic*, macroplastic*, microfibres, marine debris, litter and debris) and effects on biophysical processes (i.e., climate change, greenhouse gas emission, greenhouse gases, carbon cycle, carbon sequestration, marine snow, nitrogen cycle, phosphorus cycle, aerosol loading, atmosphere, biodiversity loss, biodiversity, soil, land ecosystem, terrestrial ecosystem, and antibiotics). We manually excluded those articles without a specific focus on investigating potential biophysical impacts of plastics (e.g., articles focusing on social perceptions, marketing, social media, public discourses, methods identification, policy views, or cleanup technologies). Of the remaining articles, we prioritized empirical research focusing specifically on direct impacts of plastics pollution on biophysical systems, ecosystems, and organisms. We also included articles that were not returned in the WoS search but were found via references cited in the articles we use.

The Google Scholar search enabled to add other texts outside the scope of WoS (e.g., reports and documents from the UN Environment Programme and other international organizations, and other grey literature relevant to this research). We believe our selection provides a robust and current, though no exhaustive, overview of this rapidly evolving and expanding area for research, policy and practice; the literature database is provided as supplementary material.

ANALYSIS AND DISCUSSION

Here we present findings of the literature review structured as an analysis of the three stages in our impact pathway. This approach offers options for definition, selection and combination of operational control variables for the novel entities' planetary boundary summarized in Table 1.

Plastics production – too much plastic to handle

A focus on the production stage of the plastics impact pathway seeks to avoid Earth system perturbation at source, in line with the 'prevention principle' (Principle 2 of the Rio Declaration; UN 1992); and Article 191(2) (TFEU 2016). We propose *global production volume* as a control variable, as an aggregate indicator of environmental impacts (which extend far beyond national jurisdictions). At present the dearth of robust scientific evidence makes it difficult to link planet-scale quantifications of specific causal drivers to policies to cap plastics production or phase out problematic substances. Because of this, we also propose using the *global proportion of plastics with under-documented chemical additives*, which could incentivize the industry to bring more plastics into the governable domain of known harms and well-characterized risks.

Production volumes, rates and capacity: More than 10 000 million metric tonnes (Mt) of non-fiber resins have been produced from 1950s to 2020 (see Supplementary Information, Table 1). Annual production of virgin plastics have increased from 2 Mt in 1950 (Geyer et al. 2017) to 460 Mt in 2019 (OECD 2022). Additionally, synthetic fiber production increased from 7.4 Mt in 1975 (BSI 2019) to over 68 Mt in 2020, representing approximately 62% of all fibers produced (Textile Exchange 2021). 63.7% of all plastics ever made from virgin sources were produced during the period 2000-2020 (see Table 2 of Supplementary material). The OECD (2022) assesses that increased economic growth, a rising middle class globally and population growth will continue to drive increasing plastic production rates.

Table 1: Possible control variables for a plastics planetary boundary. Adapted from Persson et al. (2022): F, feasibility; R, relevance; C, comprehensiveness. Note: Plastics comprise plastic polymers and chemical additives. See body text for source references and discussion.

Proposed Control Variables		**Control variable criteria assessment**			
Impact pathway stage	**Specific quantification examples**	**High**	**Low**	**Current state**	**Comments concerning the boundary**
Plastics production	Production volume of virgin plastics, Mt per year	**F** – global trade and industry data available. **C** – strong correlation with global environmental impacts	**R** – only captures aggregate effects, not specific changes in biophysical functioning	Global production 469 Mt in 2019 (OECD 2022), 99% fossil fuel feedstock(UNEP 2021), ~10% recycled (Geyer 2020)	Current production already contributes significantly to breached planetary boundary for climate change. Shift to bio-based plastics contributes to biodiversity loss.
	Share of plastics lacking safety data or regulatory assessment, % of plastics available on global market	**R** – safety-assessed chemicals less likely to perturb biophysical functioning	**F** – significant data gaps, lack of ecotoxicological assessment, shortfalls in regulatory capacity **C** – only known biophysical effects are assessed, could miss Earth system impacts	Undocumented / unmonitored.	~2400 substances of concern in the 10 000 chemicals currently used in plastics production and manufacturing(Wiesinger et al. 2021). Lack of available data on how these chemicals behave once combined in the natural environment.
Environmental release of plastics pollution	Quantity of plastics released into the environment, Mt per year	**R –** pollution effects increasingly documented **C –** correlation with global environmental impacts	**F** - limited reporting and monitoring by manufacturers; reliant on expert assessments and model projections	Leakage of at least 22 Mt per year to environment in 2019 (OECD 2022).	Current releases are increasing
	Presence of plastics in remote environments	**F** – detection at present, rather than monitoring **R** – novel entity introduction is a perturbation of pristine ecosystems	**C** – biophysical effects not readily detectable or predictable	Plastic detected in open ocean, polar regions, mountain-tops, deep ocean sediments, and beyond the atmospheric boundary layer	Plastics accumulate in these environments
Impact of plastics on Earth system processes	Number of species encountering plastics pollution	**R –** many known cause-effect links for ecosystem function	**F –** many substances, many organisms, many exposures **C –** challenging scaling up from organism to planet	> 1565 terrestrial and aquatic species across all ecosystems ingest plastics, evidence of trophic transfer across all environments(Santos et al. 2021)	Toxicity and harm at organism and long-term community level can produce cascade effects across ecosystems
	Number of planetary boundaries processes affected by plastics pollution	**R –** each planetary boundary is an Earth system process under anthropogenic pressure **C –** multiple impacts on Earth system processes	**F –** a nontrivial process-based assessment currently relies on lab studies; field data lacking	Effects seen in all other planetary boundaries processes	Exacerbation of other planetary boundaries processes through feedback

99% of all plastics are synthesized from fossil fuel feedstocks (UNEP 2021). Plastics production accounts for up to 4-8% of global oil consumption (WEF 2016), and projections by the International Energy Agency estimate that plastics will drive the global oil demand to account for more than a third by 2030 and approximately half by 2050 (IEA 2018). Geyer (Geyer 2020) calculated that in 2017 plastic packaging accounted for 42% of global primary plastic production (excluding synthetic fibers), highlighting that 90% was composed of three types of polymers: polyethylene, polypropylene, and polyethylene terephthalate. Single-use plastic production is expected to increase by 30% from 2020-2025 (Charles et al. 2021) and all plastics production are projected to triple by 2060 (OECD 2022).

The current scale of plastics production perturbs Earth system dynamics primarily because fossil fuels extraction and use are tightly coupled to the climate system. The greater the production rate, the greater the direct pressure on the climate planetary boundary, which is already exceeded. A shift to biobased feedstocks could decouple plastics from fossil-fuel carbon emissions (Gerassimidou et al. 2021), however, it will affect biosphere integrity, land and water systems, biogeochemical flows which are also already breached planetary boundaries.

The industries that produce, manufacture, convert and produce end plastics products such as packaging increasingly emphasize that recycling as a way to reduce waste and meet demand. Despite current and historic failures to meet target recycling rates worldwide (Vogt et al. 2021). Mah (2021) argues that producers and manufacturers downplay plastics pollution as merely a waste management issue to avoid disruptions from legislation or public perception. Perpetuating the narrative of recycling as the primary solution to deal with plastics waste only delays the final disposal of plastics (Zink and Geyer 2018). Single-use plastics packaging represented 46% of all plastic waste generated in 2017 (Geyer 2020). Geyer (2020) estimates that out of all plastic waste ever generated from 1950 to 2017 globally, only 10% (700 Mt, mostly downcycled) was recycled, 14% was incinerated (excluding informal incineration practices), and the vast majority, 76% (5300 Mt) was discarded into landfills, open dumps or directly into the environment. Under current business as usual scenarios, recycled plastics will make up only 12% of all plastics in the market by 2060 (OECD 2022). For recycling to significantly impact the current situation, the production of virgin plastics material has to be considerably reduced (Zink and Geyer 2018, Geyer 2020), coupled with improved regulations and design standards to enable materials reuse and recovery.

Share of plastics (including chemical additives) lacking information on environmental and social harm or regulatory assessment.

It is important to consider the chemical diversity of plastics. While plastics are often touted as inert and therefore safe by producers and industry representatives (Roy et al. 2011, Abdullahi 2014), these kinds of statement disregard: the potentially harmful and toxic monomers and chemical additives used in plastics production, the property of plastics to sorb other chemical pollutants already in the environment. Additives (plasticizers, flame retardants, pigments, etc) modify and enhance plastic polymers' mechanical, physical and chemical properties (Wiesinger et al. 2021). Estimations predicts that by 2018, primary plastics contained at least 400 Mt of additives (Geyer 2020). Wiesinger et al. (2021) reported that at least 10,000 different chemicals are used in plastics production and manufacturing, of which 2,400 are substances of concern. The diverse hazard properties of these chemicals include endocrine disruption, developmental toxicity, carcinogenicity, nerve damage, metabolic effects, and biocide effects (Wiesinger et al. 2021). Primary data on chemical diversity, risk assessments, and ecotoxicological studies are only available for a small fraction of chemical additives, and the type and abundance of additives used are often a producer's proprietary information, and thus, there is lack of well documented public data sources available (Wang et al. 2021).

A high proportion of plastics with poorly documented chemical additives available on global markets raises the risks of perturbing Earth system processes, while also reducing societies' response capacity to emergent problem. From a planetary boundaries perspective, although assessing releases is looking upstream of the biophysical processes of concern, this is still a useful control variable because it captures many potential downstream fates. Most research to date has focused on the marine environment and current knowledge indicates that plastic materials undergo several types of changes during physical, chemical and biologically mediated degradation processes in the ocean (Niaounakis 2017), breaking down into ever smaller particles (Napper and Thompson 2019, Gerritse et al. 2020), but they are persistent. Wind and water currents drive plastic around the world, exposing many more ecosystems than the immediate receiving environment (Ferrero et al. 2022) as discussed further below.

Pathways and fates.

Plastics are ubiquitous in all compartments and transported by all Earth systems (Fig. 2). From mountaintops (Napper et al. 2020) to the deepest ocean sediments (Peng et al. 2018), plastics have become a geological indicator of the Anthropocene (Zalasiewicz et al. 2016). The movement of plastics from soil to sea, air to ice enable researchers to piece together a global plastic cycle (Allen et al. 2020, Rochman and Hoellein 2020).

Detection of microplastics in the world's most remote compartments gives a fingerprint of human perturbation of biophysical systems. Microplastics have been detected in the atmosphere (Wright et al. 2020), polar ice (Evangeliou et al. 2020), permafrost (Chen et al. 2021) in nearly all marine surface waters (Lebreton et al. 2018), sediments (Harris 2020), rivers (Roebroek et al. 2021) and coastlines (Graca et al. 2017), with microfibers being the most abundant type of microplastic found (Barrows et al. 2018).

Recent studies further explore the complexity of airborne micro- and nanoplastic transport. Plastics may enter the atmospheric compartment as aerosol droplets from sea spray (Trainic et al. 2020) or elevated particulate by wind, traveling over 1000km before deposition by rain or fallout as dust (González-Pleiter et al. 2021). Airborne plastics have been detected in urban centers (Dris et al. 2015, Liu et al. 2019) and remote regions from the Arctic (Bergmann et al. 2019), the summit of Everest (Napper et al. 2020), to the ocean-atmosphere interface (Allen et al. 2020), and high beyond the atmospheric boundary layer (González-Pleiter et al. 2021).

The transport of plastics by Earth systems between and within all biological and physical compartments accounts for the vast abundance and distribution, and is therefore one of the tenets of a planetary boundary.

Impact of plastics pollution on Earth system processes – complex cascades.

Plastics are novel substances in natural systems penetrating deeply into Earth's biophysical systems through multiple pathways (Figure 2). Plastics and their additives are persistent, bioaccumulate, and impact the environment from subcellular to population (Galloway et al. 2017) and ecosystem level (Huang et al. 2021). A macro-scale perspective on health and toxicity effects of plastics pollution is now emerging, scaling up from organisms to the planetary ecosystem, giving a basis for a control variable based on *toxicity effects on biosphere integrity*. We also propose a final control variable based on the multiple *Earth system interactions* affected in essentially irreversible ways by plastics, bringing a precautionary approach and long timescale into the frame.

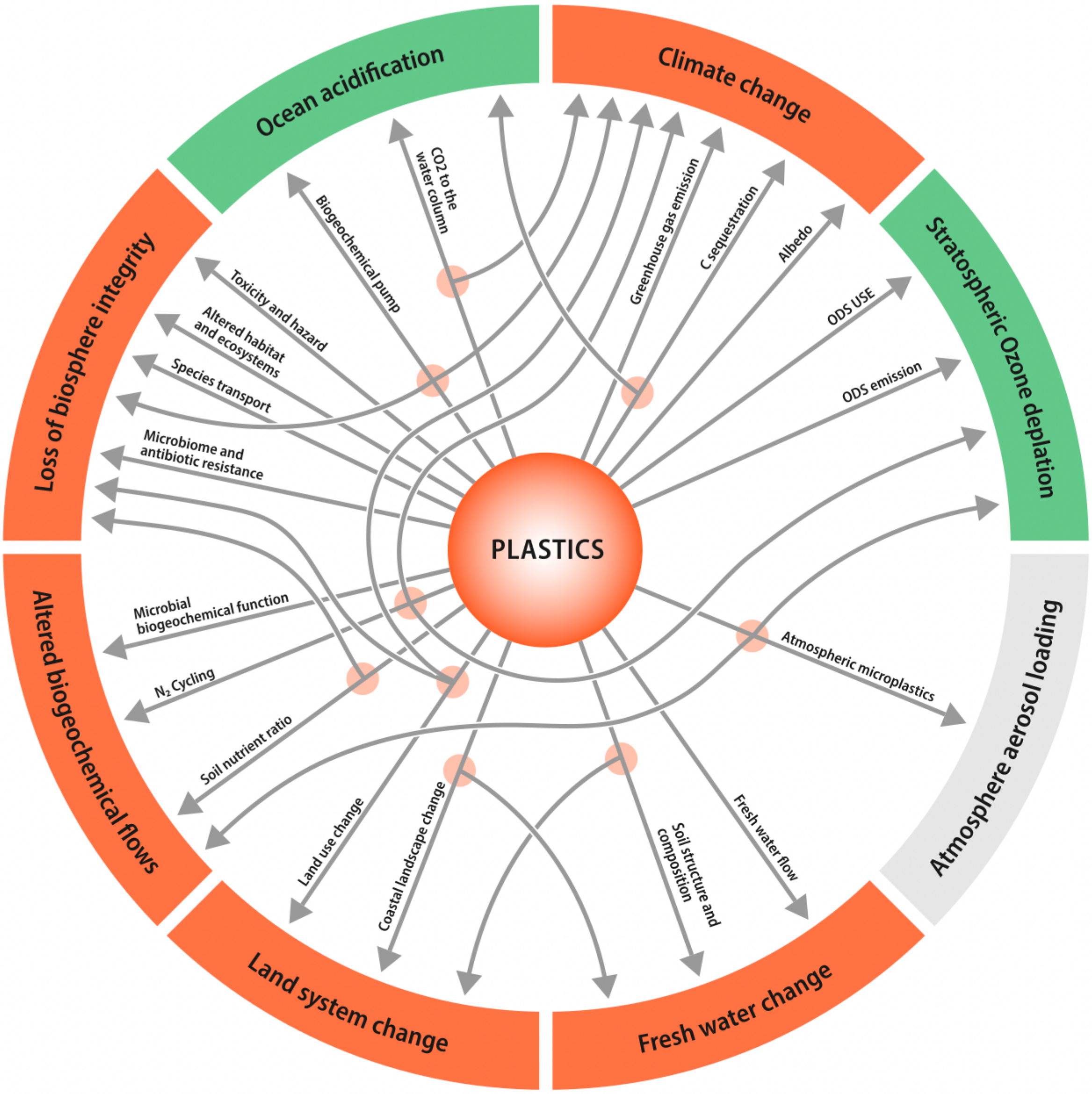

Figure 2. The plastics planetary boundary as a novel entity and cross-interactions with Earth system components. GHG = greenhouse gas emissions; ODS = ozone depleting substances. Breached planetary boundaries are shown in orange; boundaries in green are not assessed as breached, and grey denotes unquantified boundaries. Image credit: E. Wikander / Azote, concept based on Gleeson et al. (2020).

Bottom-up approach – Toxic Effects from organism to planetary ecosystem

Traditional ecotoxicology applies a bottom-up approach, addressing mechanisms of toxicity, cause and effect relationships and dose responses in individual organisms, information that allows us to understand the impacts of plastics and associated chemicals (Munkittrick and McCarty 1995). Integration of toxicity data into knowledge of ecosystem functions is essential, demonstrating how potential toxicity-driven changes in organisms at the 'bottom' of the food chain (e.g., primary producers, grazers) can impact food chain stability (Fleeger et al. 2003, Ma et al. 2020). By integrating information on exposure burdens, the indirect ecosystem risks associated with plastics can be predicted, though usually on shorter time scales and at lower ecological relevance.

Understanding of microplastic toxicity in aquatic ecosystems and humans is growing (Thornton Hampton et al. 2022) and plastics are now reaching all food webs (Mateos-Cárdenas et al. 2021), drinking water (WHO 2019), human placenta (Ragusa et al. 2021), lung tissue (Jenner et al. 2022) and the bloodstream (Leslie et al. 2022). Disposed plastics are also enhancing the spread and severity of vector-borne diseases (e.g., dengue, malaria, zika) (Krystosik et al. 2020), which are expected to worsen in combination with rising temperatures and climate change. Understanding risks at a planetary level becomes increasingly possible.

A concerning trend is to push chemical recycling and incineration practices to deal with plastics waste (Ekvall et al. 2021). These practices create further toxicity, due to the resulting sludge and/pr ash which has a large climate impact (Eriksson and Finnveden 2009). Chemical recycling can produce contaminated products and release of hazardous waste including PAHs, PCBs, metals and dioxins, as well as greenhouse gases (Hann and Connock 2020). These compounds cause harm to organisms in the environment, as well as human populations.

Beyond environmental toxicity, these compounds also have social and policy implications as chemical recycling facilities are often located in communities of lower socioeconomic status (NRDC 2022).

Top-down approach – Earth system effects seen on other planetary boundaries

A rapidly growing body of evidence indicates that plastics pollution impacts Earth system processes and is an overlooked pressure on planetary boundaries (Table 2). Changes in these processes can trigger cascading events through altered biophysical and biogeochemical feedbacks between climate and the world's ecosystems (Seeley et al. 2020, Galgani and Loiselle 2021, Sanz-Lázaro et al. 2021).

Table 2: Early evidence of plastic pollution's contribution to pressure on other planetary boundaries. (A more comprehensive overview and bibliography is given in Table 3 in the Supplementary Material).

Earth system process	**Effects**	**Earth-System compartment impacted**
Climate Change	**Increased greenhouse gas emissions** from: fossil fuel production for plastics; land-use change; waste management; and biological activity in the plastisphere	Atmosphere
	Changes in albedo	Cryosphere
	Altered carbon sinks: changes in the carbon cycle of marine and terrestrial environments; changes in marine carbon flux into sediments; and the inclusion of plastics-carbon into ecosystems	Atmosphere Biosphere Hydrosphere
Ocean Acidification	**Increased CO_2 to water column**: changes in the marine carbon cycle	Atmosphere Hydrosphere
	Altered biological carbon pump: disruptions to aquatic primary producers (e.g., phytoplankton) and consumers (e.g., zooplankton)	Atmosphere Biosphere Hydrosphere
Altered biogeochemical flows (nitrogen and phosphorus)	**Changes in nitrogen cycling:** altered microbial biogeochemical function in the water column and in sediments; and shifts in nitrification and denitrification	Biosphere Geosphere Hydrosphere
	Changes in soil nutrient ratio: soil-plants traits altered by changing C:N:P content	Biosphere Geosphere Hydrosphere
Loss of Biodiversity Integrity	**Exposure to toxicity and hazard**: lethal and sublethal effects due to toxicity; impaired reproduction, growth and survival of marine primary producers; changes in structure and composition of microbial communities; changes in community composition and ecosystem functions in all aquatic environments; impact on keystone species through ingestion, entanglement, suffocation, and death; and changes in feeding behavior and energy levels	Biosphere
	Altered habitat and ecosystems: changes in soil diversity; and changes in ecosystems physical properties (e.g., temperature)	Biosphere Cryosphere Geosphere Hydrosphere
	Species transport: increase of transboundary transport of pathogens, toxicity and invasive species	Biosphere
	Microbiome and antibiotic resistance: genetic transfer for antibiotic resistance and pathogens in seawater, estuarine water, aquaculture, and terrestrial ecosystems	Biosphere
Freshwater change	**Changes in soil structure and composition (green water):** changes in physical properties altering hydrological performance	Biosphere Geosphere Hydrosphere
	Changes in freshwater (blue water) flow: exacerbation of the effects of flooding events in urban and riverine areas	Biosphere Hydrosphere
Land system change	**Changes in land uses**: clearing for the extraction of fossil fuel; land clearing to cultivate raw material for bio-based plastics; land clearing to place landfills, dumpsites, and incineration facilities;	Biosphere Geosphere
	Changes in coastal landscape due to longer term plastic accumulation; and changing water flows	Geosphere Hydrosphere
Atmospheric aerosol loading	**Ubiquity of atmospheric microplastics**: in urban areas; land-sea interface; remote regions; and above the atmospheric boundary layer	Atmosphere Geosphere Hydrosphere Cryosphere
Stratospheric ozone depletion	**Use of ozone depleting substances:** leakage of ozone depleting substances and hydrofluorocarbon feedstocks used in plastics manufacture	Atmosphere

	Emissions of ozone depleting substances from biobased materials production and plastic waste management, including legacy of phased-out CFCs	Atmosphere

Climate Change and Ocean Acidification

Plastics contribute to climate change and ocean acidification during their whole life cycle, but awareness of these links is recent (Hamilton et al. 2019, Zheng and Suh 2019, Ford et al. 2022, Bauer et al. 2022). Fossil-fuel feedstock extraction and refinery directly emit ethane and methane through flaring and venting. These processes contribute to increased CO_2 in the atmosphere and the oceans; however, amounts emitted remain unreported (Hamilton et al. 2019). The production of single-use plastic products alone is projected to introduce 56 gigatons (billion tonnes, Gt) of cumulative greenhouse emissions by 2050, contributing from 10% (Hamilton et al. 2019) to 15% (Zheng and Suh 2019) of the world's remaining carbon budget. Hamilton et al. (Hamilton et al. 2019) did not include greenhouse gas contributions from plastics made from coal-to-olefins processes, nor plastics additives which can account for 40% by volume of the final plastic item (Carney Almroth and Slunge 2022). Thus, these projections underrepresent actual emissions due to lack of industry transparency, with low reporting and data availability on topics such as transport, fuel used to power machinery and equipment, minor accidents, leaks, and unplanned releases. The petrochemicals and plastics industry does not account for many of these negative externalities from extraction and production stages (Hamilton et al. 2019, Sicotte and Seamon 2021). Unless bold international policies and actions are introduced, annual emissions of greenhouse gases during production, use and waste management of traditional plastics are projected to increase from 1.8 $GtCO_2e$ in 2019 (OECD 2022) to between 2.8 $GtCO_2e$ (Hamilton et al. 2019) and 6.5 $GtCO_2e$ (Zheng and Suh 2019) by 2050. Similarly, estimates that plastics life-cycle greenhouse emissions may reach 4.8 $GtCO_2e$ by 2060 (OECD 2022), taking up 88% of the global CO_2e budget for keeping global mean temperature below 1.5°C (Byers et al. 2022, Riahi et al. 2022).

Once plastics enter the environment, biological and chemical degradation processes may cause the emission of climate-active (and ultimately ocean-acidifying) gases such as methane, ethylene and CO_2 (Royer et al. 2018). Biological activity in the microbial communities living on plastic pollution (Amaral-Zettler et al. 2020) can contribute novel additions of CO_2 and nitrous oxide (N_2O) (Cornejo-D'Ottone et al. 2020). Emissions vary depending on the type of plastics, morphology, and age, but occur in both fossil fuel-based plastic and bioplastic (Zheng and Suh 2019, Benavides et al. 2020).

‘Bioplastic’ is a term used to describe many polymers derived from non-fossil fuel feedstocks. Agricultural plant waste may be used to produce bio-based bioplastics, which may be chemically identical to polymers derived from fossil fuels, like PE, PP and PET. These are different from biodegradable plastics, which are derived from biological processes and can degrade in natural environments on varied time scales, such as PLA and PHA. Both bio-based and biodegradable plastics generally show lower life-cycle greenhouse emissions than traditional plastics (Zheng and Suh 2019), largely due to the carbon footprint of their feedstocks compared to conventional plastics derived from fossil fuels. However, biodegradable plastics can release twice as much CO_2 in the marine water column during biodegradation than traditional microplastics that resist degradation (Sanz-Lázaro et al. 2021), which is associated with perturbations to the carbon cycle in sediments, and carbon sequestration in the marine environment.

Researchers have also observed that microplastics might have the capacity to alter Earth’s albedo. Permafrost, sea-ice and glaciers in the Arctic currently serve as a sink of microplastics (Chen et al. 2021). Geilfus et al. (2019) conducted sea-ice microcosm experiments, and Evangeliou et al. (2020) simulated the global airborne transportation of road traffic microplastics reaching the Arctic.

These studies show that microplastics in snow and ice can increase light absorption, decreasing surface albedo, leading to faster warming and melting of polar ecosystems. Additionally, permafrost freeze-thaw processes under climate change conditions could induce additional microplastics mixtures with soil and other terrestrial ecosystems, impacting cycles of carbon and other essential elements (Chen et al. 2021).

Plastics pollution thus plays a largely-overlooked role in climate and ocean pH through changes in the carbon cycle through varied processes.

Biogeochemical flows

Although biogeochemical effects of plastics are under-researched to date, microbes of the plastisphere can influence the cycling of the nutrient elements nitrogen, phosphorus and iron in marine systems (Mincer et al. 2016). Studies show that both traditional and biodegradable plastics can perturb nitrogen fluxes (Green et al. 2017, Seeley et al. 2020), decreasing the release of inorganic nitrogen from marine sediments to the water column and promoting nitrification-denitrification coupling (Sanz-Lázaro et al. 2021). Other essential elements may also be affected: microplastic-paint biofilm communities have been found to be unusually rich in sulphate-reducing bacteria (Tagg et al. 2019).

Biosphere integrity

Biodiversity impacts of plastics are evident from the very base of ecosystems. Micro-sized particles are a particular concern due to their high absorption-surface/volume ratio and their distribution across ecosystems (López-Rojo et al. 2020, Na et al. 2021), but the increasing presence and accumulation of microplastics in the environment still poses a widely underrated threat. Microplastics can change the composition and function of microbial communities in soils (de Souza Machado et al. 2019, Boots et al. 2019), marine systems (Amaral-Zettler et al. 2020, Chai et al. 2020), and aquatic biofilms (Guasch et al. 2022). The microbes in these diverse niches are ecologically important assemblages composed of viruses, bacteria, algae, cyanobacteria, fungi, and meiofauna. As indicated above, they fulfil important functions in carbon and nutrient cycling and underpin many food chains.

On their surfaces, macro- and microplastics can transport pathogens and non-native and invasive species and toxic substances in aquatic and terrestrial ecosystems (Radisic et al. 2020, Bowley et al. 2021). The marine plastisphere can harbor pathogens (Zettler et al. 2013), and function as reservoirs for antimicrobial resistance genes (Kaur et al. 2022). Antibiotic resistance already has globally significant health, social and economic consequences (Lambraki et al. 2021). Microplastics pollution can also contribute to transfer of pathogens and antibiotic resistance, and horizontal gene transfer, shifting microbial evolution and niche adaptation in seawater (Laganà et al. 2019, Sathicq et al. 2021), estuarine waters (Laverty et al. 2020, Guo et al. 2020) and aquaculture environments (Dong et al. 2021). Moreover, airborne microplastic can also carry microbiota and pathogens for long distances, reaching ecosystems in remote areas (Trainic et al. 2020).

Plastics pollution can have lethal and sublethal effects on organisms and change the functional diversity in ecosystems. Ingestion, entanglement, suffocation and death of animals by plastics are widely researched. Studies confirm that over 1565 animal species across all environments ingest plastics (Santos et al. 2021). This includes endangered species and keystone species, such as zooplankton (Cole et al. 2015), marine worms (Wright et al. 2013), earthworms (Huerta Lwanga et al. 2017), turtles (Wilcox et al. 2018, Eastman et al. 2020), whales (Panti et al. 2019), and camels (Eriksen et al. 2021). Microplastic ingestion may affect feeding behavior, energy intake, and energy allocation, all of which can impact marine species' structural growth and reproductive health and change functional biodiversity (Cole et al. 2015, Jiang et al. 2022).

Plastics also alter habitats. Reproduction and sex determination can be impacted in highly temperature-dependent species, such as marine turtles, when plastics accumulation changes the physical properties of sand and soil (Yntema and Mrosovsky 1982), potentially leading into long-term trophic cascade effects. Geilfus et al. (2019) warn about potential consequences in sea-ice biota imposed by microplastic disruption of light penetration depth and changes in photochemical and photobiological processes.

Freshwater change

The water planetary boundary has focused on the use of blue water as a "proxy for overall water flux changes in a river basin" (Wang-Erlandsson et al. 2022). However, Wang-Erlandsson et al.(Wang-Erlandsson et al. 2022) argue that this approach under-recognizes human impacts on freshwater changes, proposing a control variable for green water (i.e., the water available to land plants through rainfall, evaporation, and soil moisture). We applied this broader conceptualization in exploring early evidence of impacts of plastics pollution on the freshwater change boundary.

The accumulation of macroplastics pollution leads to changes in the natural flows of freshwater, and also to clogging of drain-water and sewage systems, amplifying the effects of extreme weather events such as flooding in urban and riverine areas (Honingh et al. 2020, Roebroek et al. 2021). The accumulation in soils of plastics of all shapes and sizes may have significant impact on green water flows. Plastics disrupt normal physical structure and composition of soils, changing the soil evapotranspiration, structural stability, and the rhizosphere (de Souza Machado et al. 2019, Boots et al. 2019, Rillig et al. 2021), which further impacts on agroecosystems and terrestrial biodiversity.

Land system change

Plastics play a role in land system change at various stages in their life cycle. Resource extraction, refinery, transport, and manufacturing of fossil-fuel-based significantly increase deforestation (Hamilton et al. 2019). Bio-based plastics can have a significant indirect impact on land-use change by land clearing to grow raw-material crops such as sugarcane, cassava and corn (Zheng and Suh 2019, Escobar and Britz 2021), although researchers point out that the impacts largely depend on how much plant-based plastics raw materials are grown on existing agricultural land. The creation of landfills, informal dumpsites, and building infrastructure for incineration plants is also a major contributor to land-use change, as identified by the OECD (2022).

Agriculture introduces large amounts of plastics to the land environment, affecting links among climate, land and water. According to UNEP (2021), between 7.3 and 9 Mt of plastics were used globally in 2015 in agriculture. Observations show that microplastics concentrations on agricultural sites can increased from 2 to 4 orders of magnitude due to the wide use of plastic mulching and the addition of sewage sludge to agricultural soil (Büks et al. 2020). FAO (2021) warns that the single-use plastics products used in agriculture will persist in the soil, “transfer and accumulate in food chains, threatening food security, food safety, and potentially human health.”

Landscapes are also changing because of plastics pollution. A recent investigation of two sites on the western coast of Norway found significant stratigraphical land changes due to plastic accumulation (Bastesen et al. 2021), with plastics covering more than 50% of the surface of some study areas. Observed changes included the growth of storm embankments and changes in the level of ponds, forming dams in rivers and wetlands. Since soil properties changed, the vegetation growing over the combined plastic and organic material also changed. (Bastesen et al. 2021) argue that this kind of plastic and organic accumulation occurs on all coastlines, so the continued leakage of plastics into the aquatic environment could have landscape impacts on a global scale.

Atmospheric interactions: Aerosol Loading and Stratospheric Ozone Depletion

The presence of microplastics suspended in the atmosphere and their long-range transport and deposition to remote land, marine, and polar environments has been discussed above. Biophysical effects of plastics as atmospheric aerosol are not well studied.

The interactions of plastics pollution and ozone depletion have also not received much attention. Ozone-depleting substances previously used in plastics production (e.g., CFCs used as foaming agents) are being phased out under the Montreal Protocol. Other ozone-depleters are still being used. Early evidence shows that plastic waste management may affect stratospheric ozone depletion through emissions of N_2O (Bishop et al. 2022).

CONCLUSIONS

The planetary boundary has been breached for plastic pollution

We have reported on evidence that plastics have an impact on all Earth system processes in the planetary boundaries framework. We have also shown examples where plastics trigger unexpected changes through interactions and altered feedbacks among climate dynamics, functional biodiversity, landscapes, and flows of nutrients and water, enhancing the impacts of other breached planetary boundaries. Similarly, changes in other planetary boundaries (notably climate change, ocean acidification and freshwater change) can intensify the global ecological impacts of novel entities such as plastic pollution.

Wholly synthetic materials that are known to disrupt living processes at all scales on Earth would surely require the most stringent controls. We strongly believe we should not strive for quantifying a singular planetary boundary for plastics pollution. On the contrary, we believe this would not adequately capture the complex reality of these substances and would be detrimental to the global governance of plastics. Instead, efforts should be oriented towards further development and monitoring of a set of control variables that describe the actual state of the system along the impact pathway. There are thousands of kinds of plastics, involving tens of thousands of different chemicals for their production. New chemical combinations arise once plastics are released into the environment. The environmental impacts of each type of plastic depend on their size, composition, concentration and residence time; the environments in which they are present and where and how they degrade; and the effects on different species at different stages of life. Societies have to deal not only with the plastic we produce now, but with the legacy of plastics produced in past decades. The plastics industry currently fails to report many of the negative externalities associated with the extraction of fossil fuel and bio-based plastics resources. There is a general lack of openly available data on the chemicals in plastics, the volume of chemical additives, or even the diversity of additives being produced, creating major obstacles to shifts towards a less polluting circular economy. To date, the vast majority of plastics and additives lack ecotoxicological studies, obstructing an understanding of the extent to which plastics pollution impacts ecosystems and human health. Traditional risk assessments have been applied to microplastics at different environmental concentrations (Everaert et al. 2020), with mathematical models increasingly accounting for exposure pathways and microplastics particles' diversity themselves. However, cross-scale hazard assessment methods, including global impacts, are still in their infancy.

Despite these serious information gaps, we consider that there is already a good basis for initial global quantifications that together show the world has breached the planetary boundary for plastics as novel entities in the Earth system. Scientific and international policy communities have data and systemic process understanding for operationalizing control variables along the full life-cycle of plastics:

- Annual production volume of virgin plastics, Mt per year;
- Detection of the presence of microplastics in remote environments and in all 'spheres';
- Attribution of perturbations to other planetary boundaries processes by plastic pollution, and assessment of intensified pressures and impacts.

Control variables that can currently only be estimated on the basis of strong assumptions can be made more operational through greater industry transparency and more comprehensive monitoring and reporting:

- Share of plastics and additives available on the global markets lacking safety data or regulatory assessment;
- Total quantity of plastics released annually into the environment;
- Ecotoxicity of plastics and their additives across micro- to macro-scales, from sub-organism to biome and Earth system functioning.

What can societies do about this breached boundary?

The planetary problem of plastics is increasingly recognized, but it has largely been defined as a waste problem. Most policy, from local to international scale, targets “marine litter” or “marine plastic debris and microplastics”. Even the problematization of “plastic pollution” as a planetary social-ecological and economic problem has focused narrowly – mainly on microplastics at sea. Treating the plastics problem as merely a waste management issue may bias research, policies and companies to prioritize the end-life of plastics. The problematization of plastics should consider a systemic full life-cycle approach, avoiding the funneled narrative of plastics being a waste problem created by consumers. Policy discourses should include the chemical diversity and toxicity of plastic additives (as novel entities), and other impacts related to feedstock extraction.

As debates develop about a multilateral plastics treaty (UNEP/EA.5/L.23/Rev.1 2022), there is an opportunity to depart from business-as-usual to a systemic approach that also recognizes the diverse impacts in ecosystems, and on human health, water quality and food security. A cap on production is being discussed as the most effective solution (Hamilton et al. 2019, Bergmann et al. 2022). In the absence of transparency, monitoring and reporting about plastics and their life-cycles, this would be the only sure way to reduce global impacts. The principle of common but differentiated responsibilities should be applied to this international legislation[1].

All actors from the plastics industry (i.e., fossil fuel companies, petrochemicals, converters, and end-product manufacturers) have a vital role to play in resolving information gaps to inform more responsive control variables, and to support sustainable global governance and management of plastics. According to (Mah 2022), big plastics corporations have been lobbying over decades and opposing initiatives and regulations which threaten the growth of plastics production, though they are aware of the negative socio-ecological impacts of plastics pollution. Sound, controlled chemical recycling and incineration are expensive and their economic viability depends on continuous operation. (Eriksen et al. 2018) explain the counterproductive implications of the need to maintain waste quotas to permanently run incinerators. Locked-in dependence on high material flows into waste-to-energy plants (Ekvall

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[1] https://press.un.org/en/2022/envdev2048.doc.htm

et al. 2021) may delay much-needed long-term systemic solutions to deal with the social root causes of plastics pollution.

We already have enough evidence to make the assessment that the planetary boundary is breached but to define operational control variables that are linked to human drivers requires further process understanding. With all these early indications on how plastics pollution is changing the Earth system, it is clear that the complex issue of plastics can no longer be overlooked. We call for experts and policymakers to take urgent action, to consider plastics pollution as not only a waste management problem but as an integrative part of climate change, biodiversity and natural resource use policy.

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AUTHORS CONTRIBUTION

P.V.G. led the planning and writing of the paper, collated and reviewed the literature, and carried out most of the analysis. All authors collaborated on the conceptualization and discussion of content, contributed to the analysis, writing and editing of the paper. S.C. and B.C.A. supervised the development of the research methodology.

COMPETING INTERESTS

The authors declare no competing interests.

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SUPPLEMENTARY MATERIAL

PLASTICS POLLUTION AND THE PLANETARY BOUNDARIES FRAMEWORK.

AUTHORS LIST:
Patricia Villarrubia-Gómez,[*a] Bethanie Carney Almroth,[b] Marcus Eriksen,[c] Morten Ryberg,[d,e] and Sarah E. Cornell,[a]

[a] *Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden.*
[b] *Department of Biological and Environmental Sciences, University of Gothenburg, Box 463, SE-405 30 Göteborg, Sweden.*
[c] 5Gyres Institute. *Five Gyres Institute, Los Angeles, California, United States of America CA, 90016, USA*
[d] Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[e] Sweco Denmark, Copenhagen S, Denmark

*Corresponding author: patricia.villarrubia@su.se

Table 1. Production of plastic from 1950 to 2020. These results do not include PS, PET or Polyacryl fibres. Sources: Geyer et al. (2017) and PlasticsEurope (2021)

Year	**Production (million metric tons)**	**Reference**
1950s-2015	8300	Geyer et al. 2017
2016	335	PlasticsEurope 2021
2017	349	
2018	359	
2019	368	
2020	367	
Total =	10078	

Table 2. Production of plastic from 2000-2020

Year	Production (million metric tons)	Reference
2020	367	PlasticsEurope 2021
2019	368	
2018	359	
2017	349	
2016	335	
2015	381	Geyer et al. 2017
2014	367	
2013	352	
2012	338	
2011	325	
2010	313	
2009	288	
2008	281	
2007	295	
2006	280	
2005	263	
2004	256	

2003	241
2022	231
2001	218
2000	213
Total	6420

Table 3: Early evidence of plastic pollution contribution to pressure on other planetary boundaries:

Earth system process	Effects	Representative articles
Climate Change	**Increased greenhouse gas emissions**	
	Emissions of CO2, methane and land clearance due to the extraction and transportation of oil, gas natural and coal	Hamilton et al. 2019, Zheng and Suh 2019, Charles et al. 2021, Ford et al. 2022
	Emissions of GHG waste management and end-of-life plastics	Hamilton et al. 2019, Zheng and Suh 2019, Benavides et al. 2020
	Emissions of methane and ethylene due to breakdown of macro, microplastic	Royer et al. 2018
	Introduction of additional CO2 to the marine water column by bioplastics	Sanz-Lázaro et al. 2021
	Increase of biological activity in the plastisphere, microplastics plastisphere produce and consume CO2 and N2O in the marine environment	Cornejo-D'Ottone et al. 2020
	Changes in albedo effect	
	Presence of microplastics	Geilfus et al. 2019, Evangeliou et al. 2020
	Altered carbon sinks	
	Change on the carbon cycle and flux through microplastics biding with marine snow	Cole et al. 2016, Porter et al. 2018, Kvale et al. 2020, Nguyen et al. 2020, Tekman et al. 2020, Galgani and Loiselle 2021
	Decrease of marine carbon sequestration, disruption of the biological pump.	Cole et al. 2015, Royer et al. 2018, Wieczorek et al. 2019, Shen et al. 2020, Tekman et al. 2020, Sanz-Lázaro et al. 2021
	Inclusion of plastic-carbon into ecosystems	Shen et al. 2020, Rillig et al. 2021, Stubbins et al. 2021
Ocean Acidification	**Increased CO_2 to water column**	
	CO_2 emissions from feedstock extraction and materials production; indirect effects via altered carbon fluxes	Litchfield et al. 2020, Harvey et al. 2020
	Altered biological carbon pump as a consequence of microplastics presence and toxicity (e.g., additives)	
	Disruption to aquatic primary producers (e.g., phytoplankton)	Bhattacharya et al. 2010, Sjollema et al. 2016, Zhang et al. 2017, Nolte et al. 2017, Chae et al. 2019, Tetu et al. 2019, Shen et al. 2020
	Disruption to aquatic primary consumers (e.g., zooplankton)	Cole et al. 2015, 2016
Altered biogeochemical flows (nitrogen and phosphorus)	**Changes in nitrogen cycling**	
	Altered microbial biogeochemical function in the water column and in sediments; and shifts in nitrification and denitrification	Green et al. 2017, Seeley et al. 2020, Sanz-Lázaro et al. 2021
	Changes in soil nutrient ratio:	
	Soil-plants traits altered by changing C:N:P content	Rillig et al. 2021
Loss of Biodiversity Integrity	**Exposure to toxicity and hazard**	
	Lethal and sublethal effects due to plastic toxicity	López-Rojo et al. 2020, Na et al. 2021
	Impaired reproduction, growth and survival of marine primary producers	Bhattacharya et al. 2010, Cole et al. 2015, Sussarellu et al. 2016, Nolte et al. 2017, Tetu et al. 2019, Shen et al. 2020

	Changes in feeding behavior and energy levels	Wright et al. 2013, Cole et al. 2015
	Changes structure and composition of microbial communities	Oberbeckmann et al. 2015, Bandopadhyay et al. 2018, Ogonowski et al. 2018, Hu et al. 2019, Sanz-Lázaro et al. 2021
	Changes in community composition and ecosystem functions in the marine and aquatic environment	Zettler et al. 2013, Debroas et al. 2017, Amaral-Zettler et al. 2020, Chai et al. 2020, Ford et al. 2022
	Impact of keystone species through plastics ingestion, entanglement, suffocation, and death;	(Laist 1987, Pierce et al. 2004, Ivar do Sul and Costa 2007, Gregory 2009, Votier et al. 2011, Barreiros and Raykov 2014, Gall and Thompson 2015, Butterworth 2016, Nelms et al. 2016, Anderson and Menden-Deuer 2017, Reinert et al. 2017, de Carvalho-Souza et al. 2018, Wilcox et al. 2018, Panti et al. 2019, Roman et al. 2019, Eastman et al. 2020, Eriksen et al. 2021, Savoca et al. 2021, MacLeod et al. 2021, Santos et al. 2021, Fulfer and Menden-Deuer 2021
	Altered habitat and ecosystems	
	Changes in soil diversity	de Souza Machado et al. 2019, Boots et al. 2019
	Changes in ecosystems physical properties (e.g., soil temperature)	Yntema and Mrosovsky 1982
	Species transport	
	Increase of uncontrolled transboundary transport of pathogens, toxicity and invasive species	Gregory 2009, Debroas et al. 2017, Miralles et al. 2018, Radisic et al. 2020, Bowley et al. 2021, Al-Khayat et al. 2021, Radisic and Marathe 2021, Gkoutselis et al. 2021
	Microbiome and antibiotic resistance	
	Seawater	Arias-Andres et al. 2018, Laganà et al. 2019, Yang et al. 2019, Guo et al. 2020, Sathicq et al. 2021, Radisic and Marathe 2021, Stenger et al. 2021
	Estuarine water	Laverty et al. 2020, Guo et al. 2020
	Aquaculture	Lu et al. 2019, Dong et al. 2021
	Terrestrial ecosystems	Yan et al. 2020, Rasool et al. 2021, Wang et al. 2021, Zhu et al. 2022
Freshwater change	**Changes in green water** by:	
	Changing soil physical structure and composition altering hydrological performance	de Souza Machado et al. 2019, Boots et al. 2019, Bastesen et al. 2021, Rillig et al. 2021, FAO 2021
	Changes in freshwater (blue water) flow	
	Exacerbation of the effects of flooding events in urban and riverine areas	Galgani et al. 2015, Welden and Lusher 2017, van Sebille et al. 2020, Honingh et al. 2020, Roebroek et al. 2021
Land system change	**Changes in land-use**	
	Land clearing for the extraction of fossil fuel	Hamilton et al. 2019, Liboiron 2021
	Land clearing to cultivate raw material for bio-based plastics	Zheng and Suh 2019, Escobar and Britz 2021, Bishop et al. 2022, OECD 2022, Piemonte and Gironi n.d.
	Change to place of landfills, dumpsites, and incineration facilities	OECD 2022

	Land changes in coastline landscape due to plastic accumulation	Bastesen et al. 2021
Atmospheric aerosol loading	**Airborne microplastics** in	
	Urban areas	Dris et al. 2015, 2016, 2017, Gasperi et al. 2018, Klein and Fischer 2019, Wright et al. 2020, Brahney et al. 2021
	Land-sea interface	Allen et al. 2020, 2022, Ding et al. 2021, Ferrero et al. 2022
	Remote regions	Allen et al. 2019, 2020, Evangeliou et al. 2020, Trainic et al. 2020
	Above the atmospheric boundary layer	González-Pleiter et al. 2021
Stratospheric ozone depletion	**Use of ozone depleting substances**	
	Leakage of ozone depleting substances and hydrofluorocarbon feedstocks used in plastics manufacture	Andersen et al. 2021, Cañado et al. 2022
	Emissions of ozone depleting substances	
	Biobased materials production and plastic waste management, including legacy of phased-out CFCs.	Weiss et al. 2012, Rigamonti et al. 2014

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