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Developing a Science of Infrastructure Ecology for Sustainable Urban Systems

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Over half of the world's population now lives in cities and this figure may reach 60% by 2030.[1] Although urban centers have become a primary driver of resource consumption and waste production, they are also key leverage points in our efforts to foster a sustainable society. Engineering research has conceptualized and modeled cities as an organismic metabolism, consuming energy and materials, metabolizing them, and generating emissions and waste.[2] But through this material and energy flow analysis, the specific complex interactions *between* infrastructure systems that shape these flows remain poorly understood. In fact, the urban metabolism analogy often obscures the critical processes because unlike organisms (but like ecosystems), cities are complex systems that are not under central control, have no true equilibrium state, and do not have a particular developmental end point.[3] Understanding the city as ecosystem requires knowledge of how human and natural infrastructure systems interact to create the emergent properties. This includes engineering infrastructure systems and their cointeraction (e.g., water–energy nexus), but also a variety of other "infrastructures", including ecological infrastructure, information and communications technology (ICT) infrastructure, socio-economic infrastructure (e.g., banking, finance) and social network infrastructure (Figure 1). Understanding how these infrastructures interact with each other and how city-level properties emerge from such underlying interactions is fundamental to the design, development, and operation of sustainable urban systems.

Recently, ecological hierarchy theory has been applied to cities, leading to some striking observations and new models.[4] Like ecosystems, different mechanisms may govern interactions across different scales within cities, to confer resilience and adaptability. Whereas analogies to ecosystems have guided analysis, in very few cases have ecological principles been used to provide an understanding of the potential mechanisms. For instance, although food web models have been used to trace material and energy flows among components within cities, principles that relate to how food web architecture scales with size have not been applied or examined. Similarly, stability and resilience of ecological food webs are related to specific ecological mechanisms,[5] which also have not been examined for urban infrastructure.

Evidence thus suggests analogies to ecological systems may reveal new ways to analyze urban systems and provide design and decision guidelines for sustainable cities. We propose the concept of ***infrastructure ecology*** as a way to analyze, via analogical mapping of urban to natural systems, the complex interdependence of urban infrastructure systems, as broadly conceived above.

We offer the following fundamental research questions to foster the science of infrastructure ecology:

- **What theories and models in ecology can help us foster the sustainability of urban infrastructure systems?** In order to determine if and how ecological principles are useful in the reorganization of infrastructure systems, we need to translate ecological properties and representations (e.g., food web models) into similar models for infrastructure systems. Mapping knowledge from the ecological domain to engineering analysis of urban infrastructure raises a number of fundamental questions: How do we define "species" and functional diversity in urban infrastructure systems? What do human and infrastructure networks look like? What are their attributes (e.g., geometric diameter, algebraic connectiveness), and can comparisons to

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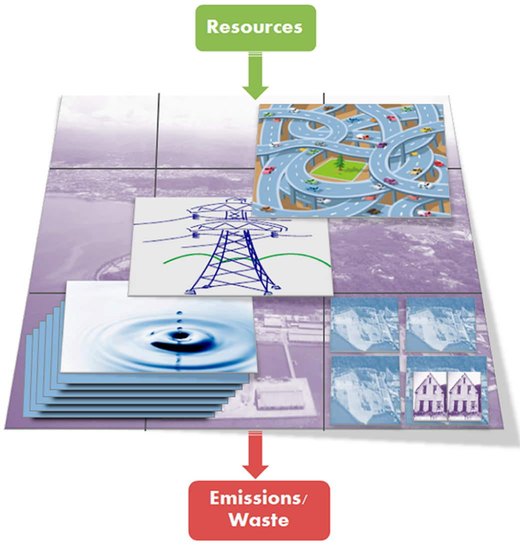

Figure 1. The ecology of urban infrastructure systems.

ecological systems facilitate better design rules and decision guidelines? How do we relate the key ecological concept of interaction strength to infrastructure systems? How do we characterize the food web architecture in infrastructure systems? How do we express multi-regime resilience of ecological systems for infrastructure systems? Are there other ecological models for the exchange of material and energy in urban systems aside from food webs?

- **What data do we need to characterize the ecology of urban infrastructure systems?** Scaling analysis (i.e., the relationship of variables with some measure of size or scale) has provided insight into governing processes in ecological and biological systems. Metrics studied mainly include social and economic variables. Although these scaling rules seem to be robust across cities of different sizes and from different regions, much more infrastructure sustainability-related data need to be collected and analyzed to test this hypothesis. In addition to robust regularities across cities, local dynamics always exist and are equally important because they may shape and govern location-specific processes. In fact, it may be necessary to define scalar hierarchies for infrastructure systems similar to that shown useful for analyzing ecological systems. That is, we need to understand how different processes work across different geographic scales.
- **How does the exchange of material and energy in cities emerge from the design, development, operation, and interactions of urban infrastructure systems?** Features that seem to explain the emergence of universal regularities in ecological systems include: ecological network topology, which is nested and hierarchical; the pattern of interaction strengths; the distribution of connections among various interacting participants; and the functional diversity of the "species" in the web. These features describe the structure and properties of networks defining the system. Regularities of sustainability metrics in cities also could be explained by the structure and properties of the various infrastructure networks defining cities, and, more importantly, the interdependence of these networks. Moreover, the structure and properties of ecological networks can also explain or relate to additional emergent phenomena of ecological systems, such as resilience, stability, and adaptation, all of which are important to urban systems.
- **How can we reorganize infrastructure ecology for more sustainable and resilient urban infrastructure?** To better understand how infrastructure systems should be designed, constructed, and managed for sustainability, resilience, and adaptability we need to develop theories and models for infrastructure ecology that can be tested in real-world cities. Comparable case studies would provide the empirical insights necessary to advance our understanding of urban infrastructure systems and the socio-economic context upon which these networked infrastructures function and evolve.

Understanding the increasing complexity of interdependent urban infrastructure systems requires new models, which are fundamental to providing meaningful decision support for urban sustainability. Given its fundamental role in shaping the design, development, and operation of urban infrastructure systems, the civil and environmental engineering community, through interdisciplinary collaborations that promote incorporating deep ecological principles, has a prime opportunity to lead the development of a science of infrastructure ecology.

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Notes

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