

城市绿色基础设施 韧性设计范式转型探索

EXPLORATION OF RESILIENT DESIGN PARADIGM OF URBAN GREEN INFRASTRUCTURE



栾博

北京大学深圳研究院绿色基础设施研究所所长，环境科学博士，高级工程师

LUAN Bo

Director at Green Infrastructure Institute of Peking University Shenzhen Institute; PhD in Environmental Sciences, Peking University; Senior Engineer



丁戎

中国城市规划设计研究院风景园林分院高级工程师，注册城乡规划师

DING Rong

Senior Engineer of Landscape Architecture Institute of China Academy of Urban Planning and Design; Registered Urban and Rural Planner

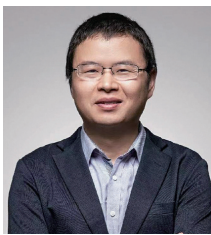


王鑫

北京大学深圳研究院绿色基础设施研究所执行副所长，北京一方天地环境景观规划设计咨询有限公司总经理，高级工程师

WANG Xin

Deputy Director at Green Infrastructure Institute of Peking University Shenzhen Institute; General Manager at Yifang Ecoscape; Senior Engineer



祝明建*

华南理工大学设计学院副教授

ZHU Mingjian

Associate Professor of School of Design, South China University of Technology

*通讯作者

地址：广东省广州市番禺区大学城华南理工大学B11中305-2

邮编：510006

邮箱：zhumj@scut.edu.cn

摘要

城市绿色基础设施是支撑基于自然的韧性城市的重要结构，目前普遍采用的以确定性控制为导向的传统设计范式不利于促进城市韧性，绿色基础设施设计范式亟待转型。本文基于文献研究，围绕韧性设计范式展开探讨。首先，提出城市绿色基础设施的韧性作用框架，为设计范式转型提供基础共识；其次，归纳韧性驱动机制，为构建韧性设计范式提供关键依据；最后，基于适应性途径建立韧性设计范式，提出全过程动态循环模型，为城市绿色基础设施动态优化配置提供方法支撑。本文所提出的韧性设计范式的建立涉及思维观念、设计流程、项目管理、工程质量验收等方面，更需要设计师、工程师、研究者、决策者及公众的多方努力。本文可为高绩效城市绿色基础设施建设提供指导，对推动韧性城市理论发展和景观设计韧性范式转型具有借鉴价值。

关键词

绿色基础设施；城市韧性；韧性设计；适应性设计；不确定性；基于自然的解决方案；动态优化

ABSTRACT

Urban green infrastructure is a fundamental physical structure that supports the construction of resilient cities based on nature. Currently, the conventional design paradigm oriented by deterministic control is not conducive to promoting urban resilience, and the design paradigm of green infrastructure is in urgent need of transformation. Based on literature review, this article discusses the establishment of resilient design paradigm: first, it proposes the common ground of the resilient design paradigm by establishing a framework for the resilience mechanism of urban green infrastructure; then it summarizes the resilience driving mechanism to provide the key basis for the resilience design paradigm; and finally, this article devises the resilient design paradigm based on adaptive approaches and proposes the whole-process dynamic cyclic model to guide the configuration optimization of urban green infrastructure. The establishment of the design paradigm relies on the shift in mindset, concept, design procedure, project management, quality inspection, etc., which requires the joint efforts by designers, engineers, researchers, decision makers, and the public. This article is expected to provide references not only to the construction of green infrastructure to support the high-performance of urban resilience, but also to the theory development of resilient city and the resilient design paradigm of landscape design.

KEYWORDS

Green Infrastructure; Urban Resilience; Resilient Design; Adaptive Design; Uncertainty; Nature-Based Solution; Dynamic Optimization

基金项目

国家自然科学基金项目“海岸带城市绿色空间的韧性驱动机制研究——以粤港澳大湾区为例”（编号：52078004）

广东省基础与应用基础研究基金项目“海平面上升对广东省沿海自然栖息地的影响及适应性保护规划策略研究”（编号：2020A1515011072）

华南理工大学中央高校基本科研业务费专项资金资助“适应气候变化的生态保护与城市发展优先区规划研究”（编号：D2200820）

RESEARCH FUNDS

Study on the Driving Mechanism of Resilience of Green Space in Coastal Cities: A Case Study of GBA, National Natural Science Foundation of China (No. 52078004)

Study on the Impacts of Sea Level Rise on Coastal Natural Habitats in Guangdong Province and Adaptive Conservation Planning Strategies, Guangdong Basic and Applied Basic Research Foundation (No. 2020A1515011072)

Study on the Identification of Conservation and Urban Development Priority Areas Adaptive to Climate Change, the Fundamental Research Funds for the Central Universities, SCUT (No. D2200820)

编辑 田晓劼 崔婧云 翻译 田晓劼 田乐 肖杰

EDITED BY TIAN Xiaojie CUI Jingyun TRANSLATED BY TIAN Xiaojie Tina TIAN XIAO Jie

1 引言

随着外界不确定性和内生不可预测性的显著增加，建立在工程学基础上的刚性城市建设模式暴露出诸多不足^[1]：这样的城市系统不仅经常失效于自然和人为灾害等突发性外界扰动，受制于气候变化、环境污染、资源短缺、生态退化等趋势性外部压力，也往往因人口集聚、经济增长、土地扩张等内生需求而导致城市发展中的脆弱性与无序性现象不断叠加。由此，提升韧性已成为实现城市可持续性的必要路径，全球范围内不断涌现出各类基于自然的韧性城市范式的探索^[2]，中国也在积极推进“海绵城市”“气候适应性城市”，以及“城市双修”等理念的落实。

近年来，基于自然的解决方案（Nature-Based Solutions，简称NBS）在响应气候变化和其他不确定性问题中备受关注，它强调通过保护、修复、管理或新建生态系统，辅助、引导和利用自然生命体做功实现韧性，以适应性方式有效应对复杂挑战^{[3]-[5]}。城市绿色基础设施是韧性城市在空间上的重要结构性支撑^{[3]-[5]}，其利用自然生命体的自适应和自组织特征来应对不确定性扰动，而静态化、控制式的工程设计途径会削弱和抑制自然系统的自调节能力，在应对扰动或胁迫时显现出不足^[6]；一旦设计不当，不仅会降低城市韧性，甚至可能造成环境负担和生态系统负面服务^{[7][8]}。因此，建立有效的城市绿色基础设施韧性设计范式成为支撑韧性城市理论实践的重要课题。

本文旨在围绕韧性设计范式展开三方面的理论探讨：1）提出对城市绿色基础设施韧性设计范式的基本理解，为设计范式转型构建基础共识；2）归纳韧性驱动机制模型，为设计范式提供关键依据；3）建立韧性设计全过程模型，为城市绿色基础设施的动态优化配置提供有效指导。

2 城市绿色基础设施与城市韧性

2.1 韧性概念演变

目前，韧性设计已成为应对不确定性挑战的热点途径。但是，由于对“韧性”概念的理解模糊，业界尚未就绿色基础设施设计的韧性

1 Introduction

Today, cities shaped in an engineering-based rigid urban construction pattern are challenged by both the increasing external uncertainties and internal unpredictability^[1]: urban systems are impacted not only by external disturbances (e.g. natural and man-made disasters) and external pressure (e.g. climate change, environmental pollution, resource depletion, and ecosystem degradation), but also by internal demands, such as population aggregation, economic growth, and urban sprawl. As a result, urban development suffers from a high vulnerability and disorder sprawls. A city's sustainability can be enhanced by resilience strengthening, and nature-based paradigms of resilient city is promising^[2], which has been explored worldwide and implemented under a series of concepts in China such as Sponge City, Climate-Resilient City, and Ecological Restoration and Urban Renovation.

In recent years, Nature-Based Solutions (NBS) has attracted much attention for its effectiveness responding to climate change and other uncertainties. By preserving, restoring, managing or creating ecosystems, NBS assists, guides, and uses natural organisms to improve ecosystem resilience so as to cope with complex challenges adaptively^{[3]-[5]}. Urban green infrastructure serves as a key spatial structure of resilient cities^{[3]-[5]}, responding to uncertainties with the self-adaptation and self-organization of the natural organisms; in contrast, static and control-oriented engineering design undermines or suppresses the self-regulation capacity of natural system against disturbances or threats^[6], even reducing urban resilience, increasing environmental burden, and aggravating ecosystem disservices once it is designed improperly^{[7][8]}. The establishment of resilient design paradigm of urban green infrastructure is critical to the theory and practice development of resilient city.

This article aims to explore the resilient design paradigm from three aspects: 1) propose the common ground of the resilient design paradigm of urban green infrastructure; 2) summarize the resilience driving mechanism of resilience model to provide the key basis of the design paradigm; and 3) establish the whole-process resilience model that can guide the dynamic optimization of urban green infrastructure.

2 Urban Green Infrastructure and Urban Resilience

2.1 The Evolution of Resilience

Currently, resilient design has become a widely used approach in coping with uncertainties. However, due to the vague or varied understanding of resilience, there is no

目标达成共识，制约了韧性设计范式的建构。

“韧性”一词的本意是“恢复到原始状态”^{[9][10]}。在设计领域，韧性概念经历了从“工程韧性”“生态韧性”到“社会—生态系统韧性”（或“演进韧性”）的演变^{[11]-[13]}，即从单纯强调受干扰后恢复、弹回至均衡状态，逐渐发展为强调适应扰动并在扰动中学习、转型和演进^{[14][15]}。兰斯·H·冈德森和克劳福德·S·霍林的适应性循环模型阐明循环演进是韧性的本质^[16]。由此可见，扰动是韧性演进的机会，韧性演进是应对扰动的储备过程。

“城市韧性”概念由“社会—生态系统韧性”概念衍生而来^{[17][18]}。由于城市之间的高度异质性、复杂性，以及扰动因素的多样性，城市韧性存在不同定义^[19]。在本文中，城市韧性是指城市在实现可持续性目标的过程中，抵御、吸收、适应各种不确定性扰动，并从中恢复和自我演进的能力，包含应对长期压力的发展韧性与应对急性扰动的灾害韧性。

2.2 城市绿色基础设施对城市韧性的作用

城市绿色基础设施是维护区域生态系统完整的空间途径，通过促进自然生命系统健康为城市提供必需的生态系统服务，而韧性是这些服务的一种表现形式。因此，城市绿色基础设施是驱动城市韧性、提升城市可持续性的重要结构，是城市刚性物理空间中的柔性缓冲器。

有关绿色基础设施对城市韧性作用的实证研究正在逐步成为热点。马蒂亚斯·迪缪泽尔等人基于大量实证文献研究发现，绿色基础设施能够通过固碳减排、减缓热岛效应、削减洪峰、改善水体和空气质量等减缓气候变化带来的影响^[20]。拉斐尔·拉福尔泰扎等人在总结了全球20个国家及地区的案例研究后，认为包括绿色基础设施在内的NBS是响应气候变化的有效策略，强调利用自然（而非高技术工程）具有成本—效益优势^[21]。一些学者开始关注绿色基础设施在从原料获取、设计实施、运营维护到处置回用的全生命周期中的韧性表现，并评估了特定的绿色雨水基础设施在材料获取、运输、建设、运营过程中的环境与经济影响^{[22][23]}。

从现有研究来看，基于个例的实证研究受限于不同的环境条件和规模尺度，结论欠缺普遍性；此外，所涉韧性研究集中于气候变化适应和极端灾害响应方面，对其他持续性压力和突发性事件缺乏认识。总之，绿色基础设施对城市韧性的作用机制是建立韧性设计范式的重要基础，目前尚缺乏全面而普适的理解。因此，在梳理相关文献研究的基础上^{[24][25]}，本文提出了绿色基础设施全过程韧性作用概念框架：城市绿色基础设施的韧性贡献应着眼于在全生命周期中帮助城市抵御、

commonly shared resilience goals of green infrastructure design yet, which hinders the establishment of resilient design paradigm.

Etymologically, “resilience” means “recovery to the original state.”^{[9][10]} Evolving from “engineering resilience,” “ecological resilience” to “social–ecosystem resilience” (or “evolutionary resilience”)^{[11]-[13]}, the definition of resilience has now emphasized the adaptation to disturbance, and the alteration, transformation, and evolution along the disturbance, instead of purely restoring to an equilibrium after being disturbed^{[14][15]}. Lance H. Gunderson and Crowford S. Holling come up with the adaptive cycle model demonstrating that the essence of resilience lies in cyclical evolution^[16]. Then, it can be concluded that disturbance brings about possibilities for the evolution of resilience, and in turn the evolution of resilience is a preparation process for responding to the disturbance.

The concept of urban resilience derives from social–ecosystem resilience^{[17][18]}. However, it is interpreted differently due to the heterogeneity, complexity, and diversity of the disturbances in cities^[19]. In this article, urban resilience refers to the ability to resist, absorb, adapt to, and recover from uncertain disturbances for a better urban sustainability through self-evolution. It includes the development resilience against continuous pressure and the disaster resilience against emergent disturbances.

2.2 The Role of Urban Green Infrastructure to a City's Resilience

Urban green infrastructure is crucial to maintaining the integrity of regional ecosystems, and provides essential ecosystem services for cities by improving natural ecosystem health. Resilience is another manifestation of those ecosystem services. In other words, urban green infrastructure, the flexible buffer in rigid physical environment, serves as vital structures to boost a city's resilience and sustainability.

Empirical studies on the role of urban green infrastructure to a city's resilience have been attracting a broad attention. Based on massive empirical studies, Matthias Demuzere et al. found that green infrastructure can alleviate the impact of climate change by storing carbon and reducing emission, mitigating the heat island effect, reducing flood peak, and improving water and air quality^[20]. After broad case studies among 20 countries and regions, Raffaele Laforteza et al. concluded that NBS including green infrastructure is an effective strategy to respond to climate change, since these natural solutions show obvious cost–benefit advantages over high-technology engineering measures^[21]. Scholars also examine the resilience performance of

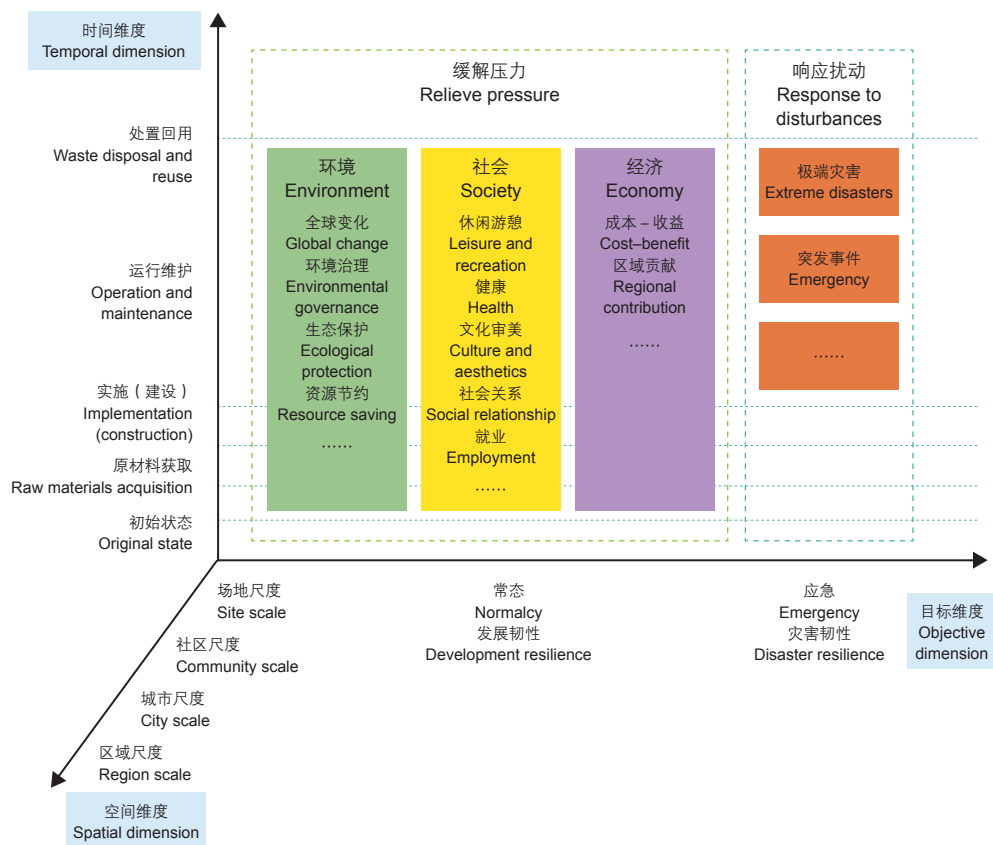


图 1
1

1. 绿色基础设施全过程韧性作用概念框架
1. The conceptual framework for the whole-life-cycle mechanism of green infrastructure to the city's resilience performance

应对、适应发展中面临的各类扰动和胁迫，并实现自我学习和演进，最终实现可持续性目标（图1）。韧性目标应体现在时间和空间两个维度上：时间维度目标是指绿色基础设施在全生命周期中具有的正常效益和应急表现；空间维度目标是指绿色基础设施能在地块、街区、城市、区域等多个尺度上发挥韧性作用。不同尺度的绿色基础设施的韧性目标基本一致，但侧重点不尽相同：宏观尺度需侧重气候变化响应等全球问题，微观尺度则更重视本地社区环境与社会问题。因此，跨尺度、相互连通的网络系统对增强绿色基础设施之于城市韧性的贡献非常重要。

绿色基础设施对城市韧性的作用可以体现在发展韧性和灾害韧性两方面。缓解城市面临的持续性压力，在低成本建设维护投入的同时，实现环境与社会效益的最大化，协同提升环境、社会、经济可持续性，是城市绿色基础设施对发展韧性的贡献，这种常态响应是帮助城市实现可持续性的基础。帮助城市抵御、吸收和适应高风险极端事件的能力是指城市绿色基础设施对灾害韧性的贡献，包括对洪水、暴雨等自然灾害的缓解和适应，以及对突发传染性疾病、恐怖袭击等公共安全危机的应对，这类应急响应对维护城市的安全底线至关重要。

城市绿色基础设施的全过程韧性作用能够影响城市可持续性：若城市绿色基础设施具有较强韧性（R+），则城市不仅能够吸收、适应扰动，而且可以在扰动中学习、提升；若韧性适中（R），则至少可帮助

green infrastructure in the whole life-cycle—from raw material acquisition, design and implementation, to operation and maintenance—and evaluate the environmental and economic impacts of certain green stormwater infrastructure during the material acquisition, transportation, construction, and operation processes^{[22][23]}.

The current empirical research based on individual cases of different environmental conditions and scales contributes little to systematic conclusions. In addition, research on the resilience of green infrastructure focuses on adaptation to climate change and extreme disaster, while lacking of a comprehensive understanding of other continuous pressures and emergencies, failing to develop holistic goals of resilient design. In short, the mechanism of green infrastructure for urban resilience is the foundation for establishing resilience design paradigm, but there is still a lack of comprehensive and universal understanding of it. Therefore, by referring to related models^{[24][25]}, this article proposes a conceptual framework for the whole-life-cycle mechanism of green infrastructure to the city's resilience performance, and argues that the resilience of green infrastructure should highlight helping cities resist, cope with, and adapt to disturbance and stress, achieving self-learning and evolution, and ultimately realizing a robust sustainability (Fig. 1). The resilience goals address the both time and space dimensions: green infrastructure should not only provide continuous benefits and be capable to respond to emergencies throughout the whole life-cycle, but also function at all the scales—from site to regional—with consistent and varied emphases. For instance, macro-scale resilience goals need to respond to global issues (such as climate change), and micro-scale ones should to deal with local environmental and social problems. Therefore, the system consists of cross-scale and inter-connected networks is crucial to promote the resilience of green infrastructure.

The role of urban green infrastructure to a city's resilience manifests in the capacity supporting urban development and responding to disasters. The former one, called as development resilience, is the capacities to relieve a city's persistent pressure to maximize environmental and social benefits with low investment, and to enhance the city's environmental, social, and economic sustainability. This capacity is vital to the city's sustainability. The later one, described as disaster resilience, is the capacity to resist, absorb, and adapt to high-risk extreme events, including natural disasters such as floods and storms, as well as public safety crises such as infectious diseases and terrorist attacks. This capacity is vital to guarantee the city's baseline of safety.

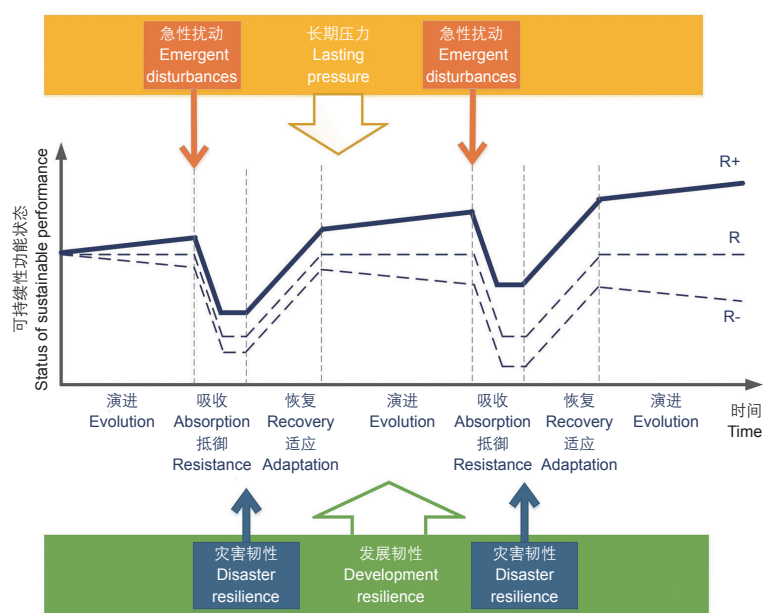
The whole life-cycle resilience of urban green infrastructure can affect urban sustainability: A city with highly-resilient (R+)

城市在经受扰动后恢复至原态；若韧性较弱（R-），不足以应对扰动或压力，城市可持续性则会减弱（图2）。由此可见，促进绿色基础设施的韧性能够促进城市可持续发展，这应成为韧性设计范式的主要目标。

3 绿色基础设施对城市韧性的驱动机制

3.1 韧性驱动机制的研究进展

建立有效的优化及调控方法是韧性设计范式的重点，而识别影响城市韧性的绿色基础设施关键配置因素及其驱动机制是设计的关键。研究发现，绿色基础设施不同类型的韧性绩效之间存在同步增减的协同关系或此消彼长的权衡关系^[26]，但导致这些协同或权衡关系的驱动机制尚待研究。以往，学界对宏观规划配置特征（如数量、面积、空间格局等）的绩效作用机制研究比较透彻，但格局内部设计配置在不确定性响应过程中的作用仍待深入研究。由此，学者们开始关注能够促进韧性协同的技术构成要素。不少学者探讨了具体设计配置与构成要素对服务绩效的影响，如玛莎·L·德克森等人对鹿特丹城市绿地的6项服务指标进行评估，发现绿地配置与构成要素对其服务绩效具有重要影响^[27]。罗毅等人基于39个建成案例的景观绩效，发现很多景观实践的环境、社会与经济效益间存在冲突，而设计配置不当是主要原因^[28]。栾博等人通过研究9种绿色雨水基础设施的组合配置情景，揭示了分散或集中、单一或组合配置方案在不同决策偏好中的绩效^[29]，并通过模型研究发现，技术组合、设计要素、材料选择是绿色基础设施配置中影响韧性协同的关键因素，使用亲自然或有生命的材料有利于提升韧



green infrastructure would have a stronger resilience (R+), and can improve its resilience by absorbing and adapting to disturbances; a city with moderately-resilient (R) green infrastructure would at least help the city recover after disturbances; and a city with weakly-resilient (R-) green infrastructure would be unable to deal with disturbances or pressure, compromising the city's sustainability (Fig. 2). Thus, the main goal of resilient design paradigm should be improving the resilience level of green infrastructure which defines the city's sustainability and future urban development.

3 The Driving Mechanism of Green Infrastructure on Urban Resilience

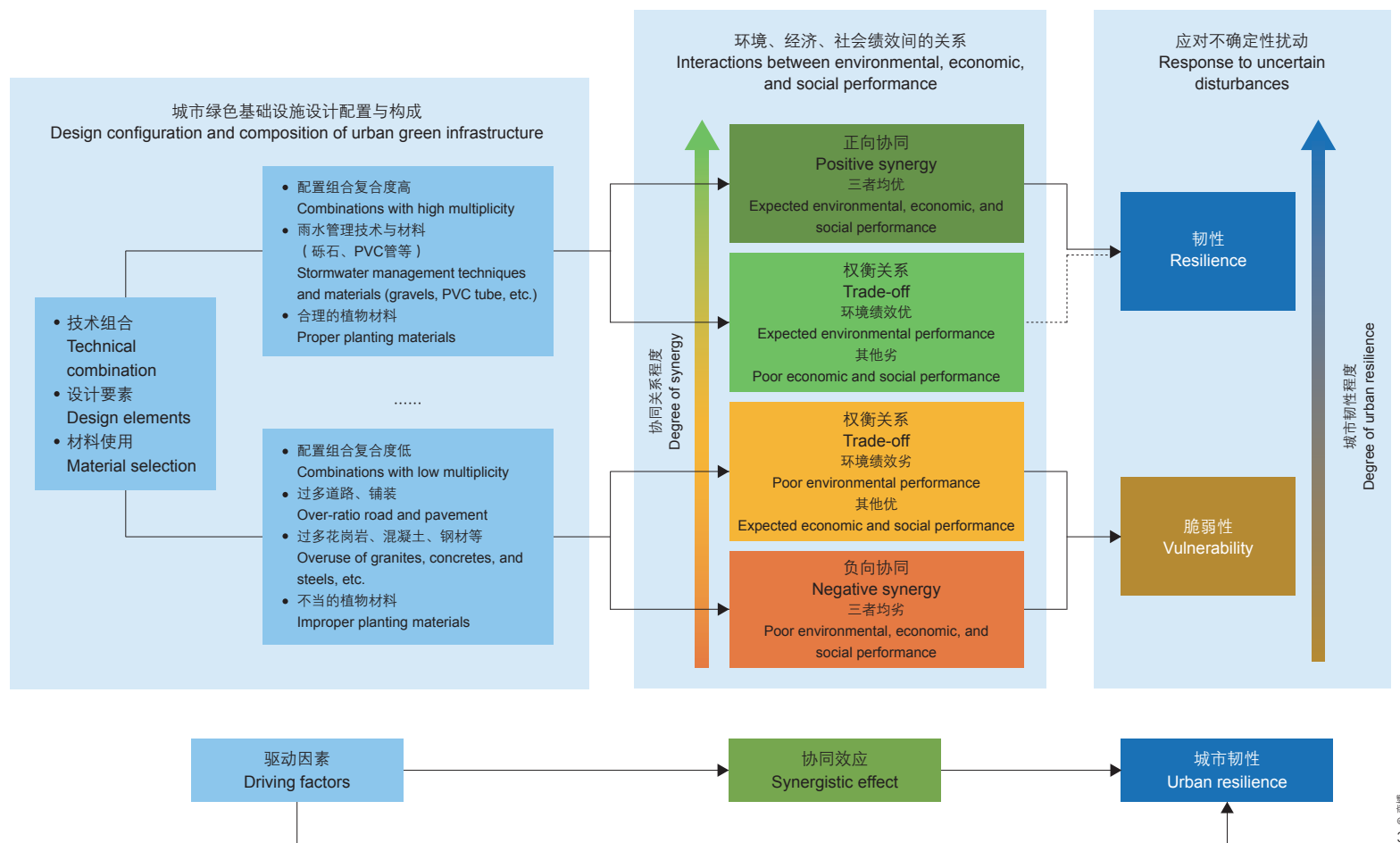
3.1 Studies on the Driving Mechanism of Resilience

Developing effective optimization and regulation methods is the focal-point of the establishment of resilient design paradigm, and the key of design is to identify critical components of green infrastructure that define urban resilience, as well as the associated driving mechanism. Studies prove that the correlations among different types of resilience performance of green infrastructure are either synergistic or trading-off^[26]. Yet the driving mechanism of these correlations remains unknown. Previously, the performance of configuration on planning level, including amount, size, and spatial pattern, has been studied thoroughly, but the configuration characteristics responding to uncertainty on design level remains unclear. Currently, scholars start to examine the technical components that facilitate resilience synergy, and some of them have explored the impact of specific design configuration and components on the service performance. For example, after evaluating the service of urban green spaces in Rotterdam with 6 indicators, Marthe L. Derkzen et al. concluded that the configuration and components of green spaces have remarkable impact on the ecosystem services^[27]. Based on case studies on the landscape performance of 39 built-up projects, Luo Yi et al. found that conflicts exist in the negotiation of environmental, social, and economic benefits of landscape practices, which is mostly caused by improper design^[28]. Luan Bo et al. studied the varied performance of 9 configuration combinations of green stormwater infrastructure (decentralized vs. centralized and single vs. combination)^[29], and through modeling research revealed that technical combination, design elements, and material selection are key factors that define the synergy effects of resilience, where biophilic or living materials are beneficial and the excessive use of traditional materials (e.g. granite and concrete) would compromise environmental

2. 全过程韧性作用模型
2. The whole life-cycle resilience model

3. 城市绿色基础设施资源配置要素的韧性驱动机制模型（改绘自参考文献[30]）

3. Resilience driving mechanism model of urban green infrastructure's resource allocation elements (Adaptation source: Ref. [30])



性，而过度使用传统建筑材料（如花岗岩、混凝土等）则会造成环境和经济负担，增加城市脆弱性风险^[30]（图3）。

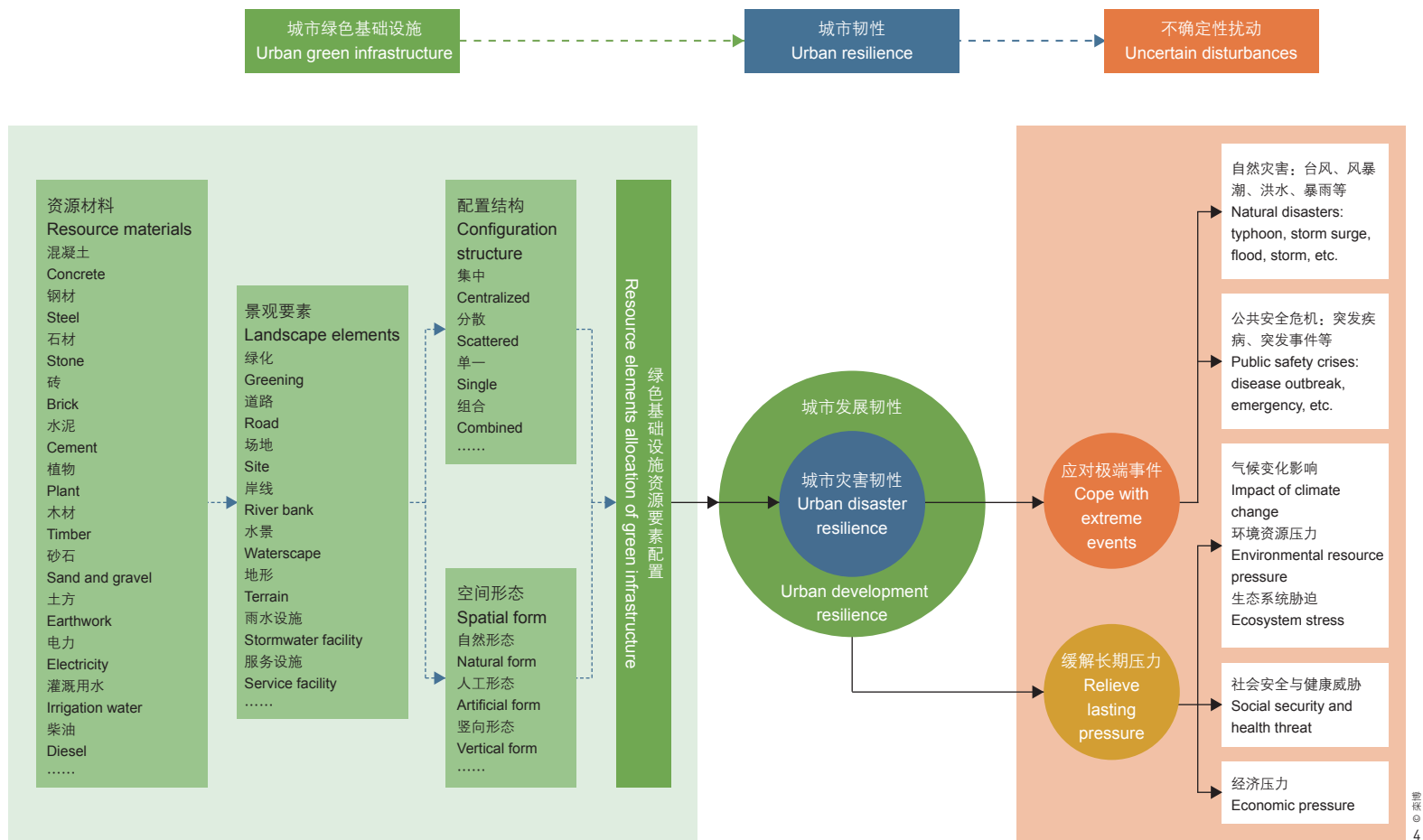
3.2 韧性驱动机制概念框架

基于对相关研究的梳理，本文提出城市绿色基础设施的韧性驱动机制概念框架（图4）。总体上，驱动韧性的关键影响要素包括配置结构、空间形态、景观要素，以及资源材料。配置结构和空间形态是界定城市绿色基础设施的总体配置要素，植被、道路、地形、雨水设施等景观要素是建构结构和形态的实质内容，而资源材料又是构成所有

and economic performances, making the city more vulnerable to risks^[30] (Fig. 3).

3.2 The Conceptual Framework for the Driving Mechanism of Resilience

Through literature review, this article proposes a conceptual framework for the driving mechanism of resilience of urban green infrastructure (Fig. 4). The key factors that promote resilience include configuration structures, spatial forms, landscape elements, and resources and materials. The configuration structures and spatial forms define the overall urban green infrastructure; landscape elements (plants, roads, terrains, and rainwater facilities, etc.) constituted with resources and materials are the components of the structure and form creation of green infrastructure. Green infrastructure with varied configurations performs differently in regard to disaster resilience and development resilience, which influences cities'



4. 城市绿色基础设施的韧性驱动机制概念框架
4. The concept framework for the driving mechanism of resilience of urban green infrastructure

要素的物质基础。不同配置的绿色基础设施对灾害韧性和发展韧性的贡献也不同，影响着城市应对极端灾害和缓解长期压力的能力。

capacity to cope with extreme disasters and continuous pressure respectively.

4 城市绿色基础设施韧性设计范式

4 The Resilient Design Paradigm of Urban Green Infrastructure

4.1 设计范式的发展历程

4.1 The Evolution of Design Paradigms

“范式”是指某专业领域在共同信念下形成的一系列基本观点、理论和方法的总合^[31]。景观范式在历史上经历了三次重大范式转型：以弗雷德里克·劳·奥姆斯特德为代表提出的城市公园模式、伊恩·麦克哈格改良的“千层饼”生态规划方法，以及以理查德·福尔曼为代表提出的“斑块—廊道—基质”景观生态模型^{[32][33]}。目前，以“斑块—廊道—基质”模型为原型衍生出的一系列模型^{[34]-[36]}被视为绿色基础设施的规划及设计范式。

A paradigm is the aggregation of a series of commonly shared viewpoints, theories, and methods in a professional field^[31]. Landscape paradigms have witnessed three major shifts—the urban park model proposed by Frederick Law Olmsted et al.; “the layer-cake” ecological planning model improved by Ian McHarg; and the “patch–corridor–matrix” landscape ecology model proposed by Richard Forman et al.^{[32][33]} Today, models derived from the “patch–corridor–matrix” paradigm^{[34]-[36]} are widely applied in green infrastructure planning and design.

5. 陕西渭柳湿地的自然演进过程 (2016-2018年)
5. The natural evolving process of Weiliu Wetland in Shaanxi (2016 - 2018)

随着现代城市不确定性的增加及灾害风险的加剧, 现有范式的缺陷逐渐显现。在规划层面上, “斑块—廊道—基质”范式强调空间维度上的永久性保护, 而对时间维度上的突发性和持续性扰动或压力缺乏积极响应。此外, 该范式以控制宏观格局结构为重, 忽略了对中观、微观尺度资源要素的调控配置。虽然关键性空间格局是保障韧性的基础, 但格局内部的资源配置方式在不确定性响应中的重要性同样不可小觑。在设计层面上, 由于以自然生命要素为主体的城市绿色基础设施本身即充满了复杂性和不确定性, 因此, 期望通过一次性设计对其全生命周期进行控制是不切实际的, 这和建筑设计有很大不同。目前, 有关韧性城市的研究范式及实践范式备受关注^{[37][38]}, 但作为韧性城市的重要组成部分, 城市绿色基础设施的设计范式转型仍滞后于现实需求。

4.2 适应性设计与适应性管理的进展

有效的设计方法是优化调控资源配置和促进韧性的保障, 适应性设计可为韧性设计范式的建立提供方法借鉴。相较于确定性规划和设计, 适应性设计需要为应对变化和促进转型做好准备并创造机会^{[39][40]}, 动态优化是促进学习演进和应对不确定性的关键, 成为适应性设计的新方向。在实践方面, 响应灾害风险的适应性设计实践逐渐增多, 代表性案例包括瑞士艾尔河及陕西渭柳湿地的生态修复等^{[41]-[44]} (图5), 但尚未形成系统性理论。在理论研究方面, 加藤禎久等人^[45]和杰克·F·埃亨等人^[46]先后提出“边学边做”和适应性设计的方法框架, 强调通过

However, the flaws of existing paradigms emerge when urban design faces with increasing uncertainties and disaster risks. The “patch-corridor-matrix” paradigm emphasizes the permanent control of physical environment and is inadequate in responding to sudden or lasting disturbances over time. In addition, this paradigm focuses more on the establishment of large-scale pattern and structure, instead of configuring materials and resources at middle or small scales, which are both critical to the promotion of resilience. Unlike architectural design, urban green infrastructure composed of natural organisms is full of complexity and uncertainty. It is therefore unrealistic to control its whole life-cycle with one-time design. Currently, studies on resilient city and its planning paradigms have attracted much attention^{[37][38]}, but the new design paradigm of urban green infrastructure that can efficiently address real demands is absent.

4.2 The Development of Adaptive Design and Adaptive Management

Effective design methods would help optimize resource allocation and promote resilience. Adaptive design can provide methodological reference to the establishment of resilient design paradigm. Unlike traditional planning and design methods, adaptive design would offer possibilities for changes and transformation^{[39][40]}. Dynamic optimization has become a new trend of adaptive design, since it is the key to coping with uncertainties through adaptation and evolution. Designs adaptive to disaster risks have been increasingly practiced, such as the ecological restoration projects of the River Aire in Switzerland and the Weiliu Wetland in Shaanxi^{[41]-[44]} (Fig. 5), while systematic theory is absent. Nevertheless, Sadahisa Kato et al.^[45] and Jack F. Ahern et al.^[46] proposed the “learning by doing” method and adaptive design frameworks that facilitate dynamic optimization through whole-process monitoring, evaluation, and feedback. All of the preliminary explorations above have not formed a



表1: 传统设计范式与韧性设计范式的比较
Table 1: The comparison between traditional design paradigm and resilient design paradigm

| | 传统设计范式 Traditional design paradigm | 韧性设计范式 Resilient design paradigm |
|---------------------------|---|---|
| 前提假设 Hypothesis | 掌握充足知识, 具备全面信息 一切确定且可控制 扰动和变化是不利的危险 Comprehensively acquire knowledge and information Everything should be certain and controllable Disturbances and changes are adverse | 承认知识的有限性及信息的不完全性 接受不确定性和不可预测性 扰动和变化是演进的机会 Recognize knowledge limits and information inadequacy Accept uncertainties and uncontrollability Disturbances and changes offer possibilities for resilience enhancement |
| 理论基础 Theoretical basis | 工程学 Engineering | 生态学 Ecology |
| 设计目标 Design goal | 增强可控性 单目标 Enhance controllability Single goal | 提高适应性, 多功能协同 多目标 Enhance adaptation and multi-function collaboration Multiple goals |
| 方法路径 Design approach | 人工准确管控 抵抗失败, 集中对抗风险 Accurate artificial control Fail-safe | 辅助系统自组织、自调节 包容失败, 系统分担风险 Assist the system for self-organization and self-adjustment Safe to fail |
| 系统状态 System state | 静态、稳定、均衡 Static, steady, and equilibrium | 动态、演进、非均衡 Dynamic, evolutionary, and disequilibrium |
| 设计过程 Design process | 线性 Linear | 循环 Cyclical |
| 设计成果 Design result | 重视结果 Result-oriented | 重视过程, 持续管理 Process-oriented and continuous management |

全过程监测、评估、反馈, 实现动态优化。总体而言, 适应性设计仍在初步探索阶段, 虽未形成有效范式, 但颇具发展前景。

与适应性设计相比, 适应性管理已形成自然资源和生态系统管理的成熟方法, 目前已有多种经实践检验的循环迭代模型^{[47]-[49]}。适应性管理更为强调过程管理, 而非结果控制, 在全过程监测评估、实时反馈优化、动态循环迭代方面已积累了丰富经验。

4.3 基于适应性途径的韧性设计范式

本文通过归纳和比较新旧范式在理论基础、设计目标、方法路径、设计过程和设计成果方面的差异(表1), 提出了绿色基础设施的韧性设计范式: 在承认掌握知识和信息的有限性、接受不确定性和不可控性的基础上, 新范式将扰动视作学习和修正的机会, 立足于生态学思维, 通过辅助自然做工的设计管理途径促进系统的自组织、自调

paradigm but offered research and practice prospects.

Compared with adaptive design, adaptive management has developed a series of advanced approaches on natural resource and ecosystem management, and several proven cyclical iterative models^{[47]-[49]}. Adaptive management focuses on process management rather than result control, having fruitful achievements in whole-process monitoring and evaluation, real-time response and optimization, and dynamic cyclical iteration.

4.3 The Resilient Design Paradigm Based on Adaptive Approach

By reviewing the differences between traditional and new paradigms in the aspects of theoretical basis, design purpose, method, design process, and design result (Table 1), this article proposes the resilient design paradigm of green infrastructure: Seeing the limits of information acquisition and knowledge learning, and recognizing uncertainties and uncontrollability, the new paradigm is established from the ecological perspective and takes disturbances as the opportunities for learning and adjustment. Self-organization and self-adjustment of green infrastructure are facilitated to cope with uncertainties and disturbances by assisting natural succession and leveraging

6. 韧性设计的全过程动态循环模型
6. The whole-process dynamic cyclic model of resilient design

节和学习演进能力，以应对不确定性变化和扰动，并吸纳风险、包容失败。这种范式将设计视为过程而非结果，通过动态循环过程实现优化配置和适应性管理。

4.4 韧性设计的全过程方法

结合适应性设计和适应性管理的经验，本文提出绿色基础设施韧性设计的全过程动态循环模型，通过循环迭代实现精细化管控和动态优化配置，为有效驱动韧性提供可靠方法。每次循环包括6个步骤（图6）：

- 1) 识别诊断：识别城市脆弱性，诊断问题，明确目标；
- 2) 设计决策：提出多解方案，进行综合优选；
- 3) 建造实施：建造、实施方案，制定运营管理和监测计划；
- 4) 运营监测：建成后进行管理维护，持续开展监测；
- 5) 评估分析：对监测数据进行分析，评估韧性绩效，制定促进适应性演进的优化措施；
- 6) 信息反馈：为优化措施提供反馈。

通过全过程监测评估和反馈优化，城市绿色基础设施在循环迭代中不断促进环境、经济与社会绩效的正向协同，从而有效应对各类扰动和压力，逐步趋近可持续性目标。

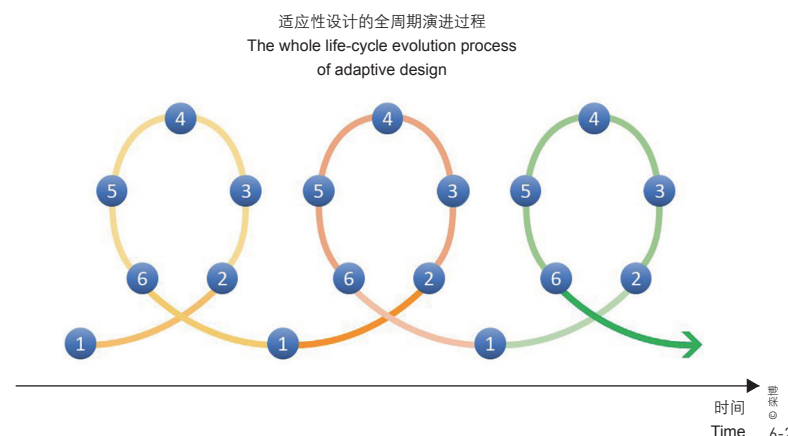
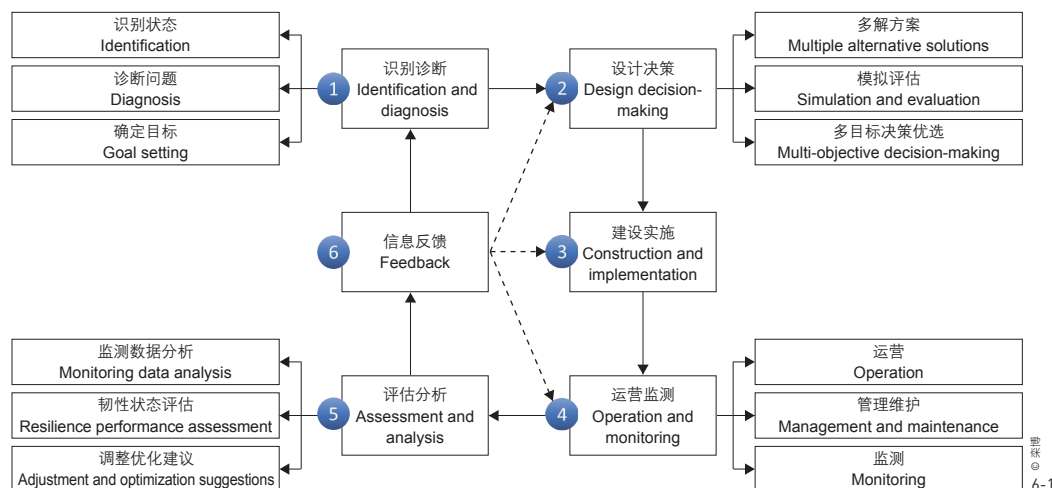
ecosystem services. It also helps the city reduce risks and tolerate failures. In this paradigm, design is a process, rather than a result, which requests dynamic optimization and adaptive management through whole process.

4.4 The Whole-Process Method of Resilient Design

Combining the advanced experience of adaptive design and management, this article proposes a whole-process dynamic cyclic model for the resilient design of green infrastructure. Cyclic iteration can facilitate the refined management and the dynamic optimization, which includes 6 steps (Fig. 6):

- 1) Problem finding and diagnosis: identify the vulnerability of the city, diagnose the problems, and formulate clear goals;
- 2) Decision-making of design proposal: determine the optimal proposal among multiple solutions;
- 3) Construction and implementation: implement design proposal and develop operation management and monitoring plans;
- 4) Operation and monitoring: conduct follow-up management, maintenance, and continuous monitoring;
- 5) Evaluation and analysis: analyze monitoring data, evaluate resilience performance, and come up with optimization measures to promote adaptive evolution;
- 6) Feedback: collect feedback for future optimization measures.

Through such measures of whole-process monitoring, evaluation, feedback, and optimization, urban green infrastructure enhances positive synergies of environmental, economic, and social performances during continuous cyclic iterations, so as to deal with various disturbances and pressures and achieve the sustainable goals.



5 建议与展望

本文探讨了城市绿色基础设施的韧性驱动机制，提出了韧性驱动机制概念框架和全过程动态设计方法，为韧性设计范式转型提供了理论依据，对不确定性响应的景观设计实践具有指导意义。本文提出的韧性设计范式从理论层面对已有研究和实践进行提炼，具有可靠性及可应用性，但仍需在未来更多的实践中进行完整应用，以对其进行检验和修正。新范式的建立涉及思维观念、设计流程、项目管理、工程质量验收等诸多方面的转变，更需要设计师、工程师、研究者、决策者及公众的多方努力。为了更好地推进韧性设计实践，本文提出以下建议：

第一，承认不确定性，接受和拥抱变化。由于自然扰动（洪水、暴雨等）而产生的冲击和改变会造成工程损耗，且往往被视为设计失误，设计师往往惧怕失控，抵触变化。但对于韧性设计而言，这是必要的学习演进过程。要改变确定性控制的思维方式，不仅需要设计思维的转变，更需要工程质量评价、运维管理制度的全方位转型。

第二，强化亲自然设计。尽可能使用有生命的自然材料及要素，一方面应利用自然有机体的自组织性和自适应性促进和提升系统韧性，另一方面需尽可能为人们创造接触、体验和感知自然的机会。

第三，刚柔并济，统筹适应性与确定性。韧性设计范式并非全盘否定确定性控制，局部刚性工程非但不影响整体的适应性，反而是韧性设计的必要组成部分。城市绿色基础设施既是基于自然的解决方案，也是为城市居民提供多种服务的城市绿色空间，关键部位的刚性结构是安全性和宜居性的保障。

第四，从成果设计思维向全过程管理思维转变。韧性设计需要的不是静态的“确定解”，而是动态的全过程设计管理。全过程监测评估和及时反馈优化决定了韧性设计的成效。全过程设计的难点是成本问题，但提高城市绿色基础设施的智慧化和信息化水平可为全过程设计管理提供有效支撑。**LAF**

5 Suggestions and Prospects

By studying the driving mechanism of the resilience of urban green infrastructure, this article comes up with a conceptual framework for the driving mechanism of resilience and a whole-process dynamic design method, laying the theoretical foundation for the resilient design paradigm that can guide the landscape design in response to uncertainties. Stemming from existing research and practice achievements, the resilient design paradigm has a sound reliability and applicability, and continuous tests, verifications, and updates are further needed. The establishment of a new paradigm relies on the shift in mindset, concept, design procedure, project management, quality inspection, etc., which requires the joint efforts by designers, engineers, researchers, decision makers, and the public. In order to promote resilient design practice, this article makes the following suggestions:

To begin with, designers need to accept uncertainties and embrace changes. In traditional design mindset, uncontrollability and changes are often averse since natural disturbances (such as floods and storms) may result in engineering damage, which is often regarded as a design failure. However, to resilient design, this is an indispensable process for evolution by learning. The change of certainty control thinking requires the shift of design mindset, engineering quality assessment, and systematic operation management.

Secondly, biophilic design should be promoted. The more biophilic or living natural materials and elements are used, the stronger the overall resilience could be: by leveraging the self-organization and self-adaptation of natural organisms, more opportunities could be created for people to access, experience, and perceive the nature.

Thirdly, the design should give consideration to both adaptation and certainty. The resilient design paradigm does not completely deny certainty control, because partial rigid engineering measures are often a required component to resilient design. Urban green infrastructure, as a NBS, provides green spaces with diverse services for urban residents, where rigid structures in key locations guarantee safety and livability.

Finally, instead of the result-oriented design thinking, the whole-process management thinking should be emphasized. Resilient design requires dynamic whole-process management methods rather than static design and determinate solutions. The performance of resilient design also depends on the whole-process monitoring, assessment, feedback, and optimization. The whole-process management, though often financially costly, could be supported as the level of intelligence and information construction of urban green infrastructure promotes. **LAF**

REFERENCES

- [1] Batty, M. (2008). The Size, Scale, and Shape of Cities. *Science*, 319(5864), 769-771. doi:10.1126/science.1151419
- [2] National Academies of Sciences, Engineering, and Medicine. (2020). *Advancing Urban Sustainability in China and the United States: Proceedings of a Workshop*. Washington, D.C.: The National Academies Press.
- [3] Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., ... Wittmer, H. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of the Total Environment*, 579(2017), 1215-1227. doi:10.1016/j.scitotenv.2016.11.106
- [4] Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.) (2016). *Nature-based Solutions to address global societal challenges*. Gland, Switzerland: IUCN. doi:10.2305/IUCN.CH.2016.13.en
- [5] Nature Editorial. (2017). Natural language: The latest attempt to brand green practices is better than it sounds. *Nature*, 541(2017), 133-134.
- [6] Ahern, J. (2012). Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology*, 28(6), 1203-1212. https://doi.org/10.1007/s10980-012-9799-z
- [7] Von Döhren, P., & Haase, D. (2015). Ecosystem disservices research: A review of the state of the art with a focus on cities. *Ecological Indicators*, 52(2015), 490-497. https://doi.org/10.1016/j.ecolind.2014.12.027
- [8] Luan, B., Chai, W., & Wang, X. (2017). Review of development, frontiers, and prospects of green infrastructure. *Acta Ecologica Sinica*, 37(15), 5246-5261. doi:10.5846/stxb201605100903
- [9] Alexander, D. E. (2013). Resilience and disaster risk reduction: an etymological journey. *Natural Hazards and Earth System Science*, 13(11), 2707-2716. https://doi.org/10.5194/nhess-13-2707-2013
- [10] Shao, Y., & Xu, J. (2015). Understanding Urban Resilience: A Conceptual Analysis Based on Integrated International Literature Review. *Urban Planning International*, 30(2), 48-54.
- [11] Gunderson, L. H. (2000). Ecological Resilience—In Theory and Application. *Annual Review of Ecology and Systematics*, 31(1), 425-439. https://doi.org/10.1146/annurev.ecolsys.31.1.425
- [12] Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, 21(3), 41. doi:10.5751/es-08748-210341
- [13] Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, 4(1), 1-23. doi:10.1146/annurev.es.04.110173.000245
- [14] Li, X., & Che, S. (2017). Progress and prospect of urban resilience research in social-ecological system. *South Architecture*, 3(2017), 7-12. doi:10.3969/j.issn.1000-0232.2017.03.007
- [15] Shao, Y., & Xu, J. (2015). Understanding urban resilience: A conceptual analysis based on integrated international literature review. *Urban Planning International*, 30(2), 48-54. doi:10.3969/j.issn.1000-0232.2017.03.007
- [16] Gunderson, L. H., & Holling, C. S. (2002). Resilience and Adaptive Cycles. In *Panarchy: Understanding Transformations in Human and Natural Systems* (pp. 25-62). Washington, D.C.: Island Press.
- [17] Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, 147(2016), 38-49. doi:10.1016/j.landurbplan.2015.11.011
- [18] Folke, C. (2006). Resilience: The emergence of a perspective for social—ecological systems analyses. *Global Environmental Change*, 16(3), 253-267. https://doi.org/10.1016/j.gloenvcha.2006.04.002
- [19] Xu, Y., Li, G., Cui, S., Xu, Y., Pan, J., Tong, N., ... Zhu, Y. (2018). Review and perspective on resilience science: From ecological theory to urban practice. *Acta Ecologica Sinica*, 38(15), 5297-5304. https://doi.org/10.5846/stxb201709081620
- [20] Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., ... Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, 146(2014), 107-115. https://doi.org/10.1016/j.jenvman.2014.07.025
- [21] Laforcezza, R., Chen, J., Van Den Bosch, C. K., & Randrup, T. B. (2018). Nature-based solutions for resilient landscapes and cities. *Environmental Research*, 165(2018), 431-441. doi:10.1016/j.envres.2017.11.038
- [22] Flynn, K. M., & Traver, R. G. (2013). Green infrastructure life cycle assessment: A bio-infiltration case study. *Ecological Engineering*, 55(2013), 9-22. https://doi.org/10.1016/j.ecoleng.2013.01.004
- [23] Wang, M., Zhang, D., Adhityan, A., Ng, W. J., Dong, J., & Tan, S. K. (2016). Assessing cost-effectiveness of bioretention on stormwater in response to climate change and urbanization for future scenarios. *Journal of Hydrology*, 543(2016), 423-432. https://doi.org/10.1016/j.jhydrol.2016.10.019
- [24] Marchese, D., Reynolds, E., Bates, M. E., Morgan, H., Clark, S. S., & Linkov, I. (2018). Resilience and sustainability: Similarities and differences in environmental management applications. *Science of The Total Environment*, 613-614(2018), 1275-1283. https://doi.org/10.1016/j.scitotenv.2017.09.086
- [25] Simmie, J., & Martin, R. (2010). The economic resilience of regions: Towards an evolutionary approach. *Cambridge Journal of Regions, Economy and Society*, 3(1), 27-43. https://doi.org/10.1093/cjres/rsp029
- [26] Meerow, S., & Newell, J. P. (2016). Urban resilience for whom, what, when, where, and why?. *Urban Geography*, 40(3), 309-329. https://doi.org/10.1080/02723638.2016.1206395
- [27] Derkzen, M. L., Van Teeffelen, A. J. A., & Verburg, P. H. (2015). Review: Quantifying urban ecosystem services based on high-resolution data of urban green space: an assessment for Rotterdam, the Netherlands. *Journal of Applied Ecology*, 52(4), 1020-1032. https://doi.org/10.1111/1365-2664.12469
- [28] Luo, Y., & Li, M.-H. (2014). A study of landscape performance: Do social, economic and environmental benefits always complement each other?. *Landscape Architecture Frontiers*, 2(1), 42-56.
- [29] Luan, B., Yin, R., Xu, P., Wang, X., Yang, X., Zhang, L., & Tang, X. (2019). Evaluating Green Stormwater Infrastructure Strategies Efficiencies in a Rapidly Urbanizing Catchment Using SWMM-Based TOPSIS. *Journal of Cleaner Production*, 223(2019), 680-691. https://doi.org/10.1016/j.jclepro.2019.03.028
- [30] Luan, B. (2019). *Study on Multi-dimensional Synergy Effects of Urban Green Infrastructure* (Doctoral dissertation). Peking University, Beijing.
- [31] Wu, Z., & Qian, C. (2009). A study on the paradigm theory in urban planning research. *Urban Planning Forum*, 5(2009), 28-35.
- [32] Wen, Q. (2009). Study on paradigm evolution of urban green open space. *Chinese Landscape Architecture*, 25(9), 11-14.
- [33] Yu, K., & Li, D. (2003). *Landscape Architecture: The Profession and Education* (pp. 70-92). Beijing, China: China Architecture and Building Press.
- [34] Yu, K. (1996). Security patterns and surface model in landscape ecological planning. *Landscape and Urban Planning*, 36(1), 1-17. https://doi.org/10.1016/S0169-2046(96)00331-3
- [35] Termorshuizen, J. W., & Opdam, P. (2009). Landscape services as a bridge between landscape ecology and sustainable development. *Landscape Ecology*, 24(8), 1037-1052. https://doi.org/10.1007/s10980-008-9314-8
- [36] Nassauer, J. I., & Opdam, P. (2008). Design in science: extending the landscape ecology paradigm. *Landscape Ecology*, 23(6), 633-644. doi:10.1007/s10980-008-9226-7
- [37] Wang, H., Wang, T., & Xiang, W. (2019). A paradigm analysis of urban resilience research through the lens of pasteur's quadrant. *Chinese Landscape Architecture*, 35(7), 51-55. doi:10.19775/j.cta.2019.07.0051
- [38] Jabareen, Y. (2013). Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities*, 31(2013), 220-229. https://doi.org/10.1016/j.cities.2012.05.004
- [39] Chapin, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., ... Swanson, F. J. (2010). Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. *Trends in Ecology and Evolution*, 25(4), 241-249. doi:10.1016/j.tree.2009.10.008
- [40] Folke, C. (2016). Resilience. In *Oxford Research Encyclopedia of Environmental Science*. Oxford, England: Oxford University Press. https://doi.org/10.1093/acrefore/9780199389414.013.8
- [41] Luan, B., Wang, X., Jin, Y., Chai, M., & Hu, C. (2017). Collaborative design of site-scale green infrastructure: A case study on the ecological restoration design of Weiliu Wetland Park in Xiangyang. *Landscape Architecture Frontiers*, 5(5), 26-43. https://doi.org/10.15302/J-LAF-20170503
- [42] Wang, M., Peng, H., Wang, J., & Wang, Y. (2017). Doing by leveraging: Resilience building and dynamic design for small island's landscape based on using natural processes. *Landscape Architecture*, 1(1), 73-79. doi:10.14085/j.fjyl.2017.11.0073.07
- [43] Li, Y. (2020). Rebuilding coastal resilience: Salt marsh restoration in San Francisco Bay and its enlightenment. *Landscape Architecture*, 27(1), 115-120. doi:10.14085/j.fjyl.2020.01.0115.06
- [44] Bajc, K., & Stokman, A. (2018). Design for Resilience: Re-Connecting Communities and Environments. *Landscape Architecture Frontiers*, 6(4), 14-31. https://doi.org/10.15302/J-LAF-20180402
- [45] Kato, S., & Ahern, J. (2008). 'Learning by doing': Adaptive planning as a strategy to address uncertainty in planning. *Journal of Environmental Planning and Management*, 51(4), 543-559. https://doi.org/10.1080/09640560802117028
- [46] Ahern, J., Cilliers, S., & Niemelä, J. (2014). The concept of ecosystem services in adaptive urban planning and design: A framework for supporting innovation. *Landscape and Urban Planning*, 125(2014), 254-259. https://doi.org/10.1016/j.landurbplan.2014.01.020
- [47] Xia, J., Shi, W., Luo, X., Hong, S., Ning, L., & Gippel, C. J. (2015). Revisions on water resources vulnerability and adaption measures under climate change. *Advances in Water Science*, 26(2), 279-286. doi:10.14042/j.cnki.32.1309.2015.02.019
- [48] Hou, X., Yin, Y., & Ding, Y. (2011). An overview and prospects for grassland adaptive management in China. *Acta Prataculturae Sinica*, 20(2), 262-269.
- [49] Xu, G., Kang, M., & Shi, Y. (2013). A review of adaptive management research on natural resources. *Journal of Natural Resource*, 28(10), 1797-1807.