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Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales

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ABSTRACT

The UK has one of the world's most urbanised societies where nearly 83% of the total population lives in cities. The continuing population growth could lead to increases in environmental pollutions and congestion within cities. The framework of urban metabolism uses an analogy between cities and ecosystems to study the metabolic processes within complex urban systems akin to natural biological systems. It remains as a challenge to fully understand the complicated distribution of resource flows within an urban network. In this paper, Ecological Network Analysis was applied to study the intra-city flows between economic sectors in 35 functional urban areas in order to investigate their respective metabolic relationships. The intra-city flows network of each area was also supplemented with the geographical distance between the workplace zones to study the impacts of spatial distribution on the density of resource flows. The metabolic systems were dominated by 64% of exploitative relationships with an average mutualism index of 0.93 and synergism index of 3.56 across all 35 areas. The consumption-control and production-dependency relationships revealed the hierarchical orders among the sectors resembling the pyramidal structure of an urban ecosystem. Network community classification emphasized the importance of inter-relationship within the organisation of each community class. The producer-type and consumer-type communities showed the tendencies of those sectors to cluster based on their respective hierarchical roles in the ecosystem. This work provides an insight into the wide range of intra-city ecological metabolic characteristics which can potentially expand to a multi-scale assessment of urban metabolism across the country.

1. Introduction

Urban population which made up to 55% of total population worldwide in 2016 is undergoing fastest growth in history, from 34% in 1960 and is projected to increase to 66% by 2050 (Department of Economic and Social Affairs (DESA, 2016). The UK has one of the world's most urbanised societies where nearly 83% of the total population lives in cities (World Bank, 2014). The continuing trend of rapid urbanisation presents a challenge for national and local governments to maintain the economic growth and standards of living in cities while ensuring the rates of resource consumption return to being within planetary limits.

The concept of urban metabolism by Wolman (Wolman, 1965) proposes an analogy between cities and ecosystems to study the metabolic processes within complex urban systems akin to a natural biological system using a hypothetical model. Since Wolman's pioneering study, research efforts have been invested to explore and expand the conceptual model by applying real data from various cities (Huang and Chen, 2009; Huang and Hsu, 2003; Newcombe et al., 2017; Warren-Rhodes and Koenig, 2001; Zucchetto, 1975). Despite the wide range of analytical frameworks developed to account for various types of material flows entering and leaving the cities (Cencic and Rechberger, 2008; Hunt et al., 2014; Page et al., 2008), it remains a challenge to fully understand the complicated distribution of resource flows within the urban network. Material flow analysis applies mass balance to quantify in- and out-flows of resources and evaluate the remaining stocks in cities. This accounting technique is useful in tracking circulations of material and to optimise disposal of waste generated from urban activities through recycling. However, it does not address the spatial distribution and resource flows within the internal

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organisation of a complex urban ecosystem (Ravalde and Keirstead, 2015). For energy flow analysis, emergy approach is proposed based on the concept of *embodied energy* in the flows of certain materials, which was developed by Odum (Odum, 1976, 1996) in his theory on the functioning of ecological system. In theory, the emergy approach addresses and rectifies the problem of incomparable flows between different subsystems and improves consistency for the losses and efficiencies of different transformations taking place within the system. The concern for such approach lies on the use of an appropriate measurement in converting the units of energy and must be determined for all flows to ensure a unified standard.

From the perspective of ecological networks (Bai, 2016; Huang, 1998; Newman, 1999), urban ecosystem is governed by the complex interactions among its components which lead to a unique mechanism in the shaping of ecological structure and social communities of a city. The Ecological Network Analysis (ENA) approach dissects the problems of urban ecosystem at each hierarchical level of the system based on its respective functioning roles and the rates of resource consumption. The concept of ENA was formed by connecting the smaller individual entities in the system as an ecological network to understand the existing direct and indirect linkages among the components, sharing a similar concept with a natural ecosystem. The work of ENA integrated with Input-Output techniques from Leontief's model to study the structural distribution of different components in an ecosystem (Hannon, 1973; Leontief, 1986), hence its impact on the interrelations between different trophic levels based on the hierarchical structure of an ecological pyramid. ENA was further improved and refined by incorporating with flow analysis (to address the total system throughflow, average path-length and cycling index) and hence, the concept of "environ" was generated to study the behaviours of an ecological network with the pre-determined input and output flows at each component (Fath and Killian, 2007; Finn, 1976; Patten, 1982). From ENA, the energy and material flows through an ecosystem were simulated to investigate the structural distributions and functionality of the system (Jørgensen, 2000; Szyrmer and Ulanowicz, 1987). ENA provides an analytical tool for various applications to study metabolism in cities from different perspectives i.e. ecological hierarchy relationship, spatial variation, energy flows in previous scholarly researches (Chen and Chen, 2015; Fan et al., 2017; Fath and Borrett, 2006; Fath et al., 2010; Zhang et al., 2010, 2016). The technique of ENA is not limited to intra-system flows scaled on a single level such as city, region or country but also applied to study interregional energy flows between connected cities at combined levels, as demonstrated in the case study of Beijing-Tianjin-Hebei in China (Zheng et al., 2018).

To understand the requirements on resource management and examine the metabolic characteristics of an urban system, application of ENA on 35 functional urban areas in England and Wales was implemented in this study. ENA linked the socio-economic sectors in the urban area in an inter-connected network and investigated the pairwise metabolic relationships through the intra-city monetary transactions, reflecting the dependencies of the urban ecological network in terms of its resources flows and consumptions. The study was further extended with the estimated geographical distance between the sectors from the respective workplace zones classifications to address the spatial impact of urban network. For city planning and policymaking, this work demonstrates a better understanding of different resource demands and circulations within the local flow network, enabling the regulation of the needs and wastes of each sector in the city. Strategic resource management should improve the efficiency of the urban metabolism and lead to long-term benefits for the society.

The goals of this paper are twofold, firstly, it presents a novel attempt to conduct an in-depth inspection of intra-city metabolism across all urban areas in England and Wales at an aggregated level, highlighting the ecological interactions between the components of the urban ecosystem as a whole. Secondly, this paper addresses the spatial characteristics of urban network community structure and discusses the impact on community classification based on flow densities.

The rest of the paper is organised as follows. The next section in this paper explains the methodology adopted in the process of data sourcing and preparation, followed by the ecological methodologies and the functional analysis implemented in this work. Furthermore, the result of metabolic relationships and network community structures are also included. The final section concludes the study with the potential implications and future investigations on intra-city metabolism.

2. Methodology

2.1. Data preparation

The UK National Input-Output Supply and Use Table 2011 published by Official National Statistics (Office for National Statistics (ONS, 2017a) was used in this study. In order to examine the flow at a local scale, the data for Gross Value Added (GVA) 2011 (Office for National Statistics (ONS, 2017b) of different sectors for each functional urban area were used to scale down the national flow data accordingly, assuming the same ratio for local production and consumption of goods and services compared to the national figures. This could result in erroneous estimations of import and export since international cross-boundary flow does not scale with the local GVA. The resultant format of the input-output data for all industrial sectors must comply with Leontief's model (Leontief, 1986). The input-output monetary flows within the city were tabulated in the form of a balanced square matrix. This was then used as the adjacency matrix was to construct the resource flow network. In this paper, 35 case studies were identified based on the boundary of functional urban areas in England and Wales. Table 1 shows the abbreviation and name for all 35 functional urban areas, in a decreasing order of their total population. The urban audit boundary was set to define the scope of the study for 35 functional urban areas in England and Wales, which includes the core central city of each area and its commuting zones (Eurostat, 2017). In this case, the wider functional urban areas might consist of multiple local authorities (the lowest administrative level of local governing councils) as data collecting units. The resultant data of urban population and GVA of the urban areas were obtained by combining all the local authorities within the respective boundaries.

The sectors in the National Input-Output Supply and Use Table at intermediate product level were categorised according to UK Standard Industrial Classification of Economic Activities (SIC2007) (Office for National Statistics (ONS, 2017d) to allocate the 105 sectors to 11 categories of the GVA data provided by the local authorities based on the types of economic activity, as shown in Table 2. This was to reduce the resolution of economic activities in order to obtain the input-output flow data at urban level through GVA scaling. See Supplementary Tables S1 and S2 for the national input-output data of 105 and 11 sectors respectively. See Supplementary Table S3 for local intra-city input-output table for 35 urban areas, scaled to local GVA.

Workplace zones classification data based on the workforce populations (Cockings et al., 2015) were applied to investigate the spatial distribution of the local community structure and its impact on resource consumption. Sector allocations were carried out based on the employment data documented by ONS (2012) in each workplace zone and two sectors with the two highest workforce populations were selected. There were two exceptional cases of special condition in this part: first, if the employment number for multiple sectors are similar, the zone is allocated under multiple sectors simultaneously; second, if one sector only exists in a particular workplace zone, it is selected regardless of its population in that area. Geographic Information System (GIS) was used to measure the spatial distance between the sectors within the urban areas and to study the relationship between the spatial connection among the sectors and their monetary flows. The "spatial join" function combined the workplace zones with each urban audit function area of the 35 cases (Office for National Statistics (ONS, 2017c) inspected in