Improving urban metabolism study for sustainable urban transformation

Huang Wei, Cui Shenghui, Masaru Yarime, Seiji Hashimoto, Shunsuke Managi

Abstract

It is important understanding urbanization where residents outside of the area come into the urbanized region. Urbanized area is the one facing more environmental problems because of intensive population density amplifying more damage to the environment. This paper targets China’s rapid urbanization and discusses research and policy needs in the field of sustainable urbanization. We discuss research needs for metabolism studies for sustainability of cities, major driving forces in the context of urbanization, and knowledge integration through stakeholder engagement.

© 2015 Elsevier B.V. All rights reserved.
1. Introduction

Since the Club of Rome report that economic growth is limited by the exhaustion of resources, sustainable development has mainly been discussed in terms of the environment and resources. The previous debate on sustainable development has focused on developing countries, leading to problem awareness along with an assumption of a rapid population increase and resource use (Managi, 2015). However, serious sustainable development problems at the center of attention in major developed countries and many other countries that have entered a mature phase are associated with population decreases, declining birthrates, and aging populations.

This study represents a significant development from the previous research framework, in which sustainable development is formalized on the basis of country- and world-level relationships (see review of policy analysis at the country and regional level for Somanathan et al., 2014). Currently, it is also extremely important understanding urbanization where residents outside of the area come into the urbanized region, in the meantime there are areas facing much less population than before. Urbanized area is the one facing more environmental problems because of intensive population density amplifying more damage to the environment. Summation of these urbanized cities could be much bigger than impact of several countries. In the same time, high income people tend to stay in urban area who request clearer environment. In addition, more the people stayed in same region, larger the damage they receive such as disaster because of larger economic loss of one big event. These request the needs for environmental and sustainable study for urbanization.

This requires constructing a database and conducting an empirical study in urban level. In addition, the construction of sustainable development index (SDI) that considers not just developed countries but societies with stable or increasing populations and mature societies is going to be increasingly required in the future. Above all, research in the domain of a major region such as urbanized cities such as mega-city in the context of sustainable development is extremely crucial. We are facing the fact that cities are becoming major targets of metabolism study as global impacts of cities have continued to grow.

China, as one of the countries experiencing the speediest urbanization, is becoming a hot spot for urbanization research throughout the world (Normile, 2008). China has the largest population in the world, and it has become the second biggest economy just after the US. For such a populous, economic and political giant, urbanization has made remarkable changes over the past few decades. An annual average growth rate of about 1% in urbanization has been recorded ever since 1980s, which means more than 10 million people migrated to urban areas each year. Social, economic and ecological implications accompanying this rapid shift are dramatic. For example, China is transforming from an agrarian society into a large urban society (Normile, 2008); it has become world top emitter of CO2 since 2007 (Guan et al., 2009); only three out of 74 major cities met the national air quality standard in 2013 (Xinhua, 2014), and more than 60% of Chinese cities are short of fresh water supply. Liu (2010); lifestyle change, ecological degradation and biodiversity loss have led to increased human diseases (Yang, 2013). Besides, given China’s huge base, any of its internal disturbances could have worldwide impacts. All of these facts make China an ideal and irresistible living laboratory for urbanization research throughout the world (Normile, 2008).

Although there have been increasing research on China’s urbanization and its sustainability, a majority of them tackled the issue from a single perspective within certain discipline (e.g. resources science, biogeochemistry, landscape geography, ecology, or epidemiology), and efforts to summarize these research works in a systematic and streamlined way have been rare. In fact, various drivers, pressures, processes and impacts, which are associated with urbanization, are coupled and interrelated to one another. In this sense, a holistic view is indispensable to draw a full picture of China’s urbanization and concomitant sustainability issues, in an attempt to shed light on future research directions.

This paper, therefore, targets China’s rapid urbanization, summarizes research in previous studies, and discusses research and policy needs in the field of sustainable urbanization. Following sections discuss and research needs for metabolism studies for sustainability of cities, major driving forces in the context of urbanization, and knowledge integration through stakeholder engagement.

2. Metabolism studies for sustainability of cities

Cities are becoming major targets of metabolism study. This is because global impacts of cities have continued to grow (Kennedy et al., 2012). An analysis of urban metabolism consists of quantification of flows and stocks of materials, energy, and water in a city as well as associated flows and stocks outside of the city. This metabolism is caused to support quality of life of people living in the city. Therefore, its metabolic profile can be regarded as an environmental and resource profile of the city because these flows and stocks bring about environmental degradation and resource scarcity as well as secondary resource supply.

Metabolic profile of a city has been increasingly used as a basis for identifying key elements and formulating effective policies associated with major urban issues, including resource and waste issues caused by increased resource demand and waste generation (see Section 3.2.1); water supply scarcity caused by climate change and increased water demand; energy and climate change issues caused by energy consumption and emissions of greenhouse gases; water pollutants caused by emissions of phosphorus, nitrogen, metals, and others; and air pollutants caused by emissions of SOx, NOx, particulate matters, and others (see Sections 3.2.2 and 3.2.3). Change in landscapes caused by transfer of large amount of construction minerals and other resources and degraded environmental quality caused by emissions...
of above pollutants inevitably affect on natural ecosystems (see Section 3.2.4) and human health (see Section 3.2.5). Therefore, understanding metabolism (flows and stocks of resources and emissions) of a city is essential to tackle these issues, especially in developing nations where rapid urbanizations are happening.

Important viewpoint for sustainability of a city is that the city cannot stand alone. Its quality of life is highly dependent on surrounding suburban and agricultural areas and other cities and countries. Therefore, accounting for indirect consumption of resources and emissions of pollutants outside of the city are critical. Research related to footprinting of a city (e.g., Ramaswami et al., 2012) helps us understand hidden impacts and dependence of the city on other areas because it shows direct and indirect inputs and outputs induced by domestic consumption. However, this consumption-based approach is not always effective because it ignores impacts of local economic activities for export of products and services to other areas, whose impacts can be locally controlled: therefore, both consumption- and production-based accountings are useful (Peters, 2008) for developing appropriate urban policies.

The major obstacle to establish urban metabolic profile is the lack of data. Kennedy and Hoornweg (2012) proposed mainstreaming urban metabolism and provided a list of items for monitoring, which is useful for cities that are to start measuring their metabolism. After Japan’s adoption of resource productivity indicator and its national target (Takiguchi and Takemoto, 2008), several local governments tried to estimate material flows in their jurisdiction, but had many difficulties because of the lack of data, especially the data on exports and imports between cities. If cities are to take their sustainability seriously, then the data collection related to urban metabolism should be a mainstream activity of cities. Alternatively, research needed to develop methodologies for estimating missing flows based on existing data. Note country level data with imputing missing data is now implemented (see Miyama and Managi, 2014; Yang et al., forthcoming and Kanie and Managi, 2014 of database called World Resource Table (WRT)), and next step would be data for major city level data estimation in the WRT.

Urban metabolism study is an integrating activity of city's environmental and resource data because many data are required to draw whole picture of its metabolism. Therefore, collected and/or compiled data can also be used for many urban sustainability indicators or SDI associated with sustainable consumption and production (e.g., resource productivity, electricity consumption of households (see review of resource productivity in Managi et al., 2004)), climate change and energy (e.g., primary energy consumption, greenhouse gas emissions by sector), sustainable transport (e.g., energy consumption of transport relative to GDP), and natural resource management (e.g., forest increment and felling). Mainstreaming urban metabolism is also reasonable from this point of view. Developing and adopting indicators can also serve as an incentive for collecting data.

In many cases urban metabolism study is just a static accounting. Next stage is to model future metabolism under certain conditions and policies. This type of modeling has been done for certain topics, e.g., for projection of waste generations and GHG emissions in a city: these estimations are very basis when planning for urban sustainability. This should be expanded to other issues and be integrated so that planners can see whole picture. In a city office, different sections tackle with different issues, but issues interact: waste management and wastewater treatment need energy and produce GHG; change in energy system can induce different composition of resource requirement and produce waste. The integrated models are particularly useful for identifying tradeoffs and solutions to multiple environmental and resource issues beyond “end of pipe” approaches. Integrated modeling is required from this point of view.

3. China’s urbanization and sustainability: case studies of urban metabolism

With the adoption of ‘Reform and Opening-up’ policy in 1978, China entered a period of fast-paced economic growth and steady urbanizing development (Managi and Kaneko, 2010). Urbanization in China increased from 17.92% in 1978 to 53.73% in 2013, with an annual growth rate of 1.02% (National Bureau of Statistics, 2014). By 2012, half of China’s 1.3 billion people are urban-dwellers (National Bureau of Statistics, 2013). According to Peng (2011), urban population is estimated to reach 1 billion by 2030 if current trends hold. In March 2014, Chinese central government released the National New-type Urbanization Plan, in which urbanization level is expected to rise by 1% annually and reach 60% by 2020.

3.1. Main driver associated with urbanization

Over the past few decades, urbanization in China has made remarkable achievements. Meanwhile, rapid urbanization is inevitably accompanied by significant demographic, social, economic and spatial transformations (exemplified as Fig. 1). Basically, these driving forces are manifested in four subareas, namely population aggregation, economic development, lifestyle change and spatial patterns change.

In 2011, the first time in China, urban population surpassed rural population (Fig. 1(a)). The transformation of rural to urban population generally occurs in two ways in China. On the one hand, massive migration of rural people alters the geographic distribution of population, resulting in high-density population aggregation in urban areas; on the other hand, local farmers who lose land because of urban sprawl into surrounding rural areas switch to non-agricultural activities, leading to employment structure transition.

Economic development, particularly industrialization, is recognized as a predominant driving factor going side by side with urbanization in China (Gu et al., 2012b). Specifically, transformation in terms of economic development includes expansion of economic magnitude and evolution of economic structure (Fig. 1(b)). China’s average annual growth rate of GDP from 1978 to 2012 is roughly 10%, with its industrialization rate (the ratio of industrial value added to GDP) ranging from 41% to 49% (National Bureau of Statistics, 2013). Compared with other developed countries, China’s urbanization (especially when measured in proportion of registered urban population) lags behind its economic growth and modernization level (Bai et al., 2014). Such imbalance has resulted in a variety of urban problems (Yang, 2013).

Social transformation occurs in terms of cognitive level improvement, information exchange, cultural communication, technological innovation, social relations evolution, institutional reform among others, which could further influence people’s behavior and lifestyle. There exist two common forms of lifestyle change: one is about material needs, such as increase of floor space and food consumption mainly due to higher income level (Fig. 1(c)); the other is about non-material demands, such as higher demands for esthetic and landscape enjoyment, hygienic standard, and indoor thermal conditions. Note that the average annual growth rate of per capita disposable income between 1978 and 2012 (roughly 7%) is below corresponding GDP growth mentioned above, implying that people enjoy less dividends from economic growth.
Along with socio-economic transformations mentioned above, cities’ spatial attributes are undergoing remarkable change, resulting in increase of cities in number and expansion of urban space as Fig. 1(d). In China, the number of city (including county-level, prefecture and above level), which appeared stable ever since the middle of 1990s though (due to decreasing growth of prefecture-level cities and rearrangement of county-level cities), grew from 193 in 1978 to 657 in 2011 (Ministry of Housing and Urban-Rural Development, 2011). Increasing demands for industrial and commercial land, public facilities, and housing are mainly responsible for the conversion of massive farmland into urban land. In the past three decades, the urban built-up area in China has grown by 486%. That is faster than its urban population growth, which is 313%.

All these transformations form the driving forces, which trigger variation of material, energy and information flow as well as landscape, bring about both positive and negative effects, and sequentially influence functions, services and wellbeing within integrated urban
ecosystems. Note that none of these driving forces exists independently, while they interact closely and interdependently with each other (as Fig. 2).

3.2. Resource, environmental and ecological effect

Among multi-disciplinary studies on urbanization, researchers in the field of resource, environment and ecology are most concerned about the interactions between human socio-economic activities and natural ecosystem upon which such anthropogenic activities depend. Given the status quo of China’s urbanization research in this field, the following discussions are categorized into five domains: (1) material resources and energy consumption, (2) biogeochemical cycle, (3) environmental quality, and (4) ecological effects, and (5) human health. Note that as modern production and consumption patterns are concentrated in urban areas, the functioning of cities are responsible for a series of transboundary effects with regional or even national implications. In this sense, many studies and information reviewed in this section, which appear to be dealing with various issues at the national level, are actually the best available embodiment of urbanization effects.

3.2.1. Material resource and energy consumption

With the acceleration of urbanization, increasing interests have been placed on the input, stock, and output of materials and energy in integrated urban ecosystems, because these occur as the direct linkages between human society and natural environment and better understanding of these metabolic processes would help develop appropriate regulatory measures (Brunner, 2007).

From a national or regional perspective, strategic resources such as minerals and fossil fuels usually become the priority of concern when studying urban metabolism. In China, the supply and demand of most raw material resources (e.g. iron ore, copper, aluminum and limestone) increases accordingly with rapid urbanization and industrialization, exemplified as Fig. 3(a). The construction industry usually stands out as the top consumer for various raw materials since China’s urbanization is commonly characterized by large-scale construction activities (Guo et al., 2014; Huang et al., 2013). With continuous increase of urban stocks, transition of investment and consumption patterns, and improvement of materials recycling, however, the trajectory of materials demand could be altered and shows a declining trend in the coming decades (Huang et al., 2013; Yin and Chen, 2013). Demand for raw materials due to rapid urbanization may also impose pressures beyond the country’s geographic boundary. For instance, China’s increasing timber imports could cause unsustainable harvesting of forests in exporting countries such as Indonesia and threaten the ecosystems therein (Cao et al., 2013). Except for mineral and timber resources, food is another basic material of importance for Chinese urbanization studies. As Fig. 3(b) shows, food consumption in China features a slight decline in cereals and starchy roots, moderate increase in sugar and vegetable oils, and notable rise in fruits, vegetables and animal products.

Energy consumption is another area with extensive studies during the course of urbanization in China. According to Wang (2014), research on energy consumption and its connection with urbanization are basically conducted from four perspectives. The first perspective studies the correlation between energy consumption and urbanization (Zhou et al., 2012); the second perspective studies the casual relationship between energy consumption and urbanization (Liu, 2009); the third perspective focuses on the energy metabolism of a specific urban system (Chen et al., 2011); the last perspective examines regional disparities in terms of the effects of urbanization on energy.
Fig. 3. Chinese urbanization effects: (a) material and energy consumption, (b) food supply, (c) creation of reactive nitrogen, (d) water quality of major watersheds, (e) air pollutant and solid waste, (f) air quality of major cities, (g) ecological footprint and biocapacity, (h) urban population health. Sources: Data from China Iron and Steel Association (2012) (Fig. 3(a)), China Cement Association (2011) (Fig. 3(a)), National Bureau of Statistics (2012) (Fig. 3(a)), The Statistics Division of the FAO (1961–2009) (Fig. 3(b)), Cui et al. (2013) (Fig. 3(c)), Ministry of Environmental Protection (1989–2012) (Fig. 3(d)), Ministry of Environmental Protection (2014) (Fig. 3(f)), Global Footprint Network (2014) (Fig. 3(g)) and Ministry of Health (2013) (Fig. 3(h)).

Although quite a few studies demonstrated that urbanization plays a positive role in boosting energy consumption (Zhang and Lin, 2012), variation exists with different analytical metrics or spatial–temporal scales. For example, (Pachauri and Jiang, 2008) found that energy consumption of urban households was lower than that of rural households in China; Liu (2009) also suggested that urbanization in the long term would contribute to the advance of energy efficiency through promoting industrial structure, technical structure and productive ability, thereby placing less reliance on energy consumption.
3.2.2. Biogeochemical cycle

In comparison with raw materials such as steel, cement, sand and gravel, which tend to have large amounts of stock in urban construction and other durable goods (e.g. machinery, automobiles, and electronics), some elements appear more dynamic as they flow within urban complex ecosystems. For such elements, research interests have been focused on their biogeochemical cycles, which are interfered by anthropogenic activities (e.g. change of spatio-temporal distributions or existence forms).

Water is an essential resource to maintain the normal operation of an urban system, not only for direct use but also embodied in various goods and services provided to urban citizens. Currently, more than 60% of China’s 669 large cities are faced with water shortages (Liu, 2010). Rapid urbanization has brought about dwindling total water availability, expanding total urban water demand (both real and virtual water), increasing wastewater discharge, groundwater depletion, water table falling, and sea water intrusion (Wu and Tan, 2012). Other than fresh water use and wastewater generation, more and more concerns are being placed on the hydrological effects of urbanization in recent years. Land use and land cover change as well as incremental impervious surface ratio have caused increase of annual runoff, daily peak flow, and flood volume, resulting in a series of urban waterlogging disasters (Chan et al., 2013; Du et al., 2012).

Carbon (C) is highly interrelated to human activities in cities, especially energy activities. Churkina (2008) argued that more than 80% of C emissions originate from urban areas. Research on impacts of urbanization on C cycle is primarily concentrated in two subareas: C flow modeling focuses on metabolic process analysis and associated flux calculation (Zhao et al., 2014); C footprint accounting places emphasis on the metabolism results accounting of a specific urban system or its subsystems such as the public transport system (Lin et al., 2013). Although conducted from different research angles, such analysis converge on that the contribution of embodied C emissions (as compared to direct emissions) to urban C metabolism is considerable, because cities generally have high dependency of energy and basic material inputs on surrounding areas.

Nitrogen (N) and phosphorous (P) are important nutrients for integrated urban ecosystems, and their biogeochemistry, which is altered by rapid urbanization, often result in a series of environmental issues such as air and water pollution. Expanding food and energy demand are two dominating driving forces for the increase of reactive N in China (Fig. 3(c)) (Cui et al., 2013; Gu et al., 2012a). Due to excessive application of N fertilizer, less-developed farm management, massive energy consumption among others, large amount of reactive N is released from agricultural ammonia volatilization and runoffs, fossil fuel combustion, and solid waste landfill (Cui et al., 2013; Gu et al., 2013). Similarly, urbanization, improved living standards, and population growth contribute to increasing P flows in terms of ore extraction, use and waste generation (Ma et al., 2012). In particular, urban food consumption becomes a principal driving force for the change of P metabolism (Li et al., 2012).

3.2.3. Environmental quality

Changes of resources consumption and biogeochemical cycles as discussed above often result in a series of environmental pollution issues, which in essence could be regarded as uneven distribution and excessive accumulation of materials and energy spatially or temporally. Studies on variation of environmental quality induced by urbanization commonly aim at specific environmental medium, such as atmospheric, aquatic, and soil environment.

In terms of air quality, only 60.5% of prefecture-level cities in China meet the standards of Ministry of Environmental Protection (Wang and Chen, 2010). In 2013, the percentages of days reaching standards for 74 major cities (including municipality directly under the Central Government, provincial capital and city specifically designated in the state plan) are shown in Fig. 3(f). Booming construction material industry, modern transportation system and building energy consumption (largely from coal combustion shown as Fig. 3(e)), which are directly related to urban growth, are responsible for severe air pollution such as extremely high PM 2.5 and haze events (Cao et al., 2013). Additionally, transformation of land use patterns leads to change of urban microclimate (e.g., urban heat island effect), which could exacerbate air pollution by trapping pollutants. Rapid urbanization is closely correlated with degradation of water quality through change of land use pattern and production of large amount of pollution (Ren et al., 2003). Sharp decline in vegetation landscape undermines its buffering capacity; expanding food demand from shrinking farmland requires increasing use of fertilizers and pesticides, resulting in agricultural non-point source pollution; fast industrialization and living standards improvement are accompanied by increased organic pollution (He et al., 2008). Currently, more than 80% of China’s rivers are subject to some degree of contamination (Fig. 3(d)). Urbanization, through shift of soil utilization, waste disposal (Fig. 3(e)) and acid deposition caused by urban air pollution, can also increase the risk of soil pollution (Chen, 2007).

3.2.4. Ecological effect

Landscape, habitat, biodiversity and ecosystem service are the major concerns for studies on urbanization and its attendant ecological effects. With urban sprawl and human footprint expansion (as Fig. 3(g)), vegetation coverage decreases and natural landscapes become lost, fragmented, transformed and isolated (Su et al., 2011). A dramatic transition from agriculture-dominant landscapes to urban-dominant landscapes is being experienced by those most urbanized regions in China (Deng et al., 2009). Because of habitat loss and environmental degradation, species number, abundance and biodiversity commonly show a declining trend from outskirts to urban center (Huang et al., 2010). Though there are some case studies claiming urbanization as an encouraging factor for the increase of plant diversity or green space (Ye et al., 2012; Zhao et al., 2013), it is undoubted that urbanization have caused the decline of ecosystem service values in many areas of China (Haas and Ban, 2014; Wu et al., 2013).

3.2.5. Human health

With demographic, social, economic and ecological transformations, the relationship between urbanization and human health is complex. Zhu et al. (2011) explored the impacts of rapid urbanization on environmental health and human wellbeing in China. The results unraveled that the incidence of chronic conditions such as cardiovascular and metabolic diseases had risen in urban regions, although a better control of infectious diseases was achieved due to general improvements in life quality and healthcare provision. This changing burden of disease is a most prominent characteristic of public health in China from 1990 to 2010 (Yang et al., 2013). As reviewed by
Gong et al. (2012), shifts in nutrition and lifestyle choices, degradation of urban environmental quality and occupational and traffic accidents, which are associated with rapid urbanization, pose increasing public health threats on urban population in China, particularly on non-communicable diseases (Fig. 3(h)).

4. Science need and policy recommendation for sustainable urbanization

While urbanization in China brings about economic prosperity, living standards improvement and cultural affluence, it creates tremendous challenges for the development of cities towards sustainability. If current trends hold without adequate consideration of ecological and social costs, many cities might go beyond their carrying capacities and lead to collapse eventually. To mitigate the detrimental impacts of rapid urbanization and promote sustainable urban development, scientific research needs and corresponding policy measures are suggested to be focused on the following aspects.

Urban metabolism analysis is a useful approach to reveal the sources, stocks and fates of raw materials, energy and key chemical elements which are consumed by and flow within urban systems. It can help depict a full picture of metabolic processes, assess the efficiency of metabolic flows, and explore metabolic mechanisms. Based on it, policies to enhance urban efficiency (e.g., energy efficiency, resource use efficiency) can be directed and optimized, such as strengthening construction materials recycling, recovering nutrients from urban waste streams, improving energy efficiency, and developing a circular economy. The rationale is to promote the internal circulation of materials and energy within urban systems and transfer a ‘from cradle to grave’ pattern into a ‘from cradle to cradle’ paradigm. To this end, a series of legislative, economic and financial approaches are needed to facilitate policy implementation. Instruments such as construction design codes, market access regulations, transferable discharge permits, preferential tax and subsidies are increasingly adopted by governments. Furthermore, advanced urban metabolism research should embrace a regional perspective in the sense that trade flows and interconnections among urban, suburban and rural systems are included. Then a more comprehensive policy portfolio could be designed by incorporating source control, fate tracing, balanced development strategies, etc.

Environmental quality profiling presents a global challenge for decision makers under rapidly changing urban environment. A holistic view of environmental effects is a first gap that future research is expected to fill. Unlike most studies mentioned in Section 3.2 which took a piecemeal perspective by concentrating on specific environmental medium, the holistic approach requires that effects of all surrounding environmental components (e.g., air, water, soil and landscape) are assessed in an integrated framework. A second gap is the lack of understanding of the connections between urban metabolism outcomes and environmental conditions. Most metabolism analysis as above mentioned stop at metabolic flux calculation (in volume units) without examining their environmental quality effects (in concentration units), which are usually more relevant to policy making. Efforts to address this problem include development of environmental simulation models, carrying capacity analysis, and GIS-based spatial analysis. More importantly, knowledge about the nexus between metabolism outcomes and environmental effects should be translated into implementable policies, such as mass-based controls, pollution load distribution, and urban scale rationalization.

As to ecological conservation and human health impacts, a systematic approach that attempts to elaborate complex interconnections between anthroposphere and natural environments is imperative. The systematic approach views cities as coupled social–economic–ecological systems, in which ecological and health effects resulting from socioeconomic drivers should be well appreciated (Bai et al., 2012). In terms of its policy implication, institutional reform which requires that the sustainability of proposed developments enjoy equal privilege as their economic impacts is strongly recommended (Cao et al., 2013). This means a paradigm shift in evaluating the performance of government officials from an overwhelming focus on GDP to an emphasis on more balanced and harmonious development strategy. The proposition of ‘ecological civilization development’ and ‘designation of ecological red line’ in the Third Plenary Session of the 18th Central Committee of the Chinese Communist Party is a best representation of the institutional reform. The scope of ‘ecological red line’ should encompass key ecological functional regions, ecological sensitive regions and ecological vulnerable regions within terrestrial and marine territory, aiming at restraining ecological degradation and consolidating national ecological security. In addition to the systems approach, to integrate a social science perspective in designing research methodologies and evaluating policy performance is a future direction for science-based policy making to move forward. Furthermore, long-term monitoring of policy implementation should be emphasized to enable adaptive management.

5. Transdisciplinary approach to generating, integrating, and implementing knowledge through stakeholder engagement for sustainable urban transformation

Sustainability problems are often ill-defined and intermingled. We need to integrate knowledge effectively and efficiently from various academic disciplines in natural science, social sciences, and humanities for scientific understanding of complex and dynamic interactions between natural and human systems and societal actions for sustainable transformation (Yarime et al., 2012). With the necessary expertise and experience involving a significant degree of diversity and uncertainty, a major challenge in sustainable urban transformation is how to design and implement serious engagement and fruitful collaboration between academia and stakeholders, including industry, government, and civil society. To ensure steady progress towards sustainability, it is of critical importance to take a systemic approach to encouraging innovations from a transdisciplinary perspective (Yarime et al., 2012).

In the coming decade, the global demand for resources including water, energy and food is expected to continually rise. Most of this demand will come from developing countries, particularly from rapidly growing urban areas in Asia. Many of these areas already suffer from social and political instability, geopolitical conflict over resource scarcity, and environmental damage, which will be exacerbated by resource shortages expected in the future. The increasingly interconnected flows and interdependent relationships of these resources form a complex nexus; waste management and wastewater treatment need energy, hence producing greenhouse gases; a change in the energy system can induce a different composition of resource requirement, which would produce wastes. Previous research tends to focus on only a certain part of the nexus, without sufficiently addressing the complexity of the whole issue (Yarime et al., 2010). A systematic approach is hence required for managing and governing the nexus effectively. Integrative methodologies will be able to increase our systematic understanding of the interactions between diverse aspects of the nexus, especially by quantifying inter-linkages and structural synergies (Kenway et al., 2011).
It is therefore necessary to develop a systematic framework for governing the water–energy–food nexus, incorporating efficiency in resource use and resilience to socio-environmental disturbances for transformations to urban sustainability. We then need to explore comprehensive strategic options, addressing local-specific needs and socio-technical opportunities for improving the governance of the nexus. Given the complex interlinkages and locational specificities of the nexus in the urban setting, however, societal needs and technological opportunities are difficult to identify and assess. Without their proper assessment, urban transformations would not be successfully aligned with social, economic, resource and environmental goals for sustainability (Bai et al., 2014). In this light, it is important to conduct scientific research as a platform for generating, integrating, and implementing knowledge useful for concrete solutions to sustainability challenges with relevant stakeholders in society (Trencher et al., 2014, 2013; Yarime et al., 2012).

In order to understand the interrelationships and interactions underlying the nexus, it is of critical importance to create knowledge which would capture all the complexities involved. Hence a scientific methodology needs to be developed to identify and assess in detail the existing social–environmental inter-linkages and the levels of resource efficiency and resilience. Previous methodological efforts can be grouped as accounting approaches for tabularizing resources, life cycle approaches for tracing environmental flows and impacts, and econometric models for identifying causal relationships between specific social practices and availability of resources. While these approaches are useful in examining individual flows and relationships, methodologies are not yet well developed for evaluating system-level tradeoffs and offering insights on the resiliency of the nexus when faced with social–environmental disturbances (Kharrazi et al., 2014a,b).

One way to advance our understanding of interactions within the nexus is to use a network approach. Specifically, the ecological information-based network approach can be used as a methodological scalpel to evaluate the system-level interactions and synergies of various socio-environmental processes in terms of the efficiency and resilience (Kharrazi et al., 2013a,b). The benefit of utilizing this approach lies in its ability to objectively evaluate system-level outcomes of different socio-environmental interactions in the context of local-specific needs including availability, accessibility, and affordability of resources. The dynamic nature of social–ecological interactions, however, demands constant revaluation and reassessment, and the environmental, economic, and social dimensions that are either undesirable or untenable need to be transformed in order to create a new viable system (Walker et al., 2004).

Transformations to sustainability requires a shift in the organization of society so that existing social patterns are reevaluated and reconfigured, which will only be achieved by generating useful knowledge and experiences that can be applicable in the local settings. For example, the use of solid waste for energy in cities provides a contextualized evidence of the importance of a systematic approach to addressing the local-specific nature of the nexus. Successful waste management in the advancement of water, food and energy sustainability has also generated a host of other social benefits, including improved health, nutrition, and entrepreneurship opportunities (Mutsiya and Yarime, 2011). Given the complexity and interdependency of many urban issues, governance for sustainability needs to incorporate knowledge integration as a means to deal with multiple and uncertain dimensions of sustainability (Shiroyama et al., 2012). Since it is not clear at the beginning what knowledge from which actors based on which disciplines or expertise is relevant or required, social transformation essentially becomes an iterative process involving active engagement with all stakeholders (Mauser et al., 2013).

This iterative process with stakeholders, one akin to the hermeneutic circle of learning, can lead to the formation of strategic options for public decision making towards urban sustainability. While we could expect some similarities in the iterative process between different cases, it is important to recognize that the way how the interactions proceed would vary considerably, reflecting local-specific contexts, including technological opportunities and institutional environment. Therefore, a critical challenge in designing and implementing transdisciplinary research on transformations to sustainability is to extend knowledge networks to assemble and evaluate cases in different regions, taking into account such factors as geographical location, natural environment, economic conditions, and social structure.

The significance of scientific research we propose lies in its intention and capacity to develop scientifically-solid and socially-robust methodologies for identifying and assessing the interlinkages and system-level synergies of the nexus, integrating local-specific needs and socio-technical opportunities, and to implement them through close collaboration and serious engagement with academia, industry, government, and civil society. That will contribute to creating evidence-based and solution-oriented transformations for urban sustainability.

Scientific research needs to develop academic concepts and methodologies for transdisciplinary approaches to co-designing, co-producing, and co-disseminating knowledge with relevant stakeholders, incorporating local contexts and socio-environmental conditions. In particular, it is important to examine the characteristics of various types of sustainability metrics in evaluating resource efficiency and resilience in social and environmental systems (Kharrazi et al., 2014a,b), analyze the network flow dynamics among components of an urban system (Kharrazi and Yarime, 2012), and apply the ecological information-based approach as a tool for advancing decision making on evaluating the sustainability of the management of resources (Kharrazi et al., 2013a,b). It is also useful to develop resiliency indicators which can be applicable for the management of water, energy, and food resources, which can also serve as post-millennium development goals beyond the year 2015.

At the same time, we need to start collaborating extensively with private companies, regional and national governments, international organizations, and civil society organizations to address sustainability issues involving water, food, and energy. The experience of serious engagement with stakeholders will provide us with valuable opportunities for developing and implementing transdisciplinarity from global perspectives. The lessons in facilitating knowledge design, production, and dissemination with stakeholders based on mutual understanding and trust contribute to establishing socially robust strategies for urban sustainability. The experience and expertise will be effectively utilized towards developing solution-oriented methodologies for evaluating the efficiency and resilience of coupled human environmental systems.

These data on environmental and resource flows and exchanges will be integrated to draw a whole picture and analyzed in terms of efficiency and resilience. As a major obstacle is the difficulty in assembling relevant data (Kennedy and Hoornweg, 2012), developing and adopting sustainability indicators is expected to serve as an incentive for collecting data, while methodologies will be developed for estimating missing flows based on existing data. Going beyond a static accounting and to incorporate the process of changes and interactions, dynamic, integrated approaches will be elaborated for identifying tradeoffs and feedbacks between multiple environmental and resource issues.

Based on the detailed data on the interlinkages and interdependences of the nexus, we will be able to contribute to initiating transformations to urban sustainability through close collaboration with stakeholders. With the diversity of stakeholders in terms of perceptions, motivation, and behavior dependent upon economic, social, and historical contexts, a stakeholder platform will be established for co-creating knowledge, co-designing targets, and co-implementing processes. The stakeholder platform will be utilized effectively to im-
plement several important functions in this research. The first is the creation of visions with regard to what futures the local people would like to see and achieve in the future. Joint scenario making will be conducted with the relevant stakeholders. Collection and analysis of data on societal needs and opportunities will be facilitated by channeling the stakeholder platform. Technological and system development will be jointly explored with competent, reliable partners in academia and industry. Social experimentation will be implemented by using society as a living laboratory involving the suppliers and users of innovation. Impact evaluation and assessment will be conducted jointly with stakeholders so that transparency, objectivity, and neutrality are maintained. By doing so, recognition and legitimacy in society will be obtained, which will be particularly important in implementing transdisciplinary research. Based on the lessons from this kind of scientific research, a feedback will be explored for agenda setting and policy making at the global level.

Acknowledgments

We appreciate Yong-Guan Zhu for suggesting us to work on urbanization and sustainability in China. We thank referees and participants of “New Environmentally Sustainable Systems for China and Japan”. This research was partially funded by the Open Fund Project from Xiamen Key Lab of Urban Metabolism (no. 3502ZZ130037), and Grant-in-Aid for Specially Promoted Research (26000001) by Japan Society for the Promotion of Science.

References


