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FRIENDS OF THE EARTH GERMANY

Sustainable Chemicals and Materials Policy for Protecting the Climate and Biodiversity

Contents

Abstract

Chemicals and materials policy deals with both the risks and the opportunities of chemicals as well as with the volume of material flows from raw material extraction to waste. As with the policy areas of climate and biodiversity, there is a need for a global transformation in chemicals and materials policy with a strong focus on the guiding principles of precaution and sustainability. The boundaries of our planet must no longer be exceeded. BUND has outlined the challenges of a sustainable chemicals and materials policy in a recently published position paper [BUND 2019a].

The impacts of chemicals and materials are closely related to climate change and biodiversity. Without a substantial change in the mode we deal with substances and thus in our economic practices and lifestyles, the goals of the international agreements on climate and biodiversity will not be achieved.

About one third of greenhouse gas emissions are related to the production of substances and materials, their processing and the increasing global transport of goods. In some important processes, such as steel and cement production, it is not only the energy input during manufacture that plays a role. For example, the blast furnace process releases very high greenhouse gas emissions from the added coal. Urgent measures therefore include a rapid expansion of steel production using hydrogen instead of coal, the increased use of secondary instead of primary raw materials, and the conversion of chemical production to a renewable material basis (feedstock) in order to replace mineral oil consumption.

Climate change also has consequences for the behaviour and effects of substances in the environment: higher temperatures lead to increasing concentrations of air pollutants in the atmosphere. Some substances are transported over long distances to a greater extent and can accumulate in polar and alpine regions. Changing climatic conditions often no longer meet the needs of living organisms in their habitats. The impacts of toxicity and ecotoxicity of chemicals are increasing. In addition, extreme weather events such as floods can lead to the mobilization of pollutants.

The ever increasing chemical and material load also threatens biodiversity. Mining is devastating landscapes. Metal smelting and the manufacture of chemicals and products release toxic substances into the air, water and soil. Plastics endanger the diversity of living organisms and habitats worldwide. Intensive agriculture and the associated application of pesticides and fertilizers are damaging the biocoenosis in agrarian landscapes. The destruction of natural habitats through the cultivation of renewable raw materials is increasingly threatening the survival of endangered species. In addition, the global trade promotes the spread of invasive species, one of the most important drivers of biodiversity loss.

Biodiversity losses, in turn, result in the loss of ecosystem services and has consequences for us. It may also affect the diversity of human-used natural substances. Numerous plants, animals and microorganisms are disappearing and with them undiscovered substances that may be very important for medicine and other uses in future.

The goal is a sustainable management of chemicals and materials,

- in which reuse and recycling are considered from the outset;
- where chemical products do not exhibit hazardous properties that harm environment and human health;
- in which chemical production is designed in such a way that it does not pose a risk to people or the environment;
- where material flows are managed in such a way that they do not exceed planetary boundaries.

Three strategies are crucial to sustainable material flow management, complementing each other. In addition to improving the ratio of input to output (effi-

ciency) and focusing on human frugality (sufficiency), the strategy of consistency is particularly important. It embeds technologies and material flows in natural cycles. These three strategies require *inter alia* a trend reversal not only in chemical production, but in the entire economy and society as a whole. A significant reduction in production volumes is necessary. It is only by slowing down and reducing material flows that we can manage to achieve the goals of climate and biodiversity policy.

Biodiversity, climate change and chemicals and materials policy are closely intertwined. All three global challenges must be addressed and solved together. Binding international agreements already exist for climate change and biodiversity, but not yet for chemicals and materials policy, although it has a comparable influence on the fate of the planet. Thus, there is a need for a binding global framework agreement on substances aiming to replace the current fragmented approaches and non-binding exchange forums like SAICM.

1. Introduction

Chemicals and materials policy extends far beyond what is traditionally viewed as chemicals policy. In this publication the term "substance" is understood in a very comprehensive way. In addition to chemicals, the overarching concept of chemicals and materials policy also includes raw materials from which chemicals are isolated or manufactured, as well as products which have chemicals as their constituents. Waste, too – products which humans want to dispose of – consists of many different chemicals. Waste management is therefore part of "substance policy".

In 2019, BUND – Friends of the Earth published a position paper describing the "Challenges for a Sustainable Chemicals and Materials Policy" [BUND 2019a]. As a supplement to that position paper, this background paper explains the importance of a sustainable policy for other environmental fields of action, especially for climate protection and preservation of biodiversity.

Chemicals and materials policy must focus on the principles of precaution and sustainability. The precautionary principle requires action to be taken whenever there are good reasons for concern, even when no conclusive evidence of a causal relationship is called for [OSPAR 1992]. This has not always been taken into account in a timely manner, as for example the publications "Late lessons from early warnings: science, precaution, innovation" [EEA 2001 and 2013] of the European Environment Agency (EEA) show. Sustainability means meeting the needs of today's generation without impairing the needs of future generations [UNCTAD 1992]. This also includes distributive justice between North and South as well as within European societies.

In 2015 the General Assembly of the United Nations also adopted seventeen goals for sustainable development that are to be achieved by 2030 [UNO 2015]. These Sustainable Development Goals (SDGs) include a number of environmental and health-related goals such as clean drinking water for all people, the protection of terrestrial and marine ecosystems and also the preservation of health and the environment through fewer dangerous chemicals and less pollution of the water, soil and air. Some of these goals refer specifically to the impact of certain substances. In particular, the goal of sustainable production and consumption (SDG 12) requires chemicals and materials policy action.

Climate change and biodiversity loss are recognized global challenges for international environmental policy. In international agreements such as the 2015 Paris Agreement and the 1992 Convention on Biological Diversity, signatory countries have undertaken to align their policies with specific goals: maximum increase in global average temperature by significantly less than 2.0 °C, if possible, only by 1.5 °C compared to the pre-industrial level and the 20 Aichi biodiversity targets by 2020 [University of Regensburg 2020]. The aim is to achieve a clear turnaround in previous developments and to fall below the relevant planetary upper limits again (see Chapter 2).

Climate change and biodiversity are closely interrelated in this regard. Three examples: the first is increased water temperatures and the acidification of the oceans as a result of higher CO_2 levels in the atmosphere, leading to the bleaching and death of coral reefs. The melting of the polar ice caps and shifting of vegetation zones toward the North and South Pole is endangering the habitat of threatened species. The increased cultivation of energy crops to replace fossil fuels is increasing competition for land and destroying natural habitats, especially in the countries of the Global South.

By comparison, pollution by chemicals and materials represents a comparable global challenge but has so far only been governed by conventions that regulate individual aspects and not a comprehensive and legally binding international single conventions. Important international conventions for the protection of the climate, nature and the environment are shown in Box 1.

Box 1

Important international agreements for the protection of climate, nature and the environment

The Paris Agreement of 2015, https://unfccc.int/, foresees the limitation of human-caused global warming to well below 2 °C compared with pre-industrial levels. In addition, the states should be enabled to deal with the consequences of climate change.

The Convention on Biological Diversity (CBD) of 1992, https://cbd.int/, has the protection of the biodiversity, the sustainable use of its components, as well as access and compensation in the use of genetic resources (access and benefit-sharing) as its goal. Biodiversity is broken down into species diversity, genetic diversity and the diversity of ecosystems.

The Nagoya Protocol of 2010, https://cbd.int/nagoya, part of the Biodiversity Convention, stipulates an international legal framework for access to genetic resources and fair sharing of benefits. This is intended to curb biopiracy.

The Basel Agreement of 1989, http://www.basel.int, regulates the control of cross-border shipments of hazardous waste and their disposal.

The Stockholm Convention of 2001, https://www.pops.int/ prohibits or restricts the production and use of some persistent organic waste pollutants (POPs) and also minimizes the unintentional formation of POPs (such as polychlorinated dibenzodioxins and furans, PCCD/F) as by-products in technical and thermal processes. Further substances are continuously being identified as POPs and incorporated; 30 substances are currently regulated.

The Minamata Convention of 2013, http://www.mercuryconvention.org/, aims to reduce mercury emissions – whether they result from the use of mercury in products and processes or from the burning of coal – throughout the world.

Environmental burdens from chemicals and materials are closely related to climate change and biodiversity loss (Fig. 1). This paper illustrates this and draws conclusions from it. Substances are considered throughout their entire life cycle, from the extraction of raw materials to their disposal as waste (or recycling into new products). Chapter 2 presents the main features of a sustainable chemicals and materials policy. Chapter 3 discusses the effects of material pollution on climate change. Chapter 4 adds the consequences of climate change on the effects and behavior of substances. Chapter 5 shows how substances in turn affect biodiversity. Chapter 6 clarifies the contribution of sustainable chemistry to the protection of the climate and biodiversity, before recommendations and conclusions are listed in the concluding Chapter 7.

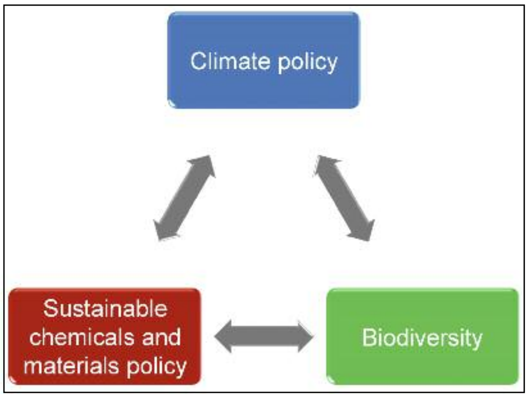

Figure 1: Relationship between chemicals and materials , climate policy and biodiversity.

2. Key Issues in Chemicals and Materials Policy

There can be no doubt about it: It is also important to use hazardous chemicals as rarely and sparingly as possible and to reduce the risks they pose in particular to people and the environment. The products of the chemicals industry can be found in numerous articles and, last but not least, in waste. Almost all areas of life such as mobility, building, energy, clothing and food are affected by "chemistry."

But it is not just about the dangerous properties of individual substances and mixtures of substances (quality), but also about the quantity of the substances used. This also applies to "non-hazardous" substances. Substances such as carbon dioxide, plant nutrients such as phosphate or sand and gravel are considered to be toxicologically harmless. For a long time, this also applied to plastics and other long-lasting (persistent) products based on synthetic chemistry.

It is therefore important in terms of precaution and sustainability, to reduce the quantities of chemicals and materials introduced into the environment, even for those currently considered to be unproblematic. Particularly problematic are persistent substances which – once released into the environment – can only disappear from it very slowly, if at all, and accumulate. Unforeseen consequences for health and ecosystems cannot be ruled out and could be irreparable with such "forever" chemicals. Hormone-disruptive substances (endocrine disruptors), which often already act at very low concentrations, also deserve special attention (see Chapter 5).

The increased turnover of such substances is revealing to a more and more obvious degree their problematic effects in relation to climate change and excessive use of fertilizers, environmental hygiene and littering as well as biotope destruction. The global increase in chemical production flows of materials, as well as the growing exploitation of our planet's resources, require that chemicals and materials policy must be conceived of and implemented more comprehensively. This makes it an overarching framework and the strategic link between various policy fields which include, apart from chemicals policy, resource, product and waste policy.

Chemicals and materials policy is also an international challenge. In addition to the individual conventions mentioned in Chapter 1 that regulate certain aspects, the Strategic Approach to International Chemicals Management (SAICM) is an essential initiative for the safe handling of chemicals and waste and should aim to achieve a common understanding of the global effects of chemicals [SAICM 2020].

In Box 2, a scientific approach for describing global exposure limits is presented.

Box 2

A scientific approach to describing the planetary boundaries of the Earth

Rockström and Steffen's concept of the planetary upper limits [Rockström 2009, Steffen et al. 2015a] defines nine areas in which human activity is endangering the Earth system. According to them, human activities have reached a level that could seriously disturb the stability of the systems that hold Earth in its current state. One of these processes is "Novel Entities" which describes the burden on the Earth system by anthropogenic substances as well as modified life forms like products of synthetic biology. It lasted until 2022, when an international team of researchers [Persson et al. 2022] assessed the impact on Earth system stability deriving from the cocktail of synthetic chemicals, plastics and other "Novel Entities". They concluded that despite of data limitations the Earth system processes are increasingly disturbed and Earth system is put at risk. Humanity has crossed the planetary boundary for novel entities. The material pollution of our planet also influences other planetary limits such as atmospheric aerosols, biogeochemical substance flows (nitrogen, phosphorus) and climate change, which are directly linked to the sustained high release of CO_2 and other greenhouse gases. The rapid increase in the use of non-renewable resources [UNEP 2019a] and material pollution, for example from waste [UNEP 2015] shows that urgent actions to reduce the production and release of these pollutants are needed, The "great acceleration" of numerous ecological and socio-economic parameters through human activities [Steffen et al. 2015b] is closely linked to the influences of chemicals and materials.

It should be noted that the countries of the Global South are more affected by the consequences of a failed policy on chemicals and materials than the industrialized countries. Raw materials and resources are increasingly being imported from the Global South in order to satisfy the needs of countries in the Global North, without the latter being adequately compensated. This transfer of resources is also leading to a loss of biodiversity and inflicting ecological damage in the Global South as well as causing an uneven distribution of material pollution. Over the past 20 years, global material flows in raw materials, chemicals, finished products and waste have multiplied.

The chemicals industry often relocates its production to developing and emerging countries with the intention of better serving regional markets, but also in order to benefit from lower wages and lax legal requirements. This leads to the export of risks. Environmental and occupational safety standards are often lower in the countries of the south and east than in the countries of the north. This also illustrates the need for a global chemicals and materials policy.

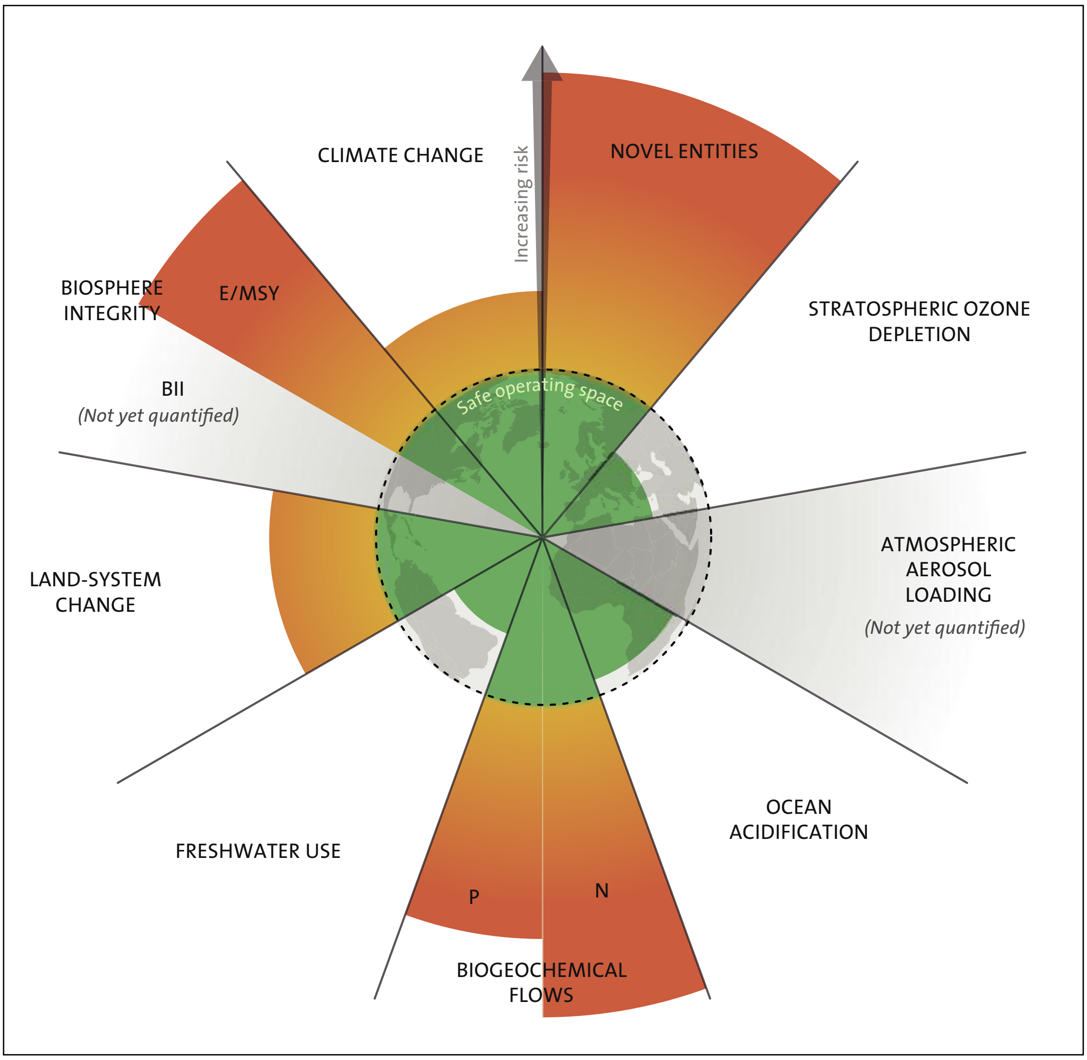

Figure 2: Planetary Boundaries; designed by Azote for Stockholm Resilience Centre, based on an analysis in Persson et al. 2022 and Steffen et al. 2015a, BII: functional diversity (Biodiversity Intactness Index), E/MSY: genetic diversity (extinctions per million species-years)

3. Materials Production and Raw Materials Extraction Are Driving Climate Change

Climate protection is currently the dominant issue in environmental policy. The dramatic consequences of global warming can be felt worldwide. In order to limit global warming to 1.5 °C compared with the pre-industrial age, in the 2015 Paris Agreement signatory states committed themselves to reducing their greenhouse gas (GHG) emissions accordingly. The emissions of carbon dioxide (CO_2) and methane (CH_4) are particularly decisive in relation to global warming.

Emissions of synthetic gases such as fluorinated hydrocarbons (HFCs) and sulfur hexafluoride (SF_6) as well as nitrous oxide (N_2O), especially due to the use of fertilizers in agriculture, play a role in this as well. Fig. 3 shows that in 2016 29.4 % of total global greenhouse gas emissions (49.4 Gt CO_2eq[1] in 2016) were attributable to the production of substances[2] (energy use and other emissions). Also the road transport sector (road, shipping, aviation, railway) emitted 11.9 % [Ritchie 2020]. According to the ITF report 2021 more than 40 % of traffic emissions come from freight transport [OECD-ITF 2021]

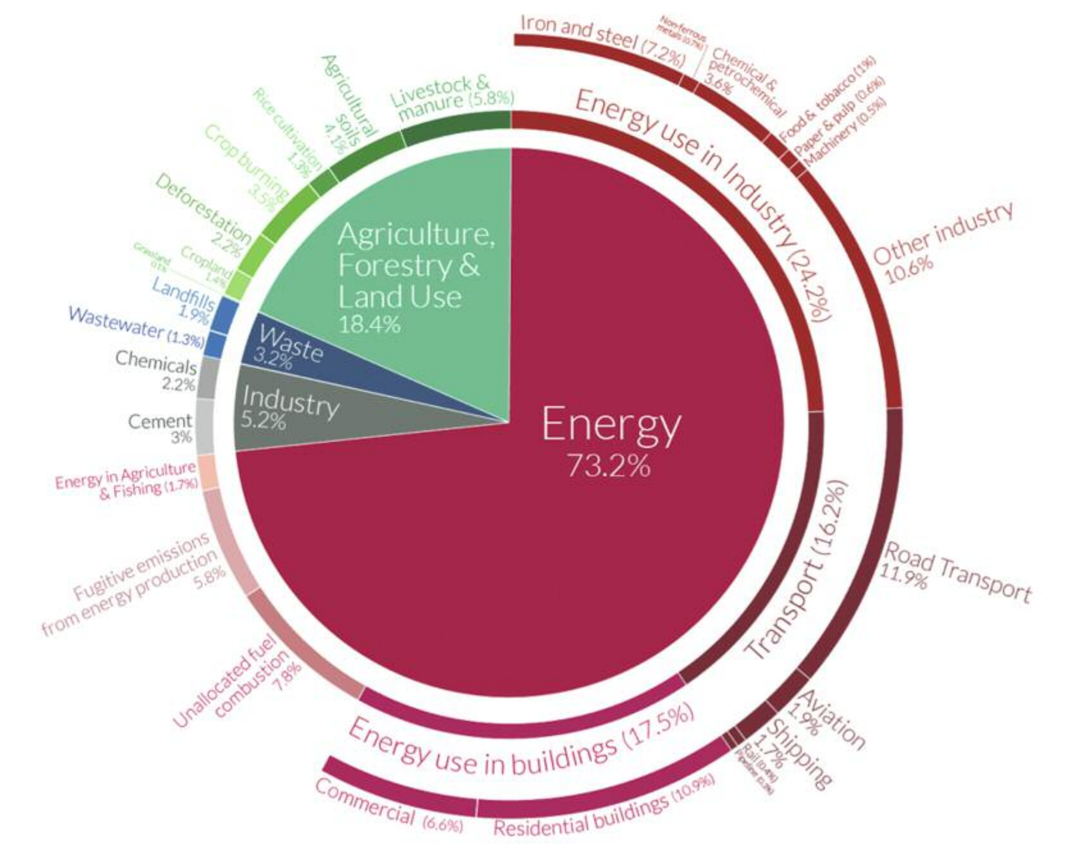

Figure 3: Global greenhouse gas emissions by sector in 2016 according to Ritchie [2020]

[1] *CO_2 equivalents describing the relative potency compared with CO_2*

[2] *Industry's global GHG include emissions for energy production in the processing and manufacturing sectors*

Manufacturing and processing of chemicals and materials

Beginning with the recovery and refining of raw materials and extending to the synthesis of chemicals and the processing of products, the production of chemicals and materials consumes energy. Across the globe, energy is obtained mainly by burning fossil fuels such as coal, oil, and natural gas. An energy shift away from fossil fuels would thus also help to reduce greenhouse gas emissions caused by the production of chemicals and materials.

Chemicals, materials and products differ in the specific energy expenditure they require for their manufacture. Manufacturing methods and the equipment in production plants lead to different levels of greenhouse gas emissions. The cumulative energy demand (CED) [VDI 2012], which covers the entire life cycle of a substance, and the sum of the associated greenhouse gas emissions are indicators of the climate impact of particular products.

It is true that the increase in energy efficiency in the past three decades has made it possible to decouple energy consumption from increases in gross domestic product (Fig. 4). However, absolute energy consumption has not decreased as a result, but has remained consistently high in Germany [UBA 2020a] and is even continuing to increase worldwide [IEA 2018a]. The reason is the so-called "rebound effect"– specific savings are more than offset by economic growth and changes in use.

Consequently, if you really want to reduce energy consumption and the associated greenhouse gas emissions involved in the manufacture of substances, you also need to avoid, reduce and slow down the flow of materials. Increasing the longevity of and ease of repairing products is a challenge faced by manufacturers, politicians and consumers alike.

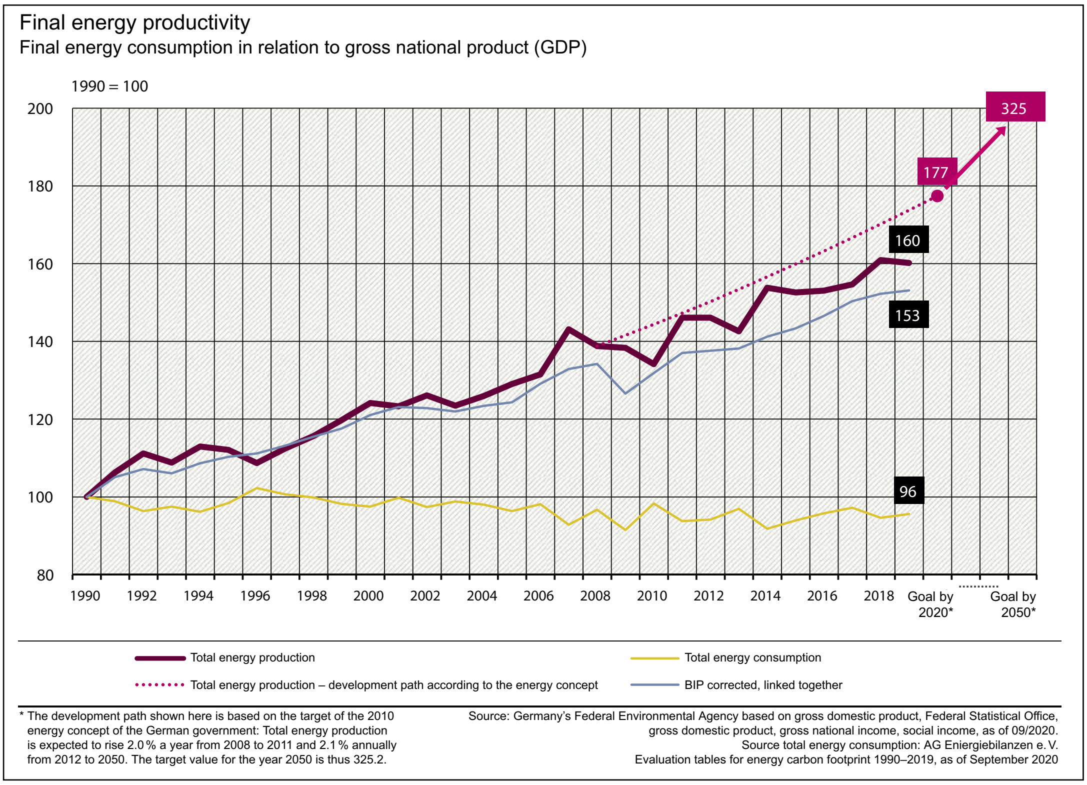

Figure 4: Final energy productivity in Germany 1990-2020 (Source: Umweltbundesamt 2021a)

The primary energy requirement for the manufacture of chemical products such as ammonia (Box 3), mineral oil products, iron, steel, non-ferrous, functional and precious metals, as well as cement, concrete and ceramics, is particularly large [UBA 2020b].

Box 3

The example of ammonia

The Haber-Bosch process for producing ammonia (NH_3) from nitrogen and hydrogen is particularly energy-intensive. Every year 150 Mt of ammonia is produced all over the world, mainly for fertilizers. This involves emissions of approximately 300 Mt CO_2eq [Deutscher Bundestag 2018]. Incidentally, the volume of ammonia produced in this way is the main reason for the frequent breaches of the planetary boundaries for reactive nitrogen.[3]

Production processes

In the case of a few important production processes such as cement and steel, the emission of greenhouse gases does not only occur via the energy demand of the production process. In the EU in 2017, GHG emissions from the production and processing of industrial products amounted to 7.82 % of total GHG emissions [EP 2021].

- During the production of cement, carbon dioxide is emitted in the process of the decomposition of calcium carbonate to calcium oxide, also referred to as "quicklime." These emissions in the course of the process are responsible for approximately two-thirds of carbon dioxide emissions in cement production, which according to the International Energy Agency (IEA) is responsible for 6.9 % of total world CO_2 emissions [Deutsche Wirtschaftsnachrichten 2019]. This is not an exceptional case: The manufacture of calcium carbide, also known as calcium acetylide, for use in the production of acetylene and calcium cyanamide ($CaCN_2$) as well as the decarboxylation of organic acids lead to the release of CO_2 through chemical reactions.

- In the metal industry coal is used as a reducing agent in the smelting of many ores. The use of blast furnaces to produce pig iron is a particularly large emitter of CO_2. Coal is usually used in blast furnaces (Figure 5) to reduce iron ore to raw iron, the intermediate product on the way to steel. This process is responsible for about 9 % of GHG emissions worldwide. Currently, about half of all steel production is taking place in China, which has massively increased its production over the last two decades.

Figure 5: Blast furnace processing leads to high GHG emissions.
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3 *All inorganic nitrogen compounds except elementary nitrogen are referred to as reactive nitrogen. Source: Reactive nitrogen in the environment | Umweltbundesamt.*

Figure 6: Increasing freight traffic (a): A container ship being unloaded at a seaport.
© pixabay.com/Karsten Bergmann

Pig iron can be produced without using coal as a reducing agent. There is increasing debate over using hydrogen instead of coal and thus potentially making this process primarily greenhouse-gas neutral [BDEW 2020]. A pilot plant for steel production with hydrogen is being built in Sweden [Arens & Vogl 2019]. In Germany, steel manufacturers are trying to replace some of the coal in the blast furnace with hydrogen, but this is only possible to a limited extent. Most of the hydrogen is still obtained from natural gas and is therefore associated with GHG emissions ("gray" hydrogen). The production of regenerative "green" hydrogen, that is, hydrogen, which is produced electrolytically from water with renewable electricity, is only just beginning. Because of the large quantities of regenerative energies required, complete conversion to "green" hydrogen will only be possible if at the same time the production of iron is reduced through systematic recycling and sufficiency strategies (see Chapter 6).

Transporting chemicals, materials and products

Together, the rising volume of material flows and greater and greater networks in international trade are causing a rapid increase in freight traffic (Fig. 6). Both road and rail transport and shipping are major emitters of greenhouse gases that are still barely regulated. The greenhouse gas emissions from this area are increasing and amount to more than 3.0 Gt in 2020 [OECD-ITF 2021]. At present, more than 80 % of global trade volume is handled via shipping. Shipping contributes around 2 % to global CO_2 emissions [UNCTAD 2019].

Replacing primary by secondary raw materials

Without achieving a transformation to a circular economy, we will not achieve the goals of the Paris Agreement or the Convention on Biological Diversity (CBD) and will exploit the planet's resources at an ever greater speed. Consequently, in its action plan for a circular economy the European Commission presents ways and means of transforming the current system of more or less linear flows with increasing quantities of waste into a system in which the reuse of products and the recycling of materials stand in the foreground [EU Commission 2020b].

The replacement of primary raw materials with those that have already been used once or several times (secondary raw materials) can, in addition to conserving

Figure 6: Increasing freight traffic (b): Delivery trucks snarled in a traffic jam on the highway.
© pixabay.com/Erich Westendarp

resources, also lead to significantly lower total energy consumption in the manufacture of products. As a first approximation, this is shown by a comparison of the cumulative energy demand (CED) [VDI 2012] for the production of the primary raw material with the CED for its recovery from products. The former can be found in studies about many important primary raw materials [UBA 2012]; the latter is highly dependent on the product from which it is to be recovered: The recycling of production waste is easier and requires less energy than the sorting out and recycling of recyclable materials from used products. The entropy factor plays a decisive role here: This means that the greater the "dilution" of the raw material to be recovered from waste, the more energy expenditure (and costs) required to recover it in a reasonably pure form. By the same token, the closer it is tried to get to the scarcely attainable goal of a 100% rate of recycling, especially with consumer waste, the more energy consumption increases as well. The energy and material requirement for recovery increases more and more as processors approach a recycling rate of 100 % (see Fig. 7) [Bunge 2016].

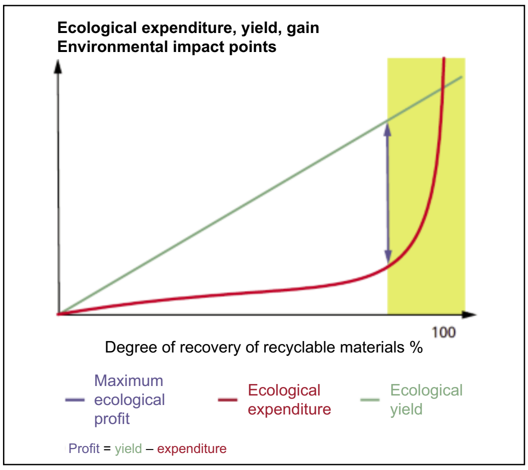

Figure 7: Ecological expenditure, yield and profit from recycling according to [Bunge 2016]: Compared with the production of primary raw materials (e. g., the production of metal from ore), the ecological yield from recycling (green curve) increases linearly with the degree of recovery. On the other hand, the ecological expenditure (red curve) increases exponentially the closer a processor gets to complete degree of recovery. The ecological profit, as the difference between the yield and the expenditure, has a maximum value. Above this degree of recovery there are no longer any ecological advantages (yellow area) (representation as environmental impact points according to [BUWAL 1990]).

But it is not just the energy consumed that restricts how much can be recycled. The cumulative resource demand (CRD) [VDI 2018] also plays a role: This describes the amount of material that is required to produce a specific amount of the particular raw material (dimension: t material/t raw material). Secondary raw materials have the advantage that their ecological rucksack, that is to say, the amount of unusable overburden, is usually less than that of primary products.

A major obstacle to high-quality recycling is also a lack of transparency concerning the material composition of many products. In addition, products sometimes contain hazardous substances that prevent recycling [Friege 2019].

The difficulties that arise with recycling can be illustrated using three examples (Box 4):

Box 4

Example 1: Recycling of metals

The recycling of metals such as iron, copper and aluminum is widespread and well established as long as the scrap metals satisfy certain purity requirements. However, accompanying tramp elements that cannot be technically removed at present (such as copper in steel or aluminum) cause increasing problems when more and more metals are in the cycle and less primary raw material is available for dilution. In the worst case, the contaminated material has to be removed from the cycle and disposed of [von Gleich 2006].

Recycling is less common with rare metals (e.g., cobalt and lithium for battery production). In the case of rare and strategically important metals, however, it can make ecological, economic and also political sense to produce a secondary raw material requiring more energy than needed for the primary raw material. This can be the case if the extraction of raw materials in a third country is ethically and ecologically problematic and/or a country does not want to be totally dependent on a single exporter. In the decades ahead, this may occur with chemical elements that are required for the generation and storage of energy from renewable sources. It is expected that the demand for raw materials will increase dramatically in the forthcoming years, precisely as a result of the expansion of future technologies. For example, an increase in annual consumption from 30 Mt to 110 Mt is expected for lithium in the period between 2013 and 2035 [DERA 2016]. It is worth noting that Germany imports more than 98 % of its metallic raw materials.

Example 2: Recycling of mineral building materials

In the case of bricks or concrete, recycling saves some of the energy required for production. This effect is insignificant in the case of sand and gravel, but their quarrying destroys natural landscapes and biotopes. Consequently, recycled concrete and secondary aggregates should also be used much more in building construction. Appropriate systems are available – something about which architects, construction companies and investors are insufficiently aware of or willing to accept.

Example 3: Recycling of plastics

Plastics are much more problematic to recycle, not least because of their variety and countless additives. Since the 1950s, more than 8 Gt of plastics have been produced globally, with production doubling approximately every 20 years and amounting to more than 400 Mt in 2015 [BUND 2019b]. Plastics are persistent substances that are distributed in the environment in substantial quantities through wear and tear or at the end of their useful life. In the EU in 2015 the GHG emissions for the manufacture, processing and disposal of plastics corresponded to an annual budget of 1,781 Mt CO_2eq [BUND 2019b]. More than a third of the amount of plastics produced in Europe is used for packaging [BUND 2019b]. In 2017 in Germany 18.9 Mt of packaging waste were produced; the proportion of plastic was a total of 3 Mt or 38 kg per capita and year [Deutscher Bundestag 2020].

The figures are similar in other EU member states [EU Commission 2018]. Many packaging films consist of multilayer systems that make single-substance recycling impossible. Numerous deformable and solid plastics (elastomers and thermosets) pose considerable problems for recycling.

Some plastics are recycled with great success, PET plastics[4] beverage bottles or HDPE[5] from post-consumer waste. The company Werner & Mertz [DBU 2019], for example, has made progress in this area. The number of bottles made from recycled PET that were used through the Recyclate Initiative, thus saving bottles made from new material, is now more than 300 million. This large number also involves a clear reduction in the burden on the environment: With 300 million bottles by 2019, this results in CO_2 savings of at least 22,800 tons. Progress has also been made with HDPE from mixed plastic waste. The recycled bottles are even suitable for food and cosmetics [EREMA 2019]. A further benefit: Plastic bottles that remain in the recycling cycle do not end up in the environment and do not pollute soil or water by breaking down into microplastics over the course of centuries.

In the EU in 2020, 42 % of the separately treated 29.5 Mt of plastic waste collected from end users (post-consumer waste) were incinerated, 23.4 % were used for landfill and only 34.6 % were recycled – of which 16 % were exported mainly to Asian countries from the EU [PlasticsEurope 2021]. In the case of mixed plastics in post-consumer waste, in particular, it often makes no ecological sense to use a great deal of energy to separate, clean, pelletize and then re-extrude contaminated plastics. It is true that such mixed plastics can still be used to manufacture cheap products such as bollards or park benches ("downcycling"); but the market for this is not very significant.

Before such waste is used exclusively for energy in waste incineration plants or cement kilns, it can make sense to use chemical recycling, such as through depolymerization, during which the monomers that make up the plastic are recovered, or by solvolysis such as the CreaSolv process, with which multilayer packaging can be processed [FHG IVV 2020]. This also enables the toxic flame retardant HBCD to be separated from polystyrene. So-called "raw material" recycling by pyrolysis or gasification is currently discussed widely. The products are synthesis gas and / or oils. These processes should be viewed critically because of the formation of hazardous by-products like tar. The oils and gases generated should not be used as fuels; direct incineration would be a better choice for unrecyclable polymers [UBA 2020c]. However, pyrolysis may be a means to close the carbon cycle and use its products as feedstock for the production of chemicals (see below) [Meys 2021]. Overall, several procedures are currently being tested [FHG Umsicht 2020], but they still have to prove that they make economic and ecological sense.

[4] PET: polyethylene terephthalate
[5] HDPE: high-density polyethylene

An effective circular economy can be an effective means of reducing the consumption of energy and resources in the manufacture and use of products, even though near 100 % material recycling remains an illusion for many groups of substances.

In addition to the development and application of technical processes, the expansion of recycling also includes the establishment of transport and collection logistics, measures to increase the acceptance of secondary raw materials in trade and among consumers and, above all, changes in product design. Products must be reusable, more durable, repairable and have a modular design so that high-quality recycling products can be made from them. Recyclability must therefore be an essential evaluation criterion for products! In addition, regional value chains avoid long transport routes.

An alternative raw materials basis for the Chemicals industry

Global chemical production is continuously increasing in terms of quantity, turnover and diversity [UNEP 2019a]. In recent decades, production has roughly doubled every twelve years. A corresponding further increase is predicted. The chemicals industry consumes around 10 % of global energy demand for its processes. Mineral oil consumption in the chemicals sector is growing the fastest in comparison with other industries [IEA 2018b].

Though it is true that the chemicals industry is making considerable efforts to use energy efficiently in production and thus to improve its carbon footprint, in the long run, however, it cannot be sustainable to use fossil raw materials – above all mineral oil (and also natural gas) – as the dominant raw material base (feedstock) for production (Fig.8). Ultimately, substances that are made from fossil raw materials also contribute to greenhouse gas emissions because they are either biodegraded at the end of their useful life or incinerated during disposal.

Because of its even greater CO_2 emissions per unit of energy compared with mineral oil and gas, the formerly widely used source of raw materials, coal, is no reasonable alternative. The direct use of the low-energy and inert carbon dioxide as a synthesis building block (Carbon Capture and Use, CCU) is possible for some production systems, but its scope is limited [Behr & Neuberg 2008].

This leaves three options for obtaining carbon for the synthesis of organic substances which may be needed altogether to achieve a fossil-free chemical production: either from products generated by chemical recycling of polymers, from biological raw materials or synthetically from carbon dioxide and hydrogen.

- Polymer waste which cannot be recovered by mechanical recycling can be treated by chemical recycling (solvolysis, pyrolysis, gasification) in order to recapture basic chemicals for chemical synthesis (see above) [Meys 2021]. It has to be proven that these processes are ecologically reasonable.
- Biological substances can have the advantage that nature's synthesis processes, such as those occurring in plants and microorganisms can be used. "White" biotechnology in closed systems is being used in the synthesis of an increasing number of chemicals. Algae cultures can also utilize organic residues and produce biomass in the form of proteins, fats and carbohydrates [DECHEMA 2016, Pleissner & Smetana 2020]. In addition, natural materials such as wood are often a sensible alternative, for example to concrete as a building material or to plastics. When producing pulp from wood, large amounts of lignin is left over as a "waste product." Lignin is basically suit-

Figure 8: Mineral oil forms the most important material basis of the chemicals industry (Burghausen plant).
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able as a raw material for the production of aromatic compounds [Wong et al. 2020].

At the same time, the potential of the bioeconomy, that is, the economy in which biological materials are used, is limited (see Box 5). Only a fraction of the current demand for mineral oil-based raw materials could be replaced by biological raw materials. That is because the production of biomass is mostly tied directly to available acreage; soil cannot be increased either in the countries of the Global North or the Global South. Land competition for the cultivation of food-producing plants, a further intensification of agriculture and forestry, and the destruction of natural areas would inevitably result [Spangenberg & Kuhlmann 2020]. Monocultures for renewable raw materials would have to be created (see Chapter 5). Biomass can also be converted into basic chemical substances by hydrogenation (Fischer-Tropsch synthesis). In doing so, however, the valuable level of complexity of natural products is destroyed. In general, it is more environmentally friendly to use waste biomass for the production of chemical raw materials than cultivated biomass.

- The third alternative is the synthesis of basic chemical substances through the reaction of carbon dioxide (CO_2) with hydrogen (H_2) using energy. With such Power to X processes (PtX)[6], synthetic fuels can also be produced. Numerous smaller plants are already in operation [IN4 Climate NRW 2020, Springer Professional 2021] and a minimum proportion of synthetic fuels in aviation fuel is being discussed at the political level [BMU 2020a]. Basically, this only helps the climate if the energy used to produce hydrogen ("green" hydrogen) and the chemical raw materials synthesized from it are renewable. Considerable amounts of energy are required for this, which have not been taken into account for a long time in estimates of future energy requirements. According to information from the chemicals industry, the electricity demand for the sector in Germany would increase by a factor of 11 if its GHG emissions were reduced by 98 % (by 2050) [DECHEMA 2019]. In addition, at the latest when burning fossil fuels to create energy is no longer practiced, demand will have to be met by filtering CO_2 from the air [IEA 2021, Viebahn et al. 2019].

Box 5

Material cycles in nature

The bioeconomy focuses on the transition from non-renewable to renewable resources as well as on nature as a model in terms of learning from nature (bionics). Trees, for example, can afford to shed their "photovoltaic cells" for breaking down water into oxygen and hydrogen in the fall to contribute to the formation of humus. Then they grow new cells in the spring. We are a long way from that both technologically and in terms of materials. Strictly speaking, there is no waste in nature. Residues from one organism are used by others as raw materials. "Industrial ecology" tries to orient itself to this when designing business clusters [Chertow 2000, Korhonen et al. 2005]. Nature also makes no use of imports of raw materials. What is immediately available is used (CO_2, water, nitrogen, lime, solar energy, etc.). Last but not least, the current bioeconomy discourse does not take nature seriously enough. In this sense, the term "renewable raw materials" is also misleading. What we are talking about are plant and animal products that we ought to use to avoid energy and raw material losses as far as possible at the high molecular and complexity level to which the organisms have already synthesized them with the help of what is immediately available. If possible, this level should not be lost through industrial processes, such as by biorefining natural materials to the level of ethene or simple hydrocarbon mixtures such as naphtha.

Methods for "direct air capture" are currently being developed but are still energy- and cost-intensive. In a 2018 report, the IPCC discussed the possibility of "negative emissions" in order to achieve the 1.5 °C target [IPCC 2018]. Geo-engineering processes for avoiding or reversing greenhouse gas emissions are extremely problematic because irreversible long-term consequences are unexplained.

It is becoming clear that not only stabilization, but nothing short of a reduction in chemical production can be sustainable – not just another argument for reducing material flows by increasing efficiency, but also by reducing needs (sufficiency).

6 Gases like Methane (PtG) or liquid hydrocarbons (PtL) could be the final products of such processes

4. The Impact of Climate Change on the Effects and Behavior of Chemicals and Materials

Climate change affects numerous physical, chemical and biological processes on Earth: Higher temperatures, changing amounts of precipitation, shrinking ice cover, changes in vegetation, ocean and air currents, all these factors also have an impact on the exposure and effects of pollutants on people and environmental organisms. Numerous stress factors affect people and environmental organisms. They can increase sensitivity to toxic substances and increase the likelihood of illness. Climate change is shifting the times of reproduction and ingestion of food, which can lead to reduced fitness of the organisms. Such influences have been demonstrated, for example, in fish and zooplankton at water reservoirs [Jäschke et al. 2013].

More airborne pollutants and greater toxic load

As temperatures rise, the tendency of solid and liquid chemicals to change into the gaseous phase increases strongly (at constant air pressure). The direct measure of a substance's tendency to evaporate into the atmosphere is its vapor pressure at a given temperature. In the range of natural ambient temperatures on Earth between polar regions and deserts, the vapor pressure of a substance can increase by one to two orders of magnitude parallel to the temperature [Klöpffer 2012]. With a moderate rise in temperature from 24 °C to 29 °C, for example, the vapor pressure of the plasticizer diethyl phthalate increases by around 60 % [calculated using the approximation formula of Schwarzenbach et al. 2002].

Thus global warming is causing a greater transfer of chemicals into the atmosphere. As a result, their transport in the atmosphere is increasing greatly, right up to global distribution.

In addition to air temperature, the duration and intensity of solar radiation on materials and products play an important role in the volatilization of chemicals. This has recently been demonstrated for the release of organic compounds, including many aromatic hydrocarbons, from the asphalt of road surfaces in California: With moderate direct sunlight exposure on the asphalt, emissions increased threefold. Upon release, the substances are oxidized by hydroxyl radicals under solar radiation to form non-volatile compounds, which combine to form liquid and solid particles (aerosols). These secondary organic aerosols are within the category of inhalable (alveolar) particulate matter (PM2.5). Extrapolated for the region of the metropolis of Los Angeles, the annual emissions from asphalt in summer already exceed the primary particulate matter emissions from road traffic in the city [Khare et al. 2020]. Sealing surfaces with asphalt is on the rise globally. Over 122 Mt of petroleum-based liquid asphalt are processed every year around the world.

In addition, volatile organic compounds entering the lower troposphere in the presence of nitrogen oxides ("NOx": NO and NO_2) and intense sun exposure result in the formation of high ozone concentrations [Graedel and Crutzen 1994]. Ozone is a respirable gas that has an irritant effect on the respiratory tract due to its strong oxidizing effect, triggers inflammation and leads to impairment of lung function.

Climate change increases the frequency and duration of summer heat waves and solar radiation. The associated decrease in summer precipitation also leads to higher concentrations of air pollutants, especially particulate matter, as rainfall does not clear the air from pollutants collected by raindrops through coagulation and a low exchange of air masses is characteristic of weather conditions featuring stable high-pressure areas. As a result, in spite of the emission reductions of volatile organic compounds (VOC) and nitrogen oxides (NOx) that have already been achieved, increasing concentrations of air pollutants are to be expected. In urban areas in particular, the temperature will rise significantly faster than the global mean [BMZ 2015]. The factor is 2 to 4 depending on the location. In 2050, compared to 2020, Berlin's summer will be up to 6 °C hotter; for Vienna even 7.6 °C more are predicted [Bastin 2019, Leahy 2019].

Experimental studies confirm the combined effects of various air pollutants such as nitrogen oxides, inhalable

particulate matter and ozone [Münzel 2018]. In urban areas in particular, people are already subjected to a high degree of stress by summer heat waves. They can become dehydrated and as a result react with greater sensitivity to pollutants. In August 2020 – the second hottest month since weather records began to be kept in 1881 – 6 % more people died in Germany than the average between 2016 and 2019 [DESTATIS 2020a]. There is evidence that the combination of climate change and exposure to air pollutants have the potential for serious adverse effects on human health in urban areas and other areas that have high levels of air pollution [Noyes et al. 2009]. What applies to humans also applies to animals and plants: air pollutants affect metabolism and growth in flora and fauna.

Semi-volatile substances

Semi-volatile substances are chemicals that do not evaporate quickly but have such a high vapor pressure that they are at least partially gaseous in the atmosphere and not only attached to fine dust particles. This includes most of the persistent organic pollutants (POPs). Typical representatives are the highly fat-soluble polychlorinated biphenyls (PCBs). Although the production and use of PCBs in Germany was stopped in the 1980s, they are currently still being released from materials containing PCBs such as joint sealing compounds and paints [Weber et al. 2015]. The PCBs spread around the globe through long-range atmospheric transport and are thus able to contaminate land and water surfaces as precipitation, especially in Arctic and subarctic regions. In these cold regions they are ingested by organisms and accumulate in high concentrations, especially in animals at the top of the food web [Desforges et al. 2018]. In alpine regions, too, there are higher levels at higher altitudes [LfU 2021]. The process of transport to higher latitudes and the accumulation there is called "global distillation" or the "grasshopper effect" (see Fig. 9) [Wania & Mackay 1996].

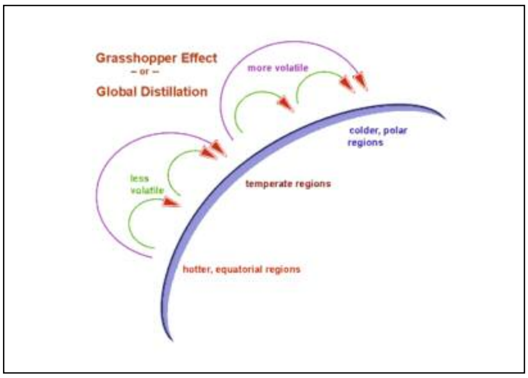

Figure 9: Global distillation of persistent organic pollutants (POPs): Semi-volatile substances evaporate in warm regions and are transported – sometimes in several steps – in the atmosphere to cold zones, where they are deposited (illustration from the University of Guelph/Canada).

Significant amounts of POPs have been deposited on glaciers and Arctic soils over the decades. The melting of the glaciers and the thawing of the permafrost soils as a result of global warming are increasingly releasing these substances with the melt and spring waters [Steinlin et al. 2016]. This leads to elevated POP concentrations in bodies of water, the soil, and finally in organisms [Noyes et al. 2009]. On the Zugspitze, organochlorine pesticides, PCBs and other POPs have already been detected in the spring water of the tunnel system below the glacier Schneeferner LfU 2014].

The increase in the frequency and duration of summer heat waves and solar radiation caused by climate change is intensifying the evaporation of substances from the surfaces and their atmospheric (long-range) transport. The same applies to the spread of semi-volatile pesticide active ingredients from plant and soil surfaces after these pesticides have been applied to fields and plants. In Brandenburg, the widespread drift of the herbicides Pendimethalin and Prosulfocarb and the widespread entry into organically managed agricultural areas of the Schorfheide-Chorin Biosphere Reserve have been demonstrated for several years [LUGV 2015]. In South Tyrol, too, high concentrations of applied pesticides (e.g., chlorpyrifos-methyl, oxadiazone) were detected at playgrounds located near orchards and vineyards [Linhart et al. 2021].

Enhanced degradation

Higher temperatures usually lead to a more rapid breakdown of organic chemicals in the environment through microbial transformation and through abiotic processes such as hydrolysis and photolysis, leading

to the decrease in their total half-life in the environment. Von Waldow et al. predicted this for various POPs in the northern hemisphere by applying a complex atmospheric-oceanic circulation model, assuming an increase in mean global temperature of 3.4 °C by the year 2100. The authors also showed that climate change increases the long-distance transport of PCBs and other POPs from the regions of their use (especially Europe, North America and East Asia) to neighboring continents and the Arctic regions [von Waldow et al. 2007]. The faster degradation of organic chemicals at higher temperatures can be advantageous, since the persistence is then less pronounced. However, toxic conversion products are also formed more quickly and in higher concentrations. The consequences resulting from climate change, such as drought and reduced vegetation, can mean that the pollution of soils, bodies of water and living organisms does not ultimately decrease despite increases in temperatures.

Human toxicity and ecotoxicity

Increases in temperature often lead to an increase in the toxic and ecotoxic effects of pollutants in the environment [Noyes et al. 2009]. It is known from both ecological and human toxicology that the action of two or more stressors on a living being is usually more harmful than if only one of the stressors acts with the same intensity. This applies regardless of whether the stressors are chemical or physical-biological or a combination of both. Physical-biological stressors can be of natural origin, such as unfavorable temperature or shortages of water or food. Climate change can cause or exacerbate these natural stressors. Organisms that cannot escape to other habitats are threatened with extinction.

For example, it has been proven that the temperature tolerance of fish decreases when they are exposed to active ingredients from various pesticides. The combined effects of high temperature and a chemical can lead to a harmful effect, even if the individual doses on their own have no noticeable effect. For example, Besson et al. [2020] found that combined exposure to a non-toxic concentration of the insecticide chlorpyrifos and an increased water temperature of only 1.5 °C in fish disrupts the thyroid hormone system – a hormone system that is vital to development and survival. If chemical and non-chemical stressors occur together in aquatic organisms, this can lead to a considerable increase in the toxic effect, so that the authors speak of "over-additive" effects [Segner et al. 2014].

There are also serious indications that high exposure to numerous POPs, many of which have been shown to cause endocrine disruptions, and other toxic substances can impair the ability of mammals and birds to adapt to environmental conditions that have changed [Steinhäuser 2007]. For example, the concentrations of polychlorinated biphenyls (PCBs) and per- and polyfluorinated alkyl substances (PFAS) in the body of some populations of polar bears are so high that they weaken the body's defenses [Liu et al. 2018]. The animals' immune system is then less able to withstand climate stress. This is important because the temperature rise in the Arctic regions is occurring to a much greater extent and more rapidly than the global average. For the adaptability of living beings to higher temperatures, it is not only the absolute increase but also the speed of global warming that is decisive [Schellnhuber 2016]. The rapid warming of the Arctic, in combination with the high POP pollution of the Arctic biota, could lead to a dramatic loss of biodiversity.

Floods release pollutants

While precipitation decreases in many regions in the summer months as a result of climate change, it will often increase in the winter months. Overall, it is expected that the frequency and intensity of heavy precipitation and floods will increase. If – as is often the case – municipal sewage treatment plants can no longer cope with substantial amounts of run-off rainwater, diluted uncleaned wastewater will flow with rainwater into streams and rivers [Tagesspiegel 2020]. Accordingly, higher levels of pollutants will find their way into the rivers.

Box 6

Mobilization of pollutants from sediments

In the event of floods, pollutants in contaminated sediments can be remobilized. From 1930 to 1945 large quantities of magnesium were produced in Bitterfeld, Aken and Staßfurt. The conversion of the raw materials with chlorine gas resulted in polychlorinated dioxins and furans (PCDD/F) as by-products, which were discharged with the washing water into the rivers Mulde, Bode and Saale. As a result, over the past 70 years floods have contaminated the sediments and floodplains of the river Elbe up to the Port of Hamburg and the confluence with the North Sea [Weber et al. 2015].

East Germany produced large amounts of organochlorine pesticides in the catchment area of the river Mulde, which accumulated in river sediment. During the major flood event in August 2002, these pollutants were remobilized and washed into the river Elbe. In the following years, significantly higher levels of these pesticide active ingredients were detected in bream of the Mulde. (see Fig. 10) [UBA 2022].

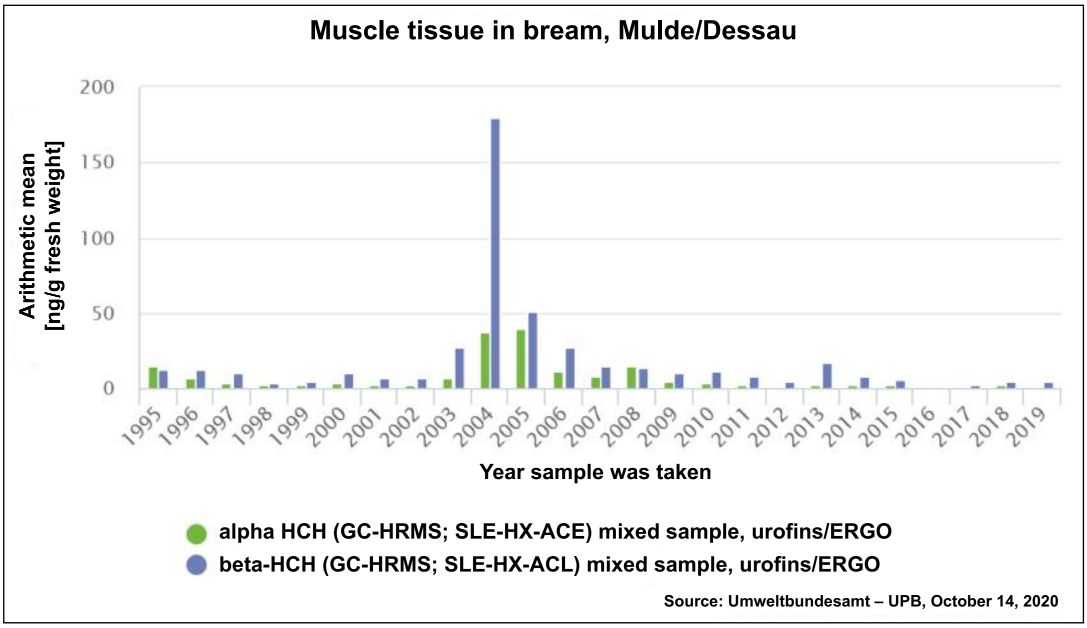

Figure 10: Concentrations of β-hexachlorocyclohexane in the muscles of bream from the river Mulde 1995–2020 (in ng/g fresh weight)

5. The Impact of Substances Leads to Loss of Biological Diversity

Biodiversity is decreasing dramatically around the world. The natural extinction rate, which up to around AD 1500 was 0.1 to 2.0 species per million species and year, is now exceeded by a factor of ten to one hundred times. Around a quarter of known species (vertebrates, invertebrates and plants) are threatened with extinction [IPBES 2019]. However, the decline in biodiversity is not limited to the number of species that are becoming extinct: The total population of wild vertebrates has decreased by 68 % since 1970 [WWF 2020].

When ecosystems are exposed to stress, it is the sensitive species that disappear first. It is true that the tolerance of the ecosystem against anthropogenic pollution, so-called "pollution-induced community tolerance" (PICT), then often increases [Blanck 2010]. Nonetheless, the ecosystem is at risk all the same. For the ability of an ecosystem to return to its original state after disruptions, so-called "resilience," decreases as diversity decreases [Elmqvist et. al. 2003].

In the Global Biodiversity Outlook 5 (GBO 5), the UNEP demonstrates in September 2020 that we'll not achieve most of the 20 Aichi targets.[7] The international community agreed on these goals in 2010 with the aim of significantly improving the situation of biological diversity by 2020 [CBD 2020]. The main reasons for this are changes in land use due to agriculture and forestry, especially deforestation, as well as urbanization and overexploitation of ecosystems such as the oceans due to fishing. The extraction of raw materials, the production and use of materials and the use of pesticides [Leopoldina 2018] also contribute significantly to the decline in biodiversity. In the opinion of the authors of GBO 5, reversing the progressive loss of biological diversity also requires lower pollution, sustainable production and reduced levels of consumption.

After land use change and direct exploitation of nature substance inputs are a major driver that is changing nature on a similar scale to climate change [IPBES 2019]. The biodiversity crisis can only be resolved if, in addition to climate protection, a sustainable chemicals and materials policy is implemented (Fig. 11).

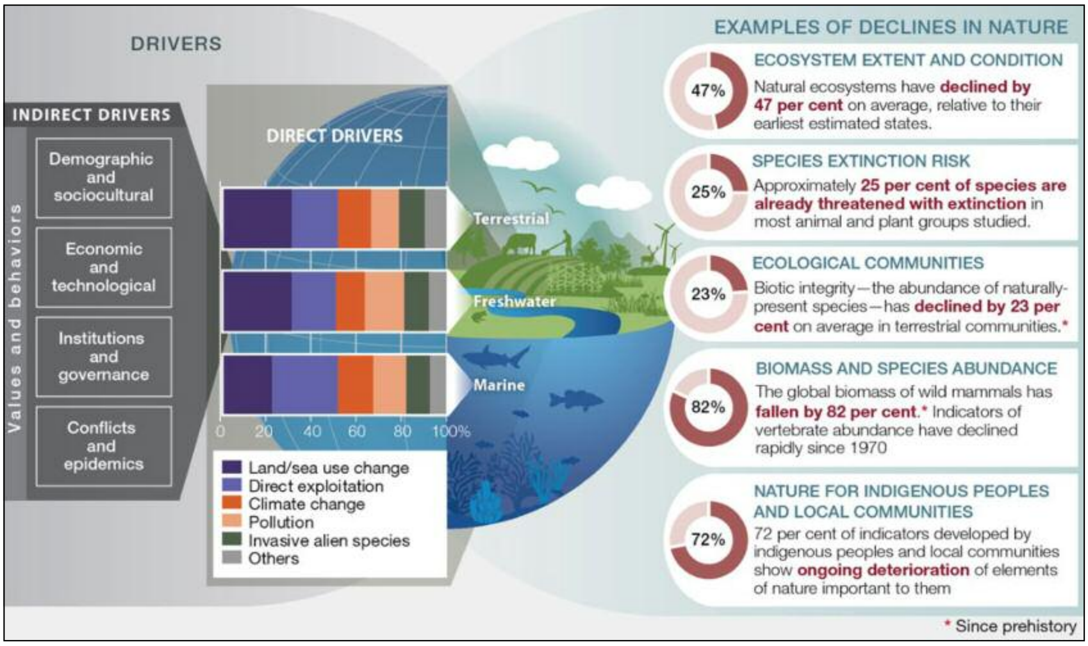

Figure 11: Drivers for biodiversity loss, based on the Summary for Policy Makers (SPM) of the global assessment of the IPBES [IPBES 2019].

[7] *The 20 Aichi targets were adopted in 2010 at the Conference of the Parties to the Convention on Biological Diversity.*

Raw materials extraction and processing

The continuous increase in material flows begins with the extraction of the raw materials. The extraction of ores and fossil raw materials increased dramatically in the past century and continues in the 21st century (see Fig. 12) [IRP 2017, UNEP 2016, de Wit et al. 2018]. A further doubling of consumption is expected by 2050. Overall raw material productivity is also increasing: It increased by 35 % in Germany between 2000 and 2016 [DESTATIS 2020b]. However, these gains were more than offset by the sharp increase in consumption.

These raw material resources are also not renewable. Since their extraction from ever lower concentrations requires steadily increasing effort, exhaustion of production is foreseeable. If the coveted metals are only contained in low concentrations in the ore, even larger spoil heaps arise during extraction and processing. In the case of open-pit mines in particular space requirements and the resulting loss of life-supporting landscape are enormous. Newly developed mine sites are getting deeper and more remote; ore content is decreasing, mining waste and the use of chemicals and consumption of energy are increasing [UBA 2018]. In the Global South, the extraction of raw materials is also associated with human rights violations in a number of cases.

Often, toxic by-products are released during mining activities. One example is the release of uranium and cadmium when phosphate is extracted. Dramatic examples of natural habitat being destroyed by the extraction of raw materials are the extraction of oil from tar sands in Alberta (Canada), the contamination of the Niger Delta in Africa with mineral oil, and the illegal extraction of gold using mercury in the Amazon rainforest (Fig. 13). The raw material requirements of the industrialized and some emerging countries are not only threatening individual species but are also destroying entire ecosystems.

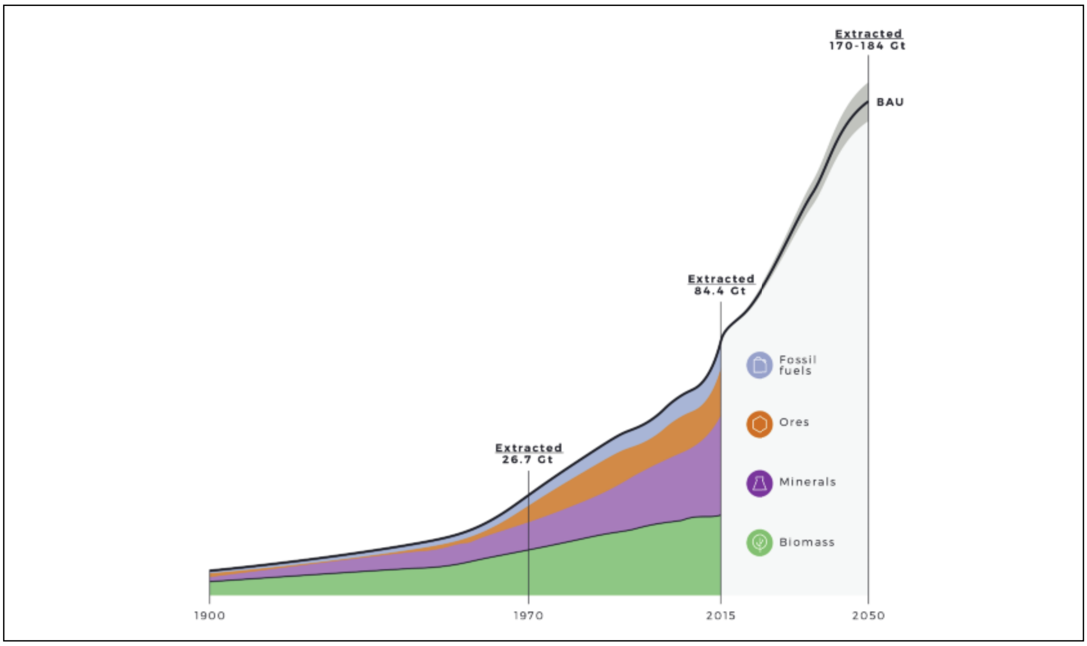

Figure 12: Global increase in raw material extraction (de Wit et al., 2018).

Because of climate change, crude oil and natural gas deposits in subpolar and polar zones are becoming more and more accessible. Mining for ore is also easier in these regions. But an accident, for example on an oil platform, would have more far-reaching consequences in these latitudes for organisms and ecosystems already threatened by climate change than such an accident in warmer regions, especially because the oil degrades more slowly at lower temperatures. The oil spill in the Siberian Norilsk in June 2020 is an example of the dramatic consequences of an environmental accident in Arctic latitudes [Spiegel 2020].

Figure 13: Devastation of landscapes through raw material extraction: (a) Extraction of oil from tar sands in Fort McMurray (Alberta, Canada) (top), (b) Illegal gold mining with mercury in the Amazon region (bottom)
© iStock.com/dan_prat (top), iStock.com/Tarcisio_Schnaider (bottom)

The processing of ores also leads to substantial toxic emissions and thus endangers thriving natural habitat. From the 19th and 20th centuries, damage resulting from smoke at smelter processing plants is known to have caused the death of forests and also to the loss of mammals and birds in the vicinity [Knolle & Knolle 1993, Schröder & Reuss 1883]. Thanks to improved cleaning of the exhaust air in such systems, this has become a thing of the past in the EU but is still widespread in the countries of the south. But even in industrialized countries like Australia today, metallurgical processes are still often associated with considerable environmental pollution [Norgate et al. 2006]. In the more recent past, after dam breaches in Hungary, Canada and Brazil, toxic ore processing sludge has exacted a toll of many lives and poisoned entire valleys and rivers. For a long time, the sintering of iron ore was also an important source of emissions for polychlorinated dibenzodioxins and furans (PCDD/F) [DGUV 1990, UBA 2014].

Emissions of toxic substances into the atmosphere

When organic substances are burned, not only carbon dioxide and water are produced, but also numerous other substances that pollute the environment and the biosphere and are then distributed across vast areas (Fig. 14). For a long time, the emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO and NO_2) from the burning of fossil fuels numbered among the most pressing environmental problems in industrialized countries. Sulfuric acid is produced from sulfur dioxide, which leads to low pH values in rainwater. That in turn is particularly damaging to forests. Nitrogen oxides – still a problem today, especially with emissions from diesel engines – are oxidized to nitric acid and, in addition to acidification, cause extensive fertilization and thus eutrophication of terrestrial ecosystems.

Figure 14: A modern power plant in Europe.
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Incomplete combustion also leads to the emission of toxic polycyclic aromatic hydrocarbons (PAHs). When incinerating waste especially products containing chlorine, polychlorinated dibenzodioxins and furans (PCDD/F) can form. These are among the most toxic substances, are persistent and can accumulate in organisms. That is why they are regulated in the Stockholm Convention on Persistent Organic Pollutants (POPs) (see Box 1 in Chapter 1). In industrialized countries, these emissions are now being minimized using state-of-the-art technology.[8]

Many substances, including their by-products, are also emitted into the air during the manufacture and processing of chemicals and products. In addition, there are unintended releases of substances due to operational disruptions or accidents during production and processing.

Thus, a sustainable chemicals and materials policy also means avoiding emissions from incineration and the manufacture and processing of substances, especially toxic substances, or, if this is not possible, reducing them to as low a level as possible. Often, harmful emissions can be avoided by choosing and changing production processes. In addition, precautions must be taken to ensure that operational disruptions, which can lead to the unintentional discharge of harmful substances, are avoided or can be controlled.

In industrialized countries, emissions must be reduced according to the best available techniques (BAT), for example by sealing off processes and optimizing exhaust gas cleaning. In many cases, however, there is disagreement between industry, authorities and environmental associations as to whether modern technologies are already state-of-the-art. Industry sometimes views new technologies as disproportionately expensive because of their cost and tries to delay their introduction. However, the state of the technology in the EU has not yet been achieved in many plants worldwide.

Box 7

Examples of shortfalls in the reduction of emissions in industrialized countries

Heavy fuel oil with a high sulfur content ("bunker fuel") is still used very frequently in maritime shipping. For example, switching to low-sulfur and therefore less harmful fuels is required in many ports, but not on the open sea.

For a long time, a toxic substance in the exhaust air from coal-fired power plants was not strictly regulated in the industrialized countries: Mercury, a poisonous heavy metal which, among other things, causes an increase in intellectual disabilities in children [ClientEarth 2020].[9] It is contained in small amounts in coal and is only incompletely filtered out during combustion. The Minamata Convention (see Box 1 in Chapter 1) calls for measures to reduce these emissions, which are greater than any other entry route for mercury into the environment. The environmental associations demand the establishment of a limit value of 1 µg/Nm3 of exhaust gas [NABU et al. 2017]. The easiest way to avoid such emissions is obvious: do not generate energy from burning coal.

Toxic wastewater and waste are endangering the biosphere

In industrial processes and also when chemicals are used in households and businesses, wastewater is generated that often contains hazardous substances. Eighty percent of global wastewater ends up in water bodies, mostly in rivers, without being treated [IPBES 2019]. Numerous substances in wastewater cannot, or can only partially, be filtered out by sewage treatment plants. One example of this is numerous active ingredients in medicinal products that mainly end up in water through human excretion [BUND 2020a]. As a rule, wastewater contains numerous chemicals so that cumulative combined effects must also be taken into account when assessing the effects on aquatic communities.

8 In Germany: among others via the 17th Federal Immission Control Ordinance (BImSchV).

9 Mercury is especially harmful because even in small amounts it has a long-term neurotoxic effect on the developing brain (nerve stem cells) of unborn babies and children [Ceccatelli et al. 2013]. For a long time, impairment of intellectual development by mercury [Surkan et al. 2009] has been proven to occur. Even if the harm to individuals is low (a few IQ points), the economic importance increases considerably due to the wide distribution of mercury, that is, the large number of people affected [Bellinger et al. 2018]. In addition, due to the epigenetic (gene-changing) effect [Culbreth & Aschner 2019] of methylmercury – (which is produced in the environment as a transformation product) – there is well-founded suspicion of cross-generational transmission/inheritance: subsequent generations also suffer negative effects to the brain without ever having been exposed to mercury. That is why BUND – Friends of the Earth demand that the best possible filter technology be required in all coal-fired power plants that emit mercury.

For some chemicals, environmental quality standards (EQS) for surface waters are stipulated in the EU or at the national level [European Union 2013]. When deriving the environmental quality standards (EQS), the ecotoxic effects of the substances under consideration on aquatic organisms are decisive. The concentrations of these substances in water are measured and, if they are exceeded, measures to reduce these concentrations should be carried out. Some active ingredients in pharmaceuticals are also discussed here and are included in a watch list [EU Commission 2020a].

Toxic substances also make their way into the marine environment via rivers, but also through direct discharges, and are sometimes detected there in dangerous concentrations [OSPAR 2019].

A reduction in water pollution from toxic wastewater can be achieved by replacing problematic pollutants, especially persistent pollutants, implementing measures at the source to reduce the load of hazardous wastewater ingredients and further expanding sewage treatment plants to include a fourth purifying stage.

Further pollution is caused by waste: people dispose of substances and products that they no longer use or want to by discarding them with household waste. If these products cannot be reused or recycled (see Chapter 3), they must be disposed of or incinerated. The EU's framework directive on waste also regulates the handling of hazardous waste [European Union 2018], which can pose a risk to the living environment. Despite EU waste law and the international Basel Convention (see Box 1 in Chapter 1), in countries of the Global South significant amounts of electrical and electronic scrap containing dangerous substances such as heavy metals and brominated flame retardants are disposed of illegally [Baird et al. 2014]. There, some valuable metals are recovered under conditions that are harmful to health and the environment [NABU 2019].

Plastic threatens the biosphere

The biosphere is not polluted by toxic substances alone. Plastic is mostly non-toxic, but extremely persistent. Once released into the environment, it can hardly be retrieved, especially if it has been added to products as microplastics or if it spreads into the environment as abrasion from plastic items, textiles or vehicle tires. Especially in countries without a functioning waste management system, plastic waste ends up in the environment and ultimately ends up in the oceans via rivers. Marine organisms, especially plankton feeders, ingest the particles, are unable to digest them and starve to death although their stomachs are full. Microplastics can also enter higher organisms such as fish and marine mammals as well as the human body via the food chain [Koelmans et al. 2017]. The irreversibility of marine plastic pollution and its global dimension induced researchers of the Stock-

Box 8

Additive in car tires endangers coho salmon

An antioxidant is usually added to the rubber of car tires and other rubber products. This substance is intended to prevent the plastic matrix from being destroyed by ozone. The antioxidant 6PPD[10] is widespread. Studies by Washington State University have now shown that tire wear from roads is washed into rivers and streams and then releases toxic substances, which could lead to the collapse of coho salmon (*Oncorhynchus kisutch*) populations on the US west coast. The oxidation product 6PPD-quinone was identified as the cause of the poisoning [Tian Z. et al. 2021].
Further investigations into the occurrence and distribution of this oxidation product and its ecotoxicological properties are urgently required. It is likely that the substance is also toxic for other fish and aquatic organisms. The case shows a serious gap in the EU chemicals regulations REACH and CLP. Base chemicals are examined and classified (here: 6PPD). When used as intended, it should react with ozone and form quinone as a secondary product. In such cases, investigations must also show that these secondary products are safe and do not endanger the environment or health.

[10] *N-1,3-dimethylbutyl-N'-phenyl-p-phenylenediamine*

Figure 15: Plastic waste on a tropical beach
© iStock.com/narvikk

holm Resilience Center to evaluate whether plastic alone exceeds the planetary boundaries for novel entities [Villarubia-Gómez et al. 2018]. They concluded that although there is still ignorance about disruptive effects on the marine environment precaution is needed and means to stop further pollution should be taken urgently.

Soils (via compost, digestate and sewage sludge), rivers and lakes now also contain ubiquitous plastic residues [UBA 2021]. Plastic is everywhere. The pollution of the oceans with microplastics and macroplastics poses an existential threat to the marine environment (Fig. 15).

The large quantities in combination with their scarce degradability make plastics one of the most pressing global environmental problems today. In addition, toxic additives in plastics, such as plasticizers, antioxidants, UV stabilizers and flame retardants, often pose a serious environmental problem [BUND 2019b]. Plastic parts in the environment can also absorb pollutants from the aqueous environment, accumulate such pollutants and transport them into the bodies of living beings (Trojan horse effect).

Until recently, unused plastic waste was exported from the EU on a large scale for recycling, mainly to Asian countries (see Chapter 3). The recycling there is often inadequate and leads to considerable environmental pollution. However, some of these countries – especially China – no longer allow imports from Europe and North America, which leads to higher amounts of waste that is incinerated. The resolutions of the Basel Convention of May 10, 2019 [UNEP 2019b] that only pure, unpolluted plastic waste may in future be exported for recycling without a permit is to be welcomed and consistently implemented.

The polluter pays principle and the proximity principle of the circular economy require that waste exports be reduced to a minimum. Waste materials should only be exported to countries that can verify that they are at least in compliance with the disposal and recycling standards of the EU.

Figure 16: An oil palm plantation in Indonesia.
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Invasive species and global trade

Invasive species are an important driver of the threats posed to biodiversity. These are organisms that are carried off or imported from other parts of the world, colonize new habitats and can displace the native species there (Neobiota) [Settele 2020]. Very often it is the various means of transportation that cause this spread. Many organisms such as termites or spiders travel on merchant ships as "stowaways"; wood from China brought in the Asian longhorn beetle [LfL 2021]; together with their load or their tires, trucks overcome natural barriers such as the Alps and bring the Asian tiger mosquito to Central Europe. The ballast water of ocean-going ships is full of alien organisms and so it must be disinfected for international shipping in accordance with the Ballast Water Convention. This agreement was adopted in 2004 and has been in force since 2017 [IMO 2022]. If the organisms that have been introduced find favorable conditions at the destination, they can establish themselves there and multiply. The increase in global flows of chemicals and materials is favorable to the spread of non-native animals and plants. Among the organisms that are spread in this way are mosquitoes and other organisms that can transmit diseases called zoonoses.

Planting renewable raw materials

Replacing fossil raw materials with renewable raw materials appears to many to be the ideal solution to sustainability, overcoming the climate crisis and reducing material risks for biodiversity. In the recent past, demand for biomass from nature has increased significantly [IPBES 2019]. Biological raw materials are an important approach for a climate-neutral economy. However, this approach has clear limits (see Chapter 3). Renewable raw materials can only replace fossil raw materials to a very limited extent, in any case. Wood – a desirable alternative to concrete in the construction sector – is also a limited resource, especially since from the point of view of nature conservation, more unused, near-natural forests are desirable.

The increasing competition for land is worrying: If more and more energy crops are grown, they displace culti-

vation areas for food-producing crops [Priefer et al. 2017]. Some energy crops such as *Silphie* or *Miscanthus* that are increasingly grown in Europe do not yet have historically established accompanying flora. Thus their cultivation leads to further species impoverishment.

Renewable raw materials are being imported from the countries of the Global South to a greater and greater extent. But a great deal of natural habitat is destroyed in order to obtain these renewable raw materials (Fig. 16). The clearing of primeval forests results in serious ecological damage, such as leaching of the soil, damage to the water balance, and also leads to the release of greenhouse gases as a result of the degradation of the soil, so that the climate balance is negative.

But in Europe too, increasing cultivation of biomass has consequences: fallow land, which was an important retreat for endangered animal species and plants, has been taken back under the plow. While around 10% of agricultural land in Germany was taken out of use at the end of the 1990s, it is only 2% to 3% today [Leopoldina 2020].

The following also applies here: There is no getting around reducing and slowing down material flows. Our consumption and our lifestyles have to adapt to the planetary boundaries (see Chapter 2).

Pesticides and fertilizers

"The real emissions of the chemicals industry … are … the products themselves." This quote from Eberhard Weise, a former management board member at Bayer AG, shows that products that are deliberately released into the environment, may pollute it and can also threaten biodiversity [Held 1991]. This applies in particular to agricultural pesticides, biocides and fertilizers.

Agriculture is one of the most important drivers of the decline in species [Leopoldina 2020]. The cause is the form of industrial cultivation to which, for example, field margins fall victim. Modern agriculture is also based on the intensive and widespread use of pesticides and fertilizers (Fig. 17). In particular, the insecticidal neonicotinoids damage biological diversity in and around the fields. Compared to 1995, the amount of pesticide active ingredients applied in agriculture has not increased in Germany – it is approximately 30,000 tons annually – but today's active ingredients are many times more effective than they were then [Leopoldina 2020]. It should also be borne in mind that the areas where pesticides are applied are generally decreasing due to the rise in organic cultivation [BÖLW 2020].

However, it is not just a matter of the direct toxic effects on target organisms. Indirect effects are also decisive: for example, herbicides such as glyphosate eliminate wild herbs that the pollinator insects then lack [Klinger 2017, Leopoldina 2018]. Food chains are broken; animals starve to death at what appears to be a richly set table. The situation is exacerbated by the cultivation of herbicide-resistant crops, which means that the quantities used per acre increase, crop rotation is avoided and resistant wild herbs develop [Schütte et al. 2017].

Fertilizers also reduce agrobiodiversity [Meyer et al. 2014]. In particular, the nitrogen content of the soils is very high across the board as a result of the application of liquid manure and mineral fertilizers. This also applies to grassland which is only used to a small extent for grazing. Thanks to intensive fertilization, the diversity of the different types of grassland is decreasing [Gilhaus et al. 2017]. Heterogeneous nutrient-rich and species-poor meadows are becoming the norm. Above all, plants with high nutrient requirements such as nettles and goutweed (*Aegopodium podagraria*) are spreading.

The accompanying flora, which are important for the arable habitat, disappears. This is a major cause of the dramatic decline in flying insects and, as a result, birds in agro-ecosystems [Lemoine 2007]. Mammals such as the brown hare or hamster and birds such as the gray partridge, Eurasian skylark or yellowhammer are among the animal species threatened with extinction. The disappearance of many animals, plants and microorganisms from agro-ecosystems leads to a

reduction in ecosystem performance, and thus endangers the long-term stability of agricultural landscapes.

The diversity of soil life is also severely impaired by intensive cultivation and the use of chemical products [KBU 2020]. Industrialized agriculture also leads to soil leaching. The content of bound organic carbon, among other forms as humus, decreases and the soil degrades.

It is becoming increasingly evident that pesticides also affect bacterial communities (microbiomes). Insecticides and in particular the common herbicide glyphosate (trade name: Roundup) damage the intestinal microflora of mammals and pollinating insects such as bees [Mesnage et al. 2019 and 2021, Motta et al. 2018, Syromiatnikov et al. 2020]: The composition of bacterial flora changes, immunity to pathogens decreases, and the reproduction and behavior of the host animals change. The microbial diversity in the soil is also adversely affected by pesticides (herbicides, fungicides, insecticides) [Meena et al. 2020]. Soil fertility and the diversity of higher soil organisms decrease.

Intensive agriculture not only reduces the diversity of plant and animal species in agricultural areas. The variety of cultivated plant varieties is also steadily decreasing. A few high-performance cultivars among cultivated plants are becoming increasingly dominant on arable land. Farmers usually cannot obtain their own seed from hybrid seeds but have to buy new seeds every year. The agro-ecological adaptation to local and regional cultivation conditions is decreasing. The varieties usually required a high level of nutrients, are sensitive to harmful organisms and susceptible to plant diseases. The consequences are the high use of fertilizers and pesticides.

Hormone-disruptive substances and infochemicals

Hormonal substances have a particularly insidious effect on ecosystems. Endocrine disruptor (ED) substances influence the hormonal systems of humans

Figure 17: Application of mineral fertilizers
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and animals even at low concentrations. They simulate or block hormones (especially the sex hormones and the thyroid hormone) or change formation, transport and breakdown of natural hormones [WHO 2012].

Numerous industrial chemicals and pesticides work this way. Endocrine disruptors that act like sex hormones can change the hormone balance of babies in early pregnancy and thus contribute to disturbances in the development of the genital organs and can even induce breast or prostate cancer. Hormones prescribed as medication are also emitted into the environment through excretion [BUND 2020a]. Endocrine disruptors not only threaten human health but can also damage natural communities. For example, the gender ratio of fish in polluted waters has changed in favor of female animals. Reproduction and development of both vertebrates and invertebrates are influenced [Mathiesen et al. 2016].

Hormones are messenger substances within an organism. In nature, information is also exchanged between living creatures through substances. Organisms such as insects and plants use chemical substances to inform each other about food sources and predators. Insects send out sexual attractants (pheromones). Other chemicals influence the swarming behavior of fish and grasshoppers [Brönmark et al. 2000, Gundlach et al. 2021]. Such chemical substances are called infochemicals and in most living things they play a decisive role in vital processes such as reproduction, social behavior, eating, defense or orientation. Some fragrances in cosmetics or detergents and cleansing agents have structures that are very similar to those of natural information chemicals [Nendza et al. 2009]. Initial findings show that some synthetic chemicals can simulate or suppress such information [Berghahn et al. 2012]. Effects like these are even observed from substances that are present in plastic waste [Pfaller et al. 2020, Trotter et al. 2018]. As a result, anthropogenic infochemicals are potential disruptive factors in a highly sensitive system of coexistence between animal and plant species [Klaschka 2009a and 2009b, Gross 2022]. For example, some neuropharmaceuticals impair the swarming behavior of fish while some pesticides impair the sense of direction of honeybees.

Reduced substance diversity

The impact of substances threatens biological diversity. Conversely, the decline in species also creates problems: Ecosystem services that are important for humans, such as pollination, are at risk. Furthermore, many genetic resources, the protection of which is regulated by international treaty in the Nagoya Protocol 2010 (see Box 1, Chapter 1), are lost, and with them natural active substances. This means an irretrievable loss for chemical diversity. Numerous plant ingredients with a pharmacological effect have not yet been discovered. The complex, species-rich ecosystem of the coral reefs and the tropical rainforests contain innumerable, as yet unknown chemicals and messenger substances that can be important for pharmaceuticals, crop protection or technical applications. These genetic resources need to be preserved in order not to lose options for suitable, environmentally compatible solutions [CBD 2010].

6. Sustainable Chemistry Protects the Climate and Biological Diversity

In the context of chemicals and materials policy sustainability means working based on regenerative principles and ensuring precautions are taken. Above all, its purpose is to avoid irreversible harm to the ecosystem. This means that

- regeneration and recycling (reuse and reapplication) are taken into account from the very beginning;
- chemical products should not have hazardous characteristics that burden the environment and health;
- chemical production should be carried out in such a way that it does not involve any danger for human beings or the environment and is efficient in regard to energy and resources;
- material flows must be managed in such a way that they do not exceed planetary boundaries and satisfy ecological criteria.

Sustainable chemistry involves both the scientific discipline of chemistry and also chemistry as an economic sector. It includes the twelve principles of "green chemistry" of Anastas and Warner as scientific criteria [Anastas and Warner 1998] and in addition examines the functions chemical substances should carry out, including social, economic and ethical aspects. The International Collaboration Center for Sustainable Chemistry (ISC3) has listed the central characteristics of sustainable chemistry [ISC3 2020].

Many functions can be carried out without the use of synthetic chemicals. Testing of whether non-chemical alternatives are more sustainable is thus needed at the early beginning. However, a "chemistry-free" world is no longer imaginable and would also be unsustainable. Without chemicals many of the sustainability goals (SDG) of the UN would be unreachable [UNO 2015]; it is only necessary to consider the necessity of medication and disinfectants for the curbing of the incidence of illness.

Sustainable chemicals

Chemicals to which humans or the environment can be exposed should, if possible, have no hazardous properties. In particular, they should not be persistent, should not accumulate in the long term and should not trigger any as yet undetected, irreversible effects. They should be "benign by design" [Kümmerer 2015], that is, structurally benign, and have a short range in terms of time and space ("short range chemicals") [Scheringer 2002]. Some hazard characteristics are indispensably linked to the function. For example, by their nature fuels have to be combustible and disinfectants must be toxic. However, dangerous properties that do not fulfill a function are basically avoidable as a rule.

To assess how sustainable a chemical is, further criteria are needed such as the consumption of resources during extraction and manufacture, the material and ecological suitability for the areas of application, the possibility of reuse and utilization (recycling) or composting, and behavior in the waste phase. Germany's Federal Environmental Agency has published a decision-making aid with a "Guide to Sustainable Chemicals" [UBA 2016]. UNEP recently published a Framework Manual on Green and Sustainable Chemistry [UNEP 2021]. The sustainability of a chemical can be answered differently from region to region: In countries without state-of-the-art waste and wastewater treatment, for example, organohalogen compounds such as chlorinated solvents in products cannot be used sustainably.

Not only are the material properties but also the function a chemical is expected to fulfill are decisive in the assessment of sustainability [Anastas and Zimmerman 2018, Kümmerer 2017]. Sustainable chemistry considers the use of chemicals in different products and productions and also the service that a chemical should provide (chemistry for what and for whom?).

The chemical-leasing business model is an example of how the use of chemicals can be reduced in line with demand, thus avoiding hazards [UNIDO 2018]. When "leasing chemicals," a chemicals company makes a substance or mixture available for a specific purpose but remains its owner and then takes responsibility for its disposal. Depending on the requirements and

the use of a product, there are various requirements for the chemicals used. The usefulness of a substance in the entire product life cycle should be optimized as much as possible and at the same time possible damage avoided.

Sustainable production

Chemicals should be manufactured in a way that meets sustainability criteria. This means, among other things, high energy and resource efficiency, effective purification of wastewater and exhaust air, low waste generation and inherently safe production processes.[11] This requires making innovative changes to current production methods: for example, changing the raw material base, bio-technical and (new) catalytic processes, use of microreactors, and conversion to syntheses at low temperature and low pressure [UBA 2009]. For a quick and sustainable changeover in production, it would be important not to issue operating permits for an unlimited period, but to adapt the systems quickly to the state-of-the-art.

Sustainable materials flow management

In its current updated sustainability strategy for Germany the national government lists, among others, the following rules for the management of resources [German Federal Government 2016]:

- Renewable natural resources (such as forests or fish stocks) may only be used long-term within the limits of their ability to regenerate. Non-renewable natural resources (such as mineral raw materials or fossil energy sources) may only be used long-term to the extent that their functions can be replaced by other materials or other energy sources. The release of substances in the long-term may not be greater than the ability of natural systems – for example climate, forests and oceans – to adapt.
- Energy and resource consumption as well as transport services must be uncoupled from economic growth.

These very generally formulated rules can be made concrete by means of three strategic approaches, which complement each other: efficiency, consistency, and sufficiency (see Box 9) [relaio 2018].

Box 9

Three strategies for sustainable materials flow management

- The efficiency strategy is based on the sparing use of materials and their long-term use. State support for companies [e. g., efa+ 2022], support for research [e. g., BMU 2020b] and specification of norms (such as the VDI guideline 4605 [VDI 2017]) are promoting resource efficiency in the production and processing of resources. This means: Specific resource consumption in relation to value creation is falling. However, this uncoupling of resource consumption and GDP has only a limited effect on consumption, which in many areas is contributing to increases or acceleration of substance flows. Miniaturization and savings in expensive resources can even generate a "rebound effect" [Deutscher Bundestag 2014].
- The aim of the **consistency** strategy is to coordinate natural systems and technical processes. This includes approaches to link industrial activities in the sense of natural production and destruction cycles ("Industrial Ecology" [Ayres and Ayres 2002]). The principle of consistency is also followed by constructions that consist of modules or materials that can be reused unchanged in other places, as well as the manufacture of materials that are based on natural models or that are constructive or functional copies of natural structures (bionics). Another aspect of this strategy is the recovery of (secondary) raw materials by recycling products with as much value as possible (see Chapter 3). In addition to recycling and resource-efficient production, a "circular economy" relies on greater durability, reparability and multiple use of products. Approaches to sustainable chemistry are particularly in demand here [Kümmerer et al. 2020]. However, there are limits to this, as is also the case with the efficiency principle, even if this is often neglected (such as when applying the cradle-to-cradle approach: Here, a complete technical return or transfer of products into biological cycles is aimed at [Lovins et al. 2014]).

[11] *The concept of inherent safety focuses on avoiding hazards in a production process from the very start. Ideally, this means, for example, that a system automatically goes into a safe state in the event of a process fault.*

- The **sufficiency** strategy poses the question of what is enough. In concrete terms, this means consciously avoiding the (non-retrievable) consumption of resources. If this strategy is translated as "frugality," then something like this is frowned upon in consumer societies because it sounds like shortages and austerity [Weber-Blaschke 2009]. However, sufficiency does not mean austere sacrifice, but raises the question of the right amount and the more conscious handling of limited resources, or to put it simply: Often is seldom more [BUND 2017, Sachs 1993].

Consequently, in addition to efficiency and consistency, which complement each other, the ground rules of sustainable management of substance flows must also include sufficiency. This is especially true in view of the finite nature of non-renewable resources, especially rare minerals or metals.

Steps toward significantly higher efficiency and consistency can be implemented in a socially and economically acceptable manner and are largely undisputed. Corresponding optimizations of value chains or business models prove this in practice. For greater acceptance and a breakthrough for the sufficiency principle, growing awareness of the finiteness of resources, new models for prosperity and growth, and a legal framework, and thus a departure from the economic-growth model, are required. But we will not achieve this goal without effective sufficiency strategies.

In addition to the quality (substitution) and quantity (reduction) of material flows, ultimately the question also being considered is whether the cycles of the techno- and ecosphere are open or closed to one another. In the case of easily degradable, compostable materials, it is possible to open up technical cycles to global biogeochemical cycles and regional ecological cycles. By contrast, persistent substances, toxins or nutrients that disrupt natural material cycles and have no place in nature need to be sealed off from the ecosphere (see Fig. 18).

The concept of the circular economy focuses primarily on cycles within the technosphere. The aim is to ensure that products made from chemical substances have the longest possible product lifetimes. They should be suitable for reuse, extended use, repair and high-quality recycling. Regional material flows should consistently have priority over global material flows.

This leads to requirements for product design (such as reparability and possibility of dismantling) and the simplest possible chemical composition that does not prevent high-quality recycling [Kümmerer et al. 2020]. This includes doing without additives and using monomaterials. The manufacturers should therefore not only be responsible for the functionality, but also for the recycling of their materials.

Particular attention should be paid to environmentally open applications, that is, all chemicals such as fertilizers, insecticides, pharmaceuticals or substances for coating surfaces that humans deliberately and purposefully introduce into the environment in order to achieve certain effects. Here the question of the benefit, the minimization and the non-chemical alternatives must be posed even more clearly. The ability to complete and rapid mineralization is then a prerequisite for sustainable use.

Possible effects on biodiversity and the climate must be considered and assessed with special consideration of the precautionary principle. The greatest challenge of the 21st century is to achieve a sustainable and globally tolerable way of life and related economy. A sustainable chemicals and materials policy can and must make a significant contribution to achieving the climate and biodiversity goals. What is needed is a socio-ecological restructuring of our society (transformation) oriented towards the common good and planetary boundaries. A reorientation of resource and materials policy is a central component of this process. The aim must be to significantly reduce the overall flow of materials. More detailed information can be found in the project "Network for Sustainable Resource Use" [BUND 2020b]. Sustainable materials flow manage-

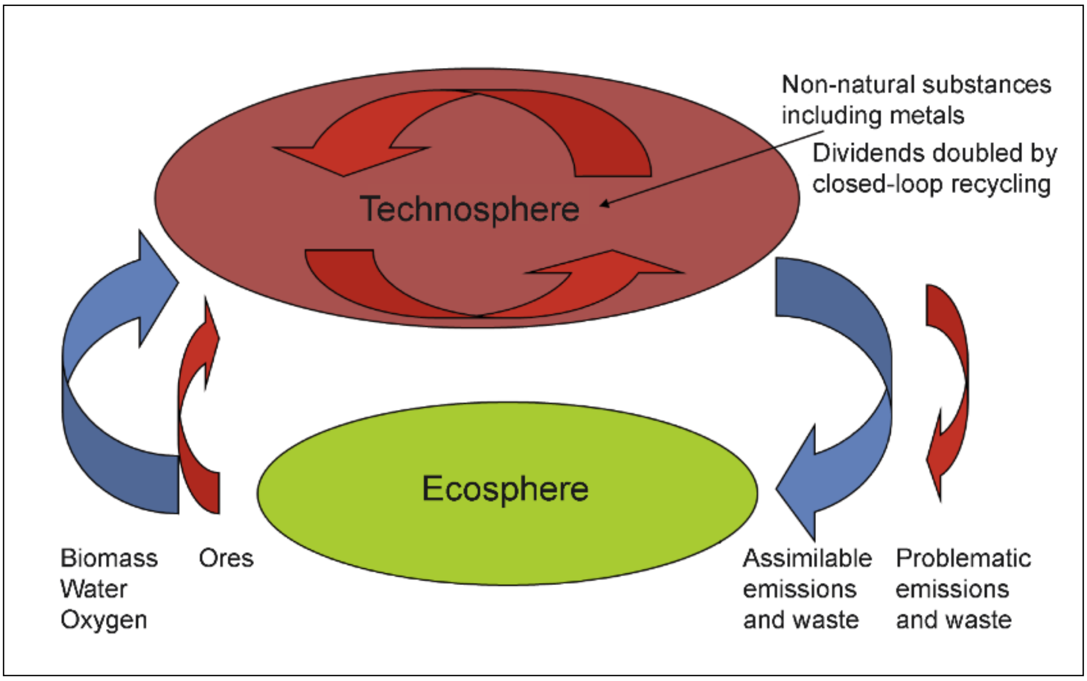

Figure 18: Opening and closing of the transitions between the eco- and technosphere
** "Non-natural" refers to substances that do not already circulate naturally in large quantities in the bio/geosphere, that is in broad terms, synthetic substances as well as elements that are only released in small quantities in the biogeochemical cycle such as many (heavy) metals: [Gößling-Reisemann, von Gleich 2009].*

ment thus requires not only sustainable chemistry, but also an ecological economy [Bringezu & Kümmerer 2012].

The report "The Economics of Biodiversity" of Dasgupta and the corresponding OECD policy guide present ways of restoring economic value to nature and thus achieving the Sustainable Development Goal of sustainable production and consumption are presented (SDG 12) [Dasgupta 2021, OECD 2021]. Fundamental changes in the economic and financial system, but also in institutions and social values, are necessary in order to bring nature back into equilibrium with human activities.

7. Recommendations and Conclusions

This background paper makes the following clear: The loss of biological diversity, climate change and overloading the planet with chemicals and materials are closely intertwined. All three global challenges must be tackled and solved together. This requires taking into account how the three fields of action mutually influence each other.

It is becoming more and more evident that global environmental problems are the result of an economy that is hostile to nature and the environment. There is an urgent need to turn away from the constantly increasing consumption of energy and resources. This will not be achieved on the required scale simply by decoupling economic growth and resource consumption. Rather, what is needed is an approach that includes consistent sufficiency strategies, especially in the countries of the Global North. Adopting a holistic approach and turning away from perpetual material growth are needed. The countries of the Global South need a sustainable development strategy that enables economic participation without emulating the waste of energy and resources as practiced by the Global North.

In an overall concept, three approaches must interlock: first, efficiency strategies, then consistency strategies, that is, in particular the recycling of materials and the use of materials that can be integrated into ecological cycles, as well as sufficiency strategies that avoid excessive use of resources. Under the heading of sufficiency, questions are asked about the benefits products deliver, the existence of alternative products, longevity and ease of repair as well as about drastic reduction in energy and resource consumption in production and use.

The consequences of excessive energy and resource consumption and the increasing depletion of the spread of hazardous substances are not only dramatic climatic changes and the increasing depletion of non-renewable resources. The global threats ultimately lead to a loss of natural habitats and biological diversity and, associated with this, pose a threat to human life and its survival.

Sustainable policies regarding biodiversity, the climate and chemicals and materials management therefore represent three pillars of a transformative international policy.

The first two policy areas are regulated globally by international framework conventions: the Paris Agreement for Climate Protection and the Convention on Biological Diversity. There is currently no corresponding global convention for the chemicals and materials sector. A legally binding international chemicals and materials framework agreement is urgently required. This must contain clearly defined reduction targets for the consumption of chemicals and resources as well as a strategy for sustainable detoxification of the environment, efficiency targets and requirements for cycle management and waste treatment.[12]

It is important to create an independent scientific and intergovernmental advisory body – analogous to the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Platform on Biodiversity and Ecosystem services (IPBES). Numerous prominent scientists have drawn attention to this need [Wang et al. 2021] and made it clear that it is important to scientifically undergird a sustainable chemicals and materials policy [Scheringer 2017]. The International Panel on Chemical Pollution (IPCP) could possibly be expanded into such a scientific stimulus [IPCP 2019].

The United Nations Environmental Assembly (UNEA 5.2) agreed at March 2, 2022 to establish such a supporting instrument. To do this, however, the institutional connection and the perspective of this body would have to be significantly broadened. Proposals and demands for a sustainable management of substances are listed in the BUND Position Paper 69 "Challenges for a Sustainable Chemicals and Materials Policy" [BUND 2019a].

Both at the international level and in the European and national framework, the interactions between biodiversity, climate and chemicals and materials policy must be taken into account and addressed more closely. An international process must be initiated at all levels, which, based on the sustainability goals of the United Nations, defines a common framework for action that links all three policy areas and sets out specific action goals and instruments analogous to Agenda 21 at the World Conference in Rio de Janeiro in 1992. The serious global environmental changes show: Time is of the essence. Fast, networked and consistent action is required.

12 The SAICM process can serve as one of the foundations but is still not legally binding and limited to topics related to sound management of chemicals and waste.

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Glossary

CBD	Convention on Biological Diversity
CED	Cumulative energy demand (based on German VDI guideline)
CLP	Classification, Labelling and Packaging, EU Regulation No. 1272/2008
CO_2eq	Carbon dioxide equivalent
CRD	Cumulative resource demand (based on German VDI guideline)
ED	Endocrine disruptor (hormone-active substance)
EEA	European Environment Agency
EQS	Environmental quality standard
HBCD	1,2,5,6,9,10 hexabromocyclododecane
HDPE	High-density polyethylene
Infochemical	Messenger substance for the transmission of information between organisms
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPCP	International Panel on Chemical Pollution
Microbiome	Community of microorganisms
Nm^3	Standard cubic meter – volume at 1013 hPa and 0 °C
OSPAR	Oslo-Paris Agreement for the Protection of the Marine Environment of the Northeast Atlantic
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PCDD/F	Polychlorinated dibenzodioxins and furans
PET	Polyethylene terephthalate
PFAS	Per- and polyfluorinated alkyl substances

PICT	Pollution-induced community tolerance
$PM_{2,5}$	Particle fraction that passes through a size-selective air inlet that has a separation efficiency of 50 % for particles with an aerodynamic diameter of 2.5 µm (particles up to a maximum of approx. 5–6 µm)
POP	Persistent organic pollutant
PtX	Power to X technology for the production of gas (PtG) or liquids (PtL) from hydrogen and carbon dioxide using electrical energy
REACH	Registration, Evaluation and Authorization of Chemicals, EU Regulation No. 1907/2006
SAICM	Strategic Approach to an International Chemicals Management
SDG	Sustainable Development Goal
UBA	Umweltbundesamt (German Federal Environment Agency)
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organisation

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