Network Environ Perspective for Urban Metabolism and Carbon Emissions: A Case Study of Vienna, Austria

ARTICLE *in* ENVIRONMENTAL SCIENCE & TECHNOLOGY · MARCH 2012

Impact Factor: 5.33 · DOI: 10.1021/es204662k · Source: PubMed

2 AUTHORS:

Shaoqing Chen
Beijing Normal University

Bin Chen
Beijing Normal University

Environmental Science & Technology

Article

pubs.acs.org/est

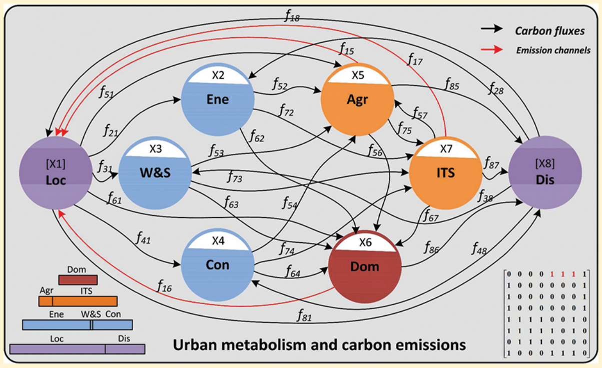
Network Environ Perspective for Urban Metabolism and Carbon Emissions: A Case Study of Vienna, Austria

Shaoqing Chen[†] and Bin Chen*[,†]

[†]State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

Supporting Information

ABSTRACT: Cities are considered major contributors to global warming, where carbon emissions are highly embedded in the overall urban metabolism. To examine urban metabolic processes and emission trajectories we developed a carbon flux model based on Network Environ Analysis (NEA). The mutual interactions and control situation within the urban ecosystem of Vienna were examined, and the system-level properties of the city's carbon metabolism were assessed. Regulatory strategies to minimize carbon emissions were identified through the tracking of the possible pathways that affect these emission trajectories. Our findings suggest that indirect flows have a strong bearing on the mutual and control relationships between urban sectors. The metabolism of a city is considered self-mutualistic and sustainable only when the local and distal environments are embraced. Energy production and construction were found to be two factors with a major impact on carbon emissions, and whose regulation is only effective via ad-hoc pathways. In comparison with the original life-cycle tracking, the application of NEA was better at revealing details from a mechanistic aspect, which is crucial for informed sustainable urban management.



1. INTRODUCTION

Supporting a variety of ecological and economic activities, cities have long been seen as metabolizing organisms, since A. Wolman[1] pioneered the notion of urban metabolism in the wake of rapid urban expansion, and resource overexploitation. More than just a metaphor borrowed from the biotic world, urban metabolism is generally recognized as the sum of all the ecological and economic processes in a city that result in the adoption of materials, consumption of energy, and elimination of waste, and which also frames the real functioning patterns of artificial ecosystems.[1,2] From this definition, a city's fluxes of materials, energy, and nutrients can be regarded as constituent parts of the bigger picture of the entire urban metabolic framework.[3] Among these fluxes, the process of carbon emissions (nontoxic) has been included into the incipient framework even though toxic pollutants have been of more interest over the last decades.[4−6] The effects of urbanization on climate change were not clearly recognized until recent observations proved >80% of the global carbon dioxide emissions originated in urban and metropolitan areas.[7] This has a strong bearing on altering the global carbon cycle,[8] and in the context of global warming, the metabolism of carbon has become unprecedentedly significant because of its close relationship with carbon emissions. Therefore, the tracking of carbon fluxes and pathways within the metabolic regime of a city will facilitate the regulation of anthropogenic carbon emissions and adjustments of the sectors responsible. Thus, it is critical to adopt a metabolism-framed methodology to the current understanding of the carbon balance.

There are currently two main streams of methodology used in urban metabolism studies. One is primarily based on the inventorying of life-cycle ecological and economic inputs/outputs, including the following: material flow analysis,[9,10] energetic balance analysis,[11−13] and metabolism-based inventorying of emission-related energy use.[14,15] The other method uses biophysical metrics in which the available energy, as a quality instead of generic energy, is utilized to indicate the resource configuration and metabolic efficiency, including the following: emergy,[16,17] exergy,[18,19] and hybrid models thereof .[20,21] Measurements of the atmospheric and soil carbon fluxes of the urban carbon balance have previously been conducted on a monitoring basis,[22−26] and there has been increasing interest in the evaluation of these fluxes by treating urban systems as ecosystems of extensive interactions.[27,28] Within an urban metabolic framework there are still no measurements other than those computed from relationships of energy consumption, material flows, and waste discharge, which trace the trajectories of carbon emissions through their source inventories.[14,29−31] This kind of computation raises the

Received: December 26, 2011
Revised: February 28, 2012
Accepted: March 18, 2012
Published: March 19, 2012

possibility of applying the concept of metabolism to pragmatic urban evaluation, i.e., the metabolizing amount of carbon flows, often serving as a primary tool for early problem recognition.[3,32] However, little information is available on the intrinsic interactions and structure of an urban carbon system beyond its metabolizing inputs/outputs, and this undermines the environmental decision support for microregulation at sector level toward emissions mitigation. This weakness is even more evident in that the current metabolism evaluation does not incorporate any indirect effects, which become too important to be omitted through the extension of carbon flow pathways.[33,34]

A system-oriented technique known as Network Environ Analysis (NEA) has received increasing attention due to its unique strength in examining the structure and direct/indirect ecological flows in ecosystems (a detailed introduction to NEA and accessible software is available[35−38]). In the context of biotic metabolism, life scientists are concerned with interactive metabolic processes and interactions that transform or transfer chemicals. Thus, it is legitimate that we consider using the same method for studying urban metabolism. In fact, NEA has previously been applied to the evaluation of energy and water fluxes of an urban metabolism, because of its capability of determining built-in relationships in the metabolic processes that form the structure, and represent the function of urban ecosystems.[39−42] However, to date, there has been no attempt to analyze the urban carbon metabolism from the network point of view, and there are still challenges with respect to a systemic comprehension of urban metabolic structure and functioning, such as methodology gap and knowledge interpretation. The adoption of NEA may conceivably provide a novel method for metabolism evaluation that addresses metabolic intensities, processes, and structure, which is useful for understanding the operation of a metabolizing city and for learning about the control of carbon emissions.

Based on a reinspection of a study of Vienna concerning carbon balance, this study presents an NEA-based methodology for carbon metabolism in urban areas and thus provides a novel angle for incorporating metabolism evaluation into the consideration of sustainable urban design. A handful of metabolism-focused urban studies have previously been conducted in various urban regions worldwide e.g., Brussels,[43] Hong Kong,[10,44] Toronto,[32] and Paris.[45] One of the most comprehensive investigations into carbon metabolism was conducted in the city of Vienna by Daxbeck et al.[46] and Obernosterer et al.,[47] the results of which were also published by Hendriks et al.[48] Over 20% of Austria's total population reside in Vienna (1.5 million inhabitants), a city which covers just 0.5% of the country's total area, making it the most densely populated urban area in Austria (3710 capita/km^2). Various programs have previously been initiated to cope with carbon emissions and other environmental problems in Vienna, and the established data set was adjusted to demonstrate the urban metabolism model presented here.

2. MATERIALS AND METHODS

2.1. System Boundary. In the current metabolic system, both the anthropogenic and natural processes of the city's carbon fluxes were taken into account. It not only embraced relative processes within the administrative boundary but also covered those metabolically linked activities that occur outside the boundaries of the city (i.e., engaged in the exchange of carbon of the city) (Figure S1). The carbon fluxes within the system boundary involved; the flows within private households, agriculture, industries (product manufactory) and trades; the distribution of carbon among internal households, agriculture and industries, as well as between Vienna and its distal environmental; and the natural carbon inflow and outflow (carbon emissions) of the city. In particular, the national and international production and supply chains are considered in the carbon flows within goods, which are followed out of the administrative boundary to their origin at the one terminal, and the final sinks at the other terminal. In terms of transportation, the flow of transport fuel induced by the Viennese (within and outside the city) and the transport of goods by truck between Vienna and its external markets were also incorporated.

2.2.1. NEA for Urban Metabolism. *Urban Metabolic Network.* Within urban ecology, a city may be conceived as an energy/resources-intensive interactive ecosystem where the regulations of social, economic, and ecological processes parallel the rules in abiotic and biotic nature.[49,50] Based on carbon dynamic processes and the relationships of these processes within an urban area, a network model called the Metabolic Network (MN) was developed for tracking carbon flows within an urban ecosystem (Figure 1), in which

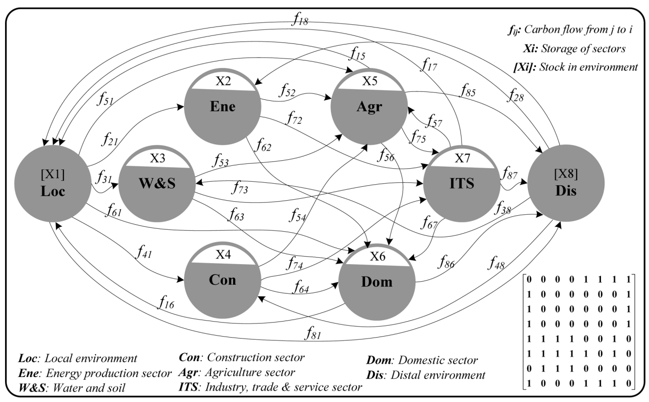


Figure 1. Metabolic network model for urban carbon metabolism. The adjacency matrix in the bottom-right corner indicates the presence ("1") or absence ("0") of a carbon flow between two compartments.

compartments are distributed according to their particular role (note that this is different from the hierarchical display of energy flows and reservoirs in Odum's system diagrams for cities[51]). MN consists of eight distinctive compartments: energy production sector (Ene), water and soil (W&S), construction sector (Con), agriculture sector (Agr), industry (product manufactory), trade, and service sector (ITS), domestic sector (Dom), local environment (Loc), and distal environment (Dis). Specific flows between these sectors were identified and characterized as the compartmental interactions within MN (in this case, carbon exchanges). To understand the operation of MN from the network environ perspective, we evaluated the mutual relationships, control conditions, and whole-system dynamics of urban metabolism, through network utility analysis, network control analysis, and system-wide indicators derived from NEA, respectively.

2.2.2. Network Utility Analysis (NUA). NUA is utilized to reveal the mutual relationships between different sectors of the urban metabolic system. In NUA, direct mutualism (mutualism is a metric to define the mutual benefit between compartments) considers the direct interactions between compartments, while integral mutualism assesses the integral relationships that encompass both direct and indirect effects.[36] Direct mutualism is presented with a direct utility matrix $\mathbf{D} = [d_{ij}]$, within which intercompartmental flow utilities are given by $d_{ij} \equiv (f_{ij} - f_{ji})/T_i$, where f_{ij} is a metabolic flow (e.g., carbon flow) from compartment j to compartment i (i *and* j are nodes defined within the network, e.g., an urban sector); T_i is the sum of flows into or out of the i-th compartment when the system is at steady state. With further consideration of network indirect influence caused by extended flow pathways, the dimensionless integral utility intensity matrix **U** is computed as (m is the total number of compartments)

$$\mathbf{U} = \mathbf{D}^0 + \mathbf{D}^1 + \mathbf{D}^2 + ... + \mathbf{D}^m = (\mathbf{I} - \mathbf{D})^{-1} \tag{1}$$

U accounts for interflows over all pathways in the system of lengths 1, 2, ..., m. Herein, pathway length is the number of arcs from an initial to a terminal node. Positive/negative signs of the mutualism index are capable of identifying the nature of the relationships between different metabolic compartments. There are always two signs for each pair of compartments in terms of the opposite directions in the matrices **D** and **U**, and the combinations of these two signs determine the nature of the inter-relationships between two compartments. *SignD* and *SignU* are developed as two sign matrices of **D** and **U**, respectively. In these two matrices, (+,+) stands for mutualistic condition, (+,−) for exploitation condition, (−,+) for exploited condition, (−,−) for competition, and (0,0) for neutrality.[52]

At the system level, network mutualism index (*MI*) and synergism index (*SI*) are adapted for the current metabolism analysis to determine the fitness of the entire metabolic system.[36,40] *MI* represents the ratio of the number of positive signs to that of negative signs in the utility intensity matrix, while *SI* quantifies the total magnitude of the positive and negative utilities, which assess the mutualistic condition of a system in two slightly different angles

$$MI \equiv SignU(+)/SignU(-) \tag{2}$$

$$SI \equiv \sum_{j=1}^{n}\sum_{i=1}^{n} u_{ij} \tag{3}$$

where $SignU\ (+) = \sum \max(Sign(u_{i,j}),0)$, $SignU\ (-) = \sum -\min(Sign(u_{i,j}),0)$.

2.2.3. Network Control Analysis (NCA). Distributed control analysis is designed to measure the control or dominance of one compartment over another via their input/output environs.[33,52−54] Network control (control is a metric to define the influence of one compartment on the other) is characterized by a pairwise integral flow through network flow analysis, representing the control each compartment exerts within the overall system configuration.[34,55,56] Therefore, the integral, or transitive closure, flow matrices, **N** and **N′** were first defined

$$\mathbf{N} = [n_{ij}] = (\mathbf{I} - \mathbf{G})^{-1}\ \mathbf{N}' = [n'_{ij}] = (\mathbf{I} - \mathbf{G}')^{-1} \tag{4}$$

where $\mathbf{G} = [g_{ij}]$, $g_{ij} = f_{ij}/T_j$; $\mathbf{G}' = [g'_{ij}]$, $g'_{ij} = f_{ij}/T_i$. Based on this, two distributed control metrics, signified as the control allocation (**CA**) and dependence allocation (**DA**), were developed to formulate the control and dependence condition within an urban ecosystem

$$\mathbf{CA} = [ca_{ij}] \equiv \begin{cases} n_{ij} - n'_{ji} > 0,\ ca_{ij} = \dfrac{n_{ij} - n'_{ji}}{\sum_{i=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \le 0,\ ca_{ij} = 0 \end{cases} \tag{5}$$

$$\mathbf{DA} = [da_{ij}] \equiv \begin{cases} n_{ij} - n'_{ji} > 0,\ da_{ij} = \dfrac{n_{ij} - n'_{ji}}{\sum_{j=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \le 0,\ da_{ij} = 0 \end{cases} \tag{6}$$

where $0 \le da_{ij}, ca_{ij} \le 1$. By definition both **CA** and **DA** are formulated by the difference of two pairwise integral flows (i.e., n_{ij} and n'_{ij}) that normalized in two involved environs. ca_{ij} indicates the control degree of compartment j on compartment i based on the controller's (the one that controls) output environ, while da_{ij} indicates the dependence degree of compartment j on i from the observer's (the one being controlled) input environ.

Based on the network control and dependence information, the system-wide control situation can be represented by the system control index (*CI*) (eq 8), which is formulated by the combined dependence-control degree on a certain network scale. By definition, *CI* indicates the overall control strength and organization capability of a system and therefore can be employed to index the self-regulation of urban metabolism

$$CI \equiv \frac{\sum_{j=1}^{m}\sum_{i=1}^{m} ca_{ij} + \sum_{j=1}^{m}\sum_{i=1}^{m} da_{ij}}{m^2} \tag{7}$$

2.2.4. System-Wide Indicators. To make an overall judgment on Vienna's metabolic scenario in terms of sustainable urban design, it is essential to address the system performance of the MN. A set of network-based indicators were aggregately defined and reinterpreted. Some of these had already been developed through NUA and NCA as elucidated above, while others were extracted from the existing NEA synthesis. Each indicator suggests a facet of the metabolism-related trait of an urban ecosystem. The basic denotations of these indicators were introduced (Table S9), and the formulations and ensuing implications in the context of metabolism were illustrated (Table 3).

2.3. NEA for Carbon Emissions. In addition to the application to generic urban metabolism evaluation, NEA was further adapted to the tracking of carbon emission trajectories. NUA was used to identify the mutual relationships between those compartments that were engaged in the emission pathways and the emitters, while NCA was responsible for quantifying the actual control of these compartments on the emission activities built on those relationships. In NUA, the intercompartmental relationships (in positive/negative signs) can be transmitted through two or more interlinked sectors in view of the indirect utilities between them. In this way, the cumulative effects of original sectors (where the track originates) on the emission outflows can be derived. To adapt NCA to carbon emissions control analysis, we further define the specific control of original sectors on the environment through emission outflow channels (Figure S3).

Table 1. Carbon Flows within the Metabolic Network of Vienna (Unit: kg capita^{-1} year^{-1})[a]

donor/recipient	Loc	Ene	W&S	Con	Agr	Dom	ITS	Dis
Loc	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	160(2.1%)	629(8.2%)	1145(14.8%)	63(0.8%)
Ene	1010(13.1%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	420(5.4%)
W&S	21(0.3%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	5(0.1%)
Con	570(7.4%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	261(3.4%)
Agr	137(1.8%)	70(0.9%)	6(0.1%)	35(0.5%)	0(0.0%)	0(0.0%)	24(0.3%)	0(0.0%)
Dom	23(0.3%)	420(5.4%)	6(0.1%)	156(2.0%)	104(1.3%)	0(0.0%)	105(1.4%)	0(0.0%)
ITS	0(0.0%)	940(12.2%)	14(0.2%)	640(8.3%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)
Dis	236(3.1%)	0(0.0%)	0(0.0%)	0(0.0%)	8(0.1%)	185(2.4%)	320(4.1%)	0(0.0%)
T_i	1997(25.9%)	1430(18.5%)	26(0.4%)	831(10.8%)	272(3.5%)	814(10.6%)	1594(20.7%)	749(9.7%)

[a] The numbers in brackets are proportional carbon flows, i.e., carbon flow value that divided by the total carbon flow in the whole system. T_i is the sum of flows into or out of the i-th compartment. The carbon flows from Ene and Con to Loc (i.e., carbon emissions) are attributed to the downstream sectors according to their metabolic activities and therefore included in the calculation despite not being shown in the MN.

UC_{10} represents the ultimate control that an original sector, A_0, indirectly exerts on the local environment through an emission channel (i.e., from a certain emission sector to Loc), which is determined by the controls from A_0 to the emission sector (i.e., ca_{e0}) and from the emission sector to Loc (i.e., ca_{le}). There are usually other sectors (A_1, A_2, ...A_i, ..., A_η) that are also controlled by the emission sector, whose total throughflow proportion is also an influential factor. Taking the simplest three-compartment network as an example, we formulated the ultimate control (UC) of a sector on the environment via a given emission outflow channel as (indicating the actual influence of a sector on the carbon emission)

$$UC_{l0} \equiv ca_{e0}ca_{le}\frac{\sum_{i=1}^{\eta} T_i}{\sum_{i=1}^{\eta} T_i + T_l} \tag{8}$$

2.4. Data. The current metabolism data set was constructed from a set of carbon balance data of Vienna. These data were derived from ad hoc investigations into the natural carbon fluxes, anthropogenic carbon composition of goods' transportation, the relationships between these flows and stocks, as well as the combined anthropogenic-natural processes.[46−48] As these original investigations of Vienna were all conducted from the life cycle perspective and within similar boundaries, they were integrated for the current framework of urban metabolism. The sensitivity and uncertainty of the synthesized data were discussed due to their influences on the model (Tables S1-a and S1-b).

3. RESULTS

3.1.1. Urban Metabolism. *Metabolic Network of Carbon Fluxes.* Carbon fluxes between sectors within Vienna's MN are illustrated in Table 1. The results show that Ene, Con, and W&S are the three major carbon donors that supply carbon (in the form of raw materials, fossil fuels, and machinery, etc.) to Agr, ITS, and Dom, supporting economic development and livelihood improvement of the latter sectors, where human activities are intensive. The ultimate suppliers of carbon are revealed to be both Loc and Dis. Overall, the total carbon throughflow of Vienna's MN amounts to 7713 kg capita^{-1} year^{-1} (assumed at steady state). The carbon balance of Vienna is dominated by ITS (25.7%), Ene (18.5%), Con (10.8%), and Dom (10.6%), while the contribution of W&S is relatively small (0.4%). The biggest carbon emissions are from ITS (1145 kg capita^{-1} year^{-1}) and Dom (629 kg capita^{-1} year^{-1}). Ene (1010 kg capita^{-1} year^{-1}) and Con (570 kg capita^{-1} year^{-1}) are two major sources of extracting carbon from the local environment, that are much higher than the natural supply by W&S (21 kg capita^{-1} year^{-1}). The carbon emission (from ITS to Loc, 14.8%), extraction (from Loc to Ene, 13.1%), and processing (from Ene to ITS, 12.2%) are the most contributive processes. The externality of carbon dynamics in Vienna is not obvious in that the total throughflow of Dis is relatively low (9.7%), though carbon imported to Ene amounts to 420 kg capita^{-1} year^{-1}.

The proportional carbon throughflows of the urban sectors reflects the ecological structure of the carbon metabolism in Vienna, which has an almost perfect pyramidal shape (Figure 2). In fact, the pyramidal configuration is one of the most

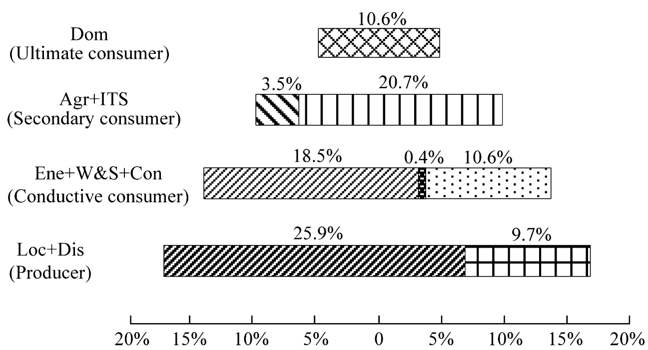


Figure 2. Ecological structure of carbon metabolism in Vienna. Reading from left to right, the values are the proportional total carbon inputs (or output) of compartments (i.e., proportional T_i in Table 1). Producers: primary carbon suppliers; Conductive consumers: carbon agents that transfer/transform carbon from natural environment to human society; Secondary consumers: Anthropogenic carbon consumers that create physiological (like breath) or economic value (like industry) from processed carbon resources by conductive consumers; Ultimate consumers: the ones consumed most of the carbon products of secondary consumers.

predominant structures in the natural world, e.g., the pyramidal energy hierarchy of food web networks. As an analogy of the natural ecosystem, the carbon metabolic system can also be understood by the composition of producers (i.e., in Vienna's case, Loc and Dis), conductive consumers (i.e., Ene, W&S, and Con), secondary consumers (i.e., Agr and ITS), and ultimate consumers (i.e., Dom). The supplying, transferring/transforming, processing, and consuming processes of carbon are carried out by these agents. The pyramidal resemblance of the structure indicates that a great similarity exists in metabolic processes between an urban system and a real ecosystem. Additionally, it can be concluded that carbon metabolism is

dx.doi.org/10.1021/es204662k | Environ. Sci. Technol. 2012, 46, 4498−4506

Table 2. Direct Utility Sign Matrix (*SignD*)/Integral Utility Sign Matrix (*SignU*) for Carbon Metabolism of Vienna[a]

	Loc	Ene	W&S	Con	Agr	Dom	ITS	Dis
Loc	0/+	∓	−/0	∓	+/+	+/+	+/+	−/−
Ene	+/+	0/+	0/−	0/−	−/−	−/−	−/−	+/+
W&S	+/+	0/−	0/+	0/−	−/−	∓	∓	+/+
Con	+/+	0/−	0/−	0/+	∓	∓	−/−	+/+
Agr	∓	+/+	+/+	+/+	0/+	−/−	+/+	∓
Dom	−/−	+/+	+/+	+/+	+/+	0/+	±	∓
ITS	−/−	+/+	+/+	+/+	−/−	−/−	0/+	∓
Dis	±	−/−	∓	−/−	+/+	+/+	+/+	0/+

[a]The signs of direct and integral utilities are isolated by "/", e.g., the "∓" and "+/+" between Ene and Loc indicate that their direct mutual relationship is (−,+), while their integral mutual relationship is (+,+).

tightly associated with the energy metabolism through traditional energy consumption activities, e.g., carbon extraction and carbon dioxide emissions, etc.[11,25]

3.1.2. Network Mutual Relationships. Table 2 shows the direct relationships (in the direct utility sign matrix, *SignD*) and integral interactions (in the integral utility sign matrix, *SignU*) between different urban sectors of Vienna. The primary calculations that lead to these results, including direct utility matrix (**D**) and the integral utility matrix (**U**) are provided in Tables S10-a and S10-b. It is evident that the positive/negative signs in the integral utility matrix occasionally vary from those in the direct utility matrix, suggesting that both the quantities and the qualities of the integral relationships (when indirect effects are incorporated) could alter compared with direct ones. Most frequently, these alterations are prone to the positive side of the relationship, i.e., from "−" to "+", or "−" to "0", or from "−" to "+", from which the whole metabolic system benefits. The findings of mutual relationships are basically supportive to the exclusive roles these sectors play in the ecological structure of carbon metabolism. At length, the local and distal environment are exploited by the conductive consumers, i.e., Ene, W&S, and Con (−,+) within both matrixes, but move toward the mutualistic direction through indirect pathways. Loc displays an exploitative trend toward Agr, Dom, and ITS (+,−), while Dis is integrally mutualistic with the three carbon consumers. Ene, W&S, and Con are exploited by the upper consumers, i.e., Agr, Dom, and ITS (−,+). In addition, through the tracking of network carbon cycles, self-promotion behaviors are unveiled for all of the sectors in that they have positive utilities with themselves ("+" integral utility signs in all diagonal values).

3.1.3. Network Control Condition. The proportional network dependence and control situation of the metabolic sectors are illustrated in Figures 3a and 3b. These results are primarily based on the dependence allocation matrix (DA) and the control allocation matrix (CA) of the MN in Vienna, which sums up the integral dependences, or controls of one urban sector on others (Tables S11-a and S11-b). In view of network dependence, three ultimate consumers (Agr, Dom, and ITS) are almost fully dependent on their energy/resource suppliers (i.e., Ene, W&S, and Con). Specifically, the carbon dynamics in Agr greatly depends on W&S (65.2%), Ene (16.0%), and Con (14.7%), whereas the influence from ITS (4.1%) is comparatively small. For ITS, the proportional controls originating from Con, Ene, and W&S were 39.2%, 33.4%, and 27.4%. All of the other five metabolic sectors (i.e., Agr, W&S, Ene, Con, and ITS) exert a degree of control on Dom, among which Agr (26.7%), W&S (25.1%), and Ene (25.0%) are the most significant. Network control suggests a similar

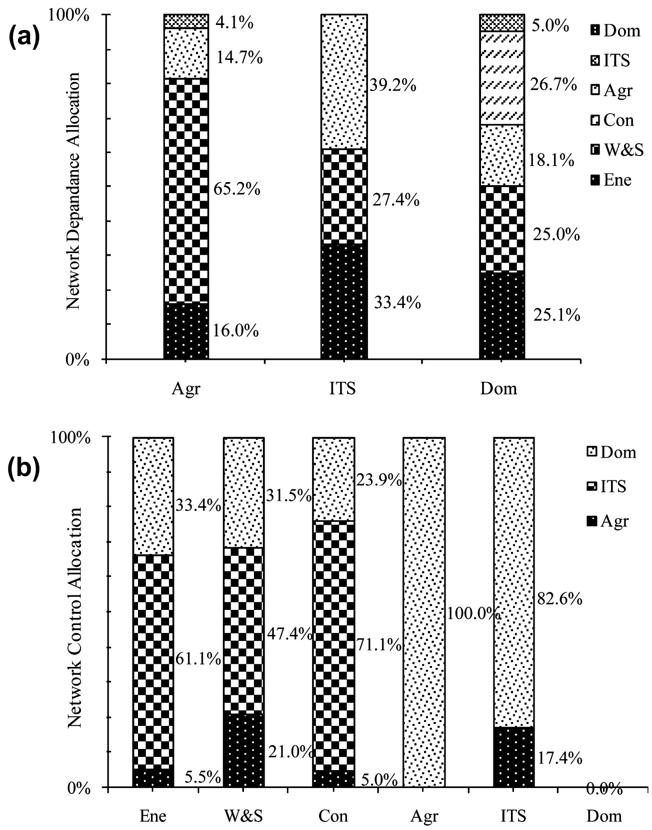


Figure 3. a. Network dependence of carbon metabolism in Vienna. b. Network control of carbon metabolism in Vienna.

situation of systemic control for carbon metabolism but from the controller's perspective. ITS and Dom are two major dominators in the carbon metabolic system in Vienna, followed by Agr. This agrees with our previous finding that the emission flows from these sectors serve as the dominant fluxes of the entire carbon metabolic system.

3.1.4. System Performance. The overall performance of Vienna's urban ecosystem was appraised based upon the established system-wide indicators that characterize the city's carbon metabolism (Table 3). Obviously, compared with the carbon flows beyond the local and distal environment (Table S12), the complete MN has more direct and indirect linkages within the urban area. The compartments of the MN are also more metabolically connective because of the intensive carbon fluxes, as shown by their higher Link Density and Connectance, which results in more diverse cycling routes, and therefore higher FCI. [Note that the FCI of the urban metabolic network

Table 3. System-Wide Properties of Carbon Metabolism in Vienna

indicator	formulation	metabolism implication	metabolic network: with Loc and Dis	metabolic network: without Loc and Dis
nodes	m	metabolic compartments	8	6
links	L[a]	metabolic linkages	28	12
link density	L/m	metabolic linking degree	3.50	2.00
connectance	L/m^2	metabolic connectivity	0.44	0.33
TST[b]	$\Sigma_{j=1}^{m}\Sigma_{I=1}^{m}f_{ij}$	metabolic size	7713	4967
FCI[c]	$\Sigma_j^n(((n_{ij}-1)/(n_{jj}))T_j)/TST$	cycling effect of metabolism	1.00	0.85
MI	eq 2	metabolic system mutualism	1.91	0.80
SI	eq 3	metabolic system synergism	9.07	2.17
CI	eq 7	self-regulation of metabolism	0.25	0.22

[a]Number of flows. [b]Total System Throughflow. [c]Finn's Cycling Index.

Table 4. Tracking of Carbon Emissions in Vienna Based on NUA and NCA[a]

emission outflow channel	effecting pathway	interactive mutual relationships in *SignU*	ultimate control of emission output (*UC*)
5→O (160 kg capita^{-1} year^{-1})	2→5→O (m = 2)	+ − − (▼)	0.208
	2→7→5→O (m = 3)	+ − + + (▲)	0.035
	3→5→O (m = 2)	+ − − (▼)	0.093
	3→7→5→O (m = 3)	+ + − − (▼)	0.027
	4→5→O (m = 2)	+ + + (▲)	0.022
	4→7→5→O (m = 3)	+ − + + (▲)	0.040
6→O (629 kg capita^{-1} year^{-1})	2→6→O (m = 2)	+ − + (▲)	0.040
	2→7→6→O (m = 3)	+ − − + (▲)	0.002
	3→6→O (m = 2)	+ + − (▼)	0.038
	3→7→6→O (m = 3)	+ + + − (▼)	0.002
	4→6→O (m = 2)	+ + − (▼)	0.029
	4→7→6→O (m = 3)	+ − − + (▲)	0.003
	7→6→O (m = 2)	− − + (▼)	0.099
7→O (1145 kg capita^{-1} year^{-1})	2→7→O (m = 2)	+ − + (▲)	0.215
	3→7→O (m = 2)	+ + − (▼)	0.166
	4→7→O (m = 2)	+ − + (▲)	0.250

[a]Consistent with Figure 1: Loc (1), Ene (2), W&S (3), Con (4), Agr (5), Dom (6), ITS (7), Dis (8). m denotes the length of an effecting pathway (number of arcs). An effecting pathway indicates the existence of a carbon flow to the atmosphere environment via a given emission outflow channel, e.g., "2→7→5→O" represents that carbon is transferred from Ene ("2") to ITS ("7") and then engages in the emission from Agr ("5") to the environment (signified as "O"). Note that cycling routes are excluded in the calculation. "▲" /"▼" denotes the positive/negative effect of the first sector (where the carbon flux originates) on the final emission output, which is determined by the mutual relationships between all of the involved compartments (e.g., via pathway "2→7→5→O", a positive effect (▲) on the increase of carbon emissions is detected based on the interactive mutualism signs "+ − + +" as defined by NUA).

is high because of the assumption that carbon is recycled fast enough in all sectors of the MN (including Loc and Dis), as in other biogeochemical networks.[57−59]][60] Furthermore, the complete MN has higher *SI* (9.07), *MI* (1.91), and *CI* (0.25) resulting from the more positive signs that the system acquires when counting indirect influences, whereas the *MI* is <1.00 when Loc and Dis are excluded. Therefore, the city's MN can only be considered self-mutualistic and sustainable when the metabolism-related environment (Loc and Dis) is embraced. In a natural ecosystem, the number of positive utilities is always greater than that of negative utilities, which sustains its self-mutualism.[61] Therefore, this might imply an ongoing or upcoming increase of carbon stock within the city of Vienna.

3.2. Carbon Emissions. The scenario of carbon emissions is highly embedded in the entire urban metabolism. Therefore, it is possible to track the trajectories of carbon dynamics related to these emission outputs. To explore the potential of NEA for carbon emissions management, the emission outflows of pertinent urban sectors were extracted for additional inspection (Table 4). The pathways that contribute to the ultimate carbon emissions in direct (pathway length (m) = 1) and indirect ways (m > 1) were investigated through the established metabolic network. The mutual relationships between the interactive compartments involved in these pathways were derived from NUA. Also, the network control of the donor sectors related to ultimate emission output was evaluated, based on the developed NCA. Our results indicated that aside from the direct emission channel, multiple effecting pathways of different lengths (i.e., m) also play a part in carbon emission, through which a donor sector may directly exert an influence on the adjacent environment. Furthermore, the impacts originating from the same sector may ultimately differ, because of the diverse mutual relationships between the compartments involved in these pathways. In the case of Vienna, three major emission sectors, i.e., Agr, Dom, and ITS, contribute 60% of the carbon outflow of the metabolic system. These consumer sectors were tracked explicitly for their potential influences on carbon emission trajectories. Ene and Con are the major impact factors toward the increase of carbon emissions from all the three sectors (consistent with NCA's result). The carbon emissions of Agr are most likely to be impacted by Ene and Con through pathways "2→7→5→O", "4→5→O", and "4→7→5→O", and are simultaneously controllable with the strengths of 0.035, 0.022, and 0.040 (*UC = 0* is deemed as uncontrollable, while *UC = 1* is totaly controllable), respectively. Other pathways either display a tendency toward carbon emission mitigation (e.g., "2→5→O") or indicate increasing carbon emissions but with null control strength (e.g., "2→6→5→O", excluded in the table). Concerning Dom, "2→6→O", "2→7→6→O", and "4→7→6→O" were revealed as effective pathways to mitigate carbon emissions. Finally, for ITS, "2→7→O", and "4→7→O" are two possible processes to focus on for emission reductions.

4. DISCUSSION

Beyond the sheer magnitudes of energy or resource flows, it has been commonly accepted in recent years that an understanding of the interactive processes within an urban metabolism framework is of equal importance to understanding the magnitudes of energy, or resource flows, for sustainable urban development.[2,8,20,62,63] In this context, NEA is useful on account of its capability of advancing empirical investigations toward an exhaustive, process-focused analysis of a system, via the unveiling of network interactions.

By mimicking the "ecosystem metabolism" of the biological world, a metabolic network was employed to model carbon flows within an urban ecosystem, whereby we can evaluate its system performance in terms of sustainable urban management. In highly self-organized natural ecosystems, it is the eco-flows that connect diverse compartments in a direct/indirect way and characterize the complex system regime through their input/output environs. Vienna's case showed that the indirect pathways connecting carbon fluxes play important roles in an urban metabolic system, whose influences within the MN cannot be neglected. An important implication of NUA is that in identifying the mutual relationships between a pair of urban sectors, other seemingly unrelated compartments or processes should also be scrutinized for their possible effects; otherwise, a distortion in the metabolism interpretation might occur (e.g., the mutual relationships between Loc and Ene in this case). Integral utility provides both a valid perspective and a practical approach for the required recognition. In terms of NCA, the network control mechanism displays another facet of MN's merit that might be useful in urban ecosystem management, i.e., it uncovers the dependence or control relationships between compartments, based on which the regulation of the carbon balance at sector level can be planned. One of the vital aims of future regional environmental management is the sustainable use of resources by optimizing and controlling the flows of materials and energy in the anthroposphere.[48] The integral control allocation highlights the cumulative pathways of flows and therefore provides a wide and precise insight into the adjustment of the resources distribution from the ecological perspective. The unique role each of the sectors play in the MN can parallel trophic natural ecosystems (e.g., producers, conductive consumers, secondary consumers, and ultimate consumers), giving a better understanding of the metabolic infrastructure that is built upon the various processes they undertake. These investigations revealed both the sector-level dynamics, and the system-wide properties that characterize the structure and functioning of an urban metabolic system.

In pursuit of the regulation of emission trajectories, an ad-hoc network tracking technique was developed by combining NUA and NCA, providing a novel way of investigating the anthropogenic processes of carbon emissions and corresponding regulation. We have accounted for different extents for the intensities of carbon emissions attached to urban sectors using life-cycle methods, such as material flow analysis[9,10] and metabolism-based inventorying.[14,15,31] Instead of the sole determination of the emission magnitude, the network approach points to another central facet of carbon emissions, i.e., tracking the cumulative pathways inside carbon metabolism and identifying the dominant processes and factors that affect emission activities. The tracking of emission trajectories through their metabolic processes is important both for tracing back to the original influential factors of emitters and for filtering control routes of emissions beyond the sole accounting of their intensities.

In comparison with the life-cycle tracking of materials,[46−48] the application of NEA revealed more details of carbon metabolism from a mechanistic aspect. In Vienna's case, there are at least three clues that lead to this: 1) the overall MI (MI = 1.91 > 1.00) indicates a positive development of Vienna's carbon metabolic system, which is also proved by the self-promotion behaviors at sector level ("+" integral utilities with themselves). An increase of 2% in the total carbon stock for the year was actually detected in the original investigation. 2) In view of material flow assessment (MFA), the carbon flows in Vienna are dominated by the consumption of fossil fuels, mostly through the processes of the heating and transportation. NCA further specifies industry and domestic consumers as two major dominators of the carbon metabolic system, while the key to controlling these flows is within two conductive consumer sectors, i.e., Ene and Con. Furthermore, effective pathways or strategies to mitigate the carbon emissions via these two sectors are also identified. 3) Life-cycle evaluation highlights that the relationships between urban domain and the environment (or "hinterland") plays significant roles in Vienna's carbon dynamics through the high ratio of the total environmental input to stock. Basically, NEA's insights point to the same fact in an explanatory way, such as the large proportion of the total throughflow (T_i) in Loc and its great contribution to metabolic linkage and cycling. Network mutualism results also suggested the high dependence of the carbon suppliers and consumers on the anthropogenic activities involving Loc and Dis. In essence, the developed NEA for an urban ecosystem is inherently compatible with former studies in terms of system scope and data set. Therefore, they can be implemented aggregately within the same metabolism framework. The confluence of these two schools will reasonably reinforce the metabolism-inspired understanding of a city from both perspectives.

There is still much work to be done to perfect the application of NEA to the urban metabolic evaluation. A fundamental constraint is that NEA is not yet friendly for time series analysis at this stage.[64] What we can do is to catch snapshots of the metabolic system (e.g., yearly assessment). Hence, it is difficult to follow the metabolic dynamics and the underlying mechanism at system or sector level. The availability and accuracy of data have posed a common challenge for all metabolism studies and particularly with NEA due to its need for huge quantities of data. Frequently, such information is scattered and needs to be synthesized.[65] When metabolic data sets for major cities around the globe have been established, it will be possible to explicitly evaluate the functioning of an urban metabolic system based on the material/energy balance network. However, until then, the comparisons of the metabolic behavior of cities worldwide will remain impossible. Despite all these limitations, this study serves as an elicitation of system-oriented mechanistic modeling for urban metabolic systems, advancing the metaphor of metabolism to a methodology both theoretically deep and sufficiently sound for decision making on sustainable urban design.

■ ASSOCIATED CONTENT

Supporting Information

A brief introduction to NEA, more system/data description, and calculation details regarding carbon metabolism. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*Phone: +86−10−58807368. Fax: +86−10−58807368. E-mail: chenb@bnu.edu.cn.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the Key Program of National Natural Science Foundation (No. 50939001), Program for New Century Excellent Talents in University (NCET-09-0226), and the National High Technology Research and Development Program of China (No. 2009AA06A419).

REFERENCES

(1) Wolman, A. The metabolism of cities. *Sci. Am.* **1965**, *213*, 179−190.

(2) Kennedy, C.; Cuddihy, J.; Engel-Yan, J. The changing metabolism of cities. *J. Ind. Ecol.* **2007**, *11* (2), 43−59.

(3) Baccini, P.; Brunner, P. H. *Metabolism of the Anthroposphere*; Springer−Verlag: Berlin, 1991.

(4) Ayres, R. U.; Kneese, A. V. Production, consumption and externalities. *Am. Econ. Rev.* **1969**, *59* (3), 282−297.

(5) Bolin, B. The carbon cycle. *Sci. Am.* **1970**, *223* (3), 47−56.

(6) Kneese, A. V.; Ayres, R. U.; Arge, R. C. D. Economics and the environment: A materials balance approach. In *The Economics of Pollution*; Wolozin, H., Eds.; General Learning Press: Morristown, NJ, 1974.

(7) O'Meara, M. *Reinventing Cities for People and the Planet*; Worldwatch: WA, 1999; Vol. *147*.

(8) Churkina, G. Modeling the carbon cycle of urban systems. *Ecol. Model.* **2008**, *216*, 107−113.

(9) Fischer-Kowalski, M. Society's Metabolism: the intellectual history of materials flow analysis, Part I, I 860− I 970. *J. Ind. Ecol.* **1998**, *2*, 61−78.

(10) Warren-Rhodes, K.; Koenig, A. Escalating trends in the urban metabolism of Hong Kong: 1971−1997. *R. Swed. Acad. Sci.* **2001**, *30*, 429−438.

(11) Decker, E. H. Energy and material flow through the urban ecosystem. *Annu. Rev. Energy Environ.* **2000**, *25*, 685−740.

(12) Haberl, H. The energetic metabolism of societies Part II: empirical examples. *J. Ind. Ecol.* **2002**, *5* (2), 71−88.

(13) Haberl, H. The global socioeconomic energetic metabolism as a sustainability problem. *Energy* **2006**, *31*, 87−99.

(14) Kennedy, C.; Steinberger, J.; Gasson, B.; et al. Greenhouse gas emissions from global cities. *Environ. Sci. Technol.* **2009**, *43*, 7297−7302.

(15) Kennedy, C.; Pincetl, S.; Bunje, P. The study of urban metabolism and its applications to urban planning and design. *Environ. Pollut.* **2011**, *159* (8−9), 1965−1973.

(16) Huang, S. L. Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. *J. Environ. Manage.* **1998**, *52*, 39−51.

(17) Huang, S. L.; Chen, C. W. Theory of urban energetics and mechanisms of urban development. *Ecol. Model.* **2005**, *189*, 49−71.

(18) Jiang, M. M.; Chen, B. Integrated urban ecosystem evaluation and modeling based on embodied cosmic exergy. *Ecol. Model.* **2011**, *222*, 2149−2165.

(19) Zhang, B.; Chen, G. Q. Physical sustainability assessment for the China society: Exergy−based systems account for resources use and environmental emissions. *Renewable Sustainable Energy Rev.* **2010**, *16* (4), 1527−1545.

(20) Giampietro, M.; Mayumi, K.; Ramos-Martin, J. Multi−scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. *Energy* **2009**, *34*, 313−322.

(21) Ramos-Martina, J.; Giampietro, M.; Mayumic, K. On China's exosomatic energy metabolism: An application of multi−scale integrated analysis of societal metabolism (MSIASM). *Ecol. Econ.* **2007**, *63*, 174−191.

(22) Pouyat, R.; Groffman, P.; Yesilonis, I.; et al. Soil carbon pools and fluxes in urban ecosystems. *Environ. Pollut.* **2002**, *116*, S107−S118.

(23) Pataki, D. E.; Tyler, B. J.; Peterson, R. E.; et al. Can carbon dioxide be used as a tracer of urban atmospheric transport? *J. Geophys. Res.* **2005**, *110*, D15102.

(24) Turnbull, J. C.; Miller, J. B.; Lehman, S. J.; Tans, P. P.; Sparks, R. J.; Southon, J. R. Comparison of 14CO2, CO and SF6 as tracers for determination of recently added fossil fuel CO2 in the atmosphere and implications for biological CO2 exchange. *Geophys. Res. Lett.* **2006**, *33*, L01817.

(25) Levin, I.; Karstens, U. Inferring high−resolution fossil fuel CO2 records at continental sites from combined 14CO2 and CO observations. *Tellus* **2007**, *59B*, 245−250.

(26) Levin, I.; Karstens, U. Quantifying fossil fuel CO2 over Europe. In *Observing the Continental Scale Greenhouse Gas Balance of Europe*; Dolman, A. J., Freibauer, A., Valentini, R., Eds.; Springer−Verlag: Heidelberg, 2007.

(27) Pickett, S. T. A.; Cadenasso, M. L.; Grove, J. M.; et al. Urban ecological systems: linking terrestrial ecological, physical, and socio-economic components of metropolitan areas. *Annu. Rev. Ecol. Syst.* **2001**, *32*, 127−157.

(28) Pataki, D. E.; Alig, R. J.; Fung, A. S.; Golubiewski, N. E.; et al. Urban ecosystems and the North American carbon cycle. *Glob. Change Biol.* **2006**, *12*, 1−11.

(29) Kennedy, C.; Steinberger, J.; Gasson, B.; et al. Methodology for inventorying greenhouse gas emissions from global cities. *Energy Policy* **2010**, *38*, 4828−4837.

(30) Ramaswami, A.; Hillman, T.; Janson, B.; Reiner, M.; Thomas, G. A demand−centered, hybrid life cycle methodology for city−scale greenhouse gas emissions. *Environ. Sci. Technol.* **2008**, *42*, 6455−6461.

(31) Kaufman, S.; Krishnan, N.; Kwon, E. Examination of the fate of carbon in waste management systems through statistical entropy and Life Cycle Analysis. *Environ. Sci. Technol.* **2008**, *42*, 8558−8563.

(32) Sahely, H. R.; Dudding, S.; Kennedy, C. A. Estimating the urban metabolism of Canadian cities: Great Toronto area case study. *Can. J. Civ. Eng.* **2003**, *30*, 468−483.

(33) Chen, S. Q.; Fath, B. D.; Chen, B. Information−based Network Environ Analysis: A system perspective for ecological risk assessment. *Ecol. Indic.* **2011**, *11*, 1664−1672.

(34) Schramski, J. R.; Gattie, D. K.; Patten, B. C.; Borrett, S. R.; Fath, B. D.; Thomas, C. R.; Whipple, S. J. Indirect effects and distributed control in ecosystems; distributed control in the environ networks of a seven−compartment model of nitrogen flow in the Neuse River estuary, USA−Steady−state analysis. *Ecol. Model.* **2006**, *194*, 189−201.

(35) Fath, B. D.; Patten, B. C. Review of the foundations of network environ analysis. *Ecosystems* **1999**, *2*, 167−179.

(36) Fath, B. D.; Borrett, S. R. A MATLAB function for Network Environ Analysis. *Environ. Model. Softw.* **2006**, *21* (3), 375−405.

(37) Kazanci, C. EcoNet, a new software for ecological model simulation and network analysis. *Ecol. Modell.* **2007**, *208* (1), 3−8.

(38) Schramski, J. R.; Kazanci, C.; Tollner, E. W. Network environ theory, simulation, and EcoNet 2.0. *Environ. Modell. Softw.* **2011**, *26*, 419−428.

(39) Zhang, Y.; Yang, Z. F.; Fath, B. D. Ecological network analysis of an urban water metabolic system: Model development, and a case study for Beijing. *Sci. Total Environ.* **2010**, *408*, 4702−4711.

(40) Zhang, Y.; Yang, Z. F.; Fath, B. D.; Li, S. S. Ecological network analysis of an urban energy metabolic system: Model development, and a case study of four Chinese cities. *Ecol. Model.* **2010**, *221*, 1865−1879.

(41) Liu, G. Y.; Yang, Z. F.; Chen, B.; Zhang, Y. Ecological network determination of sectoral linkages, utility relations and structural

characteristics on urban ecological economic system. *Ecol. Model.* **2011**, *222*, 2825−2834.
(42) Chen, S. Q.; Fath, B. D.; Chen, B. Information indices from ecological network analysis for urban metabolic system. *P. Environ. Sci.* **2010**, *2*, 720−724.
(43) Duvigneaud, P.; Denaeyer-De Smet, S. *L'ecosystéme urbain bruxellois.* [*The Brussels Urban Ecosystem.*] In *Productivité en Belgique*; Duvigneaud, P., Kestemont, P., Eds.; Traveaux de la Section Belge du Programme Biologique International, Edition Duculot: Brussels, Paris, 1977.
(44) Newcombe, K.; Kalina, J. D.; Aston, A. R. The metabolism of a city: The case of Hong Kong. *Ambio* **1978**, *7*, 3−15.
(45) Barles, S. Urban metabolism of Paris and its region. *J. Ind. Ecol.* **2009**, *13*, 898−913.
(46) Daxbeck, H.; Lampert, C.; Morf, L.; et al. *Der anthropognene Stoffhaushalt der Stadt Wien*; Pilot Project, Institute for Water Quality and Waste Management, Vienna University of Technology: Vienna, 1996.
(47) Obernosterer, R.; Brunner, P. H.; Daxbeck, H.; et al. *Material Accounting as a Tool for Decision Making in Environmental Policy—MAcTEmPo case study report—urban metabolism, the city of Vienna*; Institute for Water Quality and Waste Management, Technical University of Vienna: Vienna, 1998.
(48) Hendriks, C.; Obernosterer, R.; Muller, D.; Kytzia, S.; Baccini, P.; Brunner, P. H. Material flow analysis: a tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. *Loc. Environ.* **2000**, *5*, 311−328.
(49) Tjallingii, S. P. *Ecopolis: Strategies for Ecologically Sound Urban Development*; Backhuys Publishers: Leiden, 1993.
(50) Newman, P. W. G. Sustainability and cities: extending the metabolism model. *Landscape Urban Plan.* **1999**, *44*, 219−226.
(51) Odum, H. T. *Environmental accounting: emergy and environmental decision making*; John Wiley & Sons: New York, 1996.
(52) Fath, B. D. Network mutualism: positive community−level relations in ecosystems. *Ecol. Model.* **2007**, *208* (1), 56−67.
(53) Fath, B. D. Distributed control in ecological networks. *Ecol. Model.* **2004**, *179*, 235−246.
(54) Patten, B. C. Network perspectives on ecological indicators and actuators: enfolding, observability, and controllability. *Ecol. Indic.* **2006**, *6* (1), 6−23.
(55) Patten, B. C. Energy environments in ecosystems. In *Energy Use Management Vol. 4*; Fazzolare, R. A., Smith, C. B., Eds.; Pergamon Press: New York, 1978.
(56) Patten, B. C.; Auble, G. T. System theory of the ecological niche. *Am. Nat.* **1981**, *117*, 893−922.
(57) Schramski, J. R.; Gattie, D. K.; Patten, B. C.; Borrett, S. R.; Fath, B. D.; Whipple, S. J. Indirect effects and distributed control in ecosystems; distributed control in the environ networks of a seven−compartment model of nitrogen flow in the Neuse River estuary USA−Time series analysis. *Ecol. Model.* **2007**, *206*, 18−30.
(58) Salas, A. K.; Borrett, S. R. Evidence for the dominance of indirect effects in 50 trophic ecosystem networks. *Ecol. Model.* **2011**, *222*, 1192−1204.
(59) Gattie, D. K.; Tollner, E. W.; Foutz, T. L. Network environ analysis: a mathematical basis for describing indirect effects in ecosystems. *Trans. ASAE* **2005**, *48*, 1645−1652.
(60) Finn, J. T. Cycling index: a general measure of cycling in compartmental models. In *Environmental Chemistry and Cycling Processes Symposium*; Adriano, D. C., Brisbin, I. L., Eds.; U.S. Energy Research and Development Administration: Washington, DC, 1978; pp 138−164.
(61) Fath, B. D.; Patten, B. C. Network synergism: emergence of positive relations in ecological systems. *Ecol. Model.* **1998**, *107*, 127−143.
(62) Chen, B.; Chen, G. Q. Emergy−based energy and material metabolism of the Yellow River basin. *Commun. Nonlinear Sci. Numer. Simul.* **2009**, *14*, 923−934.
(63) Cussó, X.; Garrabou, R.; Tello, E. Social metabolism in an agrarian region of Catalonia (Spain) in 1860−1870: Flows, energy balance and land use. *Ecol. Econ.* **2006**, *58*, 49−65.
(64) Gattie, D. K.; Schramskic, J. R.; Bata, S. A. Analysis of microdynamic environ flows in an ecological network. *Ecol. Model.* **2006**, *28*, 187−204.
(65) Elliot, S.; Decker, E. H.; Smith, F. A.; Blake, D. R.; Simpson, I. J.; Rowland, F. S. Cities in the earth system. *Environ. Sci. Technol.* **2000**, *3*, 157−160.