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Determining carbon metabolism in urban areas though network environ theory

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Abstract

Carbon fluxes scenario within urban areas plays an important role in the global carbon cycle, which is critical for the adjustment of urban development activities influencing our living environment. Adapting network environ theory, a generic metabolic model is developed in this study for carbon metabolism in urban areas, in which compartmental utility analysis and system performance assessment are featured. Taking carbon dynamic of Hong Kong as a case study, the metabolic flows within urban carbon balance are illustrated though two analogous input/output networks. Based on this, the compartmental mutual relationships between different urban sectors are addressed and the overall properties of the city's carbon metabolism are aggregately evaluated. Our findings showed that each metabolic component has its specific mutual relations with other components connected, playing a unique role within the ecological system. As to Hong Kong's case, specifically, the metabolic system is considered self-mutual and stable when incorporating its interactions with its supporting environment. In light of these insights, potential extensions and applications of the network-based metabolic model in future are discussed. The recommendation is that the tracking of interactive relationships and pathways from network environ perspective be incorporated into present urban metabolism study for a more comprehensive sustainable urban design.

Keywords: Urban metabolism; Carbon balance; Network environ analysis; Sustainable urban design

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1. Introduction

Scientists have been able to treat cities as metabolic organisms since Wolman [1] coined the concept of urban metabolism in the face of urbanization and the ensuring environmental problems within American cities. However, similar as it is as to the breathing in and out of materials/energy through diverse endosomatic and exosomatic activities (see a definition in [2]), it should be somewhat an unusual idea to

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consider a city as a so-called superorganism if the situation is fully compared and reflected. There are, at least, two arguments against the introduction of “metabolism” into current urban studies. First, suppose we can address the problems coming with urban expansion based on economic and ecological knowledge, why to turn to an obscure concept within life science scope in the first place? Further, in terms of biotic metabolism, the fluctuation of each element has a unique influence on the whole functioning body, would it also applies to an urban ecosystem in which way we can call these elements metabolic components? For these and others reasons, the concept “urban metabolism” had once been niggardly used by urbanists and ecologists in material cycle and energy balance evaluation of metropolitan areas. The transfer of attitude is a recent matter that the metabolism of cities returned to the public sight due to its potential in comprehending carbon balance explicitly in 1990s [3]. In fact, carbon metabolism is emerging as a new focus in metabolism studies due to its close relation to carbon emissions. The carbon dioxide emissions in urban and metropolitan areas contribute more than 80% of the global emission volume [4, 5]. The tracking of carbon fluxes and pathways within the metabolic processes of a city will facilitate the control of anthropogenic carbon fluxes and the adjustment of responsible sectors of cities. In this sense, it is critical to adapt metabolism-framed methodology to the current understanding of carbon balance.

Methodologies designed for urban metabolism studies traditionally encompassed the analysis of life-cycle ecological and economic input/output, i.e., material flow analysis [6, 7]. A recent metabolism-based inventorying of carbon flows is based on urban energy use [3, 8], which is not a direct measurement but a computation the relations with energy consumption, material flows and wastes discharge [8, 9]. These reveal some possibilities of applying the concept of metabolism to pragmatic urban evaluation. Nonetheless, still little information is available as to the intrinsic interactions and structure of urban carbon system beyond the city’s metabolic inputs and outputs. Furthermore, the current extent of metabolism evaluation has been neglected the indirect effect through carbon fluxes which is considerable through the extension of flow pathways [10-12].

Alternatively, the present study tries to adopt a system-oriented technique called network environ analysis (NEA) to identify and evaluate the carbon dynamic within the metabolism framework. NEA has received a wide concern due to its usefulness in revealing inner relationships and properties of ecological systems underneath their complex dynamic processes [13, 14]. In fact, there are some applications of NEA with regard to urban metabolism evaluation of energy and water fluxes [15-18]. However, there have been no attempts to address the carbon metabolic scenario in urban areas from the network environ point of view so far, and there still are challenges such as knowledge integration and interpretation in pursuit of an explicit apprehension of urban metabolic structure and functioning. Hong Kong was taken as a case study to demonstrate present urban metabolism model, the metabolism-related dataset of which was investigated primarily (refer to [19, 20]). Based on Hong Kong’s case, this study presents an NEA-based model for determining carbon metabolism in urban areas, and thus provides a novel insight when incorporating metabolism evaluation into consideration of sustainable urban design

2. Network Environ Model for Carbon Metabolism

2.1. Metabolic systems as networks

It is no surprise to treat cities as energy/resources-intensive interactive ecosystems where the regulations of social, economic and ecological activities parallel the rules in nature [21]. This can be understood by the carbon metabolic behaviors of an open urban system can be parsed into: Outside the local environment, city consumes resources and energy from its surroundings and excrete wastes in the opposite direction; adjacent to the boundary [22]; material exchanges occur such as raw materials, goods, tourist, etc.; while inside the built environment, the carbon fluxes are multi-direction influenced by land use pattern and human activities [23]. Through these deliberations, we develop a network environ model for the carbon balance within an urban ecosystem. As shown in Fig.2, core constitutions of the network compose eight distinctive components including Energy production, Water and soil stock, Construction, Agriculture, Industry (product manufactory), trade and service and domestic sector. Incorporating local environment and external domain into the situation, a complete network of carbon dynamic is pictured. Specific carbon flows between these components are all identified and characterized according to the investigated carbon dynamic within urban areas.

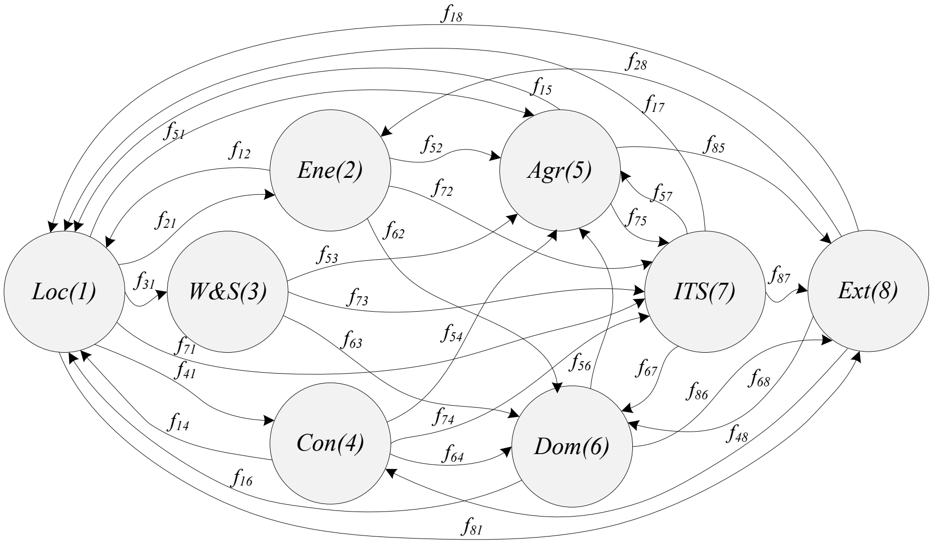


Fig. 1. Carbon metabolic network model for carbon metabolism in urban areas. *Notes:* Loc: Local environment; Ene: energy production sector; W&S: Water and soil stock; Con: Construction sector; Agr: Agriculture sector; ITS: Industry (product manufactory), trade and service sector; Dom: Domestic sector; Ext: External domain. Detected fluxes between diverse sectors are signified as fij, for example, f12 represents a carbon metabolic flow from Ene (component 2) to Loc (component 1).

2.2. Network utility analysis

Network utility [24] is one of the core concepts of network environ theory that is recently used to assess various types of mutual relationship between different sectors of the urban metabolic system [15, 16]. The combination of ovonic (two-way) relations of two connected components through their environs determines the interactive nature of them. In network utility analysis, net direct and indirect interactions between system components represent their direct and indirect mutualism, respectively. Direct mutualism indicates the direct interaction between different functional components, while indirect mutualism defines the integral relations that encompassing cumulative effect caused by extending flow pathways. Direct mutualism is presented by direct utility matrix $D = (d_{ij})$, and the dimensionless integral utility intensity matrix is designated as $U = (u_{ij})$, within which inter-compartmental flow utilities are given by [13, 14]:

$$d_{ij} = (f_{ij} - f_{ji})/T_i \qquad (1)$$

$$U = D^0 + D^1 + D^2 + \cdots + D^m + \cdots = (I - D)^{-1} \qquad (2)$$

where T_i is the sum of flows into or out of the *i*-th compartment.

Positive/negative signs of mutualism index are used to identify different relationship natures between different metabolic components [25]. On the system level, synergism index and mutualism index are also adapted for the current metabolism analysis to determine the fitness of the whole metabolic system [14]. Mutualism index (MI) indicates the proportions of positive and negative signs (signified as $sigU(+)$ and $sigU(-)$, respectively) in utility intensity matrix, while synergism index (SI) quantifies the magnitude of the positive and negative utilities.

$$MI = sigU(+)/sigU(-) \qquad (3)$$

$$SI = \sum_{j=1}^{n} \sum_{i=1}^{n} u_{ij} \qquad (4)$$

2.3. Metabolic system performance

The overall performance of urban metabolic scenario towards sustainable urban development is addressed through a set of network-based indicators (Table 1). Some of them have already been explained in the utility analysis above, while others are extracted from existing NEA synthesis. Each indicator suggests a facet of metabolism trait within the urban metabolic system. The basic indication and metabolism implication of these indicators are also provided for exploring overall situation of the metabolic system. For a comprehensive evaluation, core network and complete network are used as two different scales within the carbon metabolic system.

Table 1 System-wide indicators of NEA for urban metabolism evaluation [14, 26, 27, 28].

Indicator	Expression	Generic indication	Metabolism implication
Link Density	L/n	Network linkage density	Metabolic linkage
Connectance	L/n^2	Network connection	Metabolic connectivity
TST (Total system throughput)	$\sum_{j=1}^{n}\sum_{i=1}^{n} f_{ij}$	The size or growth of the system	Metabolic expansion
Finn's Cycling Index	TST_c/TST	The cycling proportion composing a system	Cycling effect of metabolism
Synergism Index	Eq.(4)	System synergism magnitude	Metabolic system synergism
Mutualism Index	Eq.(3)	System mutualism degree	Metabolic system mutualism

3. Model Demonstration: A Case Study of Hong Kong

3.1. Carbon metabolic network

The metabolic network of carbon flows within the metabolic network in Hong Kong is shown in Table 2. The components listed in row and in column indicate the carbon donor and recipient, respectively. The current analytical system encompasses both the anthropogenic carbon outflow to the environment and the natural carbon matter flowing into the urban areas. The results show that the carbon balance of Hong Kong is dominated by energy sector and construction sector, while the contribution of water&soil is relatively smal. Energy production sector (Ene), Construction sector (Con), and Water and soil stock (W&S) are three major carbon donors which transfer raw material, fossil fuels, machinery, etc. to Agriculture sector (Agr), Industry, trade and service sector (ITS), and Domestic sector, supporting economic development and livelihood improvement of the latter sectors where people reside. And the ultimate suppliers of carbon nutrient go to the local environment within the urban region (Loc) and the external domain the city metabolism-related (Ext). The total input/out flow of carbon from/into the urban areas of Hong Kong amounts to 2679 kg capita^{-1} year^{-1}. With regard to the carbon exchange with the environment, the biggest output carbon flows are the emissions by ITS (1518 kg capita^{-1} year^{-1}) and Dom (991 kg capita^{-1} year^{-1}), while Ene (1600 kg capita^{-1} year^{-1}) and Con (751 kg capita^{-1} year^{-1}) are two main sources of supplying carbon nutrient from environment.

Table 2 The metabolic network of carbon balance in Hong Kong (kg capita^{-1} year^{-1})

	Loc	Ene	W&S	Con	Agr	Dom	ITS	Ext
Loc	0	0	0	0	160	629	1145	63
Ene	1010	0	0	0	0	0	0	420
W&S	21	0	0	0	0	0	0	5
Con	570	0	0	0	0	0	0	261
Agr	137	70	6	35	0	0	24	0
Dom	23	420	6	156	104	0	105	0
ITS	0	940	14	640	0	0	0	0
Ext	236	0	0	0	8	185	320	0

3.2. Network utility situation

The mutual relationships between different components within carbon metabolic system of Hong Kong are determined based on network utility analysis, via which the direct relations are shown in direct utility matrix (D) (Table 3), while the integral interactions are presented in integral utility matrix (U) (Table 4). In addition, direct utility sign matrix and integral utility sign matrix of the system are developed on basis of the positive/negative/zero signs of matrix D and U (shown in blue/red/gray, respectively). The combination of a pair of ovonic signs determines the nature of the inter-relations between the carbon metabolic components. To be brief, (+) stands for gain, (−) for loss and (0) for neutrality (basic implications of the possible combinations can be referred to [25]).

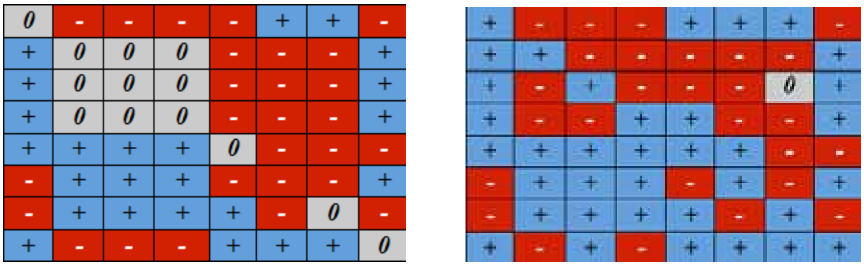
What can be concluded from utility analysis is that positive/negative/zero signs in integral utility matrix vary from those in direct utility matrix occasionally, suggesting that not only the quantities but also the qualities of relations can actually differ from direct ones. It turns out that the indirect effect beneath carbon dynamic play a significant role in the carbon metabolic system and in which circumstance cannot be neglected. Ene, W&S and Con sector have exploitation relationships with local environment, basically perform as the combination as (+,-), while Agr, Dom and ITS sectors are exploited directly by local and external environment (with the combination of (+,-)) but moving towards the mutualistic direction when accounting their indirect effects. An important implication of network mutualism for urban development management is that when tracking the carbon fluxes through a specific sector within holistic carbon balance, other seemingly unrelated components or processes should also be taken into account for their possible influences on the final outcome, and network utility analysis provides both systemic perspective and methodology to achieve so.

Table 3 Direct utility matrix (D) of carbon metabolism in Hong Kong

	Loc	Ene	W&S	Con	Agr	Dom	ITS	Ext
Loc	0	-0.52	-0.01	-0.29	-0.01	0.62	0.27	-0.07
Ene	0.76	0	0	0	-0.09	-0.56	-0.35	0.24
W&S	0.70	0	0	0	-0.10	-0.83	-0.07	0.30
Con	0.89	0	0	0	-0.07	-0.72	-0.21	0.11
Agr	0.03	0.41	0.01	0.14	0	0.07	-0.53	-0.12
Dom	-0.93	0.57	0.02	0.35	-0.02	0	-0.01	0.03
ITS	-0.64	0.57	0.00	0.16	0.20	0.02	0	-0.30
Ext	0.27	-0.59	-0.01	-0.13	0.07	-0.08	0.47	0

Table 4 Integral utility matrix (U) of carbon metabolism in Hong Kong

	Loc	Ene	W&S	Con	Agr	Dom	ITS	Ext
Loc	0.96	-0.08	-0.00	-0.05	0.00	0.13	0.06	-0.02
Ene	0.19	0.97	-0.00	-0.02	-0.02	-0.10	-0.07	0.05
W&S	0.00	-0.00	1.00	-0.00	-0.00	-0.00	0	0.00
Con	0.14	-0.02	-0.00	0.99	-0.01	-0.09	-0.02	0.01
Agr	0.01	0.02	0.00	0.01	1.00	0.00	-0.03	-0.00
Dom	-0.10	0.08	0.00	0.05	-0.00	0.97	-0.01	0.01
ITS	-0.04	0.06	0.00	0.02	0.02	-0.01	0.99	-0.02
Ext	0.01	-0.03	0.00	-0.01	0.01	0.00	0.03	1.00



0	-	-	-	-	+	+	-
+	0	0	0	-	-	-	+
+	0	0	0	-	-	-	+
+	0	0	0	-	-	-	+
+	+	+	+	0	-	-	-
-	+	+	+	-	-	-	+
-	+	+	+	+	-	0	-
+	-	-	-	+	+	+	0

(a)

+	-	-	-	+	+	+	-
+	+	-	-	-	-	-	+
+	-	+	-	-	-	0	+
+	-	-	+	+	-	-	+
+	+	+	+	+	+	-	-
-	+	+	+	-	+	-	+
-	+	+	+	+	-	+	-
+	-	+	-	+	+	+	+

(b)

Figure 2 Direct utility sign matrix (a) and integral utility sign matrix (b) for carbon metabolism in Hong Kong

3.3. System-wide performance

Based on the utility analysis results as well as basic inspections of the established networks, the system-wide properties of carbon metabolism in Hong Kong are evaluated via the established indicator system (Table 5). In terms of carbon TST, the complete network is larger than core network with the incorporation of local environment and external domain and has more direct and indirect linkages within the metabolic system. The components of complete network are also more metabolically connective and intensive as shown by their higher Link Density and Connectance, which resulting in more diverse cycling routes (revealed by Finn's Cycling Index). Another difference is that the complete regime has the higher synergism/mutualism. Evidently, the carbon metabolic system of Hong Kong is overall self-mutual and resilient towards possible disturbances, of course, by incorporating the environment within urban footprint. It is significant that these aspects inside carbon metabolic situation are unveiled for holistic carbon balance identification.

Table 5 System-wide properties for carbon metabolism in Hong Kong

Indicator	Complete network	Core network
Nodes	8	6
Links	29	12
Link Density	3.62	2.00
Connectance	0.45	0.33
TST	8278	5300
Finn's Cycling Index	1.00	0
Synergism Index (SI)	8.54	2.16
Mutualism Index (MI)	1.13	0.79

4. Future Prospects

Besides the sole magnitudes of material flows, it has been commonly realized in recent years that understanding accumulation processes within the urban metabolism framework is also crucial for sustainable urban design [2, 29]. For many global cities, carbon cycle dataset for metabolism studies have been established, thus the time is ripe for the modeling of urban metabolic system based on sophisticated nutrient dynamic details. Among the accessible models, network environ analysis is capable of advancing empirical investigation towards a theoretically deeper and more exhaustive understanding via the unveiling of network interactions, which would be useful in this context.

The truth is that the metabolism of biotic systems as a whole (e.g., human body) still remains a luggage of puzzle concerning the intricate effecting processes, now as ever before, and so is for urban ecosystems. This study serves as one of the endeavors that take the apprehension of interactive relationships and properties that characterize the overall metabolism of urban ecosystems on step further and possibly the control of them, although more studies on model perfection and time series analysis are needed in the future.

5. Conclusions

Presented in this study is a NEA-based model for urban metabolism based on network utility analysis and system-wide indicators. On basis of a reinspection into the case of Hong Kong concerning carbon dynamic, the established methods are interpreted for their applications to current urban ecosystem management of carbon balance. Within carbon metabolic network, the mutual relationships between different urban sectors are determined and the overall properties of the carbon metabolic system are aggregately evaluated. Our findings indicate each metabolic component has its unique mutualism or control relations with other components, analogous as natural ecosystems. For Hong Kong, specifically, the metabolic system is considered self-mutual and stable when incorporating the interactions with its supporting environment. It is concluded that NEA is capable of a more exhaustive understanding through the unveiling of indirect interactions, thus advancing empirical investigation towards a theoretically deeper stage.

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