Urban ecological infrastructure: an integrated network for ecosystem services and sustainable urban systems

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ABSTRACT

The sharp increase in global urban population and rapid expansion of impervious urban surfaces is raising concerns over more than just the quality of human life; researchers are also worried about ecosystem services and the stability and security of urban ecosystems and the infrastructures. In this paper, we define “urban ecological infrastructure” and propose an integrated framework in which the infrastructure network provides ecosystem services and sustainable urban systems despite changing landscapes and climate. We define the urban ecological infrastructure (UEI) as an organic integration of blue (water-based), green (vegetated), and grey (non-living) landscapes, combined with exits (outflows, treatment, or recycling) and arteries (corridors), at an ecosystem scale. The UEI framework represents the biotic and abiotic interactions within an ecosystem, and stresses an integrated relationship between artificial and natural systems. It links the grey, blue, and green infrastructures, and integrates them via both exits and arteries. Its insights can help to improve the circulation and reuse of resources throughout the urban ecosystem. This comprehensive conceptual framework can facilitate more rational urban development, and can improve urban ecosystem services and regional sustainability. Although understanding the form and function of UEIs is an important first step, innovative strategies are needed to address challenging obstacles such as rigid thinking, institutional fragmentation and inflexible policies. New thinking and innovative ways of acting will be required to provide a more resilient, stable, and sustainable urban system.

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1. Introduction

More than half the world's population now lives in cities, and this figure may reach 60 percent by 2030 (United Nations, 2012; Zhang, 2016). The sharp increase in the urban population and rapid expansion of impervious urban surfaces is raising concerns over more than just the quality of human life; researchers are also worried about ecosystem services and the stability and security of urban ecosystems and their infrastructures (Daily, 1997; Daily et al.,

2002; Li et al., 2009, 2015; Tao et al., 2015) (Table 1). Different infrastructures are built to address the increasing human demands. At current stage, ecological infrastructure is still seriously lacking. Infrastructures are the basic physical and organizational structures that society requires for its operations, and they provide the facilities required to bridge the gap between the economy and the human functions it serves (Patterson and Apostolakis, 2007; Sun et al., 2015). No city can operate without infrastructure, but infrastructures interact with ecosystems in complex ways.

Traditional infrastructure designs (also called grey infrastructure) date back to cities of antiquity, and include roads and highways, electrical grids, and systems that transport or treat potable water, sewage and storm water. However, landscape modification, habitat loss and landscape fragmentation caused by the development of grey infrastructure pose significant threats to urban

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Table 1
Challenges of constructing urban infrastructure.

Category	Basically complete municipal infrastructure	Incomplete environmental infrastructure	Absent ecological infrastructure
Demand	water, electricity, gas, heating, greenery, sanitation and wastewater treatment facilities (water flush and electricity consumption)	garbage, wastewater, exhaust gas, toilet (improvement and cyclic regeneration)	renewal of impervious surface, roof greening, rain garden, wetlands, waste heat utilization, connections between corridors

ecosystem coherence and sustainability (Cagno et al., 2011; Kjolle et al., 2012; Serrano et al., 2002). Moreover, urban problems such as flooding, air pollution and traffic jams have revealed the weakness of the traditional grey infrastructure and its inability to cope with factors such as climate change (Kessler, 2011). Thus, great emphasis has been placed on creating infrastructure systems that are inherently more adaptable and resilient.

Urban forests, parks, woodlands, green roofs, wetlands, rivers, and other natural spaces play key roles in enhancing urban ecosystem services, improving urban environments, combating climate change, and maintaining ecological balance (Jim and Chen, 2008; Li et al., 2005). Thus, the concept of green infrastructure has been developed, referring to the combined structure, position, connectivity, and types of green spaces which together enable delivery of multiple benefits as goods and services (Mell, 2009; Schrijnen, 2000). At present, green infrastructure is considered to be an essential and effective way to promote ecosystem and human health in urban areas (Tzoulas et al., 2007). In addition, multiple benefits or functions, together with the planning and engineering methods, have been heavily emphasized in current studies on green infrastructure – especially practices of green roofs, permeable pavement, and sunken green space (Getter and Rowe, 2006; Scholz and Grabowiecki, 2007). Gill et al. (2007) suggest that increasing green space could reduce runoff by 4.9 percent, while increasing tree cover could reduce runoff by 5.7 percent and utilizing green roofs could reduce runoff by 11.8–14.1 percent. Foster et al. (2011) report that permeable pavement can reduce rain runoff by 70–90 percent, which is equivalent to the performance of lawns and woodlands. Researchers have also found that green infrastructure can have a much smaller startup cost, provide multiple functions and require less on-going maintenance (Li et al., 2014).

Although green infrastructure can make up for many of the shortages of traditional grey infrastructure, urban green infrastructure can only be identified as a ‘best practice’ to achieve greater urban sustainability and safety when it is combined with traditional grey infrastructure (Sijtsma et al., 2012; Wald and Hostetler, 2010). How well nearby residential and commercial areas are designed and managed greatly influences the conservation of urban biodiversity and the functionality of green infrastructure. If improperly constructed, green space can become an urban pollution source instead of a purifier. For example, storm water runoff through areas with extensive flower gardens, turf grass, and impervious surfaces can contain excessive amounts of nutrients (e.g., phosphates and nitrates), causing water eutrophication, fish deaths and the growth of invasive exotic plants (Hostetler et al., 2011). Thus, it is essential to coordinate the relationship between grey infrastructures and green infrastructures, and to create built areas that are compatible with the green infrastructure.

Because cities are complex ecosystems driven by both socio-economic activities and natural processes, urban ecosystems need more integrated, effective, comprehensive, and multi-functional ecological infrastructures (Li et al., 2014; Wang et al., 2014). These should integrate the green and grey infrastructures with related landscape characteristics at an ecosystem scale. In this way, a collaborative symbiosis can be achieved in the form of an

infrastructure that facilitates recycling and regeneration and can maintain the functionality, sustainability and vitality of the urban ecosystem. In this paper, we define “urban ecological infrastructure,” and propose an integrated framework in which the infrastructure network provides ecosystem services and sustainable urban systems despite changing landscapes and climate.

2. What is urban ecological infrastructure?

2.1. Definition

The concept of Ecological Infrastructure (EI) first appeared in UNESCO's annual reports on the Man and Biosphere (MAB) Program. In the MAB report, EI was put forward as one of five principles for understanding the natural landscapes of the city, but no precise definition or description was provided. During the 1990s, the concept of urban ecological infrastructure was used in theoretical and practical research (Lockhart, 2009; Mell, 2009; Weber et al., 2008). The Conservation Fund (2009) defined EI as “strategically planned and managed networks of natural lands, working landscapes and other open spaces that conserve ecosystem values and functions and provide associated benefits to society.” This emphasized the importance of natural environmental and life support systems in urban land-use planning, including green roofs, rain gardens, wetlands, and other natural or constructed facilities that promote a healthier environment.

In China, Yu's first applied the concept of EI to urban spatial planning in 2002 (Yu et al., 2001, 2005, 2008). Other scholars also put forward relevant concepts, such as the habitat network, ecological corridor, green channel, and ecological network (Ahern, 1995; Nolfi and Parisi, 1994). After approximately twenty years' development, the concept of EI and its benefits for ecosystem service and human well-being have been accepted by scientists, engineers and decision-makers. However, the definition and connotations of EI are quite vague, and the differences between EI and green infrastructure unclear. Thus, researchers preferred to use the concept of green infrastructure rather than EI.

In this study, urban ecological infrastructure (UEI) is defined as the organic integration of blue (water-based), green (vegetated), and grey (non-living) landscapes, combined with “exits” (outflows, treatment, or recycling) and “arteries” (corridors) at an ecosystem scale. The UEI plays a fundamental role in sustainably providing the ecosystem services that urban residents require. UEIs include a comprehensive set of functions: water supply and recycling, energy supply and heat dissipation, soil fertility and biodiversity, metabolism or breakdown of materials and regeneration of wastes, runoff reduction and nutrient retention, and the provision of recreational, educational and cultural services. The purpose of UEI development is to improve a city's ecological integrity and sustainability. A complete and healthy UEI is a basic requirement for secure and sustainable urban development and social interactions.

Traditional grey infrastructure uses a physical approach to transport the wastes and pollutions in cities to natural ecosystems, thus purifying the environment in urban areas. Green infrastructure pays attention to the biological approach (green and blue space etc.) to solve environmental problems and realize the importance

of integration of different components, which is manifested by the pervasive practice of combining green spaces, greenways, natural reserves and wetlands. This integration is insufficient, however, as it only considers the connection of different components of green infrastructure and overlooks the wider inclusion of grey infrastructure. In addition, the integration is mainly at the structural level. The coupling of ecological processes and ecosystem function is only an assumption. Ecological infrastructure takes a holistic view and integrates ecological planning, engineering, design and technological approaches to solve urban environmental problems (e.g. pollution) and reduce the environmental impact of urban development on natural ecosystems. It combines grey and green infrastructure at an ecosystem scale and emphasizes the coordination of each component and the maximization of multiple system functions, instead of the function of single component (Li et al., 2014). A comparison of the reliability, cost-effectiveness, capacity of ecological infrastructure, green and grey infrastructures are shown in Fig. 3, which is further supported by the case study in Section 4.

2.2. Structure

UEI consists of blue land, green land, grey land, exits and arteries (Fig. 1) where:

- **Blue land** includes wetlands, lakes, ponds, streams and rivers with flowing and fluctuating water. It is an important constituent of urban ecological infrastructure and plays a crucial role in the urban environment, principally in water purification, flood control, groundwater replenishment and protection from storms.
- **Green land** includes urban parks, forests, farmland, green roofs and other natural or artificial green spaces. It provides indispensable ecosystem services, such as improving air quality, regulating the microclimate, maintaining biodiversity and beautifying the urban landscape.
- **Grey land** includes roads and highways, the electrical grid, artificial drainage systems and utilities. The presence of an activated or permeable surface allows the exchange of gas, water and nutrients between the soil and the atmosphere, thereby improving urban soil functions such as storage,

Fig. 2. Eco-integration in urban-rural waste management.

regulation, filtering, and biomass production, and remediating the adverse impacts caused by sealed urban soils. Restoring a permeable surface near important ecosystem services in urban areas would improve ecological functions.

- **Exits** represent flows of urban wastes, such as sewage treatment facilities, air and emissions outlets and buffering belts. These differ from traditional waste discharge outlets, as they serve multiple functions: reduction and disposal, natural buffering and purification, artificial disinfection, “mining” of wastes, and resource regeneration and recycling.
- **Arteries** (corridors) include wind and water systems, channels, traffic lines, metabolism networks and any other ecological corridors that permit flows of materials between components of the UEI. Traffic networks (grey) and river systems (blue) are the basic arteries of the urban ecosystem. Practical, connected and unblocked arteries would alleviate traffic jams, mitigate air pollution and the heat island effect, and support ecosystem services

Although urban ecological infrastructure is different from grey infrastructure, green infrastructure and ecological networks, there are close relationships between them. Grey infrastructure is rigid, and mostly has a single function. It is expensive, energy-intensive, prone to deterioration or obsolescence, and does not scale. In contrast, green infrastructure is flexible and serves multiple functions. It is also less expensive and requires less on-going maintenance (Forest Research, 2010; Tzoulas et al., 2007). Blue infrastructure relates to flows of water through the system. Researchers have emphasized the creation and measurement of ecological (grey + green + blue) infrastructure systems that are inherently more systematic, adaptable and resilient than grey systems (Xu et al., 2012).

2.3. Measurement

Previous studies usually adopted ecological service function indicators and landscape pattern indicators to evaluate the function of EI. For the new concept of UEI proposed in this study, a more comprehensive set of indices should be developed for assessing UEI. This could include water use ratio (ratio of total water diverted away from natural use), fraction of land serving ecosystem services functions, renewable energy use ratio, proportion of native species, eco-efficiency of urban recycling and regeneration, and other similar indicators (Table 2).

3. Building urban ecological infrastructure

3.1. Integration of each component

3.1.1. Blue land

Wetlands and rivers are the main components of blue land in an urban ecosystem (Mitscha and Day, 2006). The links between rivers

Fig. 1. Illustration of the integrated network for an urban ecological infrastructure. Grey land includes roads and highways, the electrical grid, drainage systems, and utilities. Green land includes urban forest, parks, woodland, green roofs, wetlands, rivers, and other natural spaces (see text for definitions).

Fig. 3. Comparison of UEI, green and grey infrastructure. Note: UEI refers to urban ecological infrastructure.

Table 2

Comprehensive measurement indicators for urban ecological infrastructure.

Measurement Indicators	Definitions	Critical Values
Ratio of water for urban use versus natural use	Ratio of water used for urban life and production to that used for basic functions of the natural ecosystem.	Lower than 35%
Land for ecosystem services	Ratio of area of urban agriculture, forestry, grasslands, wetlands, and nature reserves to area of urban construction.	No less than twice the area of construction land
Renewable energy use ratio	Ratio of geothermal, solar energy, wind energy, biomass energy, hydropower, and other renewable energy usage to the total energy usage.	No less than 10%
Ratio of native species	Ratio of native species to all species.	No less than 65%
Recycling rate	Recycling rate of renewable materials in urban metabolism.	No less than 90%

and lakes can increase the communication of organisms and materials in waters, and can enhance the abilities of water self-purification, pollution digestion and ecological restoration. This helps protect urban wetlands, water resources, and aquatic biodiversity, and provides habitat for the ecological restoration of urban aquatic ecosystems (Li et al., 2011). On the other hand, blocked connections between rivers and lakes in urban areas will directly lead to the reduction of wetlands function and biodiversity, thus exacerbating the conflicts between urban environmental protection and socioeconomic development. In addition, through the organic combination and careful layout of wetlands of different types, the multiple functions and ecosystem services of wetlands – such as water conservation and purification, climate regulation, water activation, and beautification of the landscape can be achieved. This would help to solve water eutrophication, flood disasters, decreasing biodiversity and other relevant urban environmental problems. Wetlands, ponds, rivers, etc., are natural “sponges” playing an important role in water seepage, retention, storage, purification and drainage, thus the reasonable layout of blue lands is a key step in sponge city construction. Through the integration of UEI (wetlands, green land, permeable pavements, etc.), the urban water ecological environment is repaired and the city is turned into a “sponge” with the capability for water retention, penetration and purification (Wu, 2016).

3.1.2. Green land

Currently, most of cities pay more attention to the form of green space rather than to its function, and in terms of quantity rather than quality, which results in urban green space that is fragmented and inefficient. In addition, uneven resource distribution and the invasion of urban green space by alien species not only aggravates the decline of urban ecological services, but also reduces the balance and sustainability of the urban ecosystem. Therefore, it is essential to integrate urban green spaces and form a network in order to improve ecosystem services, provide ecological corridors and habitat for urban organisms and guarantee urban ecological security (Cameron et al., 2012). This requires connected green

spaces in and around urban and urban-fringe landscapes, including green parks, street-side green strips and, green roofs that are distributed in the inner city; and farmland, woodland, forest, etc., that are located in suburban areas; as well as green corridors and other ribbons of green space located throughout the city and its surroundings.

3.1.3. Grey land

Globally, the total impervious pavement area has reached 580,000 km², larger than Spain's land area (Raciti et al., 2012). The massive extent of impervious surfaces in urban areas, including building surfaces, roads, ditches, banks, and other impervious pavement, blocks the exchange of air, water, and nutrients between soils and the atmosphere, thus significantly affecting urban ecosystem services and urban environments (Scalenghe and Marsan, 2009; Zhao et al., 2012). The integration of urban grey land into the UEI should reconstruct or restore the ecological functions of the urban “skin” (surface). Permeable pavement and vertical plantings are commonly used methods to mitigate the negative effects of impervious pavements, and have been demonstrated to be an effective tool for water conservation, storm-water runoff and water quality management, pollutant control, electricity savings, habitat provision for wildlife and soil function improvement.

3.1.4. Exits

The ecological infrastructure referred to as “exits” requires the integration and eco-renovation of pollutant discharge outlets, surrounding ecological buffer zones, and disposal facilities, as well as pollution reduction and purification systems, including pollution emissions, artificial disposal systems, natural buffer systems, and circulation feedback systems. This should be an ecological purification, disposal, circulation and regeneration system that combines artificial facilities and ecological facilities to achieve the goals of pollution reduction and neutralization, recycling, industrialization, and socialization. As shown in Fig. 2, the system shifts from a single pollutant discharge to ecosystem circulation, with an emphasis on

waste reduction, reuse and recycling. In brief, using comprehensive social, economic and environmental management methods and carrying out adaptive ecological management should bring about effective solutions to urban pollution problems.

3.1.5. Arteries

Traffic, channels and wind and water systems are the framework of the urban ecosystem. The integration of urban “arteries” or corridors, based on function, can help to control urban sprawl and mitigate the problem of traffic congestion. The measures that could be taken may include the following: 1) distributing the urban ecological corridors throughout, with multiple functions for urban social and economic development; 2) highlight the city growth axis, shifting from urban sprawl to an ecologically sound development pattern (Li et al., 2005); 3) maintaining the functioning of the circulation network of city, people, material, air, and water—especially the urban wind channel and transportation network; 4) reconfigure and optimize the traffic hub, node, and transfer sites at different levels; and connect disconnected river segments and recover the groundwater drainage for surface water flows, thus allowing stagnant water to flow again; and 5) break up large areas of constructed landscape into smaller pieces through ecological engineering using green spaces, thus coupling urban ecological landscapes with constructed landscapes. In addition, urban corridors — namely the main traffic arteries — should carry more than 50 percent of the energy flow. Ecological traffic networks should serve more than 80 percent of the urban population. The time from any station of the main network to the city center by fast direct bus should be no more than half an hour, and from residential areas to work place normally not more than half an hour by bus.

3.2. Integration of the system

Unified planning, design, construction and management of blue land, green land, grey land, exits and arteries are essential for UEI integration, and can lead to the coordination, sustainability and stability of the whole system. Each component is not an isolated infrastructure, but functions in conjunction with other components to achieve multiple benefits and high efficiency. For instance, the complementary functions of wetlands, green space, and permeable pavement in organic combination with drainage pipelines and other arteries would efficiently reduce the risk of flood disasters.

Furthermore, we must look at the city as an integrated holistic urban ecosystem, where the UEI plays a crucial role. A spatial planning approach is one of the most effective ways to build up UEI. Previously, grey infrastructures and green infrastructure were considered to be two separate systems, each with its own advantages and disadvantages. Integrated spatial planning can bring different sectors together in order to combine their maximum force and effect, thus providing a more resilient, stable, and sustainable urban infrastructure system.

4. Urban ecological infrastructure practices

4.1. A multiple wetlands system for flood control — a case study of Yangzhou City

Yangzhou City is located at the intersection of the Yangtze River and the Great Canal, in Jiangsu Province, China. Frequent flooding has negatively affected the sustainable development of Yangzhou City. Wetlands restoration engineering in Shugang, Yangzhou, was adopted in 2008–2009, aiming to explore flood mitigation measures in an urban area and to provide a replicable demonstration project. In this project, we integrated blue land (three wetlands),

green land (numerous green spaces) and grey land (permeable pavements) in a comprehensive ecologically engineered wetlands complex. After the completion of the project, the average annual maximum flood peak and average annual runoff were reduced by 91.27 percent and 98.81 percent, respectively. Moreover, the COD_{Cr} and NH₃–N reduction ratios reached 42.8–64.6 percent and 25.2–64.9 percent, respectively. If Yangzhou City can further restore wetlands of equal effectiveness, the area inundated and the water pollution caused by flooding would be well controlled.

4.2. Composite methods for pollution control — a case study in Hefei City

In this case study, the control of water pollution was conducted at the river basin level. After calculating the sources and contributions of water pollution for Hefei City, China, we found that external pollution contributed 98–100 percent of the pollution; far more than internal pollution. External pollution can be further divided into point source pollution (28 percent) and non-point source pollution (71 percent) from industrial, domestic and urban-rural areas (He et al., 2013). Different approaches and measures, described below, were integrated to reduce the pollutants in order to improve the water quality in Chaohu Lake, Hefei City — one of the five largest freshwater lakes in China.

4.2.1. Point source pollution: integrating exits and blue land

Point source pollution was managed through a combination of grey infrastructure (urban sewage treatment systems) and the ecological engineering and management of rivers. In brief, industrial and domestic wastewater was first discharged into sewage treatment plants and then channeled into the eco-engineered land treatment (multi-stage ponds and wetlands) system established at the outlets of the sewage pipes. This successfully reduced water pollution and improved the water quality of Chaohu Lake.

4.2.2. Non-point source pollution: multifunction wetlands systems

Besides enhancing the UEI, the rural Bei-Tang system, used 3000 years ago in China, was also used to reduce non-point source pollution. The Bei-Tang system has multiple eco-services, including water storage, rainwater catchment, irrigation, transportation, flood control, drought prevention, nutrient recycling, micro-climate regulation, pollutant treatment and degradation, and landscape aesthetics (Gao et al., 2015), and can be characterized as small scale, diversified, energy saving, and self-maintaining.

4.2.3. Internal source pollution: multiple management approaches

Lake and canal dredging, together with sediment management, were used to manage the internal source pollution. However, the key was in changing traditional ideas with eco-innovation: from environmental engineering to ecological engineering; from end-of-pipe to life-cycle management; from structure optimization to the evolution of functions; from external high-cost treatment to internal low-cost rehabilitation; and from physical restoration to comprehensive restoration based on social–economic–natural complex ecosystem.

4.3. Integrated waste management systems at varied scales

There are different scales of ecological infrastructure for integrated municipal solid waste management. At the household scale, scrapes of food waste can be put inside a small composter in a kitchen, and turned into compost within twenty-four hours; then the compost can then be applied to the yard and garden plants.

On the community scale, a waste recycling and organics composting center could provide an ecological infrastructure for

municipal solid waste. Wastes would be separated by the household inhabitants and the recycling staff, then organic matter (normally more than 60 percent in China) would be aerobically treated in composting machines within twenty-four hours. The organics could be reduced to 70 percent wet weight, with a resulting nutrient content has been estimated at $N = 0.294\text{--}0.848$ mg per kg; $P_2O_5 = 0.499\text{--}1.105$ mg per kg; $K_2O = 0.274\text{--}0.899$ mg per kg. This compost could then be applied as a sound organic fertilizer.

On the city scale, material recycling centers for papers, plastics, metals, etc., could be established to supply recycling services and reverse logistics for nearby communities. Regional composters could also be established for the communities that do not have enough space for decentralized waste management.

5. Conclusions

In summary, the UEI framework takes into account the biotic and abiotic interactions within an ecosystem emphasizes the connections among species (including humans) and the conservation of wildlife. It stresses a functional relationship between artificial systems and natural systems, links the grey, blue, and green infrastructures, and integrates these infrastructures via exits and arteries. It can improve the circulation and reuse of resources throughout the urban ecosystem. A comprehensive urban ecological infrastructure facilitates more rational urban development, and improves urban ecosystem services and regional sustainability.

Under the UEI framework, cities represent integrated holistic ecosystems. UEI construction provides the foundation for sustainable urban development and a suitable quality of life for urban residents. Therefore, the development of a forward-looking, integrated UEI is essential for sustainable urban systems. It is necessary to have unified planning, design, construction, and management of blue, green, and grey land, and their integration with exits and arteries, is necessary. No component can be isolated or have an independent infrastructure; rather, each must function in combination with the other components to provide multiple benefits and high resource-utilization efficiency. For instance, the organic combination and complementarity of wetlands, green space, permeable pavements, ecological corridors, drainage pipelines and arteries can reduce the risk of flood disasters while also improving the management of water resources.

In spite of the merits of ecological infrastructure, however, there are limitations. UEIs are based on understanding of the urban systems and how each component works in the complex urban system. Although understanding the form and function of UEIs is an important first step, innovative strategies must address challenging obstacles such as rigid thinking, institutional fragmentation and inflexible policies. New thinking and new ways of acting will be required to provide a more resilient, stable, and sustainable urban system.

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