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Sinks a Vital Element of Modern Waste Management
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Final Sinks as key elements for building a sustainable recycling society

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Abstract

Two phenomena characterize the development of the material world of the last 100 years: The per capita growth in material consumption, and the introduction of a myriad of new materials. Together with the growth in population, this resulted in large, growing and complex material flows and stocks, particularly in urban areas. The objective of future materials management is to ensure long-term supply of resources on one hand, and safe disposal of emissions and wastes on the other hand.

This paper focuses on the consequences that arise from the high material turnover for waste management. Ultimately, all materials that are taken from the earth crust are either incorporated into the anthroposphere or released to the environment. Waste management acts as a key "filter" between anthroposphere and environment, controlling substance flows across the border. Waste management must either recover materials for safe reuse, or transform substances into inert materials that can be landfilled or dispersed safely in the environment. For future waste management it is crucial to define sinks and final sinks; to establish a knowledge base about sources, pathways, and final sinks of key substances; to investigate into possible sink limitations of anthropogenic activities; to systematically allocate substances to appropriate sinks; to promote waste management as key for directing hazardous substances to appropriate final sinks, and to regulate the use of specific substances if environmentally safe final sink capacities are not available.

Keywords: anthroposphere, metabolism, waste management, environment, hazardous materials, sink.

1 Introduction

The result of the unprecedented development during the last 100 years of industrial and economic revolution is a very large per capita flow and stock of materials. Because parallel to this development, urbanisation increased, too, modern cities of today are hotspots of material density and turnover. It is remarkable that so far - with exceptions of war and other catastrophic extremes – the supply of the huge amounts of materials required to fuel the metabolism of cities has never been a major problem, even for megacities comprising 10 million inhabitants or more.

Considering an annual per capita turnover of about 200 tons (Baccini and Brunner 2012), a future world of 8 billion inhabitants will require 1.6 trillion tons of "direct" materials. Indirectly, the mass turnover is much higher, because mining and extraction cause large material flows that are not included in the "direct" materials. Three fourth of the material used is water, one sixth is air, and the remaining 10 % consist of fuel and solid materials for infrastructure and consumption. On a substance specific level, the throughputs through private households are given in Table 1.

Table 1: Input and output of selected substances in private households of affluent societies. Calculated after Baccini et al (1993).

Subst.	INPUT					OUTPUT				STOCK	
	Long-living goods	Short-living goods	Fuel	Water	Air	Off-gas	Sewage	Separately collected waste	MSW	Stock	Δ stock per year
	[kg/c.y]									[kg/c]	[kg/c.y]
C	33,0	220,0	847,0	0,0	0,0	990,0	22,0	33,0	55,0	400,0	10
P	0,03	0,82	0,03	0,01	0,01	0,00	0,68	0,05	0,15	0,96	0,01
Al	3,1	3,5	0,1	0,0	0,0	0,9	0,0	0,5	2,6	33,0	0,1
Cu	0,76	0,03	0,00	0,00	0,00	0,00	0,00	0,44	0,12	7,40	0,2
S	0,08	1,72	1,30	0,88	0,21	1,43	1,97	0,38	0,34	22,00	0,1
Cl	3,10	5,40	0,20	1,20	0,10	0,20	4,50	2,50	1,80	30,00	0,1
Fe	37,8	3,8	0,4	0,0	0,0	0,0	0,0	26,0	5,5	420,0	10,5
Zn	0,49	0,25	0,01	0,00	0,00	0,00	0,02	0,36	0,25	5,0	0,2

The mass flows range between 0,75 kg/c.y for zinc and 1,100 kg/c.y for carbon. The per capita substance stocks amount from 1 kg of P to 420 kg of iron. Table 1 focuses on a few substances only; one has to take into account that about 30,000 substances are produced and consumed in large amounts, and that close to one million new substances are discovered and described every year. Outputs are either recycled, or they must be accommodated in sinks. In the future, the amounts of materials for recycling and disposal will be much larger due to the fact that the large amount of materials in stocks reach the end of their life time and must be managed together with the output flows.

The objective of this paper is to address the question: What will happen with these materials when they reach the end of their lifetime? We advocate taking a comprehensive look at the metabolism of the anthroposphere in order to prevent an overloading of sinks. The case of climate change proves that material inputs are linked to outputs, and that use and disposal of materials must be looked at together: If we use a very large amount of carbon in fossil fuels (see table 1), there will be an equally large amount of carbon dioxide produced causing global warming. If halogenated hydrocarbons (chlorinated and fluorinated hydrocarbons CFCs) are manufactured and utilized, these chemicals will either travel the globe according to their chemodynamic behaviour, and ultimately will contribute to ozone depletion in the stratosphere. Or they are properly collected and transformed into harmless CO_2, H_2O, chlorides and fluorides. Eutrophication of surface waters due to high nutrient application rates, and heavy metal pollution of urban soils belong to the same category of problems that are due to high input

amounts. A key question is, if such sink limitation is a specific phenomenon for carbon, CFCs and a few other substances, or if in future there are generic boundaries at the backend of the economic system that limit the use of many more substances. The goal of the paper is to present general conclusions for waste management in view of the large and complex flows of substances entering the anthroposphere and ultimately looking for sinks.

2 Material and Methods

The concepts and methods used in this paper have been developed over the last few decades, and are described in Baccini and Brunner (2012), UNEP (2010), and Brunner and Rechberger (2004). The basis of the approach are the mass balance principle and the second law of thermodynamics: Materials cannot be lost, and it takes energy to reduce the entropy of a material in a closed system. For mass balancing, substance flow analysis has proven to be a valuable approach - particularly in waste management - because of its rigidness, reproducibility and transparency: "What comes in obviously must come out", as a waste manager put it when he realized that his waste treatment process did not hold the promises to produce a high quality output from a contaminated waste input. The consequences of the entropy law are that without special care materials are dispersed easily, requiring energy for collection and concentration.
Data has been collected from numerous regional, national and global statistics. In most cases sources are cited in the literature referred to above. The advantage of a mass balance approach is that the data can be crosschecked. In fact, if plenty of data is available, metabolic systems are often over-determined, allowing for data reconciliation and resulting in decreasing uncertainty. In case of a lack of data, the mass balance approach allows calculating missing data. For more information, see the references (Cencic and Rechberger 2008) and (Brunner and Rechberger 2004).

3 Results and Discussion

Anthropogenic materials taken from the environment are either built into the infrastructure and used as long living goods, or are consumed, recycled or disposed of in the environment by waste and environmental management. The challenge is huge: What to do with the 200 tons of material per capita and year when the lifetime of a material is over? Some materials are emitted to the environment after centuries, others immediately after use: The residence times of water->waste water and air/fuel->offgas is very short, and thus the inputs turn immediately into outputs. Fortunately, more than 90 % of the 200 tons of materials used are liquid or gaseous, thus the natural dilution pathways of the hydrosphere and atmosphere support the rapid transport of materials into sinks. Nevertheless, due to the high concentration of people and intense materials use, sophisticated waste water treatment (WWTP) and air pollution control (AC) are required to ensure good quality of water and air. Usually economic net inputs (defined as total input minus export products), stock changes, and outputs of substances in waste and sewage of urban systems match quite well (Figure 1), and the remaining emissions are only a minor part of total material turnover: But for some substances the amounts emitted to water, air or soil are huge because they are used in a manner that they inevitably end up in the environment. E.g. (1) carbon: It is a main feature of all human beings and animals, of combustion engines, and of coal fired power plants to oxidize carbon to carbon dioxide to utilize energy. Men as well as machines depend upon the atmosphere to dilute the resulting CO_2. Or (2) phosphorous: The amount of phosphorous and nitrogen directed to soils and water is large because the need for nutrients in agriculture. And (3) pesticides: large amounts are applied to natural systems such as soils or biocenosis in order to fight pests. Each of these substances is directed to a substance specific sink. Due to the high material turnover, some of these sinks are overloaded and lose their important regulating functions.

The turnover of solid goods such as construction materials, vehicles and consumer goods is much smaller than water and air. Still, the challenge is as big as for liquid and gaseous materials, but different: The natural processes taking place during the use phase such as corrosion, erosion, weathering, and dissolution of anthropogenic materials are comparatively slow. Thus the flows into the environment are only a very small percentage of the total turnover of solid materials. But at the end of the life time, the total solid material becomes obsolete, yielding into a problem that as a rule cannot be solved by "natural transport" and dissipation. What remains from the solid goods of a city can be seen in historical places where the vestiges of the solid part of an ancient metabolism can

still be visited. Considering the complex and partly hazardous composition of today's solid products, it would be interesting to calculate the chemical fingerprint that the decay of a modern city will imprint on the immediate surroundings in 2-4000 years, an expected average life time of a city.

Due to the strong effort in implementing environmental policies, the percentage of solid materials emitted to the environment is small and decreasing. Modern strategies are directed towards environmental protection and a cycling economy. Today, a key question is if a recycling society is feasible without emissions and wastes that require disposal in final sinks. According to the second law of thermodynamics the answer is a firm "no" because of entropy generation during all anthropogenic activities. Emissions arise from two types of – mainly dissipative - activities: The use of bulk materials such as fossil fuels or nutrients for production and services on one hand (intentional dissipation), and the wear, erosion, and corrosion of investment goods such as transportation vehicles or building surfaces on the other hand (unintentional dissipation). Both type of emissions, e.g. CO2 from combustion engines or copper from brake linings, require appropriate sinks. From a more practical point of view, emissions and wastes can be decreased to a certain extend. The need for waste disposal can be reduced by prevention and by recycling. However, due to the large flows and stocks of hazardous materials, not all wastes can be recycled, and some wastes must be treated or stored in final sinks such as incinerators (organic substances) or safe underground storages (inorganic substances). Hence, waste management plays a key role for society: On one hand, it transforms waste and energy in quality proven resources for the next cycle by separating non-recyclable hazardous materials from the waste stream. On the other hand, it takes care of the non-recyclables and is instrumental for safe disposal of hazardous residues of recycling. But there are limits to recycling due to the high and increasing economic, energetic and ecological costs that arise with mounting emission control and recycling rates.
For a sustainable society with a high material turnover, it is a crucial prerequisite to have at hand appropriate final sinks for all material flows. The most evident case discussed above is carbon, lacking of environmentally acceptable sinks and thus causing climate change. Other examples include CFCs, PCBs, heavy metals, nitrogen compounds etc. For future materials and waste management in view of limited sink capacities, we recommend the following research agenda:

1. Definition of sinks and final sinks: While sinks are acknowledged as necessary elements by different scientific disciplines, there is no stringent and widely accepted definition of the terms "sink" and "final sink". The term sink is used in several scientific disciplines in different ways. For waste management, the word "final storage" has been used before, meaning a deposit that releases only small material flows that are environmentally safe for long time periods. While "final storage" is a value laden term ("environmentally acceptable"), a more neutral term is required to express the need for places where material flows from the anthroposphere to the environment can be disposed of. Sinks can be environmentally safe or unsafe according to the flow rate and the accumulation in the sink. The term final sink is required because a sink is most often a temporary sink, and substances are transported further to subsequent sinks. E g. a river receives phosphorous in purified waste water from a sewage treatment plant, and continues to transport this phosphorous to the next lake or ocean where the immobilized phosphorous might be accumulating "forever" in the sediments. An incinerator acts as a "final sink" for organic substances (not for carbon!) because all organic carbon compounds are being decomposed during incineration. In order to have a common terminology and a base for establishing sink related methodologies, a frim definition of sinks and final sinks is required.
2. Establishing a knowledge base about sources, pathways, and final sinks of key substances: At present, analyses of substance flows from resource extraction to sinks and final sinks are rare. Except for some special cases such as carbon, gold or plutonium, comprehensive balances of substances do not exist. In order to make informed decisions about resource conservation and environmental protection, it is important to know: which amounts of materials have been exploited from the earth crust respectively have been synthesized in chemical processes? Which pathways are these goods taking though the economy, which stocks are building up, and what happens after the lifetime of the stocks, how much is suited for be recycling, and which sinks are necessary and appropriate to take up the lost materials and substances? Without such a comprehensive knowledge base, future requirements and capacities for sinks cannot be assessed.
3. Allocation of substances to sinks: Each substance requires a substance specific sink that is determined by the biogeochemical properties of the substance, and the application and utilization within the anthroposphere. For example: Carbon which is mainly used in oxidation processes resulting in gaseous carbon compounds

will be transported as CO_2 to the sink atmosphere. Hence, the atmosphere with its mixing processes is a well suited sink for a certain limited amount of carbon. Today, this sink is overloaded, resulting in climate change. The atmosphere is not a final sink, and atmospheric carbon might finally reach the ocean sediments which act as a final sink. If carbon dioxide from burning fossil fuels could be economically transformed into carbonates, ocean sediments or landfills and underground storages would be appropriate choices for allocating carbon to final sinks.
The substance chlorine is primarily directed to the sink surface waters, with only little chlorine compounds emitted to the atmosphere. Leaving the waste water treatment plant, chlorine is further transported via surface waters to the final sink "seawater". The oceans act as final sinks for chlorine with a very long residence time of > 10.000 years. For the Black Sea it has been calculated that, if all chlorine that is used in the drainage basin is allocated as chloride to the Black Sea, the concentration of chlorine in the sea will change very little over the next thousands of years, thus acting as an appropriate final sink for chlorine. Oceans are appropriate final sinks for salts of the halogen group. For sustainable materials management, it is necessary to provide for adequate sinks, and to allocate substances to those sinks that subsequently transport substances to appropriate final sinks. Sink considerations including allocation of substances to sinks should be taken into account when designing products, particularly for mass products that will be produced and utilized in large amounts.
4. Sink limitations: A key question is if sinks are a limiting resource for the future development of the anthroposphere as a whole. History has shown by a few examples (carbon, Hg, DDT, CFCs and others) that sometimes not the provision of goods but their disposal is the controlling factor in the utilization chain. Considering the enormous material turnover, the question arises if we have plenty of appropriate sink capacities for all the substances extracted from the earth crust to be disposed of safely. This question must be answered before capacities are filled up. The large stock of materials built up in the anthroposphere has a long residence time. Thus, once sink limitations becomes evident, it may be too late to accommodate the large amounts of materials that are already in the stock and that in future have to be disposed of in sinks. Thus, an early recognition strategy has to be developed, linking materials production (mining, synthesis) with final sink capacities.
5. Governance: Who is responsible for not overloading of final sinks? Who regulates access to sinks and final sinks, particularly for cross border sinks such as the atmosphere or the oceans? While resources are located in individual countries with defined ownership, sinks can be common goods such as air or ocean sediments. The examples of carbon and climate change, DDT and biodiversity, CFC and the ozone layer, and global mercury pollution point out the difficulties in governing global sink issues.
6. Promoting the role of waste management as a key sink and final sink: Traditionally, waste management has acted as the key control mechanism between the anthroposphere and the environment, directing valuable materials towards recycling and hazardous substances to appropriate final sinks. With globally increasing material turn over, and the growing need for resources, "urban mining" and recycling became the dominant issues on the agenda of modern waste management. It is important to point out that a "clean cycles" strategy inevitably results not only in valuable secondary products but also in hazardous residues that have to be disposed of safely in final sinks. Thus, the disposal function of waste management is as important as the recycling function. Actually, incinerators or other means to completely transform hazardous organic materials into harmless substances are a necessary final sink for every society. And for the inorganic non recyclables, disposal sites such as landfills, or underground storages for hazardous inorganic compounds, are mandatory as well.

4 Conclusions

Ultimately, all materials taken from the earth crust and synthesized end up either in the anthropogenic stock or in the environment. Taking into account high material turnovers over long time periods (centuries), large amounts of off-materials such as wastes and emissions have to be accommodated in intermediary and final sinks. At present, with a few examples pointing out possible future sink limitation, it is not known if sink capacities are plentiful for substances we use today. Thus, it is recommended to systematically investigate into potential sink limitations, and to take into account the results of such investigations when new products and systems are designed. Waste management plays a crucial role in accommodating and allocating materials in appropriate sinks. Waste management systems should favour a "clean cycle" and "safe final sink" strategy, acknowledging that recycling requires sinks for non-recyclables. The new research agenda for a cycling society should also include residues and

emissions from cycling. For those substances that cannot be recycled sinks must be assigned. Sinks receive substance flows form many activities, not just waste management. If sink capacities are limited, it is important to take a comprehensive view at the loading of sinks, and to control those flows that fill up sink capacities the fastest. A proactive approach allows assessing the scale of the sink issue, a first step towards avoiding future sink limitation.

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Session A - Safe Final Sinks

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