



# Materials come around and go around: Adapting to nature's circularity

Dominique Schüpfer, Ronja Wagner-Wenz,\* Katharina Hendrich,  
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The present multiple crises, such as climate change, war, and the recent pandemic, highlight the need for a stable and secure resource supply chain to overcome resource scarcity and shortages in manufacturing as well as in goods for everyday needs. Today's linear production chains and waste management systems contribute to disruptions in resource availability as well as to greenhouse gas emissions. The concept of a holistic circular economy, inspired by natural processes, could help to mitigate these challenges. With a primary goal of maintaining resources, as much as possible, in "closed loops," the following three challenges should be addressed: (1) Dissipation of resources, (2) Irreversibility of some processes, and (3) Logistical, technological, and information. These challenges can be addressed, in part, by implementing computational technology and cascading mechanical and chemical recycling processes in waste and resource management. This article emphasizes the interconnection between resource scarcity and pollution and climate change, and proposes a holistic circular economy as an important contribution to addressing this challenge. This holistic circular economy can be inspired, in part, by nature's self-healing, self-transformation, and self-disintegration capabilities. Another crucial part is a comprehensive understanding of the limited resources of the planet and the impact on the planet of using up these resources and, thereby, leading to a shift toward sustainable material use and waste management. The transition to a circular economy requires changes at many levels, encompassing materials research, technical engineering, industrial implementation, and societal adaptation. In both product and process development, regardless of the technological readiness level, life-cycle analyses must be performed that consider the impact on the planet. With the help of a "product passport," a suitable legal framework can be created and implemented. Radical changes in the way we carry out research into technologically relevant materials can pave the way to a holistic circular economy.

## Today's challenges

In the present time of heightened interacting global crises including climate change, war, and the recent pandemic, a circular economy is ever more worthwhile as part of a solution to these serious problems. The extensive use of communications and computing equipment, both hardware and software, for home office and schooling during the COVID-19 pandemic, together with impact to the supply chain and shortages of manufactured products, has amplified the need for a system of reuse of materials and components. Additionally, the current crises have led to shortages in the supply chain of raw materials that could be mitigated, at least in part, by the development of a circular economy. However, production is severely linear nowadays and associated with environmental pollution.

Materials handling and their use accounts for almost 70% of the global greenhouse gas emissions and the needed resources are scarce.<sup>1</sup> **Figure 1** illustrates the interconnection between the three main causes of these challenges: climate change, pollution, and resource scarcity including their resulting environmental and economic effects. Establishing a holistic circular economy that is as complete as possible and taking biological processes in nature as a model can assist in mitigating the multiple challenges we are facing today. No material, whether functionally used or not, should circulate without purpose.

Climate change is primarily caused by the harmful pollution of the atmosphere and buildup of carbon dioxide. The steady decline in global resources by unrestrained mining of primary raw materials is accompanied by increasing pollution.

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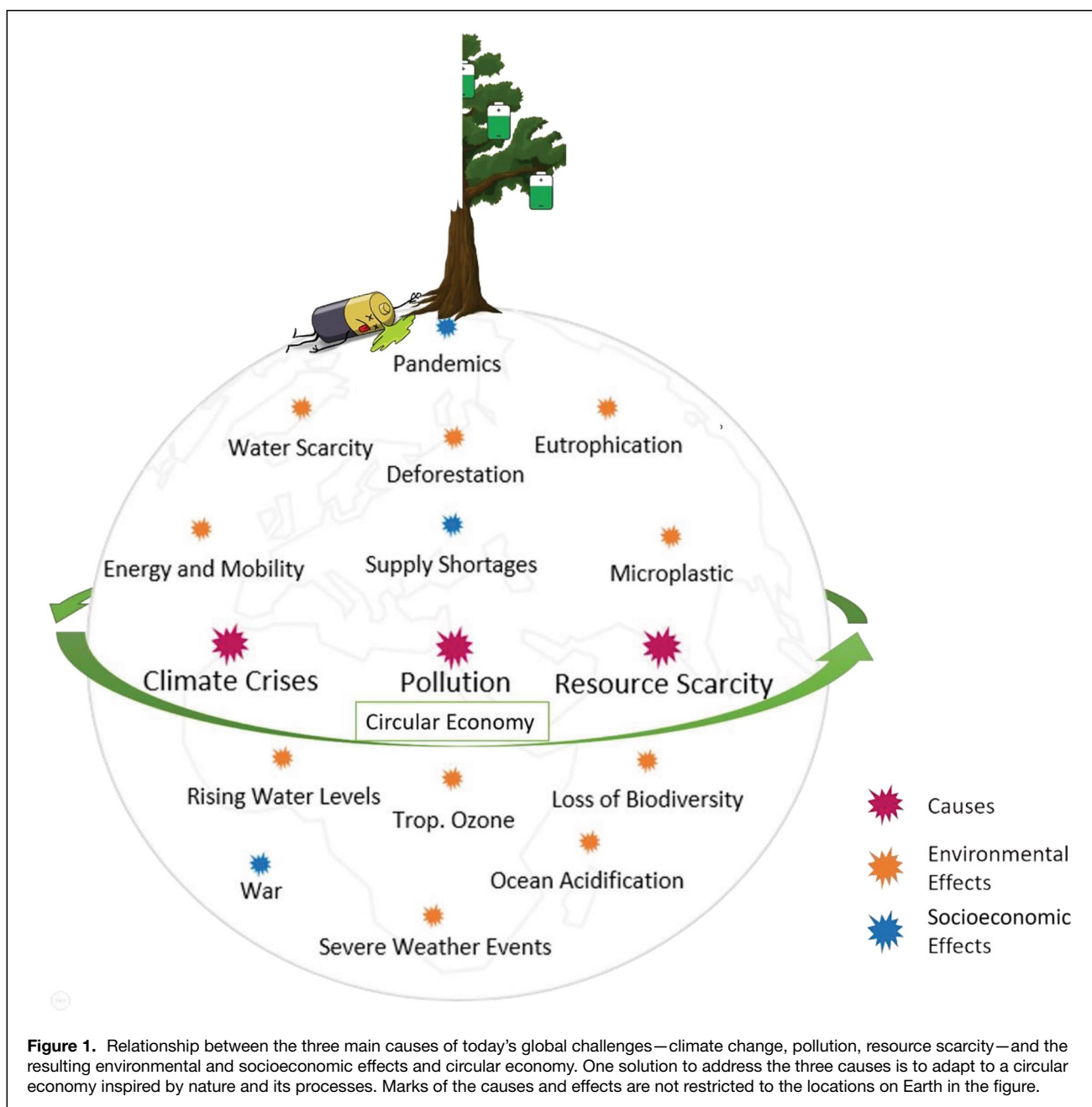
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doi:10.1557/s43577-023-00603-7

The deposition of end-of-life products and waste pollutes the environment and also leads to losses of valuable resources in the form of dissipation. Without the management of material flows, uncontrolled emission of pollutants occurs. They dissipate within the ecological system as liquid, solid, or gaseous emissions. These resources become scarce when needed for production. These depositions in the environment often are associated with a variety of socioeconomic obstacles and create a rising environmental inequity. Instead of dealing with the underlying causes, the policy and political approach at present is to fight the resulting symptoms of the crises, which in the course of time become visible.

To illustrate the close link between valuable resources and pollution, phosphorus, a critical raw material, can be used as an example. The EU has defined 30 raw materials or groups of raw materials that are associated with a supply risk and a high economic impact as critical raw materials (CRMs).<sup>2</sup> Humanity needs phosphorus for survival, because phosphorus is part of every biological cell,<sup>3</sup> but it is also essential for technological applications, for example, batteries. Phosphorus is often the limiting factor in plant growth, making it an important component of mineral fertilizers.<sup>4</sup> However, excess phosphorus in water bodies can lead to the growth of algae and plants (eutrophication), which in the long term leads to siltation of water bodies.



The challenge is to quit a silo mentality and linear thinking in single impact categories. Learning from biological processes in nature can be a crucial step as a response. A starting point is to take into account all *planetary boundaries* and tipping points—elements of the earth system showing a threshold—such as the melting of glaciers.<sup>5–7</sup> The planetary boundaries include climate change, ocean acidification, stratospheric ozone depletion, biogeochemical flow boundaries (nitrogen and phosphorus cycle), change in land use, biodiversity loss, atmospheric aerosol loading, and chemical pollution or novel entities.<sup>5,7–9</sup> They describe human-made changes to the earth. Long-term sustainable management can be achieved only by considering and evaluating all of these boundaries.

Recently, Rockström et al. developed the Earth system boundaries, which go beyond the planetary boundaries. In Earth system boundaries, harm to humans from changes of the earth system is considered instead of focusing on the consequences of human-made damages to the environment.<sup>10</sup>

Each planetary boundary represents a range and most are in principle quantitatively definable such as biogeochemical flows of phosphorus, but the precise value of their limits is blurred due to data and knowledge gaps.<sup>5,7</sup> Furthermore, they show complex interdependencies.<sup>7,9</sup> Details can be found, for example, in the work of Steffen et al.<sup>9</sup> Transgressing these limits will lead to irreversible and intolerable consequences.<sup>5,7–9</sup> The data availability for the respective limits and their values can be found in several publications. For pollutants, respectively, novel entities such as novel materials, no value and so no boundary has yet been identified.<sup>9,11</sup>

Steffen et al. renamed the planetary boundary chemical pollution as *novel entities*.<sup>9</sup> Novel entities are synthetic substances or modified organisms of anthropogenic origin that would not naturally occur on Earth or are circulated by humans for their applications.<sup>8,9</sup> These are, for example, materials made from cobalt, lead, or phosphorus.<sup>2</sup> Toxic novel entities have led to many negative impacts on the environment and health and their emissions must be averted in the future. As new studies have shown, 9 million people per year die due to pollution of, for example, the air and the water or directly during the recycling of lead-acid batteries and electronic waste without any control of toxic emissions.<sup>12</sup> Humans have to learn from these consequences and act immediately to avoid the repetition of such irreversible errors. A circular economy has the potential to lower damages to the environment and to the health of humans. In this sense, the described issues are coupled to a transformation of the current use of materials. In the future, the need and use of raw materials will increase and require a strong sensibility concerning the intersection of CRMs and novel entities. Therefore, the gap in circularity must be closed further. Contrary to current effort, it is in fact continuing to grow.<sup>1,13</sup> To prevent resource scarcity and the emission of novel entities, a circular economy must be realized.

## Materials science, materials management, and circular economy

The basic concept of the circular economy is that materials are recirculated and, ideally, only a non-substitutable portion is introduced into the cycle as virgin material. With regard to the circular economy, three limiting factors can be identified that make it difficult to implement:

1. Material losses, for example, due to consumption leading to dissipation of resources, as previously described. This leads to a dilution of valuable materials.
2. The second law of thermodynamics and the resulting inevitable decay and aging. Also, not all processes are reversible and thus not all products can be recycled infinitely mechanically.
3. Logistical and information challenges that must be overcome to realize its full potential.

A distinction must be made here between mechanical and chemical recycling processes. In the case of mechanical recycling, the material remains intact and maintains its composition, for example, plastics. The second limiting factor (2) concerns mechanical recycling. The properties of the contained materials change continuously with the increasing number of life cycles and cannot be recycled as the same material indefinitely due to the second law of thermodynamics. Inevitably their primary function is lost. New areas of application are currently being identified for the aged materials, for which lower material standards apply—so-called downcycling, for example using plastic waste with degraded quality to build bricks.

Nature takes a different path. Here, the materials can undergo self-healing, self-transformation, and self-disintegration. Thus, the use potential of these altered products as secondary raw materials has to be well elaborated and implemented in the nature-adapting circular economy. One example is the phosphorus cycle in nature. Plants release phosphorus by shedding leaves and fruits; through metabolization by microorganisms and animals, this phosphorus is made available again to other plants. The phosphorus is needed for energy transfer in the cells. Technically, this process is adapted and implemented in biological phosphorus elimination in wastewater treatment.

In chemical recycling, the recyclates are broken down into their components at the molecular or even elementary level and then rebuilt into a “new” product. Examples include the metallurgical processes for batteries and extraction processes or gasification for plastics. In contrast to mechanical recycling, chemical recycling processes provide products with a similar quality as virgin products, but are associated with high chemical or energy requirements. In this context, every decision made within this circular economy must be supported by an environmental and economic impact assessment. In our project Waste4Future, we are developing an entropy-based evaluation model that allows for a choice between mechanical

or chemical recycling routes and energy utilization according to ecological, entropical, and economic aspects for plastic waste.<sup>14</sup> This evaluation model is a valuable tool for implementing a circular economy. The concept can also be applied to other waste streams.

The second limiting factor (2) must be accepted as a law of physics, but even within its scope a tremendous reduction of environmental impact is possible. Now we have to develop radically new production processes, and directly use waste as a starting material, that is, secondary raw materials. Thus, we must consider the life cycle in reverse. An end-of-life strategy must be developed as early as possible in the product development stage. One of the important factors is the design phase, because around 80% of the environmental impact of products is already destined at this stage.<sup>13</sup>

Today, waste management focuses on urban mining. Urban mining recovers only particularly valuable materials from waste without considering the amount of slag, wastewater, and emissions that are released and dissipated in the process. The difference between urban mining and the goal of a circular economy is illustrated in **Figure 2**. In order for waste managers to conclude that the implementation of a circular economy is more profitable than urban mining, policies and the political framework must be created through CO<sub>2</sub> tax and emission guidelines. Additionally, the usage of the nearly unlimited availability of solar energy is required for the production of recyclates. Thus, greenhouse gas emissions will be reduced and a continuous production will be ensured.

Digitization and artificial intelligence with neuromorphic concepts are important for solving the third limiting factor (3) of implementing a circular economy. With the help of digitization, data collection, and the flow of information, focused on a detailed breakdown by materials,<sup>13</sup> can be ensured. A network

can be used to check where certain recyclates are produced or needed. Smart logistics can then be used to distribute the secondary raw materials. But such systems still have to be developed and applied worldwide. In this context, the parameterization of the term “sustainable” among others, based on standardized life-cycle assessment including environmental factors and economic as well as social aspects, would support transparency. Following such a sustainability assessment, processes can be included in circular economy strategies.<sup>15</sup> Despite its limitations and complexity, the circular economy has to be realized by banishing the ongoing linear economy and avoiding further destructive impacts to the earth.

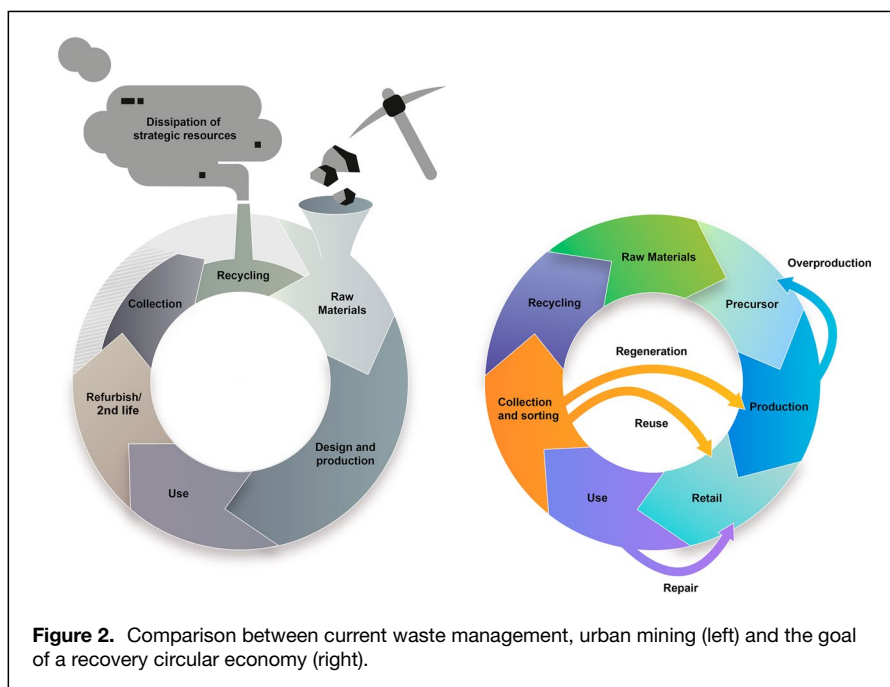
To realize a truly sustainable circular economy, all processes have to be understood and decisions must be taken on the basis of scientific data and knowledge to ensure an efficient, green, and sustainable change. As explained earlier, the “circle” of a sustainable economy must be as complete and nature-based as possible.

Such a circularity transformation requires a change at all levels, particularly in the fields of materials research, technical engineering, and the industrial implementation of the processes alongside the whole supply chain and the symbiosis with nature. Critical factors are, for example, sustainable product design, transparency of the supply chain of products in the form of a digital product pass, renaturation, and the choice and sourcing of raw materials for more balanced and efficient reuse and recycle options.<sup>16,17</sup> The digital product pass provides information on materials including ecological and health implications of materials over their lifetime.

### A fair and sustainable future

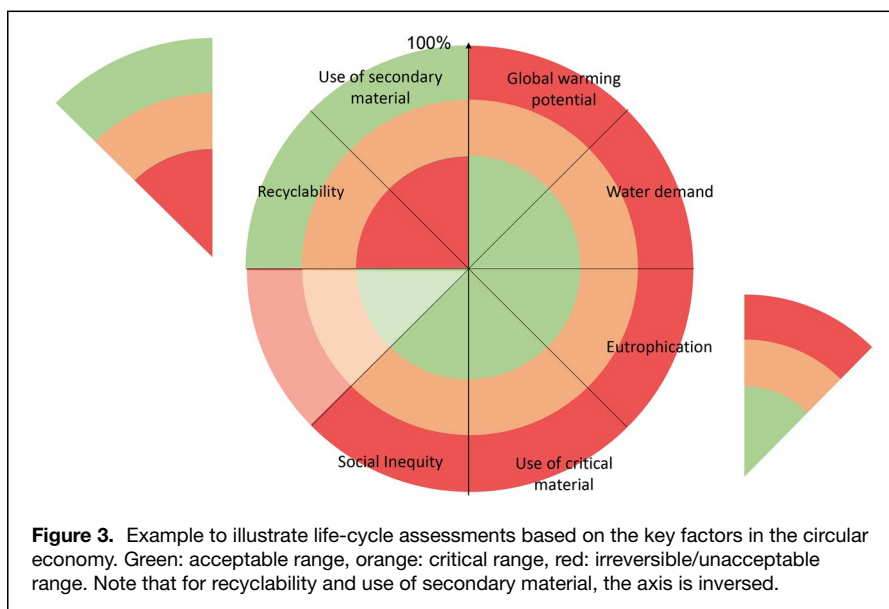
The following factors are especially important for a sustainable, equal, and fair future for humans and nature: Resilience of the earth to human-made changes, the management of CRMs, and consumption as well as associated global social inequities. These factors are directly related to climate change, pollution, and resource scarcity.

Technical progress has brought many advantages to the lives of humans and revolutionized living standards. Unfortunately, some developments resulted in a negative impact on the environment leading to societal inequities. This topic is described under the term environmental justice or racism.<sup>18–21</sup> In the previously mentioned Earth system boundaries, different facets of justice—interspecies justice and Earth system stability, intergenerational justice (between generations), intragenerational justice (between countries, communities, and individuals)—are considered.<sup>10</sup> In this context, novel entities (pollutants)



**Figure 2.** Comparison between current waste management, urban mining (left) and the goal of a recovery circular economy (right).





urgently need to be considered also, but are difficult to quantify.<sup>9–11</sup> While passing several stations of a product supply chain, pollutants are emitted. In this context the pollution, water, and carbon footprints are often displaced from wealthy countries to low-income countries and 72% of the resources are consumed by the wealthiest billion people.<sup>12,13</sup> Pollution should not be exported, but rather green technologies and knowledge should be globally shared and developed collaboratively. This is needed to overcome the problems of implementing a circular economy and to avoid social inequities. Despite the described consequences of technology in the past, technological progress itself is inevitable to overcome environmental problems and to save the existence of the coming human generations on Earth in synergy with a healthy plantal and faunal environment. Some important factors are addressed, for example, in the EU New Circular Economy Action Plan and need to be implemented efficiently in all involved sectors.<sup>22</sup>

Besides the technical part of the circular economy, a change in society and a stream of verified information on environmental impacts are necessary. The implementation of a well-performing reuse and recycle system varies with region.<sup>23</sup> An important aspect is a framework of regulations to give society the possibility to participate at best. These issues and their difficulties are the focus, for example, of the studies of Roura et al. and Jaeger-Erben et al.<sup>23,24</sup> Critical factors include refurbishment costs, certification of products, implementation of service-driven business models as well as many more.<sup>24</sup> Moreover, sharing wealth, knowledge, and technologies fairly is essential.<sup>23</sup>

As discussed, the road to the circular economy is via digitalization. However, all decisions have to be based on environmental impact assessments. With the development of the entropy-based assessment model of Waste4Future, it is possible to select a treatment route according to ecological and economic criteria. This can be transferred to

all other waste streams. Furthermore, environmental impact assessment has to consider all planetary boundaries to overcome the spiral of interdependent multiple challenges. **Figure 3** shows a proposal as to how to complement the planned product passport with an ecological evaluation that takes planetary boundaries into account. Finally, policies have to be set in place to level the path to turn the utopia of a circular economy into reality.

### Implementations for a more holistic circular economy

In conclusion, today's global crises, particularly climate change, pollution, and resource scarcity, clearly show the need for immediate actions to urgently address them. An holistic circular economy could

make a significant contribution to ameliorating these challenges. In particular, research into the production and use of sustainable materials can provide a path toward a circular economy. Life-cycle assessments can be used to identify critical material hot-spots for particular products that have wide usage. The impact on the planet as well as on humankind must be a particular focus of such assessments. The development of relevant and useful evaluation criteria for these materials, especially for their impact on the planet and on society, can only be created through intensive collaborations across multiple research fields and industrial sectors. These factors must be identified as soon as possible in order to contribute to a sustainable future on Earth.

### Acknowledgments

We would like to thank Christina Pouss for the design of Figure 2 and Stuart Parkin for proofreading the article. We would like to express our deep gratitude to Fraunhofer IWKS, the German Advisory Council on Global Change, and the Fraunhofer lighthouse project Waste4Future for funding the work.

### Conflict of interest

Authors declare no conflict of interest.

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