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Towards circular plastics within planetary boundaries

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The rapid growth of plastics production exacerbated the triple planetary crisis of habitat loss, plastic pollution and greenhouse gas (GHG) emissions. Circular strategies have been proposed for plastics to achieve net-zero GHG emissions. However, the implications of such circular strategies on absolute sustainability have not been examined on a planetary scale. This study links a bottom-up model covering both the production and end-of-life treatment of 90% of global plastics to the planetary boundaries framework. Here we show that even a circular, climate-optimal plastics industry combining current recycling technologies with biomass utilization transgresses sustainability thresholds by up to four times. However, improving recycling technologies and recycling rates up to at least 75% in combination with biomass and CO_2 utilization in plastics production can lead to a scenario in which plastics comply with their assigned safe operating space in 2030. Although being the key to sustainability and in improving the unquantified effect of novel entities on the biosphere, even enhanced recycling cannot cope with the growth in plastics demand predicted until 2050. Therefore, achieving absolute sustainability of plastics requires a fundamental change in our methods of both producing and using plastics.

Plastics are versatile, durable, and cheap, and therefore ubiquitous in our modern life. Accordingly, plastics demand has doubled in the past 20 years and is expected to double again before 2050 (refs. [1,2]). Unfortunately, the increasing demand will also intensify the global challenge of plastic pollution[3–5]. Therefore, the United Nations Environment Programme recently pledged to tackle the triple planetary crisis of habitat loss, environmental pollution because of plastic waste and greenhouse gas (GHG) emissions from production and end-of-life treatment of plastics[6]. Current fossil-based plastics are expected to claim about 15% of the remaining carbon budget by 2050 (refs. [2,7]). Therefore, mitigating life-cycle GHG emissions of plastics is crucial to cap the global mean temperature rise to 1.5 °C relative to the pre-industrial era.

Various options for reducing GHG emissions from plastics are increasingly emerging with circular technologies such as plastic recycling, bio-based production, and carbon capture and utilization (CCU)[8–10]. For example, recently, bio- and CCU-based processes have been shown to achieve net-zero GHG emission plastics when combined with recycling rates of 94%[10]. Thus, the global recycling rates need to substantially increase from their current values, which are estimated to be around 23%[11] but might actually be even lower[12]. Furthermore, achieving net-zero GHG emission plastics still requires large amounts of renewable electricity and biomass[10,13].

The utilization of renewable electricity and biomass has been shown to shift the environmental burden from climate change to other environmental impacts. In particular, life-cycle assessment (LCA) studies showed that producing biofuels from biomass intensifies land use and water consumption and that the renewable power needed for CCU could aggravate mineral resource depletion. Burden shifting because

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of renewable resource use has been identified for several industrial areas, for example, energy systems[14,15], carbon dioxide (CO_2) removal technologies[16,17], and chemical and plastic production[18,19]. However, previous LCA literature does not quantify whether burden shifting would compromise absolute environmental sustainability (hereafter referred to as sustainability), that is, exceeding the carrying capacities of nature[14].

To determine absolute sustainability thresholds, the planetary boundaries framework was proposed (ref. [20]). This framework defines global limits to human activities to avoid destabilizing the Earth system at planetary scale. These global limits jointly define the so-called safe operating space (SOS) and were defined for nine Earth-system processes, including climate change, biosphere integrity, and the biogeochemical flows of nitrogen and phosphorus[21]. Three groups developed methods to link the planetary boundaries framework to LCA, enabling the quantification of sustainability[18,22–26].

A recent study applied the planetary boundaries framework to 492 fossil-based chemicals, including monomers and polymers, and found that more than 99% of fossil-based chemicals transgress at least one planetary boundary[25]. Furthermore, it has been argued that a shift towards circular plastics based on biomass, CCU and recycling could positively influence the planetary footprints of plastics[26]. Nevertheless, it is unclear whether a climate-optimal plastics industry based on biomass, CCU and recycling[10] complies with its ecological budget in all Earth-system processes. Thus, it is yet unknown whether GHG mitigation strategies for plastics are sustainable regarding all Earth-system processes.

Here, we quantify the environmental impacts of circular plastics relative to their ecological budget. In particular, we evaluate the sustainability implications of GHG mitigation strategies for plastics and the role of plastic recycling as a potential enabler for sustainable plastics (Fig. 1). For this purpose, the life-cycle planetary footprints of plastics are calculated for 2030 to highlight the need for a fast transition and for 2050 to assess the challenge of growing plastics demand. The calculations are based on a bottom-up model of global plastic production and waste treatment, representing the life cycle of over 90% of global plastics[10]. The model enables detailed accounting of mass and energy flows throughout the plastics supply chain and identifies the optimal choice of technologies for a given objective, for example, climate change mitigation (details in Methods)[27]. We apply economic downscaling principles to define the ecological budget for sustainable plastics, that is, the share of the SOS of the plastics industry. Under the assumption of economic downscaling, we found that increasing recycling rates alone is insufficient to produce sustainable plastics. Also, producing bio- or CCU-based plastics leads to unsustainable burden shifting from climate change to other planetary boundaries. However, simultaneously increasing recycling rates, improving recycling process yields, and switching to bio- and CCU-based production shows potential for sustainable plastics in 2030. Yet, sustainable plastics in 2050 seem out of reach, considering current forecasts of demand growth.

Results

The planetary boundary footprints of plastics

The bottom-up model of the global plastics industry provides production pathways for the 14 largest-volume plastics in 2030. We consider the plastics industry sustainable if it operates within its assigned share of the SOS in all Earth-system processes. While the global SOS defines the ecological budget for all human activities, we assign 1.1% of the global SOS to plastics by applying economic downscaling principles (details in Methods)[28,29]. These downscaling principles are designed to maximize welfare by setting the consumption expenditure on plastics in relation to the global economy. Additionally, we conservatively assign the entire life-cycle emissions of plastics to the year 2030, although plastics produced in 2030 may partially be disposed of in later years.

If plastic production remains fossil-based, then the plastics industry will strongly exceed its assigned share of SOS, even using the best available fossil technology and the current recycling rate of 23% (Fig. 2, grey bars). In particular, the share of SOS is exceeded by 38 times in climate change (42% of the global SOS), 12 times in ocean acidification (14%), two times in biosphere integrity (3.8%), and one time in aerosol loading (2.5%). Notably, a high share of plastic production today is coal-based, additionally worsening environmental impacts compared to the assumed best available fossil technologies[30]. The other planetary footprints remain within the allocated share of SOS (for the excluded category of novel entities, see the Discussion). The high effects on climate change, ocean acidification and biosphere integrity result mainly from CO_2 emissions from plastic waste treatment (60–62%), whereas aerosol loading is primarily due to naphtha production (92%) and its particulate matter emissions. The drastic overshooting of the assigned share of the CO_2-related Earth-system processes renders fossil-based plastics highly unsustainable and emphasizes the urgency for GHG mitigation in production and end-of-life treatment of plastics.

A climate-optimal plastic production would employ biomass and recycling: biomass is primarily converted to methanol as a precursor for plastic monomers, while mechanical recycling treats packaging waste, and chemical recycling via pyrolysis converts non-packaging into refinery feedstock (details in Supplementary Information, section 3). This climate-optimal pathway remains within its share of SOS in climate change, ocean acidification and aerosol loading. However, the high share of bio-based plastics worsens biosphere integrity and the biogeochemical flows of nitrogen (N cycle) to about 5–6% of the global SOS, exceeding the share of SOS assigned to the plastics industry by about four times (Fig. 2, yellow bars). Biosphere integrity deteriorates mainly because of biomass cultivation requiring land occupation, which causes habitat loss and corresponding loss of biosphere integrity. The effects on the N cycle footprint result from nitrogen-containing fertilizers for biomass cultivation. The climate-optimal production minimizes biomass consumption by maximizing recycling rates up to the limit imposed by assuming 6% of residual landfilling (details in Methods)[11]. Nevertheless, a climate-optimal plastics industry is unsustainable when assuming an economically assigned share of SOS.

Focusing on climate change while assessing multiple objectives introduces an unnecessary bias. Accordingly, we assess a balanced solution that minimizes the maximum transgression across all Earth-system processes (Fig. 2, turquoise bars). The balanced solution combines bio- and CCU-based production with maximum recycling rates. Compared to the climate-optimal solution, 72% of methanol production switches from biomass utilization to CCU. The CCU route uses hydrogen from water electrolysis and CO_2 from the remaining biomass gasification and incineration processes (details in Supplementary Information, section 3). However, even the balanced solution transgresses the assigned share of SOS for climate change and the N cycle footprint by 66% and biosphere integrity and aerosol loading by about 55%. Additionally, the biogeochemical flows of phosphorus (P cycle) increase to 87% of the assigned share of SOS owing to emissions of phosphorus and phosphorus-containing substances from biomass cultivation and electricity generation. Accordingly, even the balanced solution does not lead to sustainable plastics within the environmental thresholds.

We next analyse the contributors to the overall planetary footprints of the balanced solution (recycling, biomass utilization and CCU) in more detail to identify potential levers for additional improvements to achieve sustainable plastics.

Recycling enhances the sustainability of plastics

Maximizing recycling rates from the current rate of 23% to 94% reduces all planetary footprints by 10–49% for fossil-based plastics, 33–83% for bio-based plastics and 8–58% for CCU-based plastics (Fig. 3, grey, green and blue bars). Thus, recycling does not trigger any significant

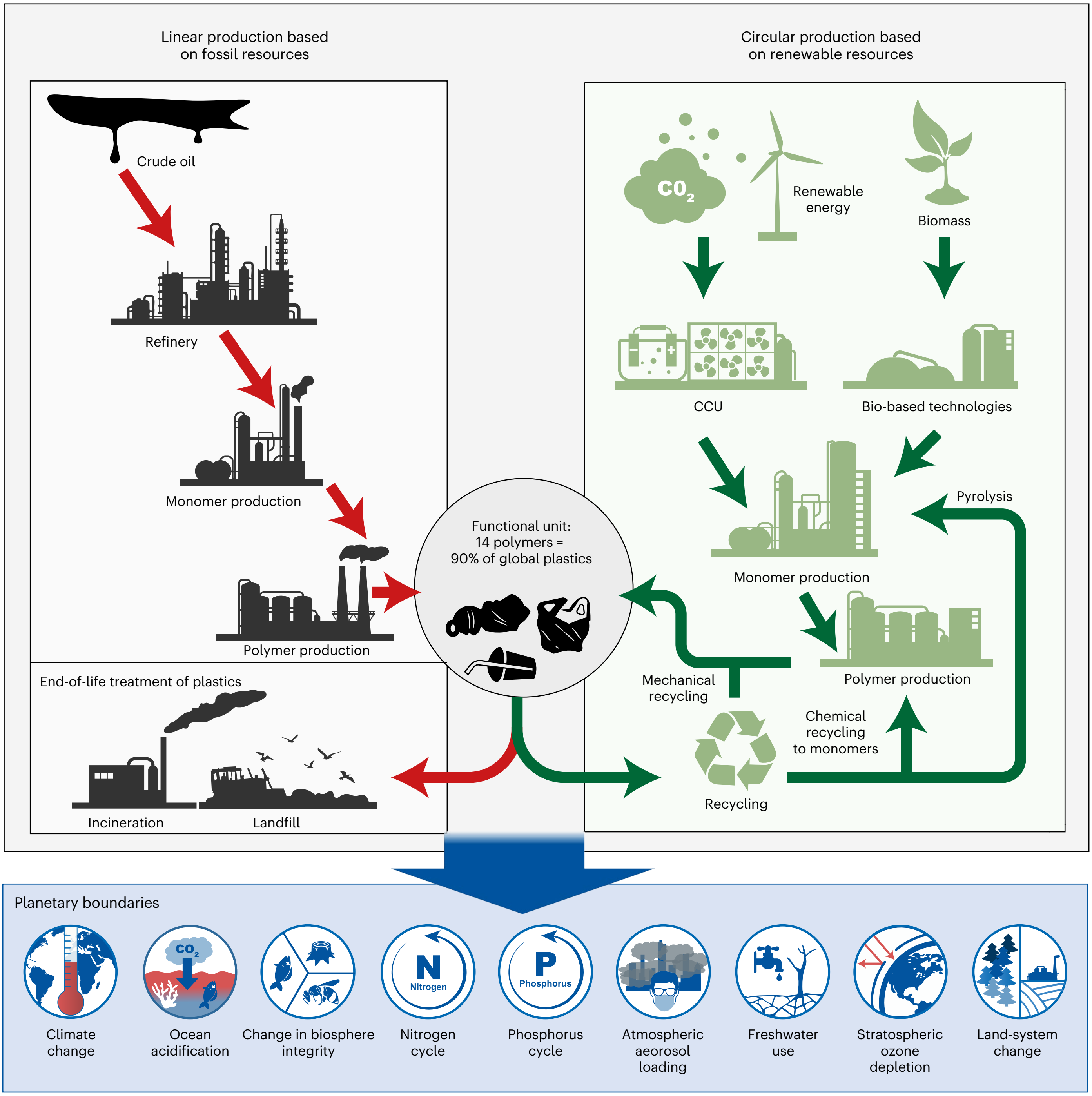

Fig. 1 | Conceptual framework. Replacement of current fossil-based plastics (left) with renewable plastics (right) based on biomass, CO_2 via CCU, and recycling, and assessment of their planetary footprints (bottom).

burden shifting in any scenario. However, even the maximum recycling rates are insufficient to achieve sustainability (Fig. 3) owing to material losses of current mature technologies, which must be compensated by virgin production and ultimately lead to the transgression of the planetary boundaries.

The maximum recycling rate of 94% includes mechanical recycling of pure plastic mono-streams (39%) and chemical recycling of mixed plastics via pyrolysis (55%). Chemical recycling treats plastics that are not suitable for mechanical recycling because of contaminants, additives or their inability to be reprocessed[31]. Material losses result from chain degradation in the mechanical recycling[32] and moderate yields of the pyrolysis-based chemical recycling of mixed plastics[33,34]. Owing to the material losses, recycling of 94% of all plastic waste corresponds to an effective recycling rate of 70%, that is, 70% of the waste is reused in plastic production. The chemical recycling of polymers such as polyethylene or polyvinyl chloride is particularly challenging owing to the strong carbon–carbon bonds in the polymer backbone. Furthermore, deconstructing plastic waste to pyrolysis oil and other hydrocarbons requires the reproduction of monomers, resulting in increased environmental impacts. Overall, the planetary footprints of plastics could be further reduced if recycling yields increase, either by improving the mature recycling technologies considered in this

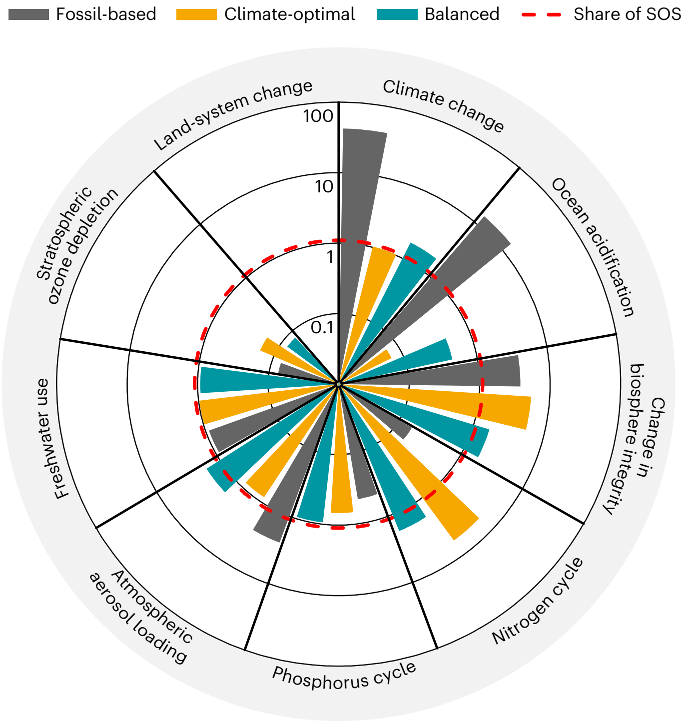

Fig. 2 | The planetary footprint of the plastics industry for three pathways. The pathways comprise a fossil reference (fossil-based), the optimal combination of circular technologies to minimize the global warming impact of the plastics industry (climate-optimal), and the optimal combination of circular technologies to minimize the maximal transgression of the share of SOS of the plastics industry (balanced). The planetary footprints are calculated for production volumes in 2030. The planetary footprints are shown as percentage of global SOS. The share of SOS assigned to the plastics industry is highlighted in red.

study or by applying highly selective emerging technologies such as solvolysis or enzymatic hydrolysis (Supplementary Fig. 1)[35].

Bio-based and CCU-based plastics can reduce climate change

The inefficiencies of current plastic recycling and the residual landfilling require the virgin production of plastics. Switching the remaining virgin production from fossil resources to biomass or CO_2 as feedstock reduces the share of climate change to 1.0 and 2.3% of the SOS, respectively (Fig. 3, green and blue bars). The bio-based production, which corresponds to the climate-optimal solution from Fig. 2, complies with the assigned share of SOS for climate change as the carbon uptake during biomass growth offsets CO_2 emissions from plastic production and waste treatment. The remaining footprint results from fossil resource use in biomass cultivation (Supplementary Information, section 3).

CCU-based production still exceeds its assigned SOS for climate change owing to the large amounts of electricity needed for hydrogen generation through water electrolysis[36]. Consistent with this, previous studies found the carbon footprint of the electricity mix to be crucial for GHG mitigation[13,37]. Even the electricity mix in 2030 from the International Energy Agency Net Zero by 2050 scenario[38] leads to a climate impact of CCU-based production that is 47% higher than fossil-based production (Fig. 3, dark blue bar). Therefore, we assume wind power representing a best-case renewable energy mix for GHG emissions and thereby assess the maximum potential of CCU to reduce the planetary footprints of plastics (Fig. 3, light blue bar).

Mitigating burden shifting from bio-based plastics

Using biomass for the remaining virgin plastic production leads to an unsustainable burden shift from climate change to other Earth-system processes if energy crops are used (Fig. 3, green bars). Impacts on biosphere integrity increase because of higher land occupation. Furthermore, the N cycle footprints result from fertilizers for biomass cultivation, stressing the importance of fertilizer management to reduce nitrogen surpluses[39]. Similarly, 70% of the P cycle footprint results from phosphorus-containing fertilizers for biomass cultivation. Biomass cultivation also causes 80% of aerosol loading (Fig. 4), of which 52% originates from agricultural machinery (Supplementary Information, section 3).

Freshwater use considers the consumption of blue water, that is, water sourced from surface or groundwater resources. Evaporated cooling water for heat removal in chemical processes contributes to 80% of freshwater use. By contrast, process water and irrigation of biomass have only a minor impact (Fig. 4). Furthermore, the planetary footprints of ozone depletion and land-system change are low and within the share of SOS for all production pathways (Fig. 3). The footprint in land-system change is low despite the land use for biomass cultivation of 1.15 m^2 per kilogram of plastics. This land is assumed to be cropland for the considered energy crops, which therefore do not require the transformation of forested land (see Supplementary Information for details). However, the control variable of the land-system change planetary boundary currently considers only the transformation of forested land, while the literature suggests that it is necessary to assess land-system changes beyond forested land in the future[40]. Nevertheless, the observed land use requirements from biomass cultivation already contribute to the biosphere integrity impact (Fig. 4).

Overall, the planetary footprints of bio-based plastics mainly result from biomass cultivation (Fig. 4). A sensitivity analysis for multiple biomass sources shows environmental trade-offs (Supplementary Fig. 3). Lignocellulosic feedstocks from forestry reduce fertilizer demand, decreasing the N cycle footprint (<0.6% of the SOS), while their lower yields increase land occupation and, thus, losses in biosphere integrity (4–20% of the SOS). Furthermore, certain biomass feedstocks might not be suitable for large-scale plastic production because of limited availability. Therefore, using multiple biomass feedstocks could help to ensure sufficient availability while keeping negative trade-offs at a minimum.

Mitigating burden shifting from CCU-based plastics

CCU-based plastic production increases aerosol loading to 2.1% and P cycle to 1.1% of the global SOS even when wind power is the energy source (Fig. 3, light blue bars). Thus, basing the remaining virgin production solely on CCU is unsustainable in terms of the assigned share of SOS. Aerosol loading originates 95% from electricity generation primarily because of coal-based steel production for wind turbines. Electricity generation also causes 96% of the P cycle footprint (Fig. 4). The emissions of phosphorus-containing substances originate from the construction of wind turbines. The P cycle footprint of wind turbines is linked to copper mine tailings (26%) and coal-based steel production (48%). However, wind turbines will not be the only large-scale renewable energy source globally. A sensitivity analysis showed that photovoltaics and geothermal power would increase the planetary footprints of climate change to 21% and 10% of the global SOS and the P cycle footprints to 7.7 and 3.0% of the global SOS, respectively (Supplementary Fig. 4). In contrast, hydro, nuclear and wind power are more promising technologies for the sustainable production of CCU-based plastics, as they all have similar planetary footprints. The analysis shows that improving sustainability requires reduction of environmental impacts from the construction of electricity generation technologies.

Towards sustainability by improving recycling processes

The plastics industry can significantly reduce its planetary footprint by switching the feedstock from fossil resources to a combination of plastic waste and renewable resources. Recycling reduces the demand for renewable resources and thus is the key enabler to mitigate burden

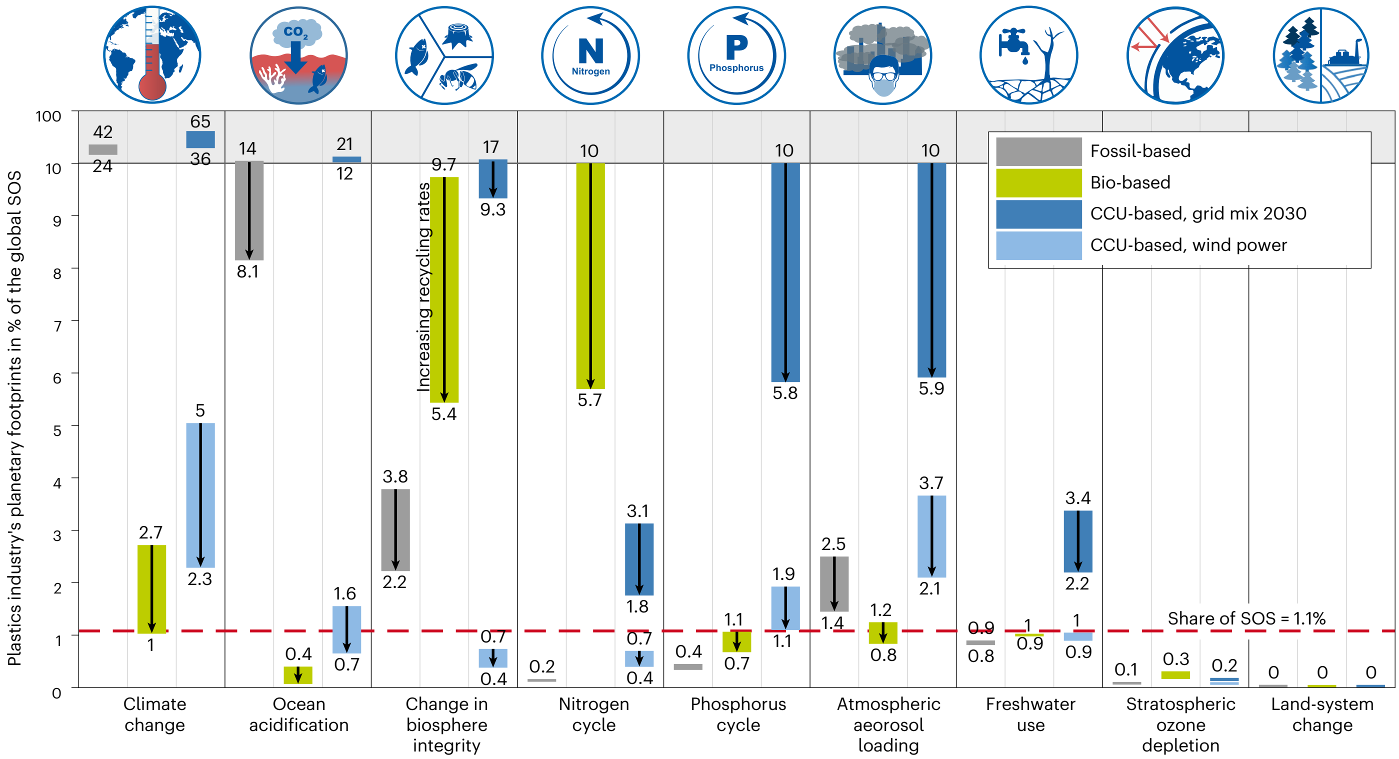

Fig. 3 | The planetary footprint of the plastics industry for three pathways. The planetary footprints are calculated by minimizing the environmental impact of climate change for production volumes in 2030 (details in Methods). The pathways include fossil-based (grey), bio-based (green) and CCU-based (light and dark blue) plastics, with recycling rates corresponding to the current value (upper value) and the maximum value of 94% (lower value). The only exception is the freshwater use of bio-based plastics, for which the lower value represents the current recycling rate. The arrows indicate increasing recycling rates. The dark blue bars for CCU-based plastics show planetary footprints when applying the grid mix in 2030 from the Net Zero by 2050 scenario of the International Energy Agency, and the light blue bars assume wind power to represent a decarbonized grid mix[38].

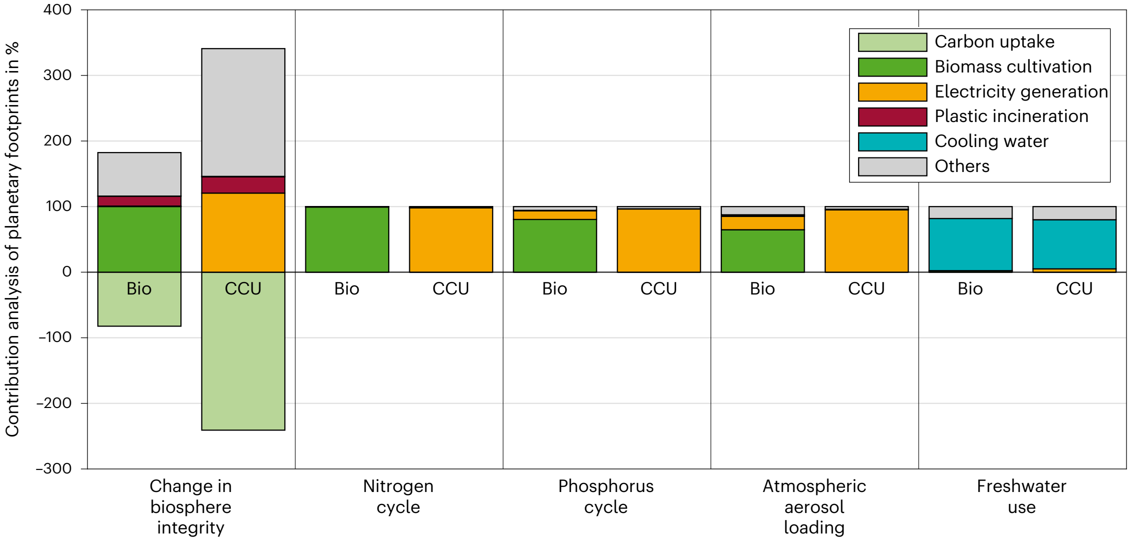

Fig. 4 | Contribution of processes to planetary footprints. The process contribution to the planetary footprints in biosphere integrity, nitrogen cycle, phosphorus cycle, atmospheric aerosol loading and freshwater use. For all other planetary footprints, see Supplementary Information. The left side of each pair shows the pathways based on biomass (Bio), and the right side shows the pathway based on CCU, both using maximum recycling rates. The net footprints correspond to the lower value of the green and light blue bars in Fig. 3.

shifting. Therefore, increasing circularity via recycling technologies is currently the most promising approach to mitigate GHG emissions and simultaneously improve sustainability (Fig. 3). Yet, current recycling technologies fail to achieve sustainability in the plastics industry.

We therefore explore the potential of increasing recycling process yields to improve the sustainability of plastics. For this purpose, we define an optimistic scenario to assess emerging chemical recycling technologies by assuming a yield of 95%. Such high yields are optimistic,

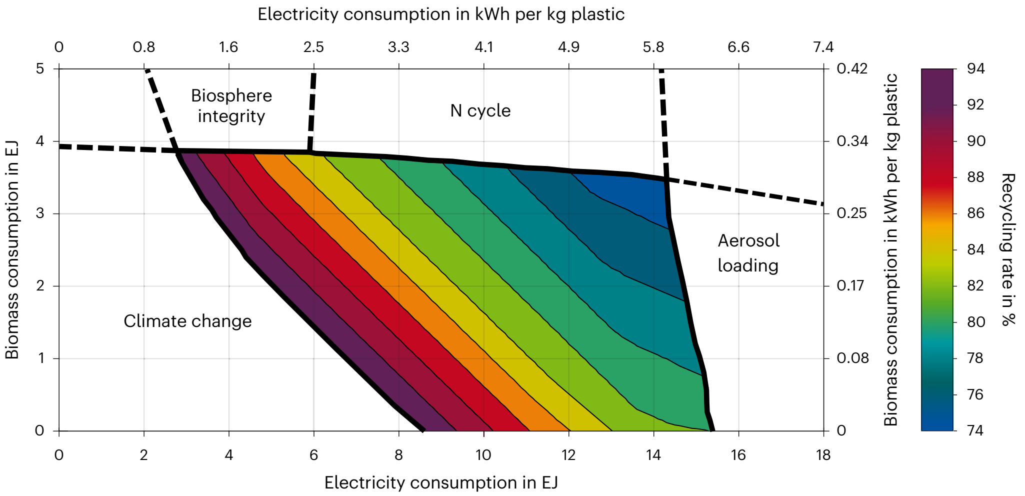

Fig. 5 | Absolute environmental sustainability of plastics as a function of renewable resource consumption and recycling rates. The planetary footprints are calculated for production volumes in 2030. The plastics industry's assigned share of the SOS is limited to 1.1% for all Earth-system processes. The coloured area represents the zone of sustainable plastics in which all planetary footprints are below the assigned share of SOS. Each point in the coloured zone represents a plastics industry that consumes wind power (*x* axis) and biomass (*y* axis) at various recycling rates (colour gradient). In contrast, plastics are considered unsustainable in white areas. Labels of the lines surrounding the solution space refer to the planetary footprint exceeded first when leaving the solution space. Chemical monomer recycling technologies are assumed to have a 95% yield (see Supplementary Information for details).

given that the highest reported yields range from 70 to 90%[41–44]. However, the 95% yield complies with the default assumption for chemical processes in the well-established LCA database ecoinvent[45]. Moreover, incumbent chemical processes achieve even higher yields, for example, by up to 99% for methanol and acetic acid production[46]. In addition to the 95% yield, the optimistic scenario considers wind power as the source of electricity, while energy crops represent biomass owing to their capacity for large-scale application[47].

This optimistic scenario indicates a potential for producing sustainable plastics in 2030 (Fig. 5): the minimum recycling rate that achieves sustainability is about 75%, with 39% of the plastics being recycled mechanically and 35% chemically. Lower recycling rates increase the demand for renewable resources to the extent that the assigned share of SOS would be transgressed because of aerosol loading from electricity supply or the N cycle footprint from biomass supply. Under the minimum recycling rate, the plastics industry consumes 14.3 EJ of wind power and 3.5 EJ of biomass compared to the 21.6 EJ of naphtha for the fossil-based plastics industry under current recycling rates and 10.5 EJ for maximum recycling.

Without biomass, a sustainable plastics industry requires a minimum recycling rate of 82%, consuming 15.3 EJ of wind power. According to the optimistic scenario, it is possible to produce circular CCU-based plastics within planetary boundaries in 2030. The demand for wind power can be decreased to 8.6 EJ by maximizing recycling rates to 94%. However, reducing the demand for wind power even further while complying with the assigned share of SOS requires biomass. Ultimately, reducing wind power is limited to about 2.8 EJ at the maximum recycling rate and a biomass demand of 3.9 EJ. Requiring more than 3.9 EJ of biomass exceeds the plastics' share of SOS in biosphere integrity. Thus, circular bio-plastics cannot achieve sustainability.

In summary, high recycling yields enable multiple sustainable pathways for 2030 when assigning the plastics industry's share of the SOS based on economic indicators. However, the development and scale up of such recycling technologies require time. Thus, reaching market readiness by 2030 is hardly achievable. In addition, covering a major share of end-of-life treatment of plastics seems unrealistic. Therefore, we extend our assessment to a scenario for 2050 (Supplementary Fig. 5)[11]. In the 2050 scenario, the planetary footprints of the plastics industry increase owing to higher demand for plastics. As a result, the plastics industry exceeds its assigned share of SOS even with high recycling yields. This finding suggests that the remaining virgin production needs to reduce its environmental impacts. Otherwise, the demand in 2050 will compromise the sustainability of plastics. Nevertheless, recycling is the key towards environmentally sustainable plastics as it keeps virgin production to a minimum.

Together, the assessments for 2030 and 2050 emphasize the potential of high recycling yields and the challenge of the growing plastics demand for achieving sustainable plastics. However, the growing plastics market is not only a challenge but may also alter the allocation of the shares of the SOS. If the plastics market grows faster than the average economy, its contribution to the economy will grow. Consequently, the share of the SOS of the plastics industry of would increase if economic indicators were used for downscaling. However, using economic indicators for downscaling is controversial (see the Discussion). Nevertheless, a growing recycling market could additionally increase the value of the plastics market by making plastic waste a valuable resource.

Discussion

This study determines the absolute environmental sustainability of GHG mitigation strategies for plastics by combining a bottom-up model of the plastic industries with the planetary boundaries framework. The key assumptions for the assessment concern the yield of recycling processes, biomass feedstocks and renewable electricity generation. Furthermore, the share of SOS of the plastics industry, and thus the sustainability threshold for plastics, is assigned based on consumption expenditure.

Our results show that combining high recycling rates with renewable feedstocks improves the absolute sustainability of plastics. If the plastics industry achieves a 75% recycling rate with advanced recycling technologies in 2030, plastics can comply with their assigned share of the SOS and be considered absolute environmentally sustainable regarding the considered eight planetary boundaries. The remaining virgin plastic production would predominantly rely on CO_2 and renewable electricity from wind, hydro or nuclear power. A smaller portion of plastics would come from biomass.

The required recycling rate contrasts with the current recycling rate, of about 23%, highlighting the need to foster recycling through efficient policies. For instance, a barrier to increasing recycling rates is the mismanagement of plastic waste. Mismanagement of plastic waste (for example, by open burning, which is also associated with human health issues) often occurs in low- and middle-income countries[1,48]. As stated by the Organisation for Economic Co-operation and Development, fostering recycling and reducing mismanagement require the development of recycled plastic markets promoted by push-and-pull strategies[1]. A suitable push strategy could extend plastic producer responsibility beyond the factory gate, whereas pull strategies could set design requirements or targets for recycled plastic content in new products. The design of plastic products already determines their current recycling ability and, thus, their sustainability. Some products made of pure plastics can already be treated efficiently by mature mechanical recycling, while mixed plastics must be treated by less efficient pyrolysis. However, the high recycling rates, technological developments and favourable policies will hardly be achievable by 2030. In contrast, these requirements might be achievable by 2050 but will still be insufficient to cope with the expected growth of the plastics market, as shown by the scenario for 2050 (Supplementary Fig. 5).

High recycling rates reduce renewable feedstock consumption and the corresponding environmental impacts. The remaining feedstock has to be supplied by renewable resources (that is, biomass or CO_2 via CCU) . However, current farming practices limit the share of bio-based production for sustainable plastics. Increasing the share of bio-based plastics requires promoting practices that close nutrient cycles and push the sustainable intensification of agriculture (details in Supplementary Information)[39].

CCU-based plastics rely heavily on renewable electricity. In this study, environmental sustainability could only be achieved using wind, hydro or nuclear power, whereas even optimistic scenarios for future grid mixes fail to achieve sustainability. Using nuclear power raises social and political concerns[49], regional topography limits the large-scale application of hydropower (Supplementary Information, section 3), and wind power is intermittent, challenging the mostly continuous production of plastics. However, the analysis shows the potential to combine several low-carbon electricity sources. If required, the dependence on renewable electricity can be reduced by combining CCU- and bio-based production, which also increases feedstock flexibility[19].

The availability and environmental impact of biomass and renewable electricity vary by region. In addition, waste management systems show large regional variations in recycling efficiencies and emissions from waste incineration[1]. Therefore, future studies should focus on regionalized assessments that address regional boundaries and deviations in ecosystem functions and species richness[50].

Assessing regional boundaries requires further downscaling. In this study, the globally averaged economic indicator of consumption expenditure was chosen to assign a share of the SOS (1.1%) to the plastics industry. However, economic indicators differ widely by region. In particular, low-income countries show other consumption behaviours by spending a higher share of their expenditures on fundamental needs such as food or healthcare. As the purchasing power of these countries is low, their fundamental needs are underrepresented by a global average. A regionally adapted indicator of consumption expenditure results in a lower share of SOS from an initial 1.1, to 1.0% (see Supplementary Information, section 2), which would add to the pressure on the plastics industry to reduce its planetary footprint. In addition, applying economic indicators themselves to represent human needs is widely discussed (see Supplementary Information for details)[28,29]. As there is currently no scientific consensus, we also discuss non-economic downscaling principles in Supplementary Information. For instance, downscaling based on a capability to reduce approach may increase the share of SOS for plastics. However, these other approaches are currently not quantifiable. Thus, downscaling should be further explored, for example, by applying science-based target methods such as the sectoral decarbonization approach[51–53].

The planetary boundaries framework has been defined for nine Earth-system processes[21]. Our analysis covers the eight systems for which quantitative methods are available. Only quantifying novel entities is not yet possible as neither control variables nor a SOS has been defined (details in Supplementary Information). The process of novel entities refers to the release of substances and modified life forms with unwanted geophysical or biological effects on the environment[21]. Nevertheless, it has been proposed that increasing plastic recycling, as suggested in this study, would reduce the amount of plastics entering the environment, thereby reducing plastic pollution and the pressure on novel entities[26].

Increasing recycling rates tackles all pillars of the triple planetary crisis addressed by the United Nations Environment Programme agreement[6]. Therefore, fostering recycling could become a win–win–win situation, avoiding pollution, habitat loss and other environmental impacts while conserving valuable resources and increasing the value of plastic waste at the same time. However, the 36–51% higher capital expenditures provide an implementation barrier for circular technologies, although total annualized costs are similar to fossil-based production[54]. Thus, additional investment incentives are required, which may come from governments or other stakeholders interested in increasing the sustainability of plastics. Overall, reducing plastic consumption while treating plastic waste as a valuable resource will be essential for reducing the planetary footprint of plastics. Accordingly, society needs to decide whether or not to stop considering plastics as cheap and disposable and to start placing a higher value on this versatile and durable product.

Methods

Goal and scope of the study

The goal of this study was to assess the planetary footprints of GHG mitigation strategies for the global production of plastics. To calculate planetary footprints, we apply LCA in combination with the planetary boundaries framework as proposed by ref. [22]. As GHG mitigation strategies, we consider recycling, bio-based production and production via CCU, and compare their planetary footprints to the planetary footprints of fossil-based plastics. We use a bottom-up model covering >90% of global plastic production for 2030 (and 2050, Supplementary Information, section 3). The bottom-up model builds on the plastic production system from ref. [10] and includes plastic production, the supply chain and the disposal of plastics at the end of life.

Functional unit

In LCA, the functional unit quantifies the functions of the investigated product system. In this study, the function of the product system is the production and disposal of >90% of global plastics. To cover >90% of global plastics, we define the functional unit as the yearly global production and disposal of 14 large-volume plastics (summarized in Supplementary Table 5). We estimated the yearly production volumes for 2030 and 2050 based on the production volumes in 2015 and the annual growth rates shown in Supplementary Table 5.

Our assessment includes plastic disposal. However, the production and disposal of plastics do not necessarily occur in the same year. For instance, while polyolefins used for plastic packaging have an average lifetime of 6 months, the average lifetime of polyurethane used in construction is 35 years[11]. Including the lifetime of plastics, and hence, the temporal difference between production and disposal, would lead to an increasing plastic stock. An increasing stock, in turn, represents a carbon sink during the production year that appears to enable the production of net-negative GHG emission plastics based on biomass or CCU. However, the plastic stock is not a permanent carbon sink, which would be required for producing net-negative GHG emission plastics[55]. To avoid misleading conclusions about net-negative bio- and

CCU-based plastics, we assign the planetary footprints from disposal to the year of plastic production. Thereby, we conservatively assess the planetary footprints of plastics.

In addition, we address the challenge highlighted in ref. [56] that the increasing demand for plastics renders determining the absolute sustainability of plastics difficult. We meet this challenge by assuming a steady-state production system with a recurring functional unit in the same amount every year. We thereby analyse discrete scenarios with constant consumption levels for plastics. Therefore, our conclusions depend on the accuracy of the demand forecasts and apply only to the production volumes considered.

System boundaries

We use cradle-to-grave system boundaries, including plastic production and supply chain, potential recycling and final disposal at the end of life. Assessing the use phase of plastics is not possible because of a lack of data. The versatile properties of plastics result in a wide range of applications that cannot be represented in a single study. Furthermore, it would be necessary to consider not only the emissions of the use phase (probably relatively small) but also the system-wide environmental consequences of using plastics in each application compared to other materials. Thus, a consequential assessment of the plastic use phase is desirable but beyond the scope of this study.

The plastics supply chain includes several intermediate chemicals such as monomers, solvents or other reactants. The bottom-up model covers the production of all intermediate chemicals in the foreground system. As a background system, we use aggregated datasets from the LCA database ecoinvent. A list of all intermediate chemicals and all aggregated datasets can be found in Supplementary Information, section 1. In addition, the foreground system of the bottom-up model does not include environmental impacts from infrastructure and transportation because of a lack of data. However, we consider the environmental impacts of infrastructure and transportation from other industrial sectors by aggregated datasets, for example, from electricity generation and biomass cultivation.

The bottom-up model includes the best available fossil-based technologies and the following technologies for plastic disposal and virgin production based on biomass and CCU.

Plastic waste disposal

The bottom-up model includes three options for plastic waste disposal: landfilling, incineration with energy recovery and recycling. Plastic waste can occur in several forms: as sorted fraction of municipal solid waste, as mixed plastics and residues from sorting, and as residues from mechanical recycling. For all fractions, we include waste incineration with energy recovery and landfilling.

Landfilled plastic waste is assumed to degrade by approximately 1% of the contained carbon, which is in line with the ecoinvent database[45]. Mechanical recycling is only modelled for sorted fractions of packaging waste owing to impurities of mixed and non-packaging wastes. In contrast, chemical recycling can be applied to all plastic fractions. In this study, we model chemical recycling as pyrolysis to refinery feedstock, that is, naphtha. The pyrolysis has yields of 29 to 69% depending on the type of plastic (details in Supplementary Information, section 1). Furthermore, we include options for chemical recycling of plastic waste to monomers, which are still early-stage technologies. To derive the minimal necessary recycling rate in Fig. 5, we apply an optimistic scenario with a 95% yield of chemical recycling processes following common modelling in life-cycle inventories of chemicals (Supplementary Information, section 3)[57]. All calculations are constrained to maximum recycling rates of 94% as the remaining 6% are assumed to be the minimal landfilling rate until the middle of the century[11]. The assumption is based on historical trends in end-of-life treatment of plastics.

Bio-based production

Bio-based GHG mitigation is frequently discussed in the literature and is often associated with competition with the food industry[58]. To avoid competition with the food industry, the bottom-up model is restricted to lignocellulosic biomass as feedstock, that is, energy crops, forest residues and by-products from other industrial biomass processes (for example, bagasse). In this study, unless mentioned otherwise, we model biomass as energy crops because of their potential for large-scale application (Supplementary Information, section 3). However, we conduct a sensitivity analysis for other lignocellulosic biomass sources to assess the sustainability of bio-based plastics in more detail.

For each biomass type, we account for the carbon uptake during the biomass growth phase by giving a credit corresponding to the biomass carbon content. We do not consider land use change emissions as current literature lacks an assessment of land use change effects on other Earth-system processes besides climate change.

For biomass processing, we include the following high-maturity processes: gasification to syngas and fermentation to ethanol, and the subsequent conversion to methanol and ethylene (Supplementary Table 1). Methanol and ethylene can be further converted to propylene and aromatics, which all together represent the building blocks for all plastics in this study.

CCU-based production

CCU-based plastic production particularly requires CO_2 and hydrogen. For CO_2 supply, we consider CO_2 capture from highly concentrated point sources within the plastics supply chain. Highly concentrated point sources include the conventional fossil-based processes, ammonia production, steam methane reforming, ethylene oxide production, the bio-based processes for ethanol and syngas, and plastic waste incineration. Capturing from processes within the plastics supply chain is limited by the amount of CO_2 emitted by these processes and avoids the corresponding emissions. For these processes, we considered the energy demand for compressing the CO_2 with 0.4 MJ of electricity[59]. For waste incineration, we consider a decrease in energy output when capturing CO_2. All further CO_2 sources are conservatively approximated by direct air capture. For 1 kg CO_2 captured via direct air capture, we include an uptake of 1 kg of CO_2 equivalent while considering the energy demand of 1.29 MJ electricity and 4.19 MJ heat[60].

Hydrogen for CCU is produced by water electrolysis, with an overall efficiency of 67%[61]. Previous studies have already shown that renewable electricity is required for CCU to be environmentally beneficial[13]. Thus, we conduct a sensitivity analysis for multiple electricity technologies to assess their influence on the sustainability of CCU-based plastics (Supplementary Information).

For CCU-based production, we include high-maturity technologies, such as CO_2-based methanol and methane, as well as subsequent production of olefins and aromatics (Supplementary Table 1). We do not consider CCS as an additional scenario, as fossil resources and storage capacities are ultimately limited. Therefore, CCS may serve as an interim solution for GHG mitigation but stands in contrast to long-term sustainability as the goal of this study.

Pathway definition

We assess nine pathways for the plastics industry towards sustainability. Pathway 1 is fossil-based plastic production (current recycling rate of 23%) that serves as a reference. We also include two pathways that combine all circular technologies: Pathway 2, which minimizes the climate change impact (climate-optimal), and pathway 3, which minimizes the maximal transgression of the share of SOS of the plastics industry (balanced) (Fig. 2). To assess the impact of switching from fossil to renewable feedstocks, we introduce pathway 4, which is bio-based, and pathway 5, which is CCU-based (Fig. 3). Pathways 4 and 5 include the current recycling rate of 23%. In addition, we introduce three pathways with the maximum recycling rates of 94%: pathway 6, in which the remaining virgin production is based on fossil resources; pathway 7, in which it is based on biomass; and pathway 8, in which it is based on CO_2 (Fig. 3). Pathway 9 combines biomass, CCU and recycling, and additionally includes chemical recycling of polymers to monomers to calculate the minimal recycling rate to achieve sustainable plastics (Fig. 5).

The planetary boundaries framework

We follow the recommendations for absolute environmental sustainability assessment in ref. [29] and choose the planetary boundaries framework for the assessment. The planetary boundaries framework suits the goal of the study best because of its precautionary principles for the definition of environmental thresholds, the SOS. We assess eight of the nine Earth-system processes suggested in ref. [21], namely, climate change, ocean acidification, changes in biosphere integrity, the biogeochemical flow of nitrogen and phosphorus (referred to as N cycle and P cycle), aerosol loading, freshwater use, stratospheric ozone depletion, and land-system change. We do not assess the Earth-system process of novel entities since neither control variables nor the boundary itself is yet adequately defined[22]. We consider the global boundaries for the Earth-system processes in line with the scope of this study. These global boundaries and the corresponding calculation of planetary footprints are subject to assumptions and thus incorporate uncertainty (Supplementary Information, section 2).

For the two subprocesses for climate change (namely, atmospheric CO_2 concentration and energy imbalance at the top-of-atmosphere), we only consider the energy imbalance at the top-of-atmosphere quantified by radiative forcing. We focus on radiative forcing, as the control variable is more inclusive and fundamental, and the global limits are stricter than for atmospheric CO_2 concentration[21]. Thereby, we conservatively assess climate change.

Biosphere integrity is divided into functional and genetic diversity of species. Preserving functional diversity ensures a stable ecosystem by maintaining all ecosystem services. We assess the functional diversity of species using the method proposed in ref. [18]. The method covers the mean species abundance loss caused by the two main stressors, direct land use and GHG emissions, as a proxy for the biodiversity intactness index. Genetic diversity provides the long-term ability of the biosphere to persist under and adapt to gradual changes of the environment[21]. Genetic diversity is often approximated by the global extinction rate. However, using the global extinction rate does not fully cover variation of genetic composition, resulting in high uncertainties when quantifying genetic diversity[18]. Thus, we focus on functional diversity.

Downscaling of the safe operating space

As the plastics industry accounts for only a fraction of all human activities, we assign a share of the SOS to plastics. The plastics industry should operate within its assigned share to be considered environmentally sustainable. To assign a share of SOS to the plastics industry, we apply utilitarian downscaling principles. Utilitarian downscaling principles are tailored to maximize welfare in society[29]. We approximate welfare by consumption expenditure on plastics as an economic indicator for consumer preferences and human needs[62]. An extensive discussion on the other downscaling principles and their implications can be found in Supplementary Information.

Although the final consumption expenditures on plastics are negligible, the industry consumes plastics to produce other goods and services. Accordingly, plastics are produced mostly in the upstream supply chain to support the final consumption of other goods and services. Thus, consuming other goods and services induces plastic production. To account for this inducement of plastic production, we used the total global plastic production x_{plastics} to represent the global intermediate and final consumption expenditure on plastics. For this purpose, we use the gross output vector x of the product-by-product input–output table of EXIOBASE for the year 2020 (ref. [63]). To calculate the share of SOS of the plastics industry, we divide the total global plastic production x_{plastics} by the gross world product. The gross world product equals the total global final consumption expenditure. Analogously, we also consider the end-of-life treatment of plastics to be consistent with the system boundaries of the environmental assessment.

We estimate the share of SOS for the plastics industry for 2030 and 2050 based on data for the year 2020. Accordingly, we assume that the market share of the plastics industry and, therefore, its share of SOS do not change in the coming years despite the increasing production volume of plastics. Thereby, we implicitly assume that all industries grow equally economically. Alternatively, economic forecasting models could estimate future market shares of plastics. However, applying economic forecasting models is complex, and the results would still be highly uncertain, especially if industry pursues low-carbon technology pathways. Therefore, estimating future market shares is beyond the scope of this study.

Technology choice model

To calculate the planetary footprint of plastics, we use a bottom-up model of the plastics industry. The model builds on the technology choice model (TCM) that allows for linear optimization of production systems[27]. The TCM represents the production system based on the following elements: technologies, intermediate flows, elementary flows and final demands. Ref. [27] describes each element in detail.

The TCM is based on the established computational structure of LCA[64]. This structure arranges the data that represent the physical production system in the technology matrix A and the elementary flow matrix B. In the technology matrix A, columns represent technologies, and rows represent intermediate flows. Therefore, the coefficient a_{ij} of the A matrix corresponds to an intermediate flow i that is either produced ($a_{ij} > 0$) or consumed ($a_{ij} < 0$) by technology j.

The final demand describes the total output of plastics and the total input of plastic waste. Thus, the final demand corresponds to the functional unit. The final demand for intermediate flow i is described by entry y_i in vector y.

The elementary flow matrix B includes all technologies j and all elementary flows e, that is, flows that are exchanged between the production system and the environment. Accordingly, the coefficient b_{ej} shows an elementary flow e that is either taken from ($b_{ej} < 0$) or emitted to ($b_{ej} > 0$) the environment by technology j. To calculate the environmental impacts of elementary flows, the elementary flows are characterized by the characterization matrix Q. In Q, columns represent elementary flows e, and rows represent life-cycle impact assessment methods z.

We incorporated the life-cycle impact assessment methods for planetary boundaries proposed in refs. [18,22–24] as environmental impact categories in the Q matrix. In addition, we adapted several characterization factors to increase consistency (Supplementary Information, section 2).

For each intermediate product, the bottom-up model includes multiple technologies, allowing for a choice between technologies. The TCM employs linear optimization to identify the technologies with the lowest environmental impact. As the goal of this study is to assess the sustainability of GHG mitigation strategies, we choose the climate change planetary footprint as the objective function, which can be calculated as

$$PF_{CC} = q_{CC}Bs \tag{1}$$

All other planetary footprints are calculated after the optimization. The scaling vector s is defined to adjust the quantities of intermediate and elementary flows. Overall, we define the optimization problem as

$$\min PF_{CC} = q_{CC}Bs \tag{2}$$

$$s.t. As = y \tag{3}$$

$$s \geq 0 \tag{4}$$

$$s \leq c \tag{5}$$

$$q_z Bs \leq PF_z \tag{6}$$

where equation (3) specifies the production and consumption of the final demand, that is, the global demand for plastics and their end-of-life treatment. Equations (4) and (5) represent the constraints that the entries of the scaling vector must be between zero and an optional technology constraint (for example, a maximum recycling rate). Equation (6) defines additional optional constraints for planetary footprints in other Earth-system processes, for example, to calculate the minimum recycling rates at which plastics are produced within all planetary boundaries or to limit the maximal transgression of the share of SOS of the plastics industry. Limiting the maximum transgression is used to find the balanced solution in Fig. 2. We normalize the resulting planetary footprints by the SOS defined by ref. [21].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are publicly available. However, in some cases a user license from IHS Markit is required to access the underlying data. To gain access, IHS Markit can be contacted (details at https://ihsmarkit.com/products/chemical-technology-pep-index.html). All data for modelling the production system are archived at Zenodo (https://doi.org/10.5281/zenodo.5118762). The characterization matrix for the elementary flows to planetary footprints is archived at Zenodo (https://doi.org/10.5281/zenodo.6701485).

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Author contributions

M.B. and C.Z. contributed to study conceptualization, methodology, data curation and validation, and wrote the original draft and the manuscript. J.H. and V.T. assisted in developing the methodology, validation, and review and editing of the manuscript. J.H. assisted in data curation. S.S. contributed to the downscaling methodology and reviewed and edited the manuscript. G.G. and A.B. supervised the project and assisted in writing the manuscript. A.B. contributed to study conceptualization and acquired funding. All authors contributed to discussions and to finalizing the manuscript.

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Competing interests

A.B. and S.S. have ownership interests in firms that render services to industry, some of which may produce polymers. A.B. has served on review committees for research and development at ExxonMobil and TotalEnergies, oil and gas companies that are also active in polymer production. All other authors have no competing interests.

Additional information

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Study description	We have conducted a simulation study based on a bottom-up model of more than 400 life cycle assessment datasets.
Research sample	Not applicable, no sampling applied
Sampling strategy	Not applicable, no sampling applied
Data collection	The bottom-up model used in this study is taken from Meys. et al (2021) as stated in the manuscript.
Timing and spatial scale	We conduct a global study on plastics production for the year 2030 and 2050.
Data exclusions	No data were excluded
Reproducibility	Not applicable, we have not conducted any experimence in this study.
Randomization	Not applicable, randomization is not relevant for a simulation study
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