https://doi.org/10.15302/J-LAF-1-030035

Eight Reflections on Quantitative Studies of Urban Green Space: A Mapping-Monitoring-Modeling-Management (4M) Perspective


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ABSTRACT

Green space is an important component in urban environment, providing considerable ecosystem services to our socio-economic-cultural activities. Metrics designed to capture green space provision, supply and demand, measuring availability, accessibility, and visibility have been widely adopted to gauge progress toward achieving sustainable development goals from local to regional scales. In this article, we offer eight reflections on quantitative studies of urban green space for mapping, monitoring, modeling, and management (4M) practices in landscape design and planning. The article's objective is to stimulate fresh and innovative thinking in the conversion of data to interventions. Eight points are made: 1) Green space mapping should be characterized in a multi-attribute conceptual model, including quantity, quality, type, and structure; 2) green space mapping sources, methods, and uses vary by definitions, approaches, and scales; 3) phenology modifies seasonal quality and quantity of urban green space; 4) spatial and temporal green space data cubes will help realize the goal of near real-time monitoring of urban green space change; 5) green space coverage reveals green space supply, but green space exposure can capture effective demand via modeling the supply–demand relationships of human–green space; 6) green space exposure measures should account for spatial, temporal, and social differences; 7) greening optimization by landscape architects and planners should consider both biophysical, biodiversity, and health benefits; and 8) urban green space management should be strategized with a long-term view. Finally, we advocate data–science–decision support systems that can help guide and promote 4M practices of urban green space. These points of reflection have broad implications for research, practice, and theory of urban green landscape design, planning, and management, and altogether constitute a set of principles that can guide scientists, policy makers, and practitioners toward strategizing optimal 4M of urban green space.

KEYWORDS

Urban Green Space;
Quantitative Metrics;
Green Space Supply–Demand;
Mapping–Monitoring–Modeling–Management Framework;
Justice of Urban Green Space

RECEIVED DATE

2022-04-15

EDITED BY
Tina TIAN, WANG Ying

HIGHLIGHTS

- A mapping-monitoring-modeling-management (4M) framework of urban green space is presented
- Eight points of reflection on 4M practice of urban green space are provided
- Stimulate fresh and innovative thinking in the conversion of data to interventions
- Generate broad implications for research, practice, and theory of quantitation of urban green scape

1 Introduction

Urban green space, typically open and undeveloped land with natural vegetation, such as parks, gardens, croplands, and forests[1]~[3], is one of the most important components in the urban environment. It provides considerable ecosystem services to the function of built environments[2][4] and protective effects on human health and well-beings in cities[5][6]. Given the recognized green space benefits, worldwide efforts from policies to practices at local and regional scales have been promoted and made to secure more green space supply and create sustainable and healthy living environments. For example, the United Nations has specified the need of providing universal access to green space for urban residents in the 11th Sustainable Development Goal of Cities and Communities[7].

Accordingly, metrics designed to capture green space supply and demand, measure availability, accessibility, and visibility have been widely adopted to gauge progress toward achieving sustainable development goals[8]~[12]. Many quantitative urban green space studies in the form of data driven approaches have been conducted at local, regional, and global scales. This article categorizes existing studies into four major groups in the loop of 4M practices—Mapping, Monitoring, Modeling, and ultimately Management—within the scope of quantitative urban green space studies. It should be noted that in this study, we regard data as a broader concept of information that can be raw (termed as raw or primary data) or processed (termed as advanced or secondary data).

Mapping, the art or process of making maps, is recognizedas the most efficient approach to providing spatially explicit information regarding urban green space distribution, composition, and pattern. For example, Song Yimeng et al. use Google Earth high-resolution imagery to calculate Normalized Difference Greenness Index as an indicator of greenness[11]. Christina Ludwig et al. integrated Sentinel-2 satellite imagery and OpenStreetMap data to generate urban green space mapping[13]. Song et al. and Chen Bin et al. applied spectral unmixing models in Sentinel-2 imagery and generated subpixel mapping of green space distribution.[10][14] In addition to remote sensing imagery from bird-view observations, street view images and observing the cityscape from an eye-view angle can provide dived-in and supplementary information of urban green space in support of identification and classification. For example, Li Xiaojiang et al. used Google Street View images to assess street-level urban greenery with a modified green view index[15]. Andrew Larkin et al. found that correlation between remote sensing and Google Street View based green space measures were low to moderate, suggesting that street view imagery can capture unique characteristics of green space environment[16].

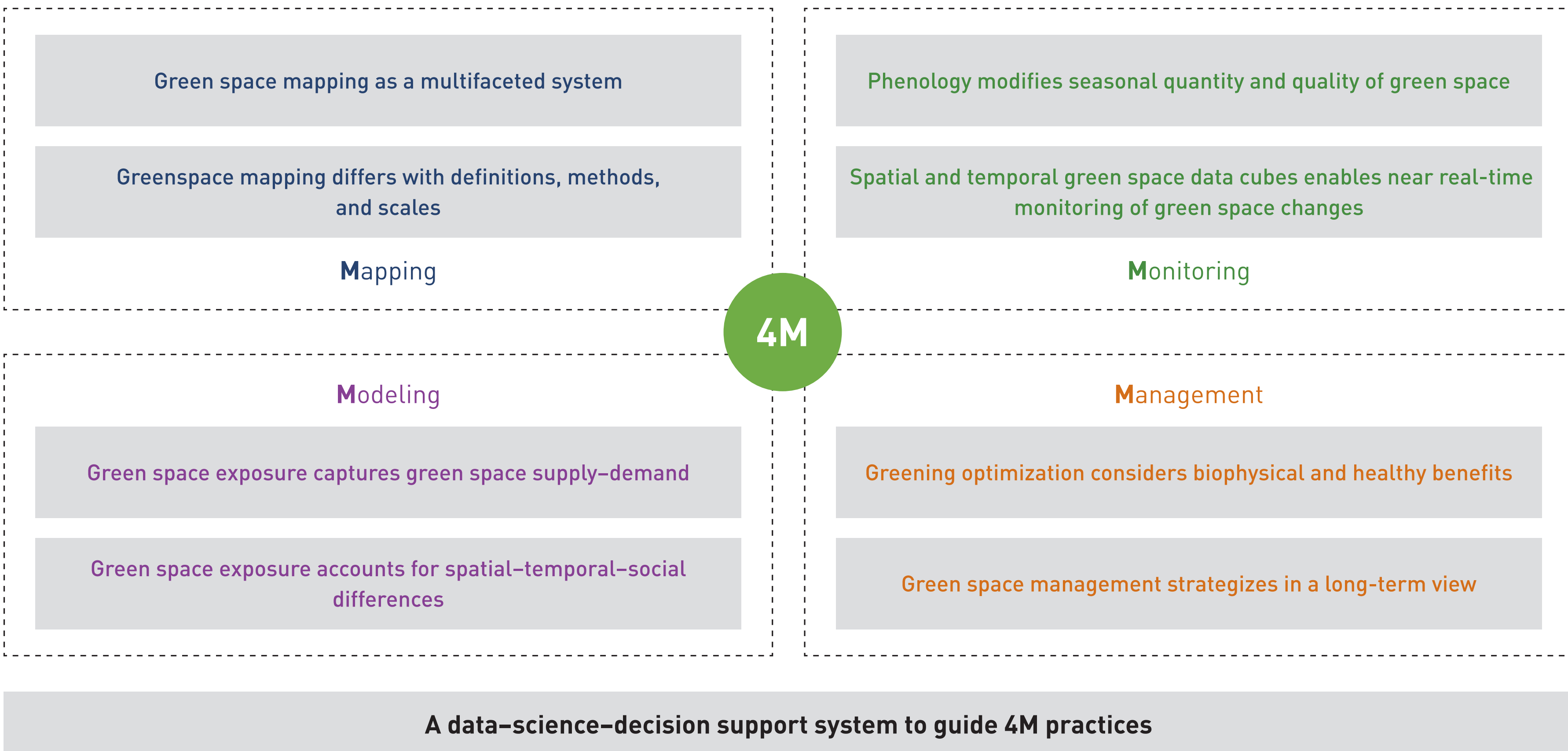
Monitoring aims to enhance our capability of identifying spatial and temporal changes of urban green space, in terms of amount, extent, and status. For example, Chen et al. employed Landsat imagery to quantify urban green space changes in Chinese populous cities from 2000 to 2014[17]. Xu Fei et al. applied a support vector regression model for Landsat imagery to derive pan-European urban green space dynamics in 1990, 2000, and 2015[18]. Although medium-resolution remote sensing observations such as Landsat and Sentinel-2 can detect urban green space changes, much finer details regarding changes of small-sized green space patches are challenging without high spatial resolution imagery. Empirical comparisons showed that in contrast to findings of stable green space in inner cities from moderate or low spatial resolution observations, urban green space was highly dynamic experiencing both gain and loss, as revealed by higher spatial resolution datasets[19].

Modeling, as a powerful leverage, aims to advance our understanding of the role of urban green space in the complex system of other natural environments and human society, and the associated interaction and feedback loops. On the one hand, green space provides individual and combined benefits to urban environments, including urban heat island effect mitigation[20], air quality purification[21], and noise pollution reduction[22]. On the other hand, growing evidences using causality analysis have reported that human exposure to green space is associated with reduced blood pressure[23], lower obesity rates[24], decreased preterm birth[25], and better mental health[26][27].

Management is the strategic planning and practical action of urban green space design, allocation, and maintenance. Green space provision, as a proxy of supplies, and green space landscape, as a measurement of spatial configuration, are two key factors in managing city greening efforts across space and time, which have also been identified as dominant controls on disparities in urban green space exposure inequality[28]. In the meantime, green space types and categories are continuously the focus of debates in the management sector. For example, formal planning documents always tend to overlook some green space types and overemphasize some others[29]. Additionally, different green spaces sometimes are managed by different stakeholders (e.g., public vs private, city vs district)[29], which will lead to inconsistent maintenance and management. There is a need of calling for coordinated practices among policymakers, city planners, and landscape architects to balance green space supply and demand as well as optimizing green space arrangement for facilitating sustainable and equitable greening management[28].

Given the abovementioned research advances and many others, a systematic thinking that synthesizes urban green space as a complex system functioned by data-science-decision-driven solutions remains underexplored. Therefore, in this article, we leverage existing knowledge to offer eight reflections on quantitative urban green space studies for mapping, monitoring, modeling, and management (4M) practices in landscape design, planning, and management (Fig. 1), to stimulate fresh and innovative thinking in the conversion from data to knowledge and intervention.

1. Eight points of reflection on quantitative urban green space studies in the 4M perspective



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2 Reflection One: Green Space Mapping Should Be Characterized in a Multifaceted Conceptual Model Including Quantity, Quality, Type, and Structure

Green space is best appreciated and characterized as a multifaceted system. However, green space mapping efforts in academia, governments, and practices have primarily focused on capturing the amount and distribution of urban green space and deriving statistics of green space provision (supply) over time[8][9][12]. To improve the potential of urban green space, observations modeling and mapping strategies need to be better designed to quantify green space quality (e.g., greenness, density, aesthetic values), differentiate green space types (e.g., trees, shrubs, and grass), and characterize green space structure (e.g., height, canopy size, shading area, and landscape metrics). The rapid development of multi-source and multi-scale remote sensing such as optical remote sensing (multispectral and hyperspectral), synthetic aperture radar (SAR), light detection and ranging (Lidar), as well as emerging social sensing big data such as street view images and volunteered geographic information, have made it much more possible to characterize urban green space in a multidimensional conceptual model and computable system[12][15][17][30]. Thematic knowledge in the form of spatially explicit maps derived from synthesizing 2-D and 3-D information might be enhanced in the future to serve as the data library of urban green space that can support a variety of practical applications at multiple scales down to individual sites.

3 Reflection Two: Green Space Mapping Sources, Methods, and Uses Vary by Definitions, Approaches, and Scales

Discrepancies exist in remote sensing based estimates of urban green space[17] and this can deter practitioners from using such data sources. The reasons are three-fold: semantic definition, mapping approach, and spatial scale. Because of these factors, a same green space ground cover can generate different mapping results. First, multiple urban green space definitions (semantics) can lead to mapping disagreement. Urban green space can be narrowly defined as outdoor places with significant amounts of vegetation, which exist mainly in semi-natural areas and managed parks and gardens and roadside locations[31]. There are so many variables in this definition, which might cause confusion in mapping. For example, what does a "significant" amount mean? Generally, land partly or completely covered by trees, shrubs, grass, and other vegetation can be classified as urban green space, but we note that to move from semantics to computed mapping, rules and thresholds need to be defined with quantitative terms. Second, different mapping approaches will lead to different green space estimates. For example, the widely-used hard classification (e.g., green and non-green maps) and fractional estimate (e.g., green space coverage) are two alternative representations. Each has its own over- or under-estimation problems for practical applications. Third, different spatial scales of remote sensing imagery will lead to varied levels of accuracy in mapping green space. Urban green space features mapped from remote sensing sources normally have scale lengths ranging from 2 to 10 meters[14][32]. Uncertainties arise from two technical consequences of scale limits: capturing green space features below the level of data resolution, and capturing green space features for larger areas. The former can be addressed by sub-pixel decomposition techniques[10][14], and the latter by pixel (and feature) classification (clustering) techniques[17][28].

4 Reflection Three: Phenology Modifies Seasonal Quality and Quantity of Urban Green Space

Green space is not static. The traditional measurement of urban green space by administrative data usually simply counts its outdoor public space. In non-tropical cities, few such parks are green all the year round. Seasonal changes in urban green space that reflect different phenological phases (i.e., from green-up to maturity, senescence, and green-off) and the dynamic quantity and quality of available green space over time. This is also true within a single city, where a steep topology can create strong North-South shade and day-time sunlight divisions of urban space. Such seasonal dynamics are not typically captured in city-level baseline mappings but will considerably impact people's actual exposure to green space. For example, if Beijing and Shenzhen have the same amount of green space coverage, given their phenology difference, we will not see much green in Beijing, but see year-around greenery in Shenzhen. The phenological effect across latitudes and species plays a crucial role in modifying the quantity of urban green space exposure and also influences green space exposure experience by changing its atheistic quality. For example, spring bloom and fall foliage are high-value attractions for people and may compensate for year-round greenery in temporal climes. A better understanding of city-scale green space phenology patterns can improve upon simpler categorical green boundary based mappings, thus providing a proxy for experienced green space potentials and dynamics of a city. Moreover, it can also help improve models and understanding of green space quality, demand, valuation, and ecosystem services provided. One major practice-focused research agenda is to value different attributes of green space for different environmental and health services. For example, the educational value of micro-wilderness green areas in a city; the health value of peaceful spaces, dementia-friendly sensory gardens, and small inclined green spaces; the biodiversity value of different phenological mixes of green corridors; and so on.

5 Reflection Four: Spatial and Temporal Green Space Data Cubes Can Help Realize Dynamic Monitoring of Urban Green Space Changes

Urban green space is vulnerable to abiotic and biotic disturbances such as drought, storms, and insects[33]~[35]. The healthy status of urban green space with spatially and temporally high-resolution information is critically important for landscape professionals. For example, canopy water content and greenness metrics can be used as a reference to identify vulnerable green space areas and prioritize irrigation and pesticide management, and to create management regimes for urban scale landscape architectural designs. Ex-ante evaluation and ex-post assessment of urban green space responding to extreme weather such as floods and typhoons are essential to optimize resilience of designs, disruption preparedness, and maintenance strategies. Spatial and temporal green space data cubes provide a conceptual and implementable model for designers and managers, which enables historical backtracking, near real-time monitoring of urban green space dynamics in bio-functional 3D units, and scenario planning for resilience. The generation of a data cube model can be realized by integrating multi-scale remote sensing imagery collections, pre-processing and on-the-fly analysis of remote sensing big data, scalable mapping, and temporal modeling of urban green space dynamics, as well as cloud-computing interactive visualizations.[36][37]

6 Reflection Five: Green Space Coverage Reveals Green Space Provision (Supply), But Green Space Exposure Can Capture Effective Demand via Modeling Human Green Space Supply–Demand Relationships

Green space supply metrics that capture coverage and distribution of urban parks, forests, water ways, and other greens have been adopted by city governments, planners, and designers since the birth of modern municipal governance in the 19th century[8][9][12]. However, these are merely inventories. Statistics (e.g. park area per capita) and maps record infrastructure supply, often via informally and professionally planning and engineering standards, equated to exposure as a rule of thumb. The nuances of the assumption do not always find their way into planning and design. The underlying assumption is that green space is evenly exposed to the population over time and space. But since urban population are never evenly spread, green space exposure metrics need to account for both green space and population distribution. For example, a measure of total green space in a city does not factor in the accessibility to the population who might use it. It makes sense at one level to use green space coverage averaged or per capita as common metrics. However, this is a faulty measure in the distance and nature of consumption.

The distance error means that a measure of aggregate city green space supply per capita does not capture spatial heterogeneity in green space demand from residents living in different places. By definition, people have to travel to public open space, and most of them have a fixed time (and possibly money) budget, meaning that they will use a farther away green space less. Economists and geographers talk about a spatial demand curve where demand falls off with distance because distance represents a cost of consumption. The way to handle this is distance and population-weighted exposure measures[38]. Measured for areal units like urban communities, districts or whole cities, higher weights can be used proportionate to population to match against green space in each unit. This is a simple aggregate measure of exposure capturing pressure of demand.[10][11] For a given stock of green space, an area with more population will be mapped as having less exposure. Another approach is to weight not only by population but by distance, using for example a simple gravity-style spatial interaction formula[39]. For example, the exposure of people in a community is measured by the quantity of green space in that and surrounding communities, divided by the distance between the community and the green spaces. This overcomes the unrealistic assumption that people only use green space in their own area. Appropriately designed green space exposure metrics can allow for comparison of green space supply across time, space, and population groups. They can be used to estimate variations in opportunities to benefit from different kinds of green spaces and different kinds of green space attributes and services. If we understand more about the value of the multiple essential attributes of green space, we can better design, plan, and manage to optimize the benefits flowing from green space attributes to the populations who use it.

The second error made by total or average green space supply metrics is because they miss the point that green space is what economists call a "public good." A public good is defined not by being supplied by a public agency but by the nature of consumption[40]. For example, when two unrelated people enjoy a green space, they are enjoying the same space—they are co-consuming the "good." This renders a green space area per capita measure theoretically inaccurate, even though it may be heuristically useful for landscape design and planning[41]. What matters more is the size of the green space in relation to the accessible population. Even with a large population, if the green space is large (like Central Park or Hyde Park), it can remain uncongested and the entire population of users is enjoying (or consuming) the same quantity as each other. Understanding and measuring size-distribution of green space in parallel to population and distance-weighted accessibility is another necessary sophistication of green mapping. Real-time and historical actual green space use is clearly important in optimizing this aspect of environmental design.

7 Reflection Six: Green Space Exposure Measures Should Account for Spatial, Temporal, and Social Differences

People living in cities move during the fulfillment of their daily routines, which exposes them to a variety of green space environments. Although previous population-weighted exposure models considering the spatial distribution of population and green space footprint[10][11][28] are appropriately interpreted as an overall assessment of human exposure to green space, the spatiotemporal interactions between humans and green space by individuals have not commonly been differentiated. People gain green exposure from home/workplace and via trips chained to shopping and recreational destinations. They also gain different kinds of value from different kinds of green space: health value from an extended commute walk that passes greenery and from leisure trips to green destinations. One study found that elderly people gain more health value from green space by walking to it rather than using it actively, suggesting that a healthier city for older people has greater distances to green space, within a limit[42]. People gain existence value or reservation value from the mere existence of large, wild, and symbolic green space even that they may rarely or never visit them personally and would consider it a loss if such space was developed. Parents gain significant pure altruistic and self-interested altruistic value from green space used by their children. These are not imagined theoretical benefits, but they can be measured by stated-preference and revealed-preference techniques. Understanding them can help structure and interpret the measures of greenness used to monitor a city's green health.

The difference in population groups in terms of sociodemographic categories such as gender, age, and income are not always considered when measuring or reporting green space exposure. In reality, urban green space will have varying environmental impacts and health benefits for different population groups during different time periods[43]. Therefore, an improved data protocol for measuring green space exposure levels should be human-centered and integrate multidimensional information to allow, where needed, for the analysis of spatial heterogeneity, temporal variability, the multiple kind of value derived from green space, and the different needs and preferences of different socio-economic and age groups.

Additionally, green space privilege is becoming an increasingly critical concern because the inequality in green space exposure has the potential to translate into inequalities in mental and physical health.[44]~[46] Evidence from the United States[47], Germany[48], and China[10][49] suggests that strong disparities in green space supply characterize cities and communities. Another recent global analysis of human exposure to green space revealed a contrasting inequality between cities of the South and North[28]. Global South cities enjoy only one third of the green space exposure level of Global North cities, even though a lot of the Global North is in tropical and sub-tropical climate zones. Furthermore, green space exposure inequality in Global South cities is nearly twice that of Global North cities[28], which is largely on account of the more informal nature of cities in the South, poorer municipal budgets, and less formal green space planning. All these observations and findings highlight the need to consider better optimization strategies in pursuit of environmental justice and efficiency within and between cities, as well as between regions.

However, efforts to lessen green space exposure inequality face two challenges. First, the inequality assessment is highly sensitive to scales we defined, which sets a high data requirement of multi-scale green space exposure estimates in terms of different statistical units, buffered distance incorporating different nearby environments, and different categories of green environments. Only if such prerequisite knowledge with spatially explicit datasets disentangling multi-scale heterogeneity in urban green space is secured, can urban greening pathways be implemented in a more efficient and cost-effective way. Second, environmental injustice is always coupled with social injustice and becomes endemic throughout the world in various guises. However, this should not be an excuse for non-action, since the combined effect of environmental and social injustice will lead to amplified impacts on health, social, and in the end, economic outcomes. A systematic thinking with integrating socio–economic–environmental–healthy perspectives is required to address the inequality issue for promoting a more equitable global built environment.

8 Reflection Seven: Greening Optimization Should Consider Biophysical, Biodiversity, and Health Benefits

In addition to human health and well-being benefits, green space has been widely recognized as a nature-based solution to climate-change mitigation and adaptation[50], for example, to mitigate the urban heat island (UHI) effect[51]. However, available space and resources associated with urban greening initiatives are limited[51], especially for high-rise and high-dense urbanization contexts. Therefore, prioritizing suitable regions and identifying the best locations for urban greening are taking on new urgency for planners, designers, and relevant stakeholders. There is an expanding social imperative for city and regional scale green (and blue) landscape planning. For a century, this has tended to be addressed by greenbelt and urban growth-boundary planning and by agricultural land preservation zoning policy. In many countries, such as China, agricultural land protection from development and urban development control have evolved under different laws and different government ministries. Multi-scale, multi-use data sources on green space can help harmonize these concerns for more effective interventions. The protection of farming land as a long-term social goal has been strengthened more recently with a broader concern for biophysical and biodiversity management. To address the challenge, multi-objective optimization that considers biophysical, biodiversity, and healthy benefits is recommended for the ex-ante simulation and evaluation of different landscape and greening design and management plans. For example, with spatially explicit datasets of land surface temperature, multifaceted green space mapping, high resolution and dynamic wildlife and ecological maps, and human population distribution, we can develop multi-objective optimization frameworks to guide future greening initiatives by maximizing the cooling effects and the human exposure to green space.

In the future, this will be done with the help of process-based modeling, artificial intelligence algorithms, and the landscape design, science, and practitioner communities. A recent study, for example, used generative planning algorithms to compute thousands of alternative development and green space configurations for Shenzhen of China, with the objective of optimizing UHI effects and other climate-responsive properties of the city[52]. Overall, green space, or green ecosystem at a broader context, has been highly valued by its ecosystem service functions to the society. The concept of gross ecosystem product (GEP), similar to economic measures like gross domestic product (GDP), was proposed to measure the aggregate monetary value of ecosystem-related goods and services in a given region over an accounting temporal period[53]. This new practice will influence assessment, management, and investment of urban ecosystem assets such as green space in a more proactive and coordinated pathway.

9 Reflection Eight: Urban Green Space Management Should Be Strategized With a Long-term View

Urban greening is, on the one hand, a weapon in the armory for climate-change mitigation, but on the other hand, an environmental component vulnerable to climate change impacts. Therefore, new urban greening initiatives and existing urban green space management should be strategized with a long-term view, which will synthesize the past and future and view even small landscapes as part of a dynamic complex system of evolving ecological spaces. History provides a massive dataset and a diverse experiment, and its lessons can be leveraged by analyzing historical observations to inform the future. For example, the response of urban green space (e.g., greenness/vigor, phenology cycle, structure) to climatic conditions (e.g., temperature, precipitation, soil moisture, air dryness) can be investigated using synchronized datasets in longitudinal studies. Earth system models forced with future scenarios (e.g., different shared socioeconomic pathways) can also help project future changes in climate conditions and consequences for landscape design and management. Empirical knowledge from historical observations can be integrated with future projections to identify regions where urban green space is likely to experience the most significant changes in terms of both magnitude and function. Multi-scale landscape and green space vulnerability analysis and mapping over mid- and long-terms is particularly crucial in coastal areas and floodplains, especially heavily populated areas.

10 Conclusions and Discussion

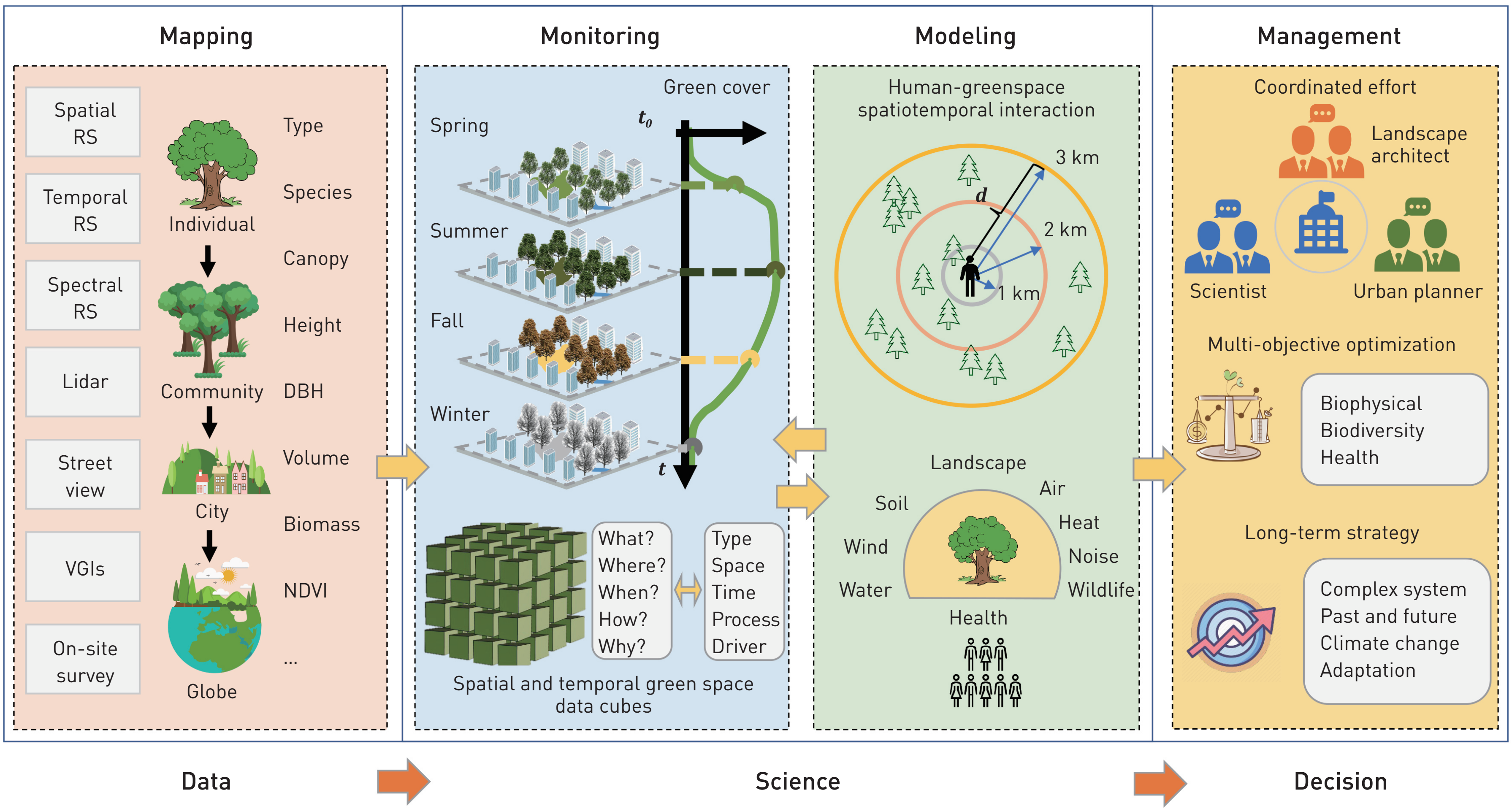
Bringing together on the eight reflections above, we raise the possibility of data-science-decision support systems that can guide and promote mapping, monitoring, modeling, and management

(4M) practices of urban green space (Fig. 2). Few smart city initiatives have focused on smart systems for managing this most precious resource. First, advancements in mapping and monitoring can massively enhance our data capabilities to characterize the multifaceted system of urban green space (from descriptive knowledge to explicit data libraries) and quantify spatiotemporal dynamics (e.g., natural phenology, abrupt disturbances, evolving changes in human activities).

Second, the spatiotemporal interaction between humans (i.e., population group, location, density, mobility) and green environments (i.e., amount, coverage, phenology) can now be measured and modeled at a detail unimaginable in the early days of analogue landscape mapping and then GIS (pioneered by landscape architecture at Harvard Graduate School of Design and elsewhere). We can now go well beyond simple inventory mapping and simple human-population-weighted exposure models. At The University of Hong Kong, we are developing models and methods for monitoring landscape supply, demand, use, value, and preference from global to region to city, neighborhood, and site scale. This requires a coming together of landscape architects, ecologists, natural resources remote sensing scientists, urban data scientists, land economists, urban economists, transport engineers, climate scientists, marine scientists, and many more. The critical insights into human-green space interactions in cities now demanded by governments, professionals, and the society across scientific domains and industrial sectors requires a new joined-up thinking. Data are driving joined-up thinking about all manner of urban issues. Health scientists are knocking on the doors of urban designers and asking how to use "big health data" to design cities as long-term public-health interventions that will shape the way people live for decades to come. Landscape professionals do not design isolated spaces. To respond to the enlarged significance of this profession, one way forward is to build landscape management data platforms and decision systems of quality and reliability suitable for the widest societal use.

The knowledge advanced by synthesizing high spatial, temporal,

2. Conceptual diagram of data-science-decision support systems to guide and promote 4M practices of urban green space



and attributional resolution green space measures and maps, and exposure assessments for normative design and planning-support and multi-objective optimization represents something of a paradigm challenge for landscape professionals. Landscape architecture has a long history with GIS and RS, but the rapid advancements in data science and spatial data science in particular, along with a smart city industry predicted to be globally worth 2,036 billion USD by 2026[54], means a new frontier and an enhanced contribution to the society's pressing environmental, health, and livability challenges. The frontier is well defined, with companies like ESRI (Environmental Systems Research Institute) active in promoting design-led GIS analysis as distinct from science-led analysis, and deeply embedded in decision-support system development with cities, national parks, and so on. This tends to be well taught in geography, planning, and environmental science schools. To prepare landscape students for the new data environment in the industry there is probably much scope for innovating with multi-dimensional data platforms and decision systems in schools of landscape, especially focusing on linking monitoring, modeling, and analysis with design. This will be a strategic focus of landscape scholars and professionals crossing design, science, social science, and humanities. For example, smart city landscape design and management systems will be increasingly essential in helping students, policymakers, urban planners, and landscape designers in monitoring the balance between green space supply and demand, and detecting vulnerable spots of green space exposure, and accordingly implementing more effective and sustainable greening programs adjusted to different local circumstances to achieve more equitable distributions of green space.

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https://doi.org/10.15302/J-LAF-1-030035 中图分类号 | TU986 文献标识码 | B

从制图—监测—建模—管理视角谈对城市绿地量化研究的八点思考

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摘要

绿地是城市环境的重要组成部分，为我们的社会经济文化活动提供了可观的生态系统服务。既有研究已广泛采用众多旨在测度绿地供需关系，衡量可用性、可达性和可见度的指标，以从局地到区域尺度评估可持续发展目标的实现情况。本文中，作者总结了对城市绿地量化研究的八点思考，以期为景观设计和规划中的4M实践——制图（mapping）、监测（monitoring）、建模（modeling）和管理（management）——提供指导，并激发将数据驱动研究转化为科学干预措施的创新思维。八点思考包括：1）绿地制图应体现多属性概念模型表征，包括数量、质量、类型和结构；2）绿地制图的来源、手段和用途因定义、方法和尺度而异；3）城市绿地的质量和数量受季节性物候条件影响；4）绿地时空数据立方体将有助于实现对城市绿地变化的近实时监测；5）绿地覆盖率能够揭示绿地的供给情况，但绿地暴露度可通过建模的方式有效测度人口–绿地的供需关系；6）测量绿地暴露度时应考虑空间、时间和社会差异；7）在制定绿化优化方案时，景观设计师和规划师应考虑生物物理、生物多样性和健康效益；8）城市绿地管理策略应着眼长远。最后，本文提出，以数据科学为支撑的决策系统有助于指导和促进城市绿地4M实践。本文中的各项思考对城市绿地景观设计、规划和管理的研究、实践和理论探索有着广泛的意义，并共同构成了一套可指导科研人员、决策者和从业者制定城市绿地最佳4M实践战略的原则。

关键词

城市绿地；
量化指标；
绿地供需；
制图–监测–建模–管理框架；
城市绿地正义

文章亮点

- 提出城市绿地制图–监测–建模–管理（4M）框架
- 提出基于城市绿地4M实践的八点思考
- 提出将数据驱动研究转化为科学干预措施的创新思考
- 为城市绿地量化研究、实践和理论提供广泛启示

收稿时间

2022-04-15

编辑 田乐，王颖