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Putting sustainable chemistry and resource use into context: The role of temporal diversity

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ABSTRACT

Fostering sustainability implies the use of better technologies, chemicals, materials, and industrial processes. This makes chemicals and resources such as metals inevitable components of and contributors to the envisioned societal sustainability transformation. At the same time, they are the source of various adverse effects that ought to be addressed and minimized, including waste and environmental pollution. Often, negative impacts are highly interconnected or only become visible after considerable time, which makes it difficult to identify cause-and-effect relations. We postulate that we must find ways to comprehensively incorporate the spatial and temporal scope of our actions, their (unintended) effects, and the opportunities that they offer for decision-making processes. The latter should be based on a clear understanding of the underlying knowledge, uncertainties, and the related times. In this article, we specifically discuss the role of time and temporal diversity at the interface of space, time, knowledge, and action. We show potential consequences that arise from considering the temporal dimension with regards to the precautionary principle. Based on major findings from time ecology, we suggest guidelines to acknowledge temporal diversity that could contribute to developing solutions with a long-term contribution to sustainability. The guidelines put special emphasis on a more profound understanding of a system's delays, the definition of windows of opportunity, and on designing interventions in accordance with a system's interconnected times.

1. Introduction

Fostering sustainable development implies and is inextricably linked to the use of suitable and improved technologies, chemicals, materials, and industrial processes. It affects fields of action as diverse as environmentally-friendly clothes-dyeing, modern communication, and low-carbon energy production. This makes chemicals and raw materials such as metals inevitable components of this fundamental change (Exner et al., 2016; Kümmerer and Clark, 2016; Moss et al., 2011). Many of the United Nations (UN) Sustainable Development Goals (SDG) signed in 2015 have some link to chemistry, and are calling for a prudent use of material resources, chemicals, materials, and products (United Nations, 2015). This, too, underlines chemistry as an integral part of a sustainable future (Kümmerer and Clark, 2016). But while the positive implications and the contribution of chemistry to our well-being, health, and standard of living cannot be dismissed, the risks and adverse effects associated with chemical use are just as evident.

Humans have visibly shaped the face of the planet over time. At an early stage, sedentism characterized the agrarian society. Impacts have increased strongly ever since the start of the industrialization (Haberl et al., 2011). Since the 1950s, various aspects – from population growth to energy and fertilizer use to ocean acidification – show similar patterns of sharp increase. This has become known as the Great Acceleration (Rockström et al., 2009; Steffen et al., 2015). Today, our impact on the functioning mechanisms of the planet, including its energy balance, its biological basis and the system of stocks and flows, cannot be ignored. This has led us into the *age of humans*, or Anthropocene (Biermann et al., 2015; Crutzen, 2002; Steffen et al., 2007). It has close links to the concept of planetary boundaries, which is also very relevant to chemistry: Keeping chemical pollution within the *safe operating space* bears significant challenges due to the large amount of different chemicals in use on a world-wide scale (Diamond et al., 2015).

Chemical use has caused many environmental burdens as well as health issues in the past. Prominent examples include male infertility of

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workers in production plants and plantations following the production and use of the pesticide Dibromochloropropane (DBCP), and the harming effects of tributylin (TBT) and its follow-up booster biocide antifoulants on marine habitats (European Environment Agency, 2013). Continuous threats do not only arise from on-going emissions of untreated waste, waste water and exhausts. They also come from past catastrophic events and accidents such as the Bhopal gas tragedy of 1984 or the Sandoz chemical spill in Schweizerhalle in 1986. Nowadays, broad-scale regulations, mechanisms, and technologies are installed for treatment and prevention of emissions at least in most developed countries. At first sight, many of these challenges seem to have been generally overcome. However, it must be kept in mind that a lot of the manufacturing and synthesizing processes have been moved to facilities in developing countries, where regulation is less strict or less strictly enforced (Kümmerer and Clark, 2016). And also in industrialized countries legacy issues remain largely unsolved: Persistent substances such as POPs (persistent organic pollutants) have accumulated in animals and humans, and have contaminated the environment over a period of many decades. They continuously leach into and volatilize in the environment, as illustrated by the case of insecurely stockpiled hexachlorocyclohexane (HCH). Even advanced effluent treatment cannot prevent the emission of chemicals and pharmaceuticals into the aquatic environment (Kümmerer et al., submitted; Schwarzenbach, 2006). This shows that further action must be taken towards the identification and safeguarding of the respective contaminated sites (Vijgen et al., 2011; Weber et al., 2012).

Metals mining and use are associated with comparable problems and challenges (Held and Reller, 2016; Kümmerer, 2016; Kümmerer and Clark, 2016). Among others, environmental hazards and social problems in the course of the extraction and purification process make the need to find solutions for these challenges an urgent matter (Ayres, 1997; Bridge, 2004; Exner et al., 2016; Mudd, 2007; Nansai et al., 2015). A broad range of studies relates to the matter of future availability and possible impacts on the industry through supply bottlenecks. Studies largely focus on critical or scarce metals, especially for specific purposes such as their use in low-carbon energy production or other emerging technologies. They provide information on supply estimates and material flows or discuss potential solution strategies (Chancerel et al., 2009; Commission of the European Communities (EC), 2014; Giurco et al., 2009; Graedel et al., 2012; Jackson et al., 2014; Strothmann et al., 2013; UNEP, 2011; Wäger et al., 2012; Weiser et al., 2015).

The potentials and challenges for sustainability in chemistry in general and metal use in particular are highly connected. The flows of materials, substances, and products are increasingly interlinked in a globalized economy, and the related time scales are getting larger and more diverse (Held and Kümmerer, 2004). Our actions have an impact on increasingly larger spatial scales, which also implies a growing need to closer consider temporal scales: (i) past actions continue to have an impact in the present and in the future; (ii) just like the spatial impact, the time scales associated with our actions increase in length; (iii) with a growing global interconnection, such large-scale processes are also increasingly difficult to oversee. This makes it hard to establish (linear) cause-and-effect relations in the case of unintended effects, and demands us to take action in the light of uncertainty.

Spatial and temporal scales are highly interwoven (Held and Kümmerer, 2004; Kümmerer and Held, 1997a). Several studies exist that incorporate or elaborate on the role of temporal and spatial scales and their interrelations (Crang, 2012; Fresco and Kroonenberg, 1992; Held, 2001; Schwanen and Kwan, 2012). The literature on risks and impacts of our actions elaborates on the strong interrelation of knowledge and uncertainties, and how the latter can make decision-making a challenging task (e.g. (Renn, 2008; Sellke and Renn, 2010; Speirs et al., 2015; von Schomberg, 2006)). Little research, however, seems to exist on the interrelation of all four aspects: time and space, knowledge, and action. One factor has largely been neglected in particular: the role of time and its impact on how we interpret our actions in relation to our knowledge base and scope of action. As we have argued above, these interrelations will be increasingly important for decisions based on a long-term and global perspective in order to achieve sustainability. We claim that

- to adequately deal with risks and uncertainty, we also need to understand the connections of space, time, knowledge, and action, including the question of responsibility for our actions in relation to time, and that
- by operationalizing and integrating temporal aspects into our research and actions more explicitly and with a close relation to their spatial scope, we can increase our understanding of (complex) systems, and contribute to better decision-making that reflects a responsible management of information, knowledge, and uncertainty.

In the following, we will sketch out challenges and concepts on the path towards sustainable chemistry and resource use, focusing on approaches to deal with adverse effects in the light of uncertainty (section two). In section three, we present basic principles of the time ecology concept, which considers time and its different forms as a vital system feature, as a conceptual basis for a stronger consideration of time in decision-making and actions. Section four illustrates the potential contribution of time ecology considerations with regards to sustainability and risk management. Finally, we provide concrete guidelines for the incorporation of temporal dimensions in research and action towards sustainable chemistry and metal use (section five).

2. On the path towards sustainable chemistry and resource use: Challenges and concepts

Two complementing perspectives on moving towards sustainable chemistry and resource use are sketched out in the following: (i) making the functions and services offered directly or indirectly by chemicals, chemical products, and metals sustainable, and (ii) managing the negative impacts and challenges associated with making use of these resources (compare Wäger et al., 2012).

2.1. Introductory thoughts on sustainable chemistry and resource use

Sustainable chemistry has evolved from environment-focused approaches like the German Enquete-Kommission (committee of inquiry) on sustainable material flows in the 1990s (Enquete-Kommission, 1994), the formulation of the 12 principles of green chemistry (Anastas and Warner, 1998), and international approaches such as the UN initiative for the better management of chemicals (UNEP, 2006). Recently, sustainable chemistry has been acknowledged as a cornerstone for sustainable development by the second United Nations Environmental Assembly (UNEP, 2016). It includes economic, social, and ethical aspects as well as new business models (Kümmerer and Clark, 2016). Achieving sustainable chemistry goes beyond improvements in synthesis, compounds and products, and "include[s] the contribution of such products to sustainability itself" (Kümmerer and Clark, 2016). New business models like chemical leasing are meant to create win-win-situations between the customer and provider of, e.g., solvents or disinfectants, by offering a service or functionality rather than trying to sell as much of a chemical product as possible. Such business models have the potential to considerably reduce or avoid resource and energy consumption, and chemical-related environmental burdens (Kümmerer and Clark, 2016; UNIDO, 2016). Nevertheless, the use of chemicals remains largely unsustainable, and new models can only be understood as the beginning of a broader transformation process.

Also for the case of mining, attention has broadened over time; from purely environmental aspects to a more inclusive scope incorpor-