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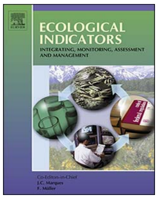

Research paper

Statistical entropy analysis to evaluate resource efficiency: Phosphorus use in Austria

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ABSTRACT

In a resource efficient economy, entropy generation must be kept low and high-entropy wastes should be transformed into low-entropy recycled products, thus saving natural resources. Based on this idea, statistical entropy analysis (SEA) was put forward as a method to evaluate material flow systems with respect to their ability to concentrate or dilute a substance throughout its life cycle using a single metric, relative statistical entropy (RSE). Whereas its application has so far been restricted to highly aggregated material flow systems or to assessments at plant or process level, in the present study the SEA method was adapted to assess the efficiency of resource use in material flow systems which consist of numerous resource flows and include multiple recycling loops. Phosphorus (P) use in Austria served as a case study to illustrate SEA-based resource efficiency assessment for different scenarios and over time. The evaluation enabled exploiting the outcomes of existing P flow studies in a straightforward way and produced additional insights related to the characteristics of resource use within the system. Changes in P management over time had a significant effect on the resource efficiency of P use. The RSE increased by 40% due to P use in Austria in the year 2000 compared to an increase of 30% in 2010. The generally favorable trend of statistical entropy (lower dissipation) in 2010 could be attributed mainly to lower dissipative emissions, more efficient bio-industry, and increasing P removal rates in waste water treatment, which overcompensated the negative impact of the ban of recycling of meat and bone meal (in 2001) on P use efficiency. Further, the SEA-based assessment applied to a scenario of optimized P management reflected the positive effects of measures to reduce emissions, enhance recycling, and reduce consumption of P on resource efficiency (50% lower RSE increase in the target system compared to the original state). In synthesis, this study shows that the SEA method is able to integrate various dimensions of resource use into a single indicator, which can serve as a basis to assess and improve the resource efficiency of macro-scale material flow systems.

1. Introduction

The turnover of materials has been described as the consumption of resources (low-entropy materials) that are used and transformed into wastes (high entropy materials), making the economy an entropy-producing process (Georgescu-Roegen, 1971). Recent initiatives on the national and, particularly, on the European level aim at a transition towards a more circular economy EC (2015) by increasing the efficiency of resource use via re-use and recycling EC (2011). In such a circular economy, entropy generation must be kept low and waste management should transform high-entropy wastes into low-entropy recycled products that can reduce the use of natural resources. Entropy reduction is achieved by the concentrating of resources in well managed material flows.

A widely applied tool to investigate patterns of resource use is Material Flow Analysis (MFA), which quantifies the stocks and flows of materials in arbitrarily complex systems (cf. Baccini and Brunner, 1991; Brunner and Rechberger, 2016). Hence, MFA is fundamental to the understanding of resource utilization in an economy and provides the basis for investigating resource use at a certain time (cf. Chen and Graedel, 2012), over time (cf. Müller et al., 2014), and with respect to scenarios aiming at enhanced recycling (e.g. Buchner et al., 2017) or reduced emissions (e.g. Schaffner et al., 2009). Due to the complexity of large scale material flow systems and the need to communicate insights from MFA unambiguously (cf. Binder et al., 2009), evaluation is an essential step on top of MFA studies. So far, recycling rates have been central to assess the efficiency of resource use from a material perspective (e.g. Chen, 2013) and are often used to describe material circularity. However, important flow-related aspects such as the functionality of recycling flows (e.g. down-cycling), the concentration of a resource in a material flow (e.g. nutrients in sewage sludge), or the dynamics of in-use material stocks are not directly reflected by

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recycling rates. Therefore, the assessment of efficient resource use (on the flow level) needs to include quality aspects in addition to mass flows. In a thermodynamic context, resource quality has been expressed using exergy, which is the maximum work output attainable by bringing a system in equilibrium with the environment. Due to the destruction of exergy in irreversible processes, exergy does not satisfy a law of conservation and exergy destruction should be minimized throughout the processes of resource use (cf. Ayres et al., 2011; Ignatenko et al., 2007; Laner et al., 2015; Szargut, 2005). With respect to macro-scale MFA, the calculation of flow exergies is impractical as information on the detailed composition (chemical compounds) and physical state is not available on that level. Therefore, the concentration of a resource in a material flow has been put forward as a proxy for resource quality and operationalized in a statistical entropy-based evaluation method tailor-made for MFA (cf. Rechberger, 1999; Rechberger and Brunner, 2002). Statistical entropy analysis (SEA) is a method to evaluate material flow systems with respect to their ability to concentrate or dilute a substance throughout its material life cycle using a single metric (Rechberger and Graedel, 2002). The SEA concept has been applied on the micro-level, to assess the ability of waste treatment as well as production processes to concentrate problematic and valuable substances, respectively, in suitable output flows (cf. Bai et al., 2015; Rechberger and Brunner, 2002). On the macro-level, it has been used to analyze the entropy trends throughout the life cycle of copper in Europe (Rechberger and Graedel, 2002) and, later on, also for copper flows in China (Yue et al., 2009). Extensions of the concept to consider impacts associated with different species of a substance were presented related to carbon emissions from waste management (Kaufman et al., 2008) as well as with respect to nitrogen emissions from waste water treatment (Sobańtka et al., 2012; Sobańtka et al., 2014). However, so far, SEA has not been used to assess the efficiency of resource use in complex material flow systems, which distinguish numerous resource flows and include multiple recycling loops. In this context, efficient material use means that a maximum of a given resource is present in utilizable material flows. Hence, the SEA-based resource efficiency assessment addresses the level of resource flows, while the benefit from resource use (i.e. the function provided by the system) is kept external from the evaluation (cf. Huysman et al., 2015).

Efficient resource use, from an entropy point of view, aims at minimizing the dilution of a substance during its use, which can be assessed by SEA. Because existing SEA applications were limited to aggregate descriptions of primarily linear resource use, the goal of the present study is to develop a SEA method to assess the efficiency of resource use in complex (high flow resolution and numerous loops) material flow systems. Therefore, Phosphorus (P) management in Austria, which is characterized by multiple internal recycling loops and a variety of material flows with different characteristics and flow domains, is chosen as a case study. The SEA-based resource efficiency assessment is carried out for different states of the system over time and for specific (optimized) management scenarios. P is a vital resource for agricultural production, but it is also associated with environmental pollution problems, in particular, related to water bodies. Efficient P use is therefore a key issue for environmental and resource management on the global, regional, and national scale (e.g. Ulrich and Schnug, 2013). Several studies on the stocks and flows of P in Austria are available (Egle et al., 2014; Zoboli et al., 2016b,a) to develop the case study layout and perform the SEA-based resource efficiency assessment. Finally, the case study results are used to analyze the effect of choices in the SEA method on the evaluation outcome and to discuss the limitations and potentials for the application of SEA in resource efficiency assessment of complex material flow systems.

2. Material and methods

2.1. Statistical entropy analysis (SEA)

2.1.1. Framework of statistical entropy analysis

Statistical entropy analysis (SEA) is a method to evaluate the outcome of material flow analysis (MFA) with respect to a material flow systems' ability to concentrate or dilute a substance (cf. Rechberger, 1999; Rechberger and Brunner, 2002). MFA is a tool to quantify the flows and stocks of materials (material serves as umbrella term for both substances and goods) in arbitrarily complex systems and has been applied at different scales, providing useful information regarding the patterns of resource use and the losses of materials entering the environment (Laner and Rechberger, 2016). The information about the flows of a substance and its concentrations in the flows containing this substance (=flows of goods) can be used to compute the evolution of statistical entropy throughout the system. Therefore, the input and output entropies are determined for each process of the system and compared to a theoretical maximum. The basic formula to calculate the statistical entropy (H) of inputs and outputs is shown in Eq. (1) (see Rechberger and Graedel (2002) and Rechberger and Brunner (2002) for the derivation from the original Shannon-entropy), where ld is the logarithm to the base 2. Because of its origin from information theory (Shannon, 1948), H is measured in bits. The concentration of substance j in the mass-flow of good i (c_{ij}, expressed in mass per mass) and the normalized mass fractions of the set of k material flows (m_i) determine the value of H. The mass fraction of material flow i (m_i) is calculated according to the formula given in Eq. (2), where M_i is the material flow i (in mass per time) and X_{ij} is the flow of substance j in goods flow i, which is the product of M_i and c_{ij} ($X_{ij} = M_i{\cdot}c_{ij}$).

$$H(c_{ij}, m_i) = -\sum_{i=1}^{k} m_i{\cdot}c_{ij}{\cdot}ld(c_{ij}) \tag{1}$$

$$m_i = \frac{M_i}{\sum_{i=1}^{k} \mathrm{X}_{ij}} \tag{2}$$

For all flows apart from gaseous and aqueous emissions, the substance concentrations in the flows of goods are defined as the concentrations in the respective material flows used for SEA. However, for emissions to the atmosphere and the hydrosphere, the concentration of the substance in the receiving environmental compartment is used to highlight the dilution of the emissions in the environment (see Eq. (3)). Hence, instead of the concentration in the emission flow itself (*cij*), the background concentration in the affected environmental media ($c_{j,geo,g}$ in case of the atmosphere and $c_{j,geo,a}$ in case of the hydrosphere) is used. This is motivated by the fact that emissions are dissipated in the environment to the background concentration level of the environmental media. The treatment of emissions in this study is different from the original approach (Rechberger and Brunner, 2002), where the background concentration in environmental media was divided by 100 to reflect the dilution mass required to limit the concentration increase in a virtual mixed flow (emission + geogenic flow) to 1%. While the focus of the original approach was on the evaluation of changes in a specific sector (i.e. waste management), the present evaluation aims at describing average effects in the whole resource system. Therefore, the usage of background concentrations in receiving media instead of virtual diluting masses seems appropriate. Furthermore, the effect on the trend of relative statistical entropy throughout the system is limited, because the division (or non-division) by 100 primarily affects the absolute level of RSE but not the RSE results of the various stages relative to each other (see Section 3.1 and Fig. S-9 of the Supporting information).