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Reverse Experiments

TO DEVELOP AND TEST A THEORY OF URBAN ECOLOGY AND THE ROLE that cities play on a planetary scale, we need to redefine research methods and experiments and rewrite the protocols for collecting and synthesizing data. Several methodological challenges have become evident in the study of urban ecosystems: the complex dynamics and multiple confounders in determining causal effects, the difficulty of generalizing across regions and scales, the mismatches of scale across human and ecological system domains, the lack of predictability and certainty, and the problems of defining reference conditions for coupled human-natural systems and of quantifying human well-being. The unprecedented availability of detailed data, increased computing capability, high-resolution real-time sensors, and widespread mobile communication offers unique opportunities to meet these challenges. This chapter discusses the idea of designing studies as reverse experiments through which we can learn how urban ecosystems function, evolve, and succeed.

Inverse Problems

Studying urban ecosystems poses new challenges to ecology. The complex interplay between natural and human systems is one such challenge. A major problem is that most of the variables and interactions driving ecosystem function in urbanizing regions are not known. Even more challenging is the fact that scientists have yet to define and describe what constitutes a functioning urban ecosystem.

Urban ecosystems are complex coupled human-natural systems in which organisms and communities interact according to mechanisms and rules not fully explained in ecosystem ecology. Evidence from an increasing number of studies indicates that the assumptions of traditional theories in ecology (e.g., the disturbance hypothesis, in which humans are not included as agents) and social science (e.g., the idea that rational agents interact through efficient and stable markets) do not hold. To understand such systems, it may be necessary to both revise concepts of ecosystem function, stability, and optimality and develop new definitions of the ecosystem concept (O'Neill 2001), its dynamics (Pickett et al. 2011), and evolutionary feedbacks (Alberti 2015). We must redefine our research approaches, methods, and experiments.

In urban ecology, we face what geophysicists call inverse problems. An inverse problem is one whose initial inputs are a collection of observed measurements that are used to infer a model (or models) of the governing system that generated the outcomes; this model is the solution to the inverse problem. To explain the nature of inverse problems, the Russian mathematician Sergey Kabanikhin (2008) pointed to the way our brain uses previous experience to reconstruct an image by interpolating the limited information our eyes provide. Similarly, if we have accumulated prior information through experience, we are far less likely to make errors in interpreting and resolving a problem. However, when we attempt to understand complex phenomena or solve problems we have not previously encountered, the probability of error increases; hence, the solution is unstable. These are what mathematicians call ill-posed problems: problems for which more than one solution may exist (Sabatier 2000).

Inverse problems are intrinsic to urban ecology. Over the centuries, human societies have experienced and learned to deal with new challenges (e.g., access to clean water, poor sanitation, and air pollution) posed by the transition to urban life. But the scale and pace of current urbanization are unparalleled in the history of humanity and Planet Earth. Most current problems that local communities face in cities are new for humanity. Equally unprecedented are the scientific and policy challenges that the emergent problems pose, especially in the face of rapid climate change. What makes urban communities resilient to extreme climate events? How can we best prepare for, and mitigate, potential impacts? How can we adapt to new conditions?

Inverse methods aim to reconstruct phenomena that are difficult to observe or measure directly but which can be inferred from available observations. Scientists have documented several examples of regime shifts in ecosystems, such as the transition from a coral reef to an algae reef, from a tropical forest to a grassland, or from clear water to eutrophication. We still do not fully understand the emergence of regime shifts and their potential effects on urban ecosystems. What, for example, are the processes through which biogeochemical and human activities, coupled with the built infrastructure, lead to urban water eutrophication or catastrophic flooding events?

In studying the Earth, geophysicists seek to determine a continuous function of the space variables representing the Earth's properties with infinitely many degrees of freedom, as Snieder and Trampert (1999) pointed out. Yet, real experiments can result in only a finite number of measurements, which implies a finite data space: mathematically, the solution is not unique. In urban ecosystems, complex patterns and processes, multiple levels of organizations, and multiple causes of phenomena are intrinsic characteristics. History plays a significant role: such systems may be simultaneously contingent on their past state and on current conditions (Gould 1980). Thus, experiments designed to tease out a single cause may not be appropriate (W. C. Thompson 1989).

Studying an inverse problem is particularly complex given that the solution is unstable, and small errors in data cause large changes in inferred explanation (G. King 1997). Furthermore, investigators make assumptions about sampling, measurement error, and probability distributions to approximate a solution that may lead to divergent results (Biondi 2014). As compared to well-defined problems, which may be solved by using a set of preestablished operations, the processes involved in solving inverse problems are far more complicated and challenging (Hayes 1989).

In complex systems, causality is an inverse problem: that is, multiple causes may produce the same effect, so we cannot rely on traditional inferential approaches. To solve an inverse problem may require using observations to infer the values of some parameters. But observations should be used only to determine that possible solutions are false, not to deduce any particular solution (Tarantola 2006). In solving inverse problems with multiple possible solutions, observations can help us to identify a set of possible causes or forward model solutions, rather than a best solution, and to develop a scheme of multiple testable hypotheses

(Gomez-Ramirez 2013). Using a Bayesian approach, which relies on prior knowledge to predict future events, Tarantola (2006) suggested that we can start from prior information to sequentially create an infinite number of models to be formally tested using new information.

Inverse thinking aims to uncover the underlying principles governing a complex system and to build robust models in the face of uncertainty and complexity (Gomez-Ramirez and Sanz 2013; Tarantola 2006). A Bayesian approach allows us to deal with uncertainty in inverse problems by using new information to update the probability distribution for the variable of interest from prior to posterior (Gomez-Ramirez and Sanz 2013; Iglesias and Stuart 2014). Monte Carlo–Markov Chain (MCMC) methods are a powerful tool for applying this approach to ecosystem modeling. However, we may need to develop specific MCMC algorithms in order to use Bayesian inverse methods with complex ecological models that have large numbers of parameters (Dowd and Meyer 2003).

The idea of starting from data to build models does not imply that urban ecology should rely exclusively on inductive reasoning. It simply establishes a starting point for developing an iterative process that more effectively combines inductive and deductive reasoning. In a recent article in *BioScience*, Marquet et al. (2014) suggested an essential first step toward achieving a new level of integration in ecology: we must develop greater balance between inductive and deductive approaches. Ecological research has been dominated primarily by inductive approaches, a tendency exacerbated in recent years by the rapid development of technologies and big data (e.g., the availability of complete genomes and metagenomes). Expanding the role of theory and developing "efficient theories" (Marquet et al. 2014) are both critical to advancing integration and achieving synthesis in ecology.

Designing Experiments

Much debate is emerging in urban ecology about the nature of experiments and the challenges to research design. The hybrid nature of urban ecosystems makes them inherently unstable and uncertain, which leads to fundamental questions: What governs stability and resilience in urban ecosystems? How can we design an experiment to address this question?

A possible strategy for rethinking the role of experimental studies in urban ecosystems is to build on the concept of inverse problems and inverse modeling to design reverse experiments. While most experiments start with a research question and testable hypotheses about how the world works, a reverse experiment starts with the real world and asks, “What do I see?” or “What works?”

In principle, real-world observations provide us with clues about the structure and function of a given system. Scientists use these clues to conceptualize observed phenomena and organize available data to both explain existing observations and make future predictions (Marquet et al. 2014). But conceptualizations do not occur in a vacuum. In studying urban ecosystems, we build on concepts and theories of ecology. And yet assumptions regarding key properties (e.g., spatial and temporal heterogeneity) of ecological systems will need to be revised to account for the dynamic interactions between human and natural systems as they occur in cities. Furthermore, the dynamics of urbanizing regions depend on multiple processes operating over multiple scales. This fact has significant implications for research design.

The stability and resilience of urban ecosystems are difficult to study via an experimental approach. Studying regime shifts and system resilience implies relying on reconstructions and proxy records; in such studies, incomplete information is used to infer the underlying parameters and processes governing system dynamics. In fact, only a few aspects of stability or resilience have been studied experimentally or quasi-experimentally, and theories and experiments are often mismatched, so the tests are inconclusive (Ives and Carpenter 2007).

Inferring the future of urban ecosystems poses significant challenges to scientific research (Coreau et al. 2010). Science requires that hypotheses be formulated and tested through experiments (Aligica 2003). But experiments cannot be conducted in future studies since patterns and processes cannot be observed. Even when we rely on past observations, we must draw an important distinction between observational and experimental research (Biondi 2014). In observational studies, investigators cannot randomly assign treatments to subjects; therefore, the potential differences in starting conditions lead to potential bias in the estimates. This is known as Simpson’s paradox (Pearl 2009).

Several factors challenge our ability to predict future conditions in coupled human-natural systems (Coreau et al. 2009). In a recent review of the literature, Coreau et al. (2010) identified some key challenges of predictive modeling and emerging approaches. The first is the complexity of coupled human-natural systems: their nonlinear dynamics, including threshold effects, spatial and temporal heterogeneity, and/or interactions between scales and processes (Carpenter and Brock 2004; Liu et al. 2007a). Also, studying complex systems often implies sample sizes too small for statistical generalization of probabilistic behaviors. And it may not always be realistic to rely on historical data and assume that current dynamics and relationships hold across time. Finally, uncertainties about drivers of changes can have major consequences for the possible futures of such systems (Carpenter 2002).

The key role of spatial heterogeneity in maintaining ecosystem function has long been recognized by landscape ecologists who challenged the traditional assumptions of homogeneity made in previous ecological studies (M. G. Turner 1987). In urban ecosystems, key properties, such as heterogeneity and connectivity, pose new challenges to those designing experiments, as both these properties have multiple sources and vary with the scale of observation. Yet such complexity cannot be disregarded since it has critical implications for the functioning and stability of such systems (Roff 1974).

Consider, for example, the heterogeneity of patch types, shapes, and sizes resulting from intermixed land uses in urban regions or the reconfiguration of resource flows and natural networks emerging from the development of built infrastructure. Despite the increasing emphasis on spatially explicit approaches to characterizing natural environments, most ecological experiments in human-dominated systems assume that space is homogeneous when they characterize the human component within the spatial social unit in order to focus primarily on emergent properties. And yet it is that internal heterogeneity, or the interplay among different heterogeneous elements, that controls system function and change.

The sources of heterogeneity and its emerging patterns in urban ecosystems also vary with scale (Pickett et al. 2008). At a finer resolution, land cover, patch type, form, and size are controlled by household preference and may reflect the demographic heterogeneity of households across diverse neighborhoods. At the city or regional scale, they may be controlled by collective behavior that drives choices about transportation or storm-water infrastructure. Furthermore, we only partially understand how human sources of heterogeneity interact with ecosystem functions in human-dominated systems, which poses additional challenges to experiment design and suggests that an exploratory approach and advanced sensitivity analyses may be more appropriate.

When we consider how human processes alter key properties of ecosystems, we see the need for important changes in both ecosystem theory and methodology.

Success Stories

Building on the concept of inverse problems and inverse modeling, we could use "success stories" to start to define *function* and *stability* in urban ecosystems. An example is seen in the study of resilience and system shifts. The design of a reverse experiment starts with the real world and asks, "What characterizes robust systems?" Resilience studies rely on the assumption that we know how ecosystems and societies maintain their functions in a given state and prevent themselves from moving into an alternative state. When a system shift occurs, or when what we expect to work does not, we define and test hypotheses about what failed, beginning with the assumptions we have made about how the system works. We design experiments with the assumption that we know how a system works and that we know its drivers, controlling variables, and boundary and reference conditions.

But when we are dealing with complex and relatively unknown hybrid systems, it is most likely that we have not identified some (or many) of the important elements at work. What if we are missing some fundamental rules or the most general principles governing the targets of our investigation? To understand resilience in urban ecosystems, a reverse experimental approach may prove more appropriate to tackling questions and could provide a road map. Such an approach could enable investigators to address questions about a broad range of topics—from the resilience of a specific system infrastructure supporting essential urban services (e.g., water supply, wastewater, and power) to the resilience of local communities.

As examples, consider the following: What enabled the community of Cedar Rapids, Iowa, to respond effectively to a vast flood, or residents of

New York and New Jersey to respond to the devastating Hurricane Sandy? What explains the capacity of communities such as New Orleans to recover from dramatic and devastating natural disasters? Are there general system properties that explain system and community resilience?

To begin to address such questions, we can articulate testable hypotheses regarding fundamental properties and principles governing the dynamics, stability, and evolvability of complex systems and networks (e.g., biological, ecological, and economic systems). As I discuss in chapters 4 and 10, studies of complex systems are revealing that systems that are more heterogeneous and modular tend to be better able to adapt compared to those whose elements are highly connected and homogeneous (Scheffer et al. 2012). Other properties of complex systems that have been posited to enhance adaptive capacity and innovation are cross-scale interaction, early warning mechanisms, and self-organization (Walker et al. 2004).

Do these properties explain community response and resilience to extreme events? Traditional design, whether experimental or quasi-experimental, requires that we observe randomly selected communities that vary with respect to these four properties over time, and/or that we have records of their response capacity before and after disaster events. Yet this approach implies that we can accurately describe key system structures and dynamics. An alternative approach would ask the same questions by exploring patterns, variability, and discontinuities that can be detected at multiple scales of space and time across communities that vary in their responses to disasters and their resilience to extreme events.

Institutional structure can play a significant role in determining the ability of communities to adapt to change. The ability of institutional capacity to change and adapt over time may be even more significant in socioecological systems. Empirical evidence reveals that a community's capacity to adapt to a new system state through increased resilience or transformation is not a short-term process; rather, it emerges over the course of years. Historical and present examples of societal planning and action in response to urban environmental stresses provide opportunities to analyze connections between resilience and transformation. Major success stories result from proactive organizations, both formal and informal, that have been able to anticipate critical transitions and expand the reference time frame of decisions.

Communities' ability to effectively incorporate uncertainty into decision-making is a key component of institutional adaptive capacity. It is possible only to predict some potential regime shifts that can result from the interaction of uncertain climate change trajectories and urbanization. Emerging research on early warnings points to signals (such as critical slowing) within complex systems that can be read to detect looming thresholds and regime shifts, but our current understanding and monitoring of potential warning signals are extremely limited. However, many communities have succeeded in adopting policies, routing investment decisions, and implementing strategies to anticipate natural disasters and reduce their vulnerabilities.

London, for example, has pioneered planning for adaptation to climate change through several innovative strategies. Since 2002, the London Climate Change Partnership has brought together experts in the environment, finance, health, development, housing, government, utilities, and communication. In 2002, the UK Environment Agency initiated the Thames Estuary 2100 Project (TE2100), intended to identify the next generation of strategic options for London and the Thames Estuary to manage escalating risks of tidal floods throughout this century. The TE2100 developed "decision adaptation pathways" (see chapter 10, box 10.1) to provide a flexible approach to accounting for the uncertainty inherent in climate change predictions. In October 2011, the city adopted its Climate Change Adaptation Strategy, a strategic framework designed to simultaneously enhance the quality of life in London and protect the environment.

Rotterdam is also among the first cities to develop and adopt a strategy to "future-proof" itself. As early as 2008, Rotterdam began exploring and designing a series of interventions to ensure that its water would remain safe and accessible and to keep the city infrastructure robust as the basis for urban development. At the same time, Copenhagen adopted drastic measures to cut CO_2 emissions and began positioning itself to become the world's first carbon-neutral city. In 2011, it also adopted measures to deal with extreme rainfall events.

The city of New York has led recent initiatives to build resilient strategies to counter extreme climate events. In response to Hurricane Sandy, New York launched a Special Initiative for Rebuilding and Resiliency (SIRR). The initiative is a major update of PlaNYC, Mayor Michael Bloomberg's major sustainability effort, which began in 2007 and is intended to address the critical interplay among an increasing population, climate change, and an aging infrastructure (see chapter 10, box 10.1). In June 2013, the city released a comprehensive report (New York City 2013) detailing a series of strategies that address coastal protection, buildings, health services, and critical infrastructure, at an estimated total cost of $20 billion.

On November 1, 2013, the city of Da Nang, Vietnam, adopted a new policy in its post-typhoon recovery support programs for damaged households. It requires that all new housing construction in the city incorporate key resilience principles, such as storm-resistant construction techniques. This success stems directly from the Storm and Flood-Resistant Credit and Housing Scheme in Da Nang City, a microcredit and technical assistance program aimed at developing storm-resistant shelters in vulnerable districts of the city.

Researchers claim that institutional change is required if communities are to manage the effects of climate change in general, and of sea level rise in particular (Biesbroek et al. 2013; Moser and Ekstrom 2010). But how can institutional innovation and change in coupled human-natural systems occur and relate to global change? This is not well understood. Numerous multistakeholder and multiscale efforts are developing strategies to help communities adapt to anticipated climate change. Agencies are setting targets, developing policies, readjusting interagency agreements, reviewing planning rules and processes, and funding projects whose successes hinge on interactions between uncertain future climate changes and equally uncertain institutional feedbacks.

Key questions emerge: What are the drivers of institutional innovation and change? How do scale-bound organizations address multiscale issues? Under which conditions can stakeholder processes best support the development of alternative institutional designs that facilitate effective adaptation, including more cooperative ways to manage commonly pooled resources? Building upon evidence from successful examples of institutional responses, we can begin to articulate and test hypotheses about the mechanisms that strengthen institutions' capacities to adapt to climate changes through careful modifications of institutional, legislative, and regulatory controls.

Big Data and Emerging Technologies

In principle, the changing nature of available data, monitoring instruments, and computing capacity should yield increasingly sophisticated designs and experiments. In particular, we can more realistically represent complex processes and interactions among a variety of variables by reducing the historic problems of oversimplification, inappropriate assumptions, and imprecise calibrations based on noisy data. Although improvements in data can only partly address central issues in experimental design, big data and emerging technologies do provide new opportunities to use data-mining techniques and conduct retrospective analyses that could better support inverse modeling. But data answer questions that we are able to formulate. They cannot answer questions that we are not asking.

A new paradigm in ecological science is necessary to address some of the challenges that urban ecosystems pose. Pickett, Kolasa, and Jones (2010) saw the emergent philosophy of science and its pluralistic view as an opportunity to advance ecological understanding by clarifying the goals of science, the role of theory, and the practice of scientific research. Insights from contemporary philosophy offer a new perspective for integrating multiple viewpoints and address key gaps in ecological understanding that result from the development of separate subdisciplines. Furthermore, the combination of advances in data and the development of new tools provides novel opportunities for such integration.

Urban Sensors and Observatories

Sensory perception allows living organisms to engage their environment—to perceive threats and discover resources—and thus to survive. Reverse problems require sophisticated sensors. Recent advances in high-resolution, mobile, ubiquitous sensor equipment suggest promising means of accelerating our capacity to observe urban systems and their functions by collecting and processing large amounts of highly detailed data in real time. But utilizing such tools will require us to develop advanced analytical methods that incorporate elements of machine learning, data mining, Bayesian statistics, social networks, and other experimental approaches.

Novel urban scale monitoring systems need to be deployed to collect a variety of data at the appropriate space and time scale to realistically represent the complexity of urban structures and processes. Advances in remote-sensing technologies and development of high-resolution data provide unprecedented opportunities to answer complex cross-disciplinary questions about urban systems. High-resolution nighttime light images from remote sensors could dynamically and precisely monitor boundary changes of urban built-up areas. Globally available sources are the nighttime light (NTL) data collected by the Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-Orbiting Partnership (Suomi NPP).

The ability to sense potential threats or impending changes in the environment has evolved throughout human history, and our ability to anticipate adverse events has gradually improved. A well-known historical example is the use of canaries in mines to signal dangerous levels of toxic gases. New sensing technologies have the potential to provide a variety of early warnings for local communities. But they can also expand our sensory capacity from the perception of merely local and immediate threats to the recognition of larger potential threats associated with global and long-term change. Global and distributed networks of urban sensors and observatories are critical but not sufficient for establishing a robust infrastructure of urban sentinels. Urban ecology will need to build a new intellectual capacity and analytical framework in order to develop and execute powerful reverse experiments.

From Experiments to Practice

Real-world problems may require action in the absence of complete information. Thinking backward from problems to data can help us to filter and prioritize our data requirements and to design experiments that target emerging policy-relevant questions, thus facilitating the translation of scientific knowledge into practice. By starting with observed problems as they design their experiments, scientists may better inform planning and design as they test the efficacy of design and management strategies and thus narrow gaps between science and practice (Grose 2014).

Broadening the objectives of science and acknowledging the plurality of approaches to defining scientific questions does not imply that all scientific questions should emerge from our current understanding of problems. In fact, scientific discovery may very well revolutionize the way that societies define or understand problems. However, real-world problems provide unique perspectives—a set of lenses for defining scientific questions—and thus a direct path between a science of cities and city-building. The multiplicity of solutions inherent in inverse problems captures current understanding of the complexity and unpredictable behaviors of urban ecosystems that lead to emergent properties (ibid.). Furthermore, the city is an excellent laboratory in which to observe general properties of urban systems and to test theories of urban dynamics.

Defining urban problems, however, is hardly a trivial undertaking. To formulate questions relevant to the practice of city-building, a large and diverse group of agents must be involved and must share in defining the problem. This is a complex task, requiring shared language among multiple stakeholders and the resolution of conflicts that are likely to emerge. Yet a shared definition of the problem is key to establishing two-way communication between science and practice.

Alternative views of experiments can also strengthen the relationship between scientific research and the practice of urban planning and management. One such approach is joint fact-finding (JFF), an emerging strategy for building shared understandings of complex socioecological systems that consists of a procedure used for collaborative decision-making in public policy (Hanna and Slocombe 2007; Susskind, McKearnen, and Thomas-Lamar 1999). JFF informs science-intensive public disputes by bringing a scientific team into the collaborative process and simultaneously builds public credibility for its scientific findings. Ozawa and Susskind (1985) first described JFF as a way to mediate science-intensive policy disputes, and it has since received attention in the fields of conflict resolution, adaptive management, policy studies, and decision sciences (Andrews 2002; Ehrman and Stinson 1999; Ozawa 1991; Susskind and Cruikshank 1987). Its commonly stated goal is to produce agreed-upon information, regardless of the ideological or personal interests of particular analysts or stakeholders (Susskind and Zion 2002).

Another emerging approach that has been used in urban design and planning is to connect scientific expertise with practical urban design through design experiments. Felson, Bradford, and Oldfield (2013) described a series of projects that embed ecological research into urban and landscape design in order to use scientific knowledge effectively. Bringing scientists into the context of design may allow researchers to engage directly in managing and shaping urban systems (ibid.).

Urban decision-makers increasingly recognize that scientific evidence is pivotal to ensuring robust solutions to the complex problems they face. Simultaneously, scientists have begun to realize that if science is to play an effective role in decision-making and practice, they must engage directly and interactively with decision-makers and the public. While policy and science inherently differ in both aims and procedures, all parties appreciate the value of producing knowledge that can effectively support complex decisions to address emerging environmental problems, and understand that such knowledge production requires collaboration among scientists, policymakers, and other actors (Cash et al. 2003; Hegger et al. 2012; Van den Hove 2007; Van Kerkhoff and Lebel 2006). Such collaboration ensures that all parties gain ownership of the process of developing, selecting, and implementing design solutions and of planning strategies (Hirsch Hadorn, Biber-Klemm, and Grossenbacher-Mansuy 2008; Wiesmann et al. 2008).

This approach to joint production of knowledge has received positive attention in recent efforts to mitigate and adapt to rapid climate change. Diverse social actors provide unique and essential contributions to the process of knowledge production in order to support adaptation strategies that succeed (Ostrom 1996, 2009). Among the most critical tasks facing the diverse array of agents of knowledge production are to redefine scientific questions and to challenge the methods of research.

Box 7.1. Inverse Modeling

An inverse modeling approach is designed to model a system whose dynamics are unknown. In such a system, the order of cause and effect is reversed: the observer starts from the effects in order to identify the set of rules that govern the evolution of the system. Using, as an example, the study of resilience in urban ecosystems, we can identify four key steps for developing inverse modeling. An urban ecosystem's resilience to climate change (e.g., extreme climatic events) can be conceptualized as an inverse problem and modeled as follows:

1. Alternative system responses. The first step is to identify critical exposures to potential regime shifts that may affect urban ecosystem functions and system stability by examining documented cases of regime responses to extreme events and regime shifts (e.g., changes in hydrological regimes and eutrophication of urban waters). Mapping the exposures and vulnerabilities of different ecosystem functions to critical exposures will allow researchers to characterize alternative system responses.
2. Slow and fast variables. The second step is to transform the identified regimes into critical environmental conditions and to identify the key slow and fast variables governing responses (e.g., extreme flooding events and droughts). Using a series of modeling applications, inverse linkages between the established observations and a series of hypothetical mechanisms governing the resilience of urban ecosystems can then be established.
3. Model testing. The third step is to test the hypothetical mechanisms, using existing data and expert knowledge to upgrade the model by combining both prior information on urban ecosystem dynamics and existing knowledge (earlier measurements) about uncertain parameters.
4. Alternative scenarios. Finally, using a series of alternative scenarios, researchers can expand the boundary conditions of forward models to assess how hypothesized mechanisms might generate alternative trajectories and to what extent those trajectories might diverge from present conditions. ●