This article was downloaded by: [University of Calgary]
On: 05 September 2013, At: 05:59
Publisher: Routledge
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Journal of Environmental Planning and Management

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/cjep20

Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues

Sabine Barles [a]

[a] Laboratoire Architecture, Urbanisme Sociétés - LTMU, Institut Français d'Urbanisme, Université de Paris 8, 4 rue Alfred Nobel, Cité Descartes, F 77420 Champs-sur-Marne, France

Published online: 19 May 2010.

To cite this article: Sabine Barles (2010) Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues, Journal of Environmental Planning and Management, 53:4, 439-455, DOI: 10.1080/09640561003703772

To link to this article: http://dx.doi.org/10.1080/09640561003703772

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms &

Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Downloaded by [University of Calgary] at 05:59 05 September 2013

Journal of Environmental Planning and Management
Vol. 53, No. 4, June 2010, 439–455

Routledge
Taylor & Francis Group

Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues

Sabine Barles*

Laboratoire Architecture, Urbanisme Sociétés – LTMU, Institut Français d'Urbanisme, Université de Paris 8, 4 rue Alfred Nobel, Cité Descartes, F 77420 Champs-sur-Marne, France

(*Received 31 January 2009; final version received 23 October 2009*)

Urban areas, in particular cities, are significant consumers of materials and energy, either directly on their land areas or indirectly through the materials, goods and services they import or export; there are upstream and downstream consequences of the removal of resources and the discharge of waste materials (to the atmosphere, water and soils), with multiple impacts on the biosphere. The processes involved need to be better characterised to reduce these environmental pressures. This is a sustainable development issue and it is a major goal of a field ecology which has been described as urban, industrial or sometimes territorial. This paper reviews the specific origins and findings of studies on urban metabolism. It describes the analysis tools used, including material and substance flows, energy balances, ecological, water and, more generally, environmental footprints. Finally, recent findings and areas for future research in the dematerialisation of urban societies are summarised.

Keywords: industrial ecology; urban ecology; territorial ecology; material flow analysis; substance flow analysis; environmental imprints

Downloaded by [University of Calgary] at 05:59 05 September 2013

1. Introduction

Sustainable development refers to the interactions between societies and the biosphere, which are considered two interdependent systems in co-evolution. The anthroposystem or socio-ecosystem concepts also incorporate these two systems: the term 'socio-ecosystem' is used in the United-States and in several European countries; however, the term 'anthroposystem' is preferred in France (Lévêque *et al.*, in Lévêque and Van der Leeuw 2003; see also Baccini and Brunner 1991, Berkes and Folke 1998). There are many interactions; the most tangible are the energy and material exchanges between societies and the biosphere. Societies, cities in particular, are significant consumers of materials and energy, either directly on their land areas or indirectly through the materials, goods and services they import or export. Urban metabolism thus has upstream and downstream consequences in terms of the removal of resources and the discharge of waste materials (to the atmosphere, water and soils), with multiple impacts on ecosystems and on the biosphere. Moreover, the pronounced trend that characterises urbanisation processes is an increase in the consumption of resources and in related emissions, which explains in part the

*Email: sabine.barles@univ-paris8.fr

ISSN 0964-0568 print/ISSN 1360-0559 online
© 2010 University of Newcastle upon Tyne
DOI: 10.1080/09640561003703772
http://www.informaworld.com

non-sustainability of urban societies – other explanations being the non-renewable nature of some consumed resources and the impossibility of renewing those that are renewable at the same pace as their consumption.

Environmental sciences use several expressions (or terms) to characterise these specific interactions. For example, the linear flow of materials refers to societies taking resources from the biosphere and returning waste (i.e. transformed materials often incompatible with the receiving area). The opening of biogeochemical cycles refers to a similar process on the scale of substances or simple chemical elements: while the natural functioning of the biosphere is characterised by closing material cycles (carbon, nitrogen, etc.), the development of anthropogenic activities not only intensifies their flows, but also linearises them since the materials do not return to their place of origin and, therefore, accumulate in a certain compartment of the biosphere. If the materials somehow return to their origin, they return in a different chemical form than the one they had at the time of their removal. Many of the environmental problems encountered today can be attributed to these abundant and linear flows: resource depletion, climate change, eutrophication, proliferation of solid waste, dispersion of toxic material and loss of biodiversity, just to name a few. These findings also suggest solutions: dematerialisation, decarbonisation and dewatering could lead to sustainability. These approaches are distinguishable from conventional environmental techniques because they challenge the 'end-of-pipe' solutions that have long been used to settle environmental problems and aim to fix them at their source – the collection of raw material and energy and material consumption.

Most of these facts are well known and have led some researchers to use the term 'anthropocene' for the current geological epoch (Crutzen 2002). This period is marked by the emergence of determinisms with anthropogenic origins alongside natural determinisms that previously conditioned the planet. However, methods allowing a more detailed characterisation of these facts, and other methods, based on these observations, allowing the identification of a better governance of energy and material flows, are still largely lacking. Furthermore, despite the considerable role cities play in these processes, they remain largely unrecognised as agents in the flow of energy and material. Their local, global or differed impacts in both space and time are also poorly recognised. Nevertheless, taking into account their inherent concentration and their structuring role in agricultural and industrial production, cities are probably significant drivers of action and could represent a special subject of study on exchanges between societies and nature.

Thus, the purpose of this paper is, once their origins have been established, to present the trends of research studies that fall within the scope of these urban issues and to place recent French work in this general overview. Urban metabolism studies are relatively scattered – and few in France – and are often classified as urban ecology (in the sense of 'ecology of cities' more than 'ecology in cities' (Grimm *et al.* 2000)), industrial ecology, territorial ecology or even social ecology. The tools and methods used are discussed, including material and substance flows, energy balances, ecological, water and, more generally, environmental footprints. Finally, areas for future research in the dematerialisation of urban societies are identified.

2. Urban, industrial, territorial and social ecologies ...

2.1. Supply, urban excreta and urban chemistry

Concerns regarding urban metabolism are not entirely new and, after having been overlooked for many years, have once again become current. The European

Downloaded by [University of Calgary] at 05:59 05 September 2013

scientific, intellectual and political communities addressed the question of supplying cities (thus the entry of energy and materials) on an on-going basis up to the First World War: since the beginning of the nineteenth century, this question provoked many thoughts and actions on the scope of urban supply (often associated with the notion of hinterland) and on the allocation of soils for this supply; problems which were partially solved with the development of transport systems and the turn to fossil energy (which severed the link between cities and forests and rendered forests less essential to cities' energy supply). During the nineteenth century, urban metabolism (a term not used at the time) primarily involved the work of chemists concerned with food production and agricultural fertilisation. Indeed, the population growth in conjunction with the limitations of rural organic fertiliser sources led to fears of soil depletion and intermittent, even permanent, food shortages. With growing population concentrations, cities began to be considered both as centres of consumption and, through their abundant output of excreta, as new sources of fertilisers: human and animal urine and excrement, organic mud produced on streets, household and pre-industrial refuse, butcher shop and slaughter (later, slaughterhouse) by-products, etc. Quantification of the potential fertilisers and the development of effective collection and conversion techniques became major issues, as important as hygiene, in the management of urban excreta.

This resulted in the birth of a true urban chemistry – which was not biochemistry before Pasteur's work – that sought to understand first the cycle of organic matter and next of nutrients (nitrogen, then phosphorus and potash). Jean-Baptiste Dumas, Jean-Baptiste Boussingault and Justus von Liebig were the most famous among European urban chemists. These chemists, and the manufacturers and engineers who followed, fought against the linear flow of materials, favouring exchanges between the city and agriculture. Similarly, many industrial activities that developed during the nineteenth century depended on using urban by-products. The fertiliser revolution and the mobilisation of new raw materials that made urban excreta useless led to the death of urban chemistry and allowed for the opening of urban metabolism (Barles 2005).

2.2. The urbs ecosystem: heterotrophic and parasitic

Several decades elapsed before a renewed interest in urban metabolism was expressed within the context of two emerging worries: the first, the capacity of the planet to feed and maintain a growing population and, the second, the destructive power of man due to Earth's finite, limited and unique characteristics. This was an idea particularly brought forward at the 'Intergovernmental Conference of Experts on the Scientific Basis for the Rational Use and Conservation of the Resources of the Biosphere', sometimes called the Biosphere Conference, held in Paris in 1968 (see Acot 1988). In addition to these planetary worries, a severe criticism of the industrial town was frequently expressed. To cite only one example, in *The City in History*, Lewis Mumford, who was aware of developments in ecology, denounced the 'myth of megalopolis' and forecast, like many of his contemporaries, the decline of industrial towns (Mumford 1961).

The resulting urban ecology, developed from the 1960s onward, fell within the scope of scientific ecology and, in particular, of the ecosystem theory brought forward by Eugene Odum (1953). In 1965, the engineer Abel Wolman thus introduced the notion of urban metabolism. He defined metabolic needs ''all the

Downloaded by [University of Calgary] at 05:59 05 September 2013

materials and commodities needed to sustain the city's inhabitants at home, at work and at play'', the metabolic cycle and urban metabolic problems (Wolman 1965, 179). Shortly after, Eugene Odum described the city as a heterotrophic system (Odum 1975) and later as a parasitic ecosystem (Odum 1989). The Belgian ecologist, Paul Duvigneaud, who played an important role in the implementation of international environmental research programmes, very closely followed him and gave the Urbs (the Latin word for city) ecosystem significant coverage in his very popular 'Synthèse écologique' (Duvigneaud 1974). He wrote: [translation] ''Scientific knowledge ... is required to ensure proper urban planning of the areas where most men live'' (Duvigneaud 1974, p. 245). These first texts on urban ecology of naturalistic origin were well received internationally, particularly in France (Mirenowicz 1982, Beaucire 1985), and were especially well conveyed by the UNESCO Man and Biosphere programme, launched in 1971 (Celecia 2000). In this framework, the cities of Rome, Barcelona and Hong Kong (Boyden *et al.* 1981) have been the subject of detailed analyses.

Nevertheless, this research did not lead to the anticipated opportunities and received fierce criticism during the 1980s (see for example, for the French case, Beaucire 1985, Theys and Emelianoff 2001). Indeed, some urban ecologists wanted to make ecology a division of science of its own, of which social sciences would constitute only a part; an idea tolerated with difficulty by social scientists. Furthermore, these urban ecologists stuck to an energy determinism and to anti-urban views (the city as a parasite) that prevented them from considering approaches to control the environmental impact of cities. Finally, the methods developed to analyse urban metabolism remained very approximate.

Downloaded by [University of Calgary] at 05:59 05 September 2013

2.3. *Ecosystem, symbiosis and industrial ecology*

The history of industrial ecology, which developed at the same time as naturalistic urban ecology,[1] reviewed by Suren Erkman (2004) in broad strokes, shows that, until the end of the 1980s, the initiatives remained relatively isolated and focused on industrial metabolism (the study of materials and energy flows) and industrial ecosystems (the study of industrial assembly) – among the pioneer texts, see Kneese *et al.* (1970), Ayres (1978) and Billen *et al.* (1983). A major characteristic of these approaches was the emphasis they placed on the need to link economic and ecologic analyses. They even incorporated some principles stemming from ecology and physics (for example, the law of conservation of matter) into the economic theory (Kneese *et al.* 1970).

The present-day industrial ecology boom dates back to 1989 following the publication of a special issue of *Scientific American* 'Managing Planet Earth', which included the article 'Strategies for Manufacturing' by Robert Frosch and Nicholas Gallopoulos (1989).[2] In the next decade, the number of research projects, experiments and publications multiplied in this field: for example Baccini and Brunner (1991), Ayres and Simonis (1994), O'Rourke *et al.* (1996). The founding of the *Journal of Industrial Ecology* in 1997 and of the International Society for Industrial Ecology in 2000 contributed to the structuring of industrial ecology as a discipline.

At first, the principle objective of industrial ecology was the study and the optimisation of the metabolism of the industrial sector. The approach was clear and had two major goals: the first was to identify and reduce loss of materials in order to reduce the environmental impact of industrial processes and the cost of raw materials; the second was to develop industrial symbioses, i.e. industrial assemblies in which the by-products and refuse of one industry become the source for raw materials or energy of another, based on Kalundborg's highly emblematic symbiosis (Jacobsen 2006). Industrial ecology often favoured a quantitative and accounting approach to metabolism, as well as a technological approach – approaches that are necessary, but not sufficient, insofar as they do not consider the effect of stakeholders with different profiles and objectives on the flows or the social dimension of industrial ecology (Boons and Howard-Grenville 2009). Furthermore, industrial ecology often considered only one part of the anthropogenic flow of materials: mainly the production sector. This three-pronged criticism was expressed by various authors at the end of the 1990s (O'Rourke *et al*. 1996, Anderberg 1998), and seems to have been heard since the organisers of the penultimate ISIE conference, held in June 2007, promoted the necessity of a full partnership with the social sciences and to consider consumption (so the industrial society more than the industrial sector) as part of the objectives of industrial ecology, together with the new need to address explicitly the issues around sustainability.[3] This concept of industrial ecology was accepted earlier by some researchers and adopted in France.[4]

2.4. Territorial ecology and social ecology

Cities were initially largely absent in industrial ecology because the approaches were generally poorly spatialised: for example, one of the reference works in the field (Ayres and Ayres 2002) devotes, on very sectional themes, only two chapters to cities out of a total of 46. However, urban issues gained in importance (see for instance Baccini and Brunner 1991). In 2007 one issue of the *Journal of Industrial Ecology* is devoted to the city (Bai 2007b), and in 2008 the ConAccount conference held in Prague specifically addressed the urban metabolism question (Havranek 2009). After 2000, this trend gave rise to a new expression specific to France: territorial ecology.[5] This field of research is based on both the accomplishments of industrial ecology and urban ecology as defined in section 1.2 and brings together scholars from various fields such as industrial ecology, urban planning, urban engineering, urban biogeochemistry and ecological economics. As such, it is an industrial ecology that is considered in a spatial context and that takes into account the stakeholders and, more generally, the agents involved in material flows, questions their management methods and considers the economic and social consequences of these flows. This expression, which also has the advantage of replacing the term 'urban ecology', is not universally used; in order to not add to the confusion, some of those in the field argue for the continued use of the original designation (industrial ecology) in view of its precedence and the existing structuring of the field. The emphasis on the spatial dimension of energy and material flows closely relates territorial ecology to the field of social ecology championed by the Institute of Social Ecology in Vienna (Austria).

3. Recent work

In this context, research projects were launched that fell, implicitly or explicitly, within the fields of urban ecology, of industrial ecology when focused on cities (or parts of cities), of territorial ecology with the same focus, or of biogeochemistry applied to urbanised systems. While not an exhaustive list, this section presents an inventory as

Downloaded by [University of Calgary] at 05:59 05 September 2013

illustrative as possible of the issues and themes examined in these studies, thanks to an overview about how four different methodological approaches (Material Flow Analysis; Substance Flow Analysis; Energy Flow Analysis and Environmental Footprinting) are used to quantify the biophysical exchange processes of cities.

The studies reviewed here either fall under the scope of primary research or of applied research and decision support. In the first case, they seek to understand how urban biogeochemistry works, the implications of the material and energy needs of cities on other spaces and the entire biosphere, and how biogeochemical and social operations interact. In the second case, the research falls within the scope of the issues of sustainable development (Walsh *et al*. 2006) and addresses the requirements that need to be met for dematerialisation (the consumption of fewer materials), decarbonisation (the consumption of less carbon), and closing the material loops, decoupling (between material consumption and economic development). These studies may involve constructing indicators, identifying special targets for sustainability (a material, an industry, etc.), developing decision support tools for strategies to dematerialise, decarbonise, etc.

There are relatively few methods for analysis: material, substance or energy balances and life-cycle analyses (however, some researchers involved in life-cycle analysis do not necessarily claim to belong to the field of industrial ecology). These methods apply the principle of conservation of matter ('Nothing is lost, nothing is created, everything is transformed') and the principles of thermodynamics (most often the first principle of energy conservation, sometimes associating it with the second: 'the entropy of the universe always increases'). Other methods, from various disciplines, can supplement these basic methods on a case-by-case basis: the history of technology, urban engineering, management sciences, sociology of organisations, urban planning etc. Yet, metabolism remains at the heart of the approach, whether it is to understand, characterise or modify it. These studies on metabolism can lead to modelling and even simulation. The research subjects are varied, even when the analyses are restricted to projects with an urban dimension (central city, urban area, region), or to a particular substance.

3.1. *The urban materials balance*

In the last few years, (*bulk*) Material Flow Analysis (MFA) has become more refined and precise (see Baccini and Brunner 1991, Bringezu *et al*. 1997, 1998, Kleinj *et al*. 1999, Hammer *et al*. 2003a, Brunner and Rechberger 2004, Barles 2009, Havranek 2009), although studies of this type remain rare at the urban level.

The key questions raised and discussed are:

- How should the system be defined and then limited? Does it correspond to a geographic or administrative unit and its natural substratum or must a boundary be placed between, on one hand, a social and economic system that is characterised by its population, its organisation and its activities and, on the other hand, the natural environment that supports it (the case in Figure 1)?
- What is the relevant scale of the research? Should consideration be given to the urban area as a whole, some subsystems within the urban area or a larger area, that is a regional one? Statistical constraints may determine the scale, but may lead to bias.

Downloaded by [University of Calgary] at 05:59 05 September 2013

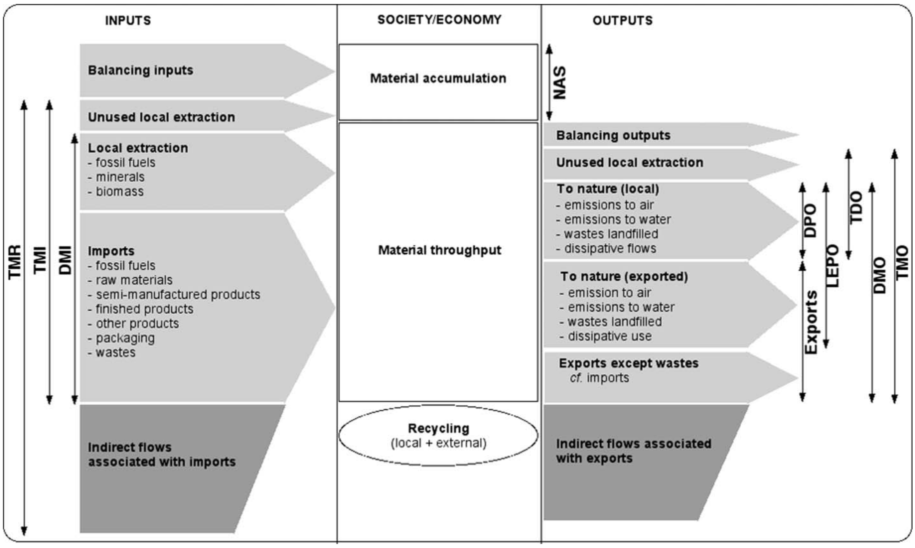

Figure 1. Schematic of the Local Bulk Material Balance, adapted from the National Balance Method of the Statistical Office of the European Community (Eurostat).
Source: Reprinted with permission from S. Barles, *Journal of Industrial Ecology*, 13(6), (2009) 898–913. Copyright © by Wiley–Blackwell.
Notes: BI: Balancing input, e.g. the oxygen consumed by combustion reaction. BO: Balancing ouputs, e.g. the water produced from the combustion reaction must be considered. BI and BO are necessary to balance the MFA. Many indicators can be defined from this analysis: TMR: Total Material Requirement; TMI: Total Material Input; DMI: Direct Material Input; NAS: Net Addition to Stock; DPO: Direct Processed Output; LEPO: Local and Exported Processed Output; TDO: Total Domestic Output; DMO: Direct Material Output; TMO: Total Material Output.

- Should the material balance be based on inputs and outputs of the system before a more detailed analysis of the involved processes (Figure 1), or is it preferable to infer the balance from the analysis of the natural and social processes that characterise material flows, that is, to describe these flows from within the system (Brunner and Rechberger 2004)?
- What pertinent indicators can be inferred from the material balance?
- How can the indirect flows be counted?

Establishing a uniform methodology is important in view of allowing comparisons in time and space of multiple studies. Nevertheless, it remains an open question at the local scale.

Furthermore, one of the objectives of bulk material balances is to characterise the impact of cities on the biosphere on a global scale – pressure on resources, air pollution and, more generally, the impact on global change. This multi-scale approach is relatively recent and there are few studies of this type to date – see, for example, beyond those previously cited: Schulz (2005), Kaye *et al*. (2006), Hammer *et al*. (2006), Bai (2007a), Kennedy *et al*. (2007). It allows the weight of the urban operation, in the full sense of the term, to be known. Thus, in the case of Paris and its suburbs, all emissions represent more than half of the total material inputs and are, consequently, more significant than conventional exports (i.e. those linked to monetary flows) (Table 1). Paris imports approximately 20,000 Kt (8.8 t/inhab) and discharges 11,000 Kt (5.1 t/inhab) of materials annually. These numbers reveal

Downloaded by [University of Calgary] at 05:59 05 September 2013

the stakes involved in dematerialisation. Nevertheless, the direct material consumption in Paris – 5.0 t/inhab – remains low compared to Hamburg's (in 2001, 8.2 t/inhab for the central city and 11.4 t/inhab for its suburbs) (Hammer *et al.* 2006).

Material balances can also be broken down into product categories. The results, presented in Figure 2, show that these balances accurately reflect the metropolitan operation: much is eaten in Paris because of the large number of jobs and tourists; a

Table 1. Material balance for Paris, Paris and its inner suburbs (PPC) and Paris Greater Metropolitan Region (Île-de-France, IdF), 2003.

	Paris (2,166,000 inhab)		PPC (6,321,000 inhab)		IdF (11,259,000 inhab)	
	kt	t/inhab	kt	t/inhab	kt	t/inhab
DMI	19,160	8.8	69,530	11.0	137,990	12.3
DPO	6860	3.2	27,410	4.3	76,290	6.8
LEPO	10,960	5.1	37,020	5.8	76,360	6.8
DMO	19,340	8.9	77,430	12.2	134,860	12.0
NAS	3100	1.4	4110	0.7	29,460	2.6
DMC_{corr}	10,780	5.0	29,120	4.6	79,490	7.1
Recycling (local & outside)	1850	0.9	4660	0.7	7320	0.7

Source: Adapted from Barles (2009).
Notes: DMI: Direct Material Input; DPO: Direct Processed Output; LEPO: Local and Exported Processed Output; DMO: Direct Material Output; NAS: Net Addition to Stock; DMCcorr: Direct Material Consumption (connected).

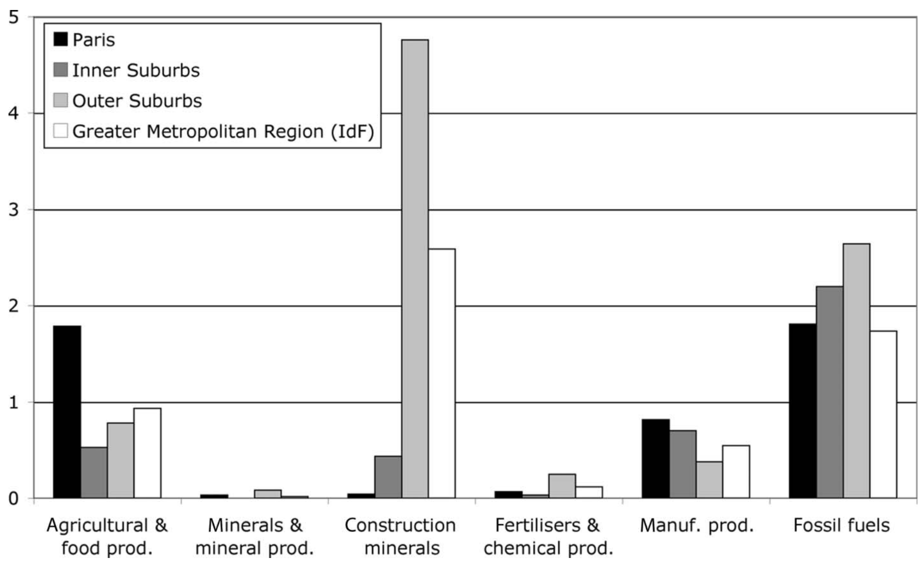

Figure 2. Direct Material Consumption (DMC) for Paris, its Inner Suburbs, Outer Suburbs and Greater Metropolitan Region (Île-de-France, IdF), 2003, t/inhab, rail transportation excluded.
Source: Reprinted with permission from S. Barles, *Journal of Industrial Ecology*, 13(6), (2009) 898–913. Copyright © by Wiley–Blackwell.

Downloaded by [University of Calgary] at 05:59 05 September 2013

large amount of construction materials are consumed in the outer suburbs due to urban sprawl (both direct and, especially, indirect consumption – linear infrastructure – related to new housing). The link between land use and urban metabolism is seen here.

It is also possible to compare and monitor local and national indicators. The Hamburg case, analysed from 1992 to 2002, is revealing in this matter (Hammer *et al*. 2003b): on the one hand, direct material inputs (DMI) are much higher than the national average (65 and 22 t/inhab, respectively) as they are driven by Hamburg's harbour functions; on the other hand, the direct material consumption (DMC), which was lower than the German average at the beginning of the 1990s (10 and 20 t/inhab respectively), seems to catch up with, even exceed, this national average 10 years later, suggesting that Hamburg's sustainability is lower in 2002 than it was in 1992.

Material balances can also be used to define targets for dematerialisation and, more generally, for improvements to the ecologic performance of cities. Such projects, still largely experimental, are on the cutting edge of research and actions and can be directly dealt with by local communities. Within the framework of its environmental policy, in 1995 the city of Stockholm launched an intensive study linking material and substance flow analyses (Burström *et al*., in Bringezu *et al*. 1998). More recently, in the township of Geneva, a law on public action for sustainable development (Agenda 21), adopted in March 2001, states in Article 12: [translation] "The State facilitates possible synergies between economic activities in order to minimise their environmental impacts" (Erkman 2006, p. 1). This principle led to the realisation of a material and energy balance that will serve as the basis of the township's sustainable development policies. For example, the balance of food material reveals that barely 25% of organic waste is recovered. This finding leads to the conclusion that both an increase in this rate and an intensification of methanisation infrastructures, the process considered to be the most effective for waste recovery, must be advocated for (Erkman 2006).

3.2. *Substance flows*

Substance flow analysis (SFA) is used to address more specific questions (like water, air or soil contamination by one substance or another), or to understand the role of cities in global biogeochemistry. In view of the broad diversity of natural and anthropogenic processes being considered, there is no standardised SFA method like the one used for the material flows. Some of the questions that have been touched on regarding bulk material remain (limits and scale, indirect flows), but they are solved on a case-by-case basis. Compared to bulk materials, the characterisation of the substance flows requires consideration of the processes internal to the system under study (a city, for example), which can no longer be considered as a black box. More generally, the same issues exist as for bulk material, from fundamental research questions (e.g. what is a city from a biogeochemical perspective?) to applied research questions.

Because cities produce little of their own food and food consumption has a considerable impact on several biogeochemical cycles, the analysis of the flows of biogenic elements is fairly developed. An initial set of research studies was carried out over the (relatively) long term and raised questions on the evolution of urban food needs and its consequence, not only in terms of agricultural production and

Downloaded by [University of Calgary] at 05:59 05 September 2013

lands required to satisfy these needs, but also in terms of the management of the resulting discharge and its release, in one form or another, into the environment. The research was directed towards phosphorus and nitrogen and has revealed the significant stress imparted by a growing urban demographic on food production. It has also shown the impact of the evolution of agricultural techniques (especially fertilisers) and food practices (meat) on the agricultural areas farmed to meet the dietary needs of cities (Schmid-Neset 2005, Billen *et al.* 2008), and the impact of urban techniques on the varying return of nutrients to cultivated soils (Figure 3). These studies constitute a textbook example of the analysis of the gradual opening of biogeochemical cycles.

The topicality of these themes appears in several studies that stress the link between land consumption and food production and/or the hugeness of the flows at play, the low level of recycling and their impacts on the environment (eutrophication, oxygen deficit) and public health (nitrates) (Gumbo *et al.* 1999, Færge *et al.* 2001, Danius and Burström 2001, Waggoner 2006, Forkes 2007). For example, Jennifer Forkes (2007) shows that in Toronto despite the development of an organic matter waste reclamation technique, the nitrogen recycling rate has decreased from 4.7% in 2001 to 2.3% in 2004. In Bangkok, 7% and 10% of dietary nitrogen and phosphorus, respectively, are currently recovered (Færge *et al.* 2001). These studies put in perspective the effect of the recycling policies that may be implemented and demonstrate the need for a better understanding of the urban flow of biogenic elements and an optimised waste reclamation technique. These findings have significant consequences in terms of clean-up techniques (liquid and solid) that adhere to ecological or sustainable sanitation perspectives.[6]

Because of their high toxicity, heavy metals are the subject of numerous studies – see for example, the Swedish programme Metals in the Urban and Forest

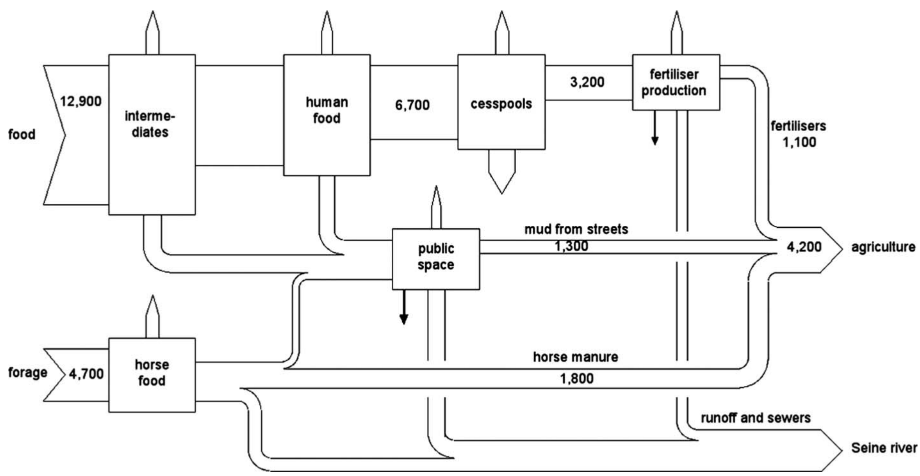

Figure 3. Flow of Dietary Nitrogen, Paris, 1869, tN.
Source: Adapted from Barles (2007).
Notes: The quantification of dietary inputs and the analysis of techniques associated with urban excreta can be used to describe the flow of nitrogen and to show that 24% of nitrogen entering in the form of food returns to agriculture (compared to 20% in 1871 and 40% in 1913). The particular importance of horse feed, that is to say of transport, in the urban nitrogen cycle is also shown.

Downloaded by [University of Calgary] at 05:59 05 September 2013

Environment – Ecocycles and Critical Loads, directed by Bo Bergbäck and Kjell Johansson at the end of the 1990s and the related special issue of *Water, air, and soil pollution* (Iverfeldt 2001). The management problem associated with heavy metals is different than the one for food substances. The consumption of metal is either directly linked to its use in industry and other human activities (for example, zinc on roofs or lead in accumulators) or a side effect of the consumption of other materials in which it may be present as an impurity (for example, in coal). Furthermore, the life of these substances, in society as in ecosystems, can be much longer. Consequently, the evaluation of both stocks and flows is necessary and, beyond the substance's general circulation, dissipative losses (wear) and various fugitive emissions must be identified and quantified. This is further emphasised by the fact that these substances are often toxic at very low doses; minor flows can thus have significant consequences on the environment and on public health.

Current research is mainly aimed at quantifying and locating the subject substance. It is possible to cite, for example, studies showing that Paris is one of the major lead mines in France because of the stock it has built up since Roman antiquity, despite a decrease in consumption since the end of the 1970s. This dip, still slight, must not be interpreted as though the problem with lead is nearing resolution. In fact, the problem still exists, as shown by the increasing number of cases of infant lead poisoning in Paris: the present situation is less a reflection of the current consumption of this metal than its past uses, and today, urban centres appear as lead stocks because this substance has been converted, used and incorporated into the urban environment. This being the case, two basic questions remain: where is it? where will it go? The analysis of the flow of substances contributes to finding answers to these questions (Lestel *et al.* 2007).

Studies on mercury in Stockholm depict similar processes: there was a significant growth in use from the end of the eighteenth century to the mid-1970s, followed by a rapid decline. Correspondingly, emissions to air, water and soil are declining as rapidly. Nevertheless, much of the mercury imported during the last 200 years is still stored, mainly in soils and sediment. As such, to understand the contamination of Stockholm and its terrestrial and aquatic environment is also to understand the manufacturing process of felt hats, mirrors and thermometers; techniques for gilding and silvering and, especially, treatments for syphilis and dental cavities (Sveden and Jonsson 2001).

Downloaded by [University of Calgary] at 05:59 05 September 2013

3.3. Energy balances

Although the notion of metabolism refers both to the energy and to the material required for the operation of a given system, studies of urban metabolism have long favoured the material balance rather than the energy balance. One reason for this is that the questions raised by interactions between human societies and nature stem more from material than energy issues, although they do involve large amounts of energy. For example, climate change is due, at least partially, to energy consumption, but it can be analysed as a particular case of the opening of biogeochemical cycles; it is indeed a case of excess material – greenhouse gases – in the atmosphere that causes it; it is indeed the exploitation of certain material resources – particularly fossil fuels – that is at the origin of the problem, even if these resources are used for their energetic qualities. Another reason is that urban energy issues are often addressed by engineers specialised in this field and who belong to scientific communities different from the one dealing with urban metabolism (Barles *et al.* 2010).

Ignoring the energy issue has resulted in major environmental and social issues being overlooked. It explains why hydraulic power is considered sustainable and yet its development has undeniable impacts; why, in a more urban perspective, the thermal island issue, despite its significance in climate change, is disregarded; why what is at the origin of the extraction of certain materials is not considered: the energy needs of societies, transportation demands, etc. Moreover, the energy issue is much greater than the simple consumption of extrasomatic energy (beyond physiological needs) since the food issue is closely linked to it. Finally, the biosphere is a biosphere thanks to solar energy, whose utilisation, indeed appropriation, allows the functioning of human societies.

These findings are behind approaches now used that are somewhat distinguishable from the traditional analysis methods of industrial or urban metabolism. Examples of such approaches are found in the research conducted at the Institute of Social Ecology in Vienna, especially by Fridolin Krausmann (2005) and Helmut Haberl (2001a, 2001b, 2006). These researchers compare the metabolism of societies to their total energy consumption, both technical and non-technical, and on this basis develop a set of indicators that characterise the impact of human societies on the biosphere (especially human appropriation of net primary productivity or HANPP, see Haberl *et al.* (2007)). The approach of these studies bears a causal connection with the notion of ecological footprint (that does not generally claim to belong to the field of industrial, urban, or territorial ecology).

3.4. The environmental footprints of cities

The idea of a footprint has been widely disseminated thanks to William Rees and Mathis Wackernagel's concept of an ecological footprint (Rees and Wackernagel 1996a, 1996b). It represents the amount of biologically productive surface needed to sustainably maintain a human society given its living standard and lifestyle; it accounts for both the surfaces consumed and those that are needed to compensate for the greenhouse gas emissions that result from the use of fossil fuels. A number of criticisms have been aimed at the concept of an ecological footprint (Van Den Bergh and Verbruggen 1999, Piguet *et al.* 2007, Billen *et al.* 2008, Fiala 2008), including the non-location of the footprint, the mono-functional characteristic attributed to soils, the bias inherent to the method (especially its aim to account for too many phenomena thanks to a unique indicator – a virtual area), the possible pernicious effects of using it as a tool for action, and the fact that it does not account for the sum of the interactions between societies and the biosphere because it gives more weight to an energy approach (biomass and fossil fuels).

The concept of environmental footprints or imprints is, however, particularly important for characterising the impacts of metabolism (urban in the context of this article) on the biosphere. The term 'footprint' (or imprint) is used to designate both the spatial dimension of the impacts (in three dimensions, the third one being its depth, that is the intensity of its environmental impact) and their varying severity. The plural of this term (footprints) is used to signify that there are many different impacts. As such, each city has a set of footprints whose size, shape, localisation and depth changes in time, but accurately reflects the city's metabolism, the lifestyle of its

Downloaded by [University of Calgary] at 05:59 05 September 2013

citizens and not only its urban, but also its national and international, socio-economic, political and technical systems.

There is a lot at stake with this concept. The aim is to show the partial and gradual delocalisation of resource consumption and the emissions and discharges magnified by globalisation, and all the consequences that ensue in terms of intra-generational solidarity. Examples include studies on the water footprint that were first conducted on a nation-wide scale and aimed at describing, both qualitatively and quantitatively, the virtual water transfers associated with international trade (Chapagain and Hoekstra 2004). Some works are also conducted at the regional (Peters *et al*. 2007) or urban level (Chatzimpiros and Barles 2009); cities import goods whose development required the consumption of a certain quantity of water elsewhere which also led to an impairment of the resource in the drainage basin concerned. Similarly, studies on the food footprint or food-print (Billen *et al*. 2008) have shown that it has decreased in area because the agricultural yield has increased since the Second World War in developed countries. Its depth, however, has increased as a result of the growing use of synthetic fertilisers and phytosanitary products. Furthermore, the food-print is increasingly discontinuous and distant from the cities supplied. In addition, the concept of environmental footprints allows spatial limits to be placed where human and urban activities develop, while emphasising the critical issue of land use and its competing allocations (Krausmann 2001).

4. Conclusion: consolidating the field

Although it is a relatively new field of research, urban metabolism in its wide sense – as suggested by the French territorial ecology – has a bisecular past and its epistemology must still be refined (however, see Fischer-Kowalski 1999, Fischer-Kowalski and Hüttler 1999). Future progress, both in the scope of the research and in the action to be taken, can be expected if the city begins to be considered not as an unsustainable parasite, but as a source of physical, energy, social and intellectual resources.

It would be necessary to consolidate the theoretical basis of urban metabolism studies, in particular, by going beyond the problems that arise from using analogies and metaphors that all too often characterise it. It would be also necessary to define methods for analysis and to infer from them disaggregatable synthetic indicators that would allow built-up areas to be monitored in time or compared to other built-up areas, whether it is to characterise or to control interactions between urban societies and the environment. Particular attention should also be paid to the identification of the latent and remote effects of cities in time and space, which are particularly critical against the background of economic globalisation and global change: their footprints are still too poorly known. In urban spaces, it would be important to link urban structures, lifestyle and urban metabolism: the impact of urban structures on energy consumption is relatively well known, but a lot less is known about their impact on material flows (see, for example, Newman and Kenworthy 1991, Haase and Nuissl 2007). Another issue that remains to be addressed is the creation of a stronger link between energy and material approaches, one not being reducible to the other.

Taking it a step further, urban metabolism studies must also go beyond energy and material accounting. The link between economy and ecology in the urban

Downloaded by [University of Calgary] at 05:59 05 September 2013

context has not been investigated enough, although there have been significant contributions in journals such as *Ecological Economics*. The analyses must consider the spatial and the territorial contexts, as well as the agriculture – industry – city triptych. In this way, it is possible to question the concepts of proximity, both spatial and social; the governance of flows, including the role of lifestyle and urban practices in material exchanges; and the role of local and territorial stakeholders. To date, this field of inter disciplinary research is fragmentary.

Notes

1. 'Naturalistic urban ecology' refers to urban ecology developed under the wider umbrella of the field of natural sciences, and not urban ecology as a branch of urban sociology (see Boons and Howard-Grenville 2009).
2. Several other founding papers in this field were published at the same time: (Ausubel and Sladovich 1989, Reconciling 1989).
3. ISIE Conference Introduction, Toronto, 17–20 June 2007. Available online [reference date 26 June 2007] from: http://www.pdc.utoronto.ca/events/International_Society_for_Industrial_Ecology_ISIE_2007/Preliminary_Schedule.htm
4. See, in particular, the results of the Prospective reflection workshops on industrial ecology, created by the National Research Agency in 2006 to promote the development of industrial ecology in France. Available from: http://www.arpege-anr.org/
5. The author obtained this expression from Benoît Duret (Auxilia) but does not know who coined it first.
6. The Environment Institute of Stockholm is piloting the project 'EcoSanRes. Closing the loop on sanitation (http://www.ecosanres.org/). This project is the basis of the *International Conference on Sustainable Sanitation: Eco-Cities and Villages*, Dongsheng (China), 26–31 August 2007. Available from: http://www.ecosanres.org/icss/

References

Acot, P., 1988. *Histoire de l'écologie*. Paris: PUF.

Anderberg, S., 1998. Industrial metabolism and the linkages between economics, ethics and the environment. *Ecological economics*, 24 (2–3), 311–320.

Ayres, R.U., 1978. *Resources, environment and economics: application of the materials/energy balance principle*. New York: John Wiley and Sons.

Ayres, R.U. and Ayres, L.W. eds., 2002. *A handbook of industrial ecology*. Cheltenham: Edward Elgar.

Ayres, R.U. and Simonis, U.K. eds., 1994. *Industrial metabolism*. Tokyo: United Nation University Press.

Ausubel, J.H. and Sladovich, H.E. eds., 1989. *Technology and environment*. Washington: National Academy Press.

Baccini, P. and Brunner, P., 1991. *Metabolism of the anthroposphere*. Berlin: Springer Verlag.

Bai, X., 2007a. Integrating global environmental concerns into urban management: the scale and readiness arguments. *Journal of industrial ecology*, 11 (2), 15–29.

Bai, X., *et al.*, eds., 2007b. The global impact of cities. Special issue. *Journal of industrial ecology*, 11 (2).

Barles, S., 2005. *L'invention des déchets urbains*. Seyssel: Champ Vallon.

Barles, S., 2007. Feeding the city: food consumption and circulation of nitrogen, Paris, 1801–1914. *The science of the total environment*, 375, 48–58.

Barles, S., 2009. Urban metabolism of Paris and its region. *Journal of industrial ecology*, 13 (6), 898–913.

Barles, S., *et al.*, eds., 2010. *Énergies et matières dans la ville: les nouveaux enjeux de l'environnement urbain*. In press.

Beaucire, F., 1985. *Enquête sur la notion et les pratiques de l'écologie urbaine en France*. Research report. Paris: CNRS.

Downloaded by [University of Calgary] at 05:59 05 September 2013

Berkes, F. and Folke, C., eds., 1998. *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press.

Billen, G., *et al*., 1983. *L'écosystème Belgique. Essai d'écologie industrielle*. Bruxelles: Centre de recherche et d'information socio-politique.

Billen, G., *et al*., eds., 2008. The food-print of Paris: long term reconstruction of the nitrogen flows imported into the city from its rural hinterland. *Regional environmental change*, 8. [online]. Available from: http://www.springerlink.com/content/e763g054m7t22050/fulltext.pdf [Accessed 16 January 2009].

Boons, F. and Howard-Grenville, J. eds., 2009. *The social embeddedness of industrial ecology*. Cheltenham: Edward Elgar.

Boyden, S., *et al*., eds., 1981. *The ecology of a city and its people: the case of Hong Kong*. Canberra: Australian National University Press.

Bringezu, S. *et al*., 1997. *Regional and national material flow accounting: from paradigm to practice*. Proceedings of the ConAccount workshop, 21–23 January 1997, Leiden. Wuppertal Institute for Climate, Environment and Energy. [online] Available from: http://www.conaccount.net [Accessed 15 January 2009].

Bringezu, S. *et al*., eds., 1998. *Analysis for action: support for policy towards sustainability by material flow accounting*. Proceedings of the ConAccount workshop, 11–12 September 1997, Wuppertal. Wuppertal Institute for Climate, Environment and Energy. [online] Available from: http://www.conaccount.net [Accessed 15 January 2009].

Brunner, P.H. and Rechberger, H., 2004. *Practical handbook of material flow analysis*. Boca Raton: Lewis Publishers.

Celecia, J., 2000. UNESCO's Man and Biosphere (MAB) programme and urban ecosystem research: A brief overview of the evolution and challenges of a three decades international experience [online]. *In*: *First meeting of the ad hoc working group to explore applications of the biosphere reserve concept to urban areas and their hinterlands – MAB Urban Group*, 9 November 2000, Paris. Available from: http://www.unesco.org/mab/ecosyst/urban/doc/jc1doc.pdf [Accessed 19 July 2008].

Chapagain, A.K. and Hoekstra, A.Y., 2004. *Water footprints of nations* [online]. Delft: UNESCO-IHE. Available from: http://www.waterfootprint.org/?page=files/Publications [Accessed 15 January 2009].

Chatzimpiros, P. and Barles, S., 2009. Quantitative water footprint of meat consumption in historical perspective: First results for Paris (France), 1817 and 1906. *In*: M. Havranek, ed. *Urban metabolism: measuring the ecological city*. Proceedings of the International Conference ConAccount 2008, September 2008. Prague: Charles University Environment Centre, 215–239.

Crutzen, P.J., 2002. Geology of mankind. *Nature*, 415, 3 January, 23.

Danius, L. and Burström, F., 2001. *Nitrogen flows in Västerås in 1995 and 1998. A practical application of material flow analysis*. Stockholm: Royal Institute of Technology, Division of Industrial Ecology.

Duvigneaud, P., 1974. *La synthèse écologique: populations, communautés, écosystèmes, biosphère, noosphère*. Paris: Doin.

Erkman, S., 2004. *Vers une écologie industrielle*. 2nd ed. Paris: éd. Charles Léopold Mayer & la librairie FPH.

Erkman, S., 2006. Mise en œuvre de l'écologie industrielle: le cas du canton de Genève. *In*: S. Barles, M. Maizia, T. Souami, and J.P. Traisnel, eds. *EMUE: energy, material, urban environment* [CD-ROM]. Proceedings of the European conference, 18–19 May 2006 Paris. Champs-sur-Marne: LTMU.

Eurostat, 2001. *Economy wide material flow accounts and balances with derived resource use indicators. A methodological guide* [online]. Luxembourg: Office for Official Publications of the European Communities. Available from: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-34-00-536/EN/KS-34-00-536-EN.PDF [Accessed 15 January 2009].

Færge, J., *et al*., 2001. Urban nutrient balance for Bangkok. *Ecological modelling*, 139 (1), 63–74.

Fiala, N., 2008. Measuring sustainability: why the ecological footprint is bad economics and bad environmental science. *Ecological economics*, 67 (4), 519–525.

Fischer-Kowalski, M., 1999. Society's metabolism: the intellectual history of material flow analysis. Part I, 1860–1970. *Journal of industrial ecology*, 2 (1), 61–78.

Downloaded by [University of Calgary] at 05:59 05 September 2013

Fischer-Kowalski, M. and Hüttler, W., 1999. Society's metabolism: the intellectual history of material flow analysis. Part II, 1970–1988. *Journal of industrial ecology*, 2 (4), 107–135.

Forkes, J., 2007. Nitrogen balance for the urban food metabolism of Toronto, Canada. *Resources, conservation and recycling*, 52, 74–94.

Frosch, R.A. and Gallopoulos, N.E., 1989. Strategies for manufacturing. *Scientific American*, 261 (3), 94–102.

Grimm, N.B., *et al*., 2000. Integrated approaches to long-term studies of urban ecological systems. *Bioscience*, 50 (7), 573–584.

Gumbo, B., Savenije, H.H.G., and Kelderman, P., 1999. Ecologising societal metabolism: the case of phosphorus [online]. *In*: *3rd international conference on environmental management in Southern Africa*, 27–30 August 2002, Johannesburg. Available from: http://www2.gtz.de/ecosan/download/CESMA2002-gumbo.pdf [Accessed 15 January 2009].

Haase, D. and Nuissl, H., 2007. Does urban sprawl drive changes in the water balance and policy? The case of Leipzig (Germany) 1870–2003. *Landscape and urban planning*, 80 (1–2), 1–13.

Haberl, H., 2001a. The energetic metabolism of societies, Part I: accounting concepts. *Journal of industrial ecology*, 5 (1), 11–33.

Haberl, H., 2001b. The energetic metabolism of societies, Part II: empirical examples. *Journal of industrial ecology*, 5 (2), 71–88.

Haberl, H., 2006. The global socioeconomic energetic metabolism as a sustainability problem. *Energy*, 31, 87–99.

Haberl, H., *et al*., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 12942–12947.

Hammer, M., *et al*., 2003a. *Material flow analysis on the regional level: questions, problems, solutions* [online]. NEDS Working Paper 2, Hamburg. Available from: http://seri.at/index.php?option=com_content&task=view&id=33&itemid=39 [Accessed 15 January 2009].

Hammer, M., Giljum, S., and Hinterberger, F., 2003b. Material flows on a local level: material flow analysis of the city of Hamburg [online]. *In*: *Workshop Quo Vadis MFA?*, 8–10 October 2003, Wuppertal. Available from: http://web205.vbox-01.inode.at/Data/seri/events/quovadis/Hammer_Giljum_Hinterberger%20-%20MFA%20Hamburg_2_MH.pdf [Accessed 15 January 2009].

Hammer, M., *et al*., 2006. Die ökologische Nachhaltigkeit regionaler Metabolismen: Materialflussanalysen der Regionen Hamburg, Wien und Leipzig [Ecological sustainability or regional metabolisms: material flow analyses of the regions of Hamburg, Vienna and Leipzig]. *Natur und kultur*, 7 (2), 62–78.

Havranek, M., ed., 2009. *Urban metabolism: measuring the ecological city*. Proceedings of the ConAccount conference, 11–12 September 2008, Prague. Prague: Charles University Environment Centre.

Iverfeldt, A., 2001. Editorial. (Special issue around the Swedish programme 'Metals in the Urban and Forest Environment – Ecocycles and Critical Loads'). *Water, air, and soil pollution*, 1 (3–4), 1.

Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Danemark: a quantitative assessment of economic and environmental aspects. *Journal of industrial ecology*, 10 (1–2), 239–255.

Kaye, J.P., *et al*., 2006. A distinct urban biogeochemistry? *Trends in ecology and evolution*, 21, 192–199.

Kennedy, C., Cuddihy, J., and Engel-Yan, J., 2007. The changing metabolism of cities. *Journal of industrial ecology*, 11 (2), 43–59.

Kleijn, R., *et al*. eds., 1999. *Ecologizing societal metabolism: designing scenarios for sustainable materials management*. Proceedings of the ConAccount Workshop, 21 November 1998, Amsterdam. Leiden: Centre for Environmental Science. [online] Available from: http://www.leidenuniv.nl/cml/ssp/publications/proc-con98.pdf [Accessed 15 January 2009].

Kneese, A.V., Ayres, R.U., and D'arge, R.C., 1970. *Economics and the environment: a material balance approach*. Washington: Resources for the Future.

Krausmann, F., 2001. Land use and industrial modernisation: an empirical analysis of human influence on the functioning of ecosystems in Austria, 1830–1995. *Land use policy*, 18 (1), 17–26.

Downloaded by [University of Calgary] at 05:59 05 September 2013

Krausmann, F., 2005. A city and its hinterland: the social metabolism of Vienna 1800–2000. *In*: *3rd ESEH conference: history and sustainability*, 17–19 February 2005, Florence.

Lestel, L., Meybeck, M., and Thévenot, D.R., 2007. Metal contamination budget at the river basin scale: an original Flux-Flow Analysis (F2A) for the Seine river. *Hydrology and earth system sciences* [online], 11, 1771–1781. Available from: http://www.hydrol-earth-syst-sci.net/11/1771/2007/hess-11-1771-2007.pdf [Accessed 15 January 2009].

Lévêque, C. and Van Der Leeuw, S., eds., 2003. *Quelles natures voulons-nous? Pour une approche socio-écologique du champ de l'environnement*. Paris: Elsevier.

Mirenowicz, P., 1982. *Bibliographie: écologie urbaine*. Paris: STU/CDU.

Mumford, L., 1961. *The city in history: its origins, its transformations and its prospects*. New York: Harcourt, Brace & World.

Newman, P. and Kenworthy, J., 1991. *Cities and automobile dependence: an international source book*. Aldershot: Avebury.

O'Rourke, D., Connelly, L., and Koshland, C., 1996. Industrial ecology: a critical review. *International journal of environment and pollution*, 6 (2–3), 89–112.

Odum, E.P., 1953. *Fundamentals of ecology*. Philadelphia: Saunders.

Odum, E.P., 1975. *Ecology: the link between the natural and the social sciences*. 2nd ed. New York: Holt, Reinhart & Winston.

Odum, E.P., 1989. *Ecology and our endangered life-support systems*. Sunderland: Sinauer.

Peters, G., *et al*., 2007. A new ecological footprint calculation for the Australian water industry: regionalisation and inclusion of downstream impacts. *Journal of applied input-output analysis*, 11–12, 73–90.

Piguet, F.P., *et al*., 2007. L'empreinte écologique: un indicateur ambigu. *Futuribles*, 334, 5–24.

Reconciling the sociosphere and the biosphere, 1989. Special issue. *International social science journal*, 121.

Rees, W. and Wackernagel, M., 1996a. *Our ecological footprint: reducing human impact on the earth*. Gabriola Island: New Society.

Rees, W. and Wackernagel, M., 1996b. Urban ecological footprints: why cities cannot be sustainable – and why they are key to sustainability. *Environmental impact assessment review*, 16, 223–248.

Schmid-Neset, T.S., 2005. *Environmental imprint of human food consumption, Linköping, Sweden, 1870–2000*. Thesis (PhD). Linköping University.

Schulz, N.B., 2005. *Contributions of material and energy flow accounting to urban ecosystems analysis: case study Singapore* [online]. UNU-IAS Working Paper No.136. Available from: http://www.ias.unu.edu/binaries2/IASWorkingPaper136.pdf [Accessed 15 January 2009].

Sveden, J. and Jonsson, A., 2001. Urban metabolism of mercury turnover, emissions and stock in Stockholm 1795–1995. *Water, air, & soil pollution: focus*, 1 (3–4), 179–196.

Theys, J. and Emelianoff, C., 2001. Les contradictions de la ville durable. *Le débat*, 113, 122–135.

Van den Bergh, J.C.J.M. and Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. *Ecological economics*, 29, 61–72.

Waggoner, P.E., 2006. How can EcoCity get its food? *Technology in society*, 28, 183–193.

Walsh, E., *et al*., 2006. Quantitative guidelines for urban sustainability. *Technology in society*, 28, 45–61.

Wolman, A., 1965. The metabolism of cities. *Scientific American*, 213 (3), 179–190.

Downloaded by [University of Calgary] at 05:59 05 September 2013