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Nurturing nature in a mega-city: a decadal assessment of the Beijing Olympic Forest Park

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Abstract
In this article, we showcase the Beijing Olympic Forest Park (BOFP), a large-scale urban park developed as part of the green infrastructure to support the 2008 Olympic Games in Beijing, China. The BOFP represents an example of using strategically-placed and well-designed public open spaces to relieve stresses from high-density living in compact urban areas. Drawing from first-hand information from leading planners and designers, we present the ideas rooted in Chinese culture and environmental aesthetics that have inspired the overall layout of the park. Anchoring itself at the northern end of the city's central axis, BOFP takes on the Chinese Shan-Shui Landscape layout and integrates into its design many elements of cultural significance. We then explain the park's design elements inspired by Frederick Law Olmsted and his sons and modern construction technologies informed by ecological science. Through an extensive review of empirical studies, we evaluate the park's performance in social and environmental aspects and identify areas in need of improvements. We suggest that the BOFP manifests a successful fusion of quintessence from both the western and eastern landscape fields. It illustrates an application of a culturally informed ecological approach to park siting, planning, and design, which has supported the park's meaningful integration into its urban context and amplified its contributions to the city. Evidence cumulated through decadal evaluations of the park's performance has revealed the accomplishments of this transformative place-making approach for both nature and people.

Keywords Place-making · Landscape performance · Shan-Shui landscape layout · Culturally informed ecological approach · Beijing Olympic Forest Park · China

1 Parks as critical urban assets

Compact urban development is among one of the well-accepted pathways to achieving sustainable urbanization. While dense urban areas see advantages in land-use and infrastructure efficiencies, concerns exist over negative psychological impacts on urban dwellers from inevitable congestion, crowdedness, and undesirable environmental qualities. It is a long planning tradition to use strategically placed and well-designed public open spaces to relieve stresses from high-density living, beginning with Central Park in New York City, designed by Frederick Olmsted and Calvert Vaux, and now frequently seen in cities such as Singapore (Sini 2020) and Beijing. The most popular of those spaces, often containing natural beauty and human-made attractions, have become urban oases to bring about enormous economic, social, and environmental benefits to their host communities.

In this article, we showcase the Beijing Olympic Forest Park (BOFP), a large-scale urban park developed as part of the urban infrastructure to support the 2008 Olympic Games in Beijing, China. The BOFP represents an example of using large parks as critical anchors of the city's public open space system to improve the environmental conditions and quality of life in dense urban areas. While the park's investment

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level and spatial scale outrival those of most urban parks in China, its design was inspired by both Chinese culture and environmental aesthetics and modern ecological science and technology, thus offering a laboratory to study context-sensitive, ecologically sound, and technologically innovative strategies for landscape planning and design. We argue that the BOFP project illustrates a unique culturally informed ecological approach to park siting, planning, and design, which is manifested in the park's meaningful integration into its urban context and its own spatial structure.

Comprehensive and in-depth analyses of park projects provide insights into the various benefits they offer and ways to improve their design, construction, and operation to strengthen their role as community assets. Based on first-hand information from leading planners and designers and an extensive review of empirical studies, we evaluate the BOFP's performance in social and ecological aspects and identify areas needing improvement. The park's high performance in various sustainability aspects, as well as lessons learned from the underachievement of some original goals, provides valuable information to planners, landscape architects, and park managers. As China continues its rapid urbanization under the influence of globalization, we hope insights gained from this study will support future efforts to create healthy landscapes with a strong cultural identity.

To connect the dots among the park's context, objectives, design strategies, performance, and future implications, we focus on exploring the following questions:

1. How did the park's design intent emerge from the project's specific political and socio-economic context?
2. What sustainability goals was the park expected to achieve and why?
3. How were those sustainability goals incorporated into the planning, design, construction, and maintenance of the park?
4. How well did the park perform to provide social and ecological benefits in the first decade of its operation? What are the reasons for underperformance?
5. What should and can be done to sustain and enhance the park's benefits provision? How can the transferable lessons learned from this study inform open space design in high-density urban environments?

2 The Beijing Olympic Forest Park landscape

At 680 hectares, the Beijing Olympic Forest Park, often known as Beijing's "Central Park," is the greatest legacy of the 2008 Beijing Olympics. Situated at the northern end of Beijing's historical South-North Central Axis (Fig. 1), the park is a distinct new ecosystem surrounded by an ultra-urban context. Guided by the *Shan-Shui* (山水, mountain-water) principle (Yang and Hu 2016, p. 9), the park's design incorporated traditional Chinese landscape planning and design principles that emphasize the harmonious human-nature relationship. Meanwhile, modern ecological science, engineering, and technological solutions were broadly employed to achieve a wide range of sustainable development goals. Designed for people, the park provides ample spaces of varying scales to accommodate events, group activities, exercising, and other recreational uses for both residents and visitors. Much-loved by Beijing citizens as a transformative public amenity that greatly enhanced people's quality of life, the park has also gained national significance as a tourist hotspot and outdoor fitness base. With its success recognized globally, the park has a profound influence on landscape design in China.

2.1 Context, intent, and layout

The story of the BOFP site started with the cultural significance of Beijing's central axis and the intent to provide residents easy and much-needed access to nature in the hustle and bustle of a mega-city. Since the 1260s, the imperial city developed around the central axis, along which the Forbidden City and other national monuments such as the Tiananmen Square are situated (Fig. 1d). In 2002, the Olympic Committee adopted the scheme of "Axis to Nature" proposed by the international design competition winner, Sasaki Associates, which literally extends the axis into the BOFP at the northern end. This was a grand gesture to recognize the significance of nature in a city and a powerful move to create a remarkable civic space to be enjoyed by people. It ensured that the park became part of the city identity, rather than a temporary glory to be neglected after the Olympics.

Besides being a cultural icon on the central axis, the BOFP was strategically placed as a critical anchor of the regional ecological infrastructure. As one of the largest green wedges connecting the inner-city open spaces to Beijing's Green Belt along the Sixth Ring Road and West Mountains (Fig. 1c), the BOFP is also part of Beijing's north–south wind corridor, which leverages natural ventilation to mitigate the urban heat island effect.

To meet the immediate demands of the Olympic Games and the long-term goal toward a multi-functional cultural and ecological center for the city, the Olympic Park was consciously planned as an integral part of the existing urban fabric. For example, the city made massive investments to enhance connections to the park through new transit lines and transportation hubs. Mixed-use urban infill with museums, conference centers, hotels, and office buildings continued to occur in the surrounding areas until today.

Within BOFP, the goals of nurturing and utilizing nature translated to a park layout with two distinct zones of varying human disturbance levels separated by the

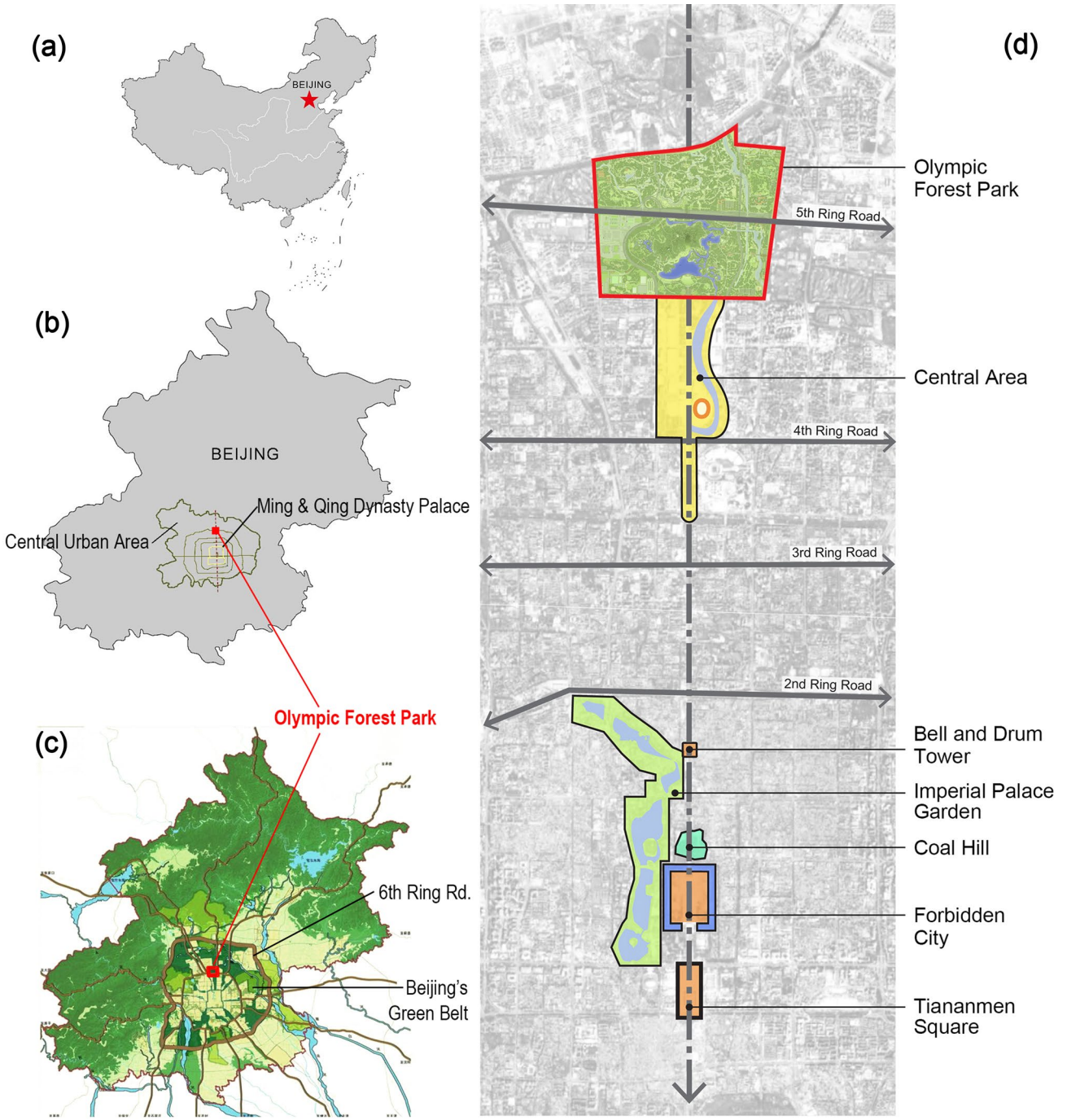

Fig. 1 The location of Beijing Olympic Forest Park; **a** Beijing in China; **b** BOFP on Beijing's central axis; **c** BOFP as a critical green wedge in Beijing's green space system; **d** the "Axis to Nature" concept by Sasaki Associates

Fifth Ring Road superhighway (Fig. 2). The densely forested north park was designed as a natural reserve critical for the regional ecosystem, protecting and rehabilitating native forest communities. Preexisting vegetation, soil, water, and wildlife were carefully surveyed and minimally disturbed during construction. Few service facilities were built inside the north park; activity spaces such as playgrounds and sports fields are mainly concentrated along the park's edges. Additionally, daily visitor volume has been carefully managed to maintain an environment favorable to plants and animals. In contrast, the south park was designed as a lively and versatile public space for culture, education, and entertainment, meanwhile, a grand garden that honors traditional Chinese landscape

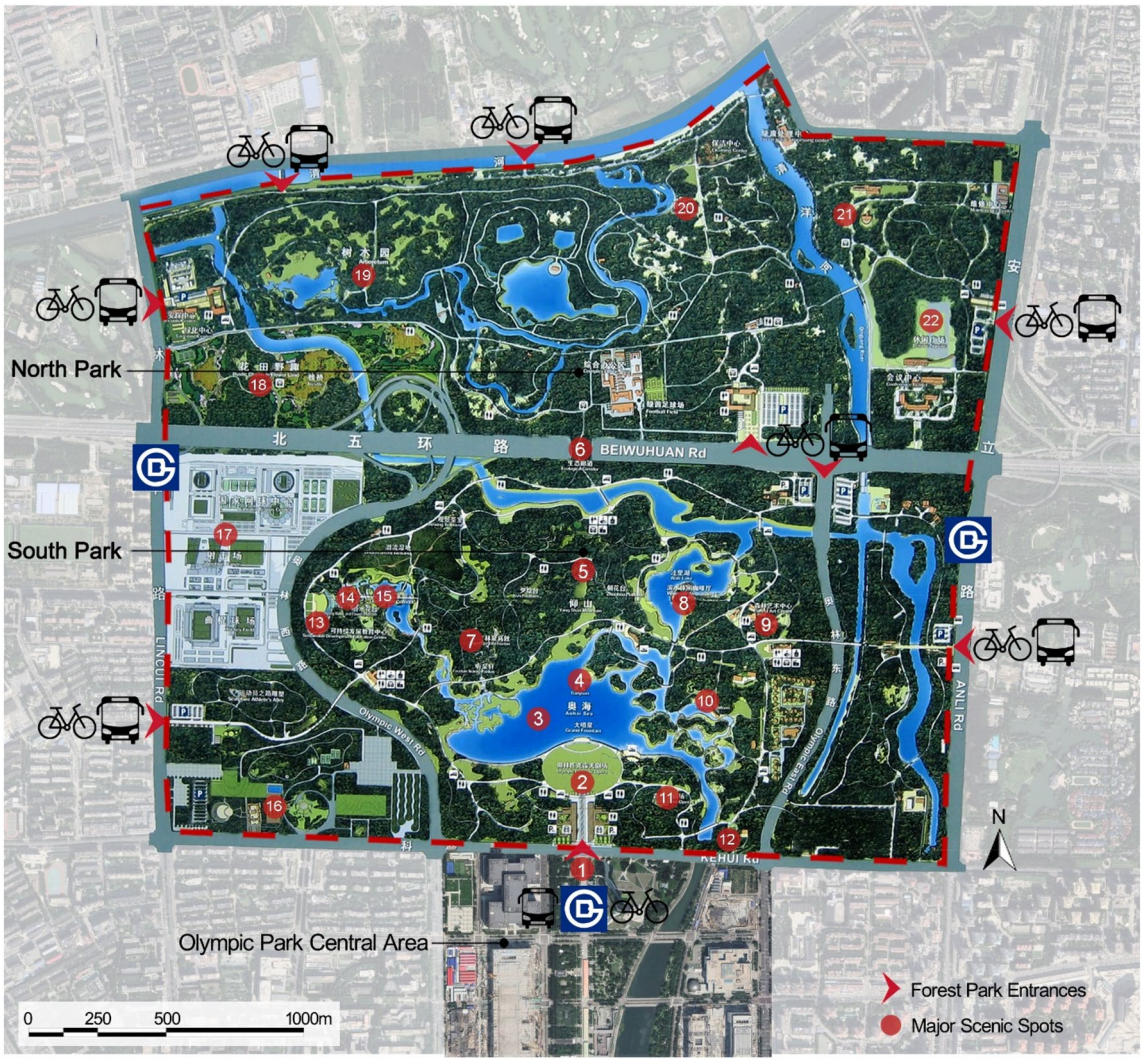

Fig. 2 The Master Plan of Beijing Olympic Forest Park (adapted from map provided by BOFP Development and Management Co., Ltd.)

concepts. Connecting the tranquil northern forests and the exciting southern Olympic venues, it exhibits a landscape gradient guided by ancient environmental planning principles, which naturally place a city on the south side of a mountain and the north side of the water (Fig. 3a). Here, a screen of hills (山, Shan) in the north and west protects the area from Beijing's harsh northwestern winds, and meandering waters (水, Shui) flow out of the main lake (Aohai) south of the hills toward the central area of the Olympic Park (Fig. 3b).

2.2 Sustainability goals and design strategies

After the international competition, the Beijing Tsinghua Tongheng Urban Planning and Design Institute (THUPDI) led a multi-disciplinary team to refine and implement Sasaki's conceptual landscape plan. Likely the largest team ever for a single project, over 200 experts from ~ 50 professional backgrounds conducted multi-layer ecological analysis following McHarg's approach (McHarg 1995, pp. 153–162) (Fig. 3c) to pursue a comprehensive set of sustainability

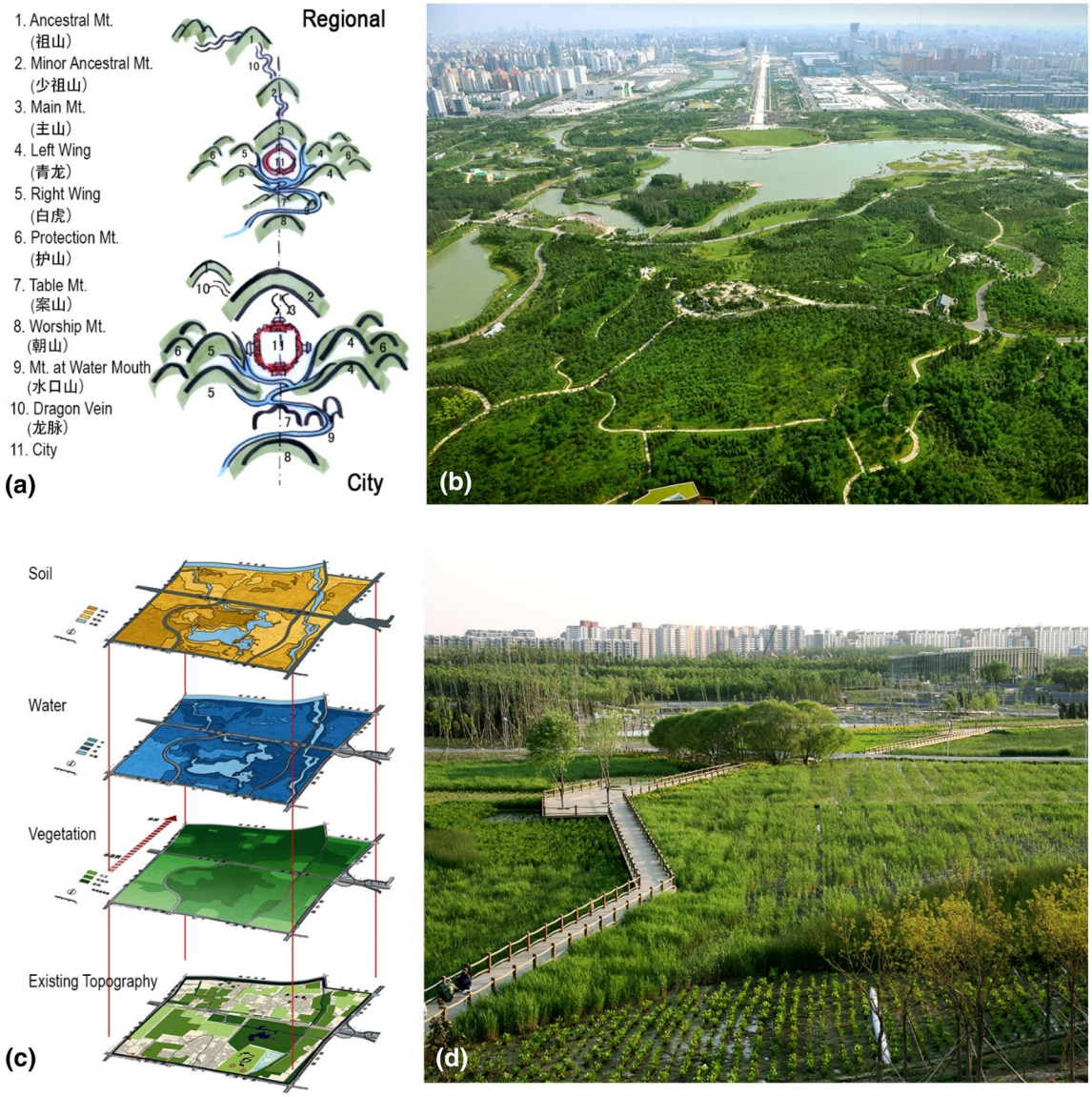

Fig. 3 The design of BOFP integrated ancient environmental planning principles (**a**) with ecological planning analyses (**c**); **b** shows the Shan-Shui structure with the mountain peak, main lake, central city axis, and meandering waters in view, and **d** shows a bird-eye view of the constructed wetland. Source: THUPDI; used with permission

goals. State-of-the-art modern technologies were incorporated into the design, construction, and maintenance of the park to achieve those goals.

(1) *Water* To construct a self-sustaining and self-regulating water system in response to Beijing's high evaporation rate and scarce municipal water supply, a 4-hectare integrated vertical-flow constructed wetland was installed in the south park (Fig. 3d). The wetland treats 2,600 m^3 of reclaimed water from the Qing River Wastewater Treatment Plant per day, which then recharges the main lake. This was the first domestic application of using reclaimed water and stormwater to supply 100% of an urban park's waterscape. Moreover, a demonstration greenhouse and underwater observational corridor accompany the wetland to provide public environmental education. To mitigate the stormwater impacts of the ~ 350,000 m^2 added paved surfaces by the Olympics, especially during the torrential summer storms, a comprehensive stormwater treatment system, including porous paving, bioswales, ponds, infiltration wells, and cisterns, was installed to store, reuse, and most importantly, infiltrate stormwater. An intelligent landscape irrigation system was also installed to further reduce water use.

(2) *Solid waste* A solid waste recycling and reuse system was constructed to treat 100% of the landscape and restroom wastes into fertilizers for park reuse.

(3) *Energy* Various strategies of energy conservation and employment of renewable energy and recycled materials were implemented in landscapes and over 90 buildings. Buildings adopted thermal insulation materials, geothermal pumps, central heating and cooling systems, and sometimes skylight illumination systems. Several structures and buildings were employed as environmental education tools, such as the solar photovoltaic panels at the south gate and another earth-sheltered building that provides research and educational opportunities for energy conservation technologies.

(4) *Habitat* Besides protecting existing habitats, new habitats were created by installing over 2 million new plants of ~ 300 species, including ~ 0.53 million trees. Plantings were designed to mimic communities that naturally occur around Beijing (Dong et al. 2006, p. 67); native species were planted to the maximum degree allowed by local nursery resources. Additionally, a 218 m-long, 60 m-wide eco-bridge (Fig. 4) was installed to maintain wildlife and pedestrian connections across the 80 m-wide Fifth Ring Road. Other habitat features included a 24 m-tall bird tower designed to accommodate over 1500 swifts culturally important to Beijing.

Besides the above sustainable features, the set of design strategies to create a philosophically meaningful place and a lively social space are particularly worth highlighting. The former ensures the preservation of the distinct Chinese landscape culture, while the latter honors the utterly most significant function of large parks in dense cities—to serve its people.

2.2.1 A philosophically meaningful place

The Shan-Shui principle, defined as following a mountain-water-city spatial structure considered optimal in Chinese culture, had emerged from cumulative practices of building human settlements in ancient China. Its applications often involved environmental analyses (however primitive) for determining the siting suitability of a potential city-building site and an assessment of the territory's aesthetic and symbolic power for place identity (Yang and Hu 2016, pp. 2–5). Contemporary interests in the Shan-Shui principle rose in the late 1990s and have given rise to its modern applications at multiple spatial scales, from new town plans, large-scale open space projects to single buildings (Hu et al. 2020, pp. 46–55; Ma 2015, Chapter 3). The siting and design of the BOFP embody this culturally informed ecological approach to placemaking. Specifically, the entire park is integrated into a Shan-Shui structure that governs the relationship between the Forbidden City and its surrounding mountains and lakes. Meanwhile, the south park adopts a Shan-Shui spatial structure in the layout of its major designed environmental elements—the hill and lake.

Fig. 4 The eco-bridge across the North Fifth Ring Road connects the north and south park (Fall 2019). Source: THUPDI; used with permission

At the scale encompassing the Forbidden city, the 45.7 m-high Coal Hill, built with excavation materials from the construction of adjacent palaces, moats, and lakes, sits right on the city's central axis directly north of the Forbidden City, establishing a Shan-Shui structure on the territory (Ko and Hu 1984). Following this vital landscape tradition, the south park's Shan-Shui structure was created by reusing excavation materials from the Olympics' massive construction. To achieve a cut-and-fill balance, the expert team meticulously reiterated the design of Mount Yang (仰山), gauging its volume and height based on multi-scalar view analyses, public accessibility, geotechnical stability, and cost.

The completed Mount Yang is extensive and majestic, providing a sense of protective power and lofty nobility. Its peak sits directly north of the main lake on the city's central axis. View analyses at the regional scale informed the design of a gentler west slope and steeper east slope. From the winding west slope, visitors can capture the views of the rolling West Mountains in Beijing's suburb, just as the emperors could from the Forbidden City. From the zigzagging east slope, the spacious main lake and meandering dragon-shaped canal remain constantly visible. Despite being entirely artificially made, the Shan-Shui landscape was designed to appear naturally created by the Lord of Heaven, which again deeply reflected the ancient environmental ideal to create a harmonious human-nature relationship.

Besides the overall Shan-Shui layout, many scenic spots were designed to revive Chinese classical garden sceneries, mark critical feng shui locations, and evoke emotional connections to ancient poems and paintings, such as the *Height of Woods and Brooks* (林泉高致) and *Land of Heaven* (天境) (Fig. 5). To take the latter as an example, here, a group of magnificent rocks surrounded by native Chinese red pines (*Pinus tabuliformis*) marks the peak of Mount Yang. Invited from Mount Tai in Shandong Province, the foremost of the five Sacred Mountains of China worshipped nationally for at least 3000 years, the distinctively textured rocks symbolize stability, peace, health, and well-being against evil spirits. Besides providing a summit for a grand view of the entire park, the *Land of Heaven* celebrates the spirit of nature with a traditional yet modern and simplistic composition of natural elements (Fig. 5).

2.2.2 A functional and joyful place for all

From the very beginning, the park was designed for long-term civic and tourist use beyond the Olympic Games. Expecting the park to rapidly grow into a national center of tourism, leisure, recreation, sports, and fitness exercises, the city made massive transportation investments that involved one new subway line and over 20 bus line connections to enhance the park's accessibility. Within the park itself, the layout of public facilities, outdoor spaces, vegetated areas, and circulation systems work together with the design of lighting, soundscape, emergency avoidance system, and intelligent management system to create a safe, multifunctional, and joyful place. All the facilities implemented accessible designs, ensuring safe and easy access for all age groups. Designated surface and underground evacuation spaces prepare the high-density mega-city for natural hazards and other emergencies such as earthquakes, fires, and disease outbreaks. Free entry to the entire park has permitted anyone in any financial status to fully enjoy the park—a bold move a decade ago when entry fees remained the primary resource to cover the maintenance expenses of public parks throughout the country.

The design team studied Beijing's entire park system to understand critical city-level functional needs, meet the immediate demands of the Olympics, and design for the long-term, diverse needs of citizens and tourists. A network of service and educational facilities, activity spaces of

Fig. 5 Cultural scenic spots such as **a** the *Height of Woods and Brooks* and **b** the *Land of Heaven.* Source: THUPDI; used with permission

various scales, paths of differing types, and viewing points offer diverse experiences throughout the park (Fig. 6). For example, the 40,000 m^2 open-air theater at the south park entrance accommodates up to 20,000 audiences per event for large-scale celebrations, performances, and other gatherings. Medium-sized spaces such as the Forest Theatre can host smaller events with ~ 100 visitors. Other smaller intimate corner spaces hosting 10–20 people at a time are dispersed throughout the park.

Recognizing the significant role large urban parks play in enhancing public health, the design team incorporated ample spaces to accommodate physical exercises. A prominent example was the three (3 km, 5 km, and 10 km) running tracks that loop around the park (Fig. 7). Exceeding the maximum width (4–6 m) in the then National Codes for Park Design, the specially designed 7–9 m wide running tracks allow large groups to stride and run together without constantly interfering with each other. As the running tracks gained increasing popularity, the park implemented significant design upgrades in 2009 and 2016, including resurfacing the paths with synthetic rubber for increased comfort and installing ten "Joy in Running" service stations for showering, resting, belongings storage, and fitness level testing.

Fig. 6 Spaces at various scales accommodate activities of groups or individuals from all age groups. Sources: (**a**, **b**) authors; (**c**) http://news.qihuiwang.com/chanpin/201901163060066; (**d**) http://www.naturewin.cn/product/detail/id/596; (**e**) http://www.bjnews.com.cn/news/2018/04/27/484936; (**f**) http://www.bjnews.com.cn/feature/2019/03/10/554641.html; (all Accessed October 20, 2020)

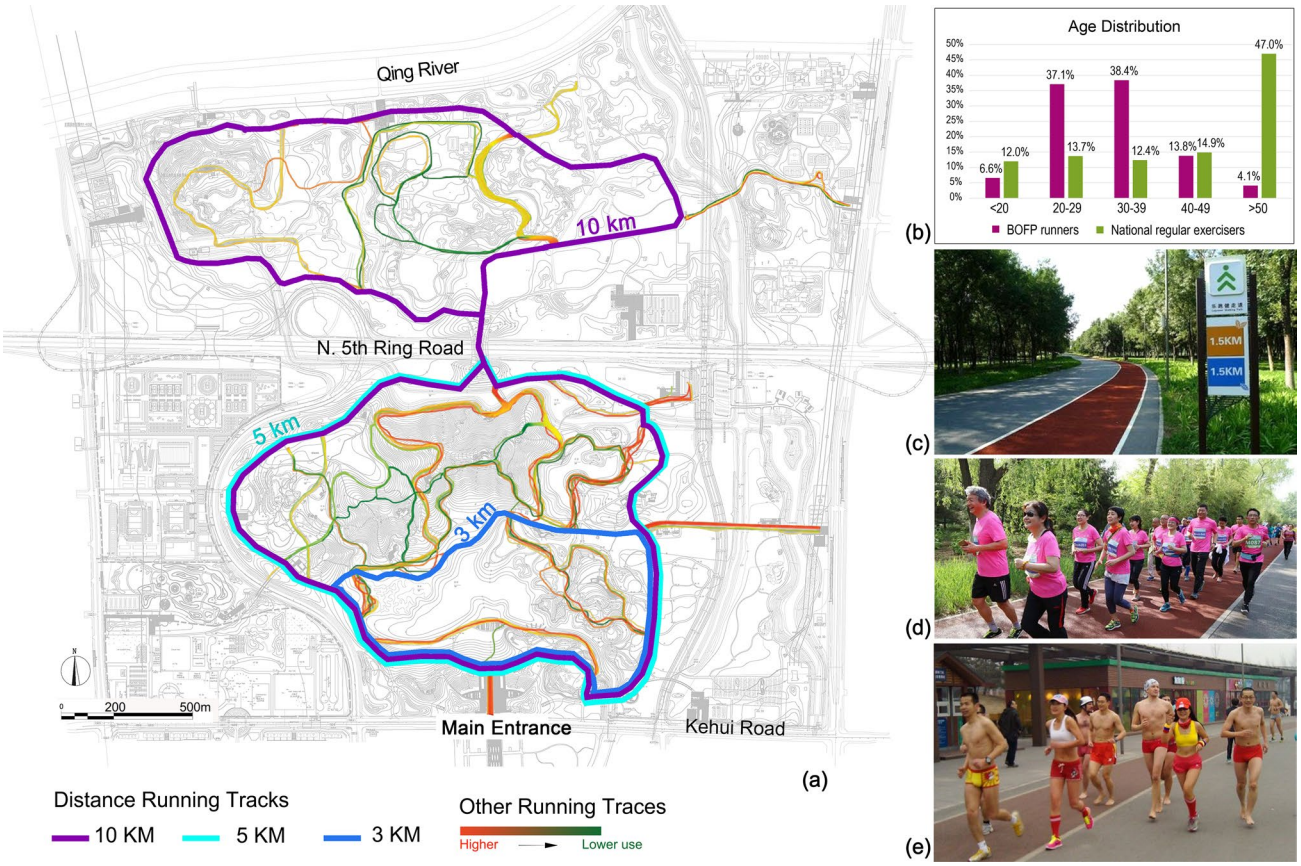

Fig. 7 Running spaces help various age groups achieve their fitness goals; **a** the distance running tracks and other running traces (adapted from Li et al. 2020, p. 68); **b** age distribution of BOFP runner versus national regular exercisers; **c–e** photographs of the running track and exercisers. Sources: (**c**) https://www.sohu.com/a/23404048_206595; (**d**) http://www.feixiubook.com/416172.html; (**e**) https://www.mafengwo.cn/g/i/1140529.html; (all accessed October 20, 2020)

3 Performance of the Olympic Forest Park landscape

With the design objectives and strategies above, how well did the park perform, providing essential benefits to its host city? Based on an extensive search of empirical research in major Chinese databases, including CNKI (China National Knowledge Infrastructure), VIP (http://www.cqvip.com/), Wanfang Data, and CSCD (Chinese Science Citation Database), we identified and reviewed ~ 429 sources with BOFP as a subject matter, including two books, 387 journal and proceeding articles, and 40 masters' and Ph.D. theses. Information on the park's social, environmental, and economic effects was extracted from ~ 95 sources and summarized using the benefit categories developed by the Landscape Architecture Foundation's Landscape Performance Series (Canfield et al. 2018, pp. 15, 51, 75). Due to a lack of quantitative research on the economic impacts of BOFP beyond its influence on adjacent residential prices (Chen et al. 2015), we address the posed performance question focusing on the social and environmental aspects.

3.1 Social performance

3.1.1 Recreational and social value

Since its opening in 2008, the BOFP has become a significant amenity for Beijing citizens and an increasingly popular tourist destination. Today the park receives between 11 and 12 million visitations a year, a roughly 300% increase from when it first opened (Fig. 8a). Peak daily visitation now amounts to ~ 110,000 during weekends and ~ 200,000 during holidays. An average of ~ 400 planned events, such as sports, performances, and other cultural and educational activities, are held in the park each year, excluding countless self-organized group events. Since 2017, the park has surpassed the Fragrant Hills in the northwest suburb and become the residents' new favorite place for viewing fall foliage, according to big data and social media rating assessments by Beijing Gardening and Greening Bureau.

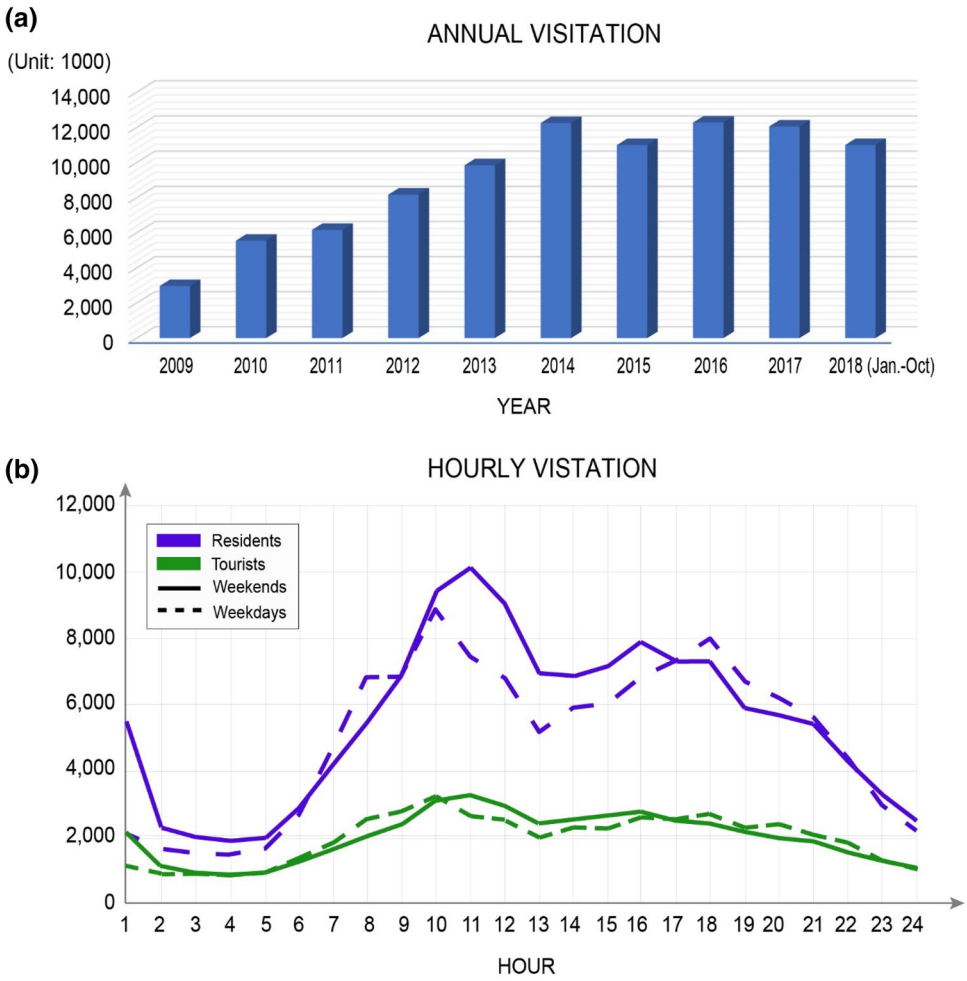

Fig. 8 Visitation to Beijing Olympic Forest Park; **a** total annual visitation (data source: BOFP Development and Management Co., Ltd.); **b** average number of residents and tourists throughout the day in summer 2018 based on cellphone location data (data source: THUPDI Innovation Center for Technology)

Attracting both residents and tourists, the BOFP primarily serves Beijing residents, according to a cellphone location data analysis in 2018 by the Innovation Center for Technology (ICT) of THUPDI (Fig. 8b). A questionnaire survey of 296 park users during 2012–2013 (Sun et al 2013, p. 62) also reported 84.4% of the participants were local. Moreover, the two largest age groups of the users were 25–44 (50.7%) and over 60 (23.1%). Over half of the users (57.2%) chose mass transit (42.4% by bus, 14.8% by subway) as their primary means of transportation, 16.9% walked, and 15.2% drove to the park. The top four reasons for visiting BOFP were to get away from the noisy city and relieve stress (59.7%), sightseeing (43.4%), plant observation (36.9%), and exercising (34.8%). These primary purposes reflected the park's critical role in addressing undesirable environmental qualities of a mega-city, providing much-needed interaction with nature, and fostering a healthy lifestyle.

The park users showed an overall high appreciation of BOFP's design. In an assessment by the Landscape Architecture Foundation (LAF)'s Case Study Investigation program (CSI) in 2011, 96% of the 373 park users surveyed agreed that BOFP improved their quality of life by providing abundant and better opportunities for recreation and physical activity (Dvorak et al. 2012, methods p. 3).

3.1.2 Health and well-being

The most well-researched social benefit of BOFP is its contribution to public health. Established as a "National Public Fitness Demonstration Base" by the General Administration of Sports of China in 2011, the park is now rated as the top first most popular running place in China (Baidu 2017, p. 20). The three generously designed running tracks with ample peripheral service stations accommodate over 300 running events of various levels every year and an average of ~ 3900 runners on a daily basis. Based on an overlay of running traces in 2018 supplied by KEEP, the top first running APP in China, an analysis by THUPDI ICT demonstrated remarkably higher usage of the BOFP than any other public green spaces in Beijing on both weekdays and weekends (Fig. 9). A runner behavior study by Li (2017, pp. 26–27), which surveyed 580 runners in the BOFP and another running hotspot Chaoyang Park, indicated that the convenient subway connection, professional-grade running

facilities, and the spacious, scenic landscape sheltered from the bustling urban areas all contributed to the congregation of running enthusiasts in the BOFP.

Another study by Qu (2018, pp. V and 50) on the Adversity Intelligence Quotient (AQ, i.e., one's resilience facing adversity) of BOFP runners surveyed 551 runners and reported medium to high AQ ratings of all the four dimensions of *control*, *origin and ownership*, *reach*, and *endurance*. Tracking AQ changes of 30 runners over five months, the study also found the ratings for origin and ownership, reach, and endurance significantly improved by the end of the study. Additionally, runners stated in interviews that running had become an important mechanism for them to cope with negative emotions and overcome adversities.

It is worth noting that the frequent presence of large numbers of marathon runners in BOFP had catalyzed the popularization of modern sports training methods in Beijing. Exposure to advanced training methods encouraged the general public to pursue more scientific and effective strategies to enhance their performance while reducing sports-related injuries (Che, 2016, pp. 26 and 29). Last but not least, Li's study (2017, p. 16) mentioned above also revealed that the

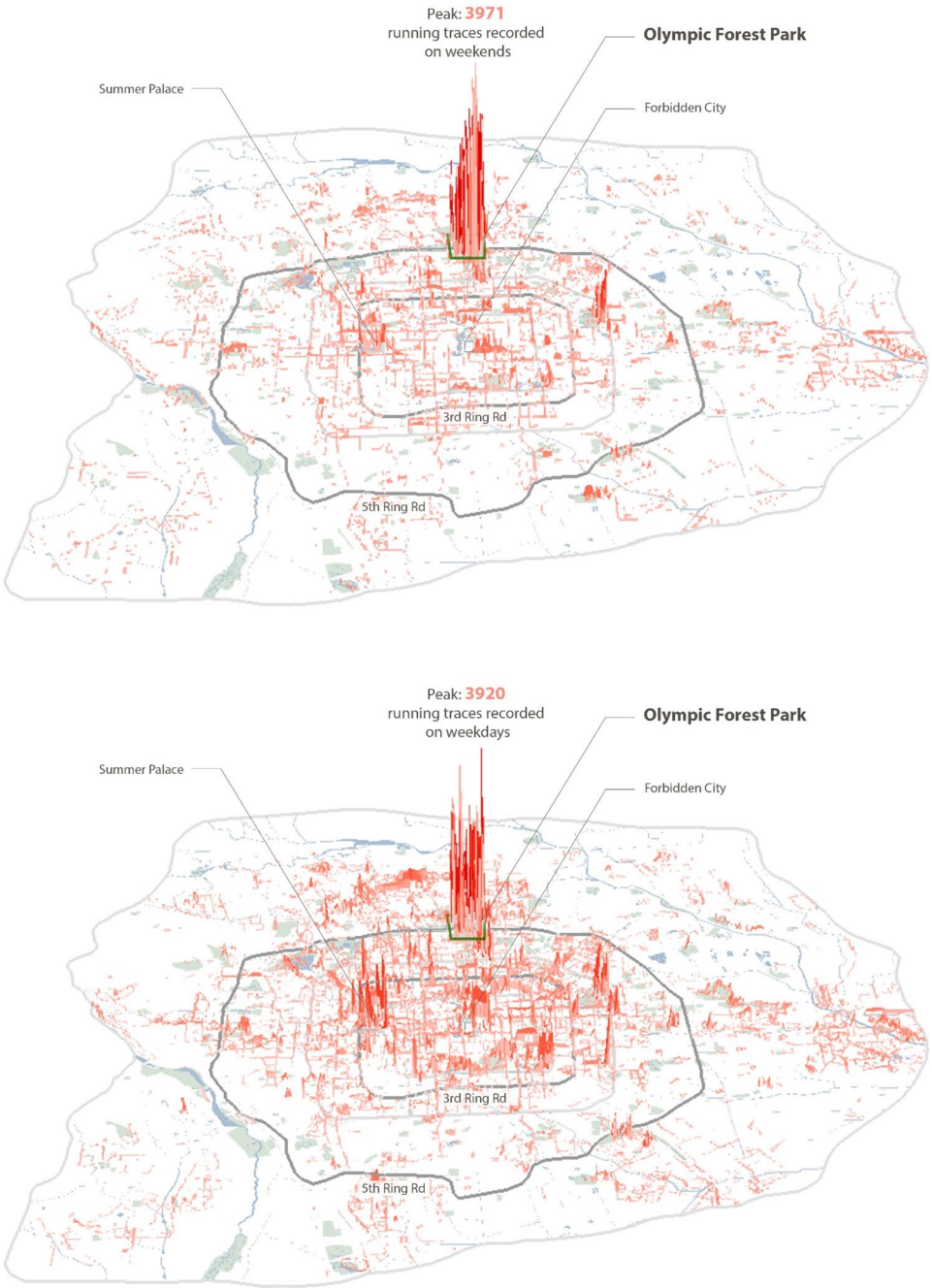

Fig. 9 Overlay of daily running traces on weekdays and weekends in public green spaces of Beijing (data source: THUPDI ICT)

primary age group for BOFP runners was 20–39 (75.5%) (Fig. 7b). In contrast, the 2014 National Fitness Activity Survey Bulletin reported that, nationally, only 26.4% in this age group regularly participated in physical exercises (i.e., > 30 min of medium to intensive exercises for at least three times a week). This substantial contrast highlighted the significance of BOFP in providing vital exercising spaces for the middle-aged—the group under the highest stress from work and family, calling for broader applications of accessible, closed-loop running spaces in future urban park designs.

Besides investigating the runner group, the study by Liu et al. (2017, pp. 226–229) shed light on the park's effects on the physical and mental health of nearby residents. Using a door-to-door survey to recruit 308 participants (6.5% < 20, 80.6% 20–40, and 13% 41–60 years old) from 50 randomly selected residences around the BOFP, they discovered that total physical activity was significantly associated with home proximity to park and park use. Park users, on average, undertook 1.5 h of moderate to vigorous physical exercise every day and were more active than non-users in all forms of physical activity except for walking caused by commuting. Out of the four major types of park activities, i.e., physical activity, nature interactions, educational and cultural activities, and social recreation, the former two contributed the greatest to improve participants' mental health. In particular, physical activity led to greater self-confidence, energy recharge, improved self-perceived health status, mood restoration, and relaxation (ranked from high to low in improvement level), while interaction with nature significantly improved self-confidence and helped people relax.

The lower level of mobile device use and lack of BOFP-specific studies on the other age groups, including children and older adults, made it challenging to summarize the park's health effects on these two groups. Based on our observations over the years, the health effects on children may be contributed by exercising with adults, outdoor play, and interaction with nature. In a family recreation satisfaction survey in 2014, walking and exercising were reported by 58% and 31%, respectively, of the 290 families surveyed as important reasons they took their kids to the BOFP (Yang and Wu 2015, p. 157).

Regarding older adults, the park contributes to their physical and mental health by providing spaces for physical and cultural activities, primarily in groups, during which they gain social interactions vital to the health of seniors (Fig. 10). Although rarely articulated in the English literature, older adults are the largest park user group in China due to the early official retirement age (60 for males and 50 or 55 for females). Tu et al. (2015, p. 933) found that older adults accounted for 54% of the 75,678 park users based on a 12-day observation in eight parks in Nanchang, a provincial capital in south China. This was a drastically higher proportion than the median of 5% in the USA (Joseph and Maddock 2016, p. 5). The older adults' primary interest in seeking health and friends through park activities has created a culturally unique park landscape in cities, often packed with active seniors on workday early mornings (Wang et al. 2011, pp. 96 and 98–99).

Similarly, at the BOFP, groups of older adults can be commonly seen dancing, singing, walking, doing *Tai Chi*, *Qigong*, Chinese martial arts, or other activities together. The naturalistic landscape and habitat diversity also made the park a favorite destination for hobby groups such as bird watching and photography clubs. Besides, older adults practicing or performing folk art or sports, such as diabolo, ribbon dance, calligraphy with water, and light gymnastics, have become unique park attractions for passersby. Based on the 2015 China Health and Retirement Longitudinal Study (Fu et al. 2018, p. 9), which interviewed 8966 individuals over 60, enhanced cognitive function significantly correlated with interaction with friends and participation in hobby and sports groups. We expect similar positive health effects of BOFP but call for future research to reveal the specifics and inform potential design improvements.

Fig. 10 Examples of older adults activities in BOFP. Sources: (**a**) http://www.xinhuanet.com//politics/2015-07/05/c_127985606.htm; (**b**) http://k.sina.com.cn/article_1400824283_p537ee1db0270048ar.html; (**c**) https://www.sohu.com/a/292913_102281; (all accessed October 20, 2020)

3.1.3 Educational and research values

The park also provides a living laboratory for environmental education and scientific research at levels from kindergarten to graduate studies. The LAF CSI study reported the park served as an outdoor classroom for ~ 2000 children through elementary school programs in 2011 (Dvorak et al. 2012, methods p. 3). Our web search as of Oct. 2020 identified 17 regular educational programs, such as the Beijing Nature Observation Day and Nature Beijing public education project at the city level, the Forest Outdoor Classroom by Beijing Forestry Society, and field trips by self-organized nature observation interest groups. Additionally, the family recreation study mentioned above reported that 34.5% of families brought their kids to observe and gain knowledge about nature (Yang and Wu 2015, p. 156). Universities, such as Tsinghua University and Beijing Forestry University, also take advantage of the park's unique natural resources for their courses with field components, such as grading, botany, and ecology. The ~ 429 sources identified through our literature search enabled the summarization of BOFP's performance in this article. The growing public curiosity in nature and enthusiasm toward nature-based activities foster greater environmental awareness, which is absolutely critical to increasing the urgently needed environment stewardship.

3.1.4 Insights from park use studies

Besides measuring performances, many studies explored how people used the park space through various methods, including behavior mapping, questionnaire surveys, cell phone location analyses, and social media content analyses. They significantly improved our understanding of the use and perception of the BOFP and offered practical implications for future design and management. For example, Hao et al. (2016, p. 3) analyzed visitor sentiments based on 576 Baidu traveler reviews and 77,539 Weibo social media postings and revealed that 82.35% of the visitors showed positive emotions and satisfaction toward their experience. Li et al. (2020, pp. 67–69) used open big data, including cell phone signal, Weibo, and Baidu Point of Interest (POI), to create a heatmap of the park's scenic spots, which revealed that the *Land of Heaven*, *Height of Woods and Brooks*, open-air theater, underwater corridor at the wetland, certain plazas for exercises, and waterfront platforms were the most popular. However, the *Land of Heaven* and open-air theater exceeded capacity during holidays, calling for volume management actions during the peak hours of 10 am–3 pm. A heatmap of running traces developed by the same study confirmed that the three distance running tracks were the most popular, but other waterfront paths were also favored by many. Broadening existing or adding new waterfront running paths, therefore, would be a worthy design revision for the future. Picnicking was another popular group activity that demanded more intentional space allocation, design revision, and management, as the current unguided use had caused erosion in heavily-used lawn areas. Other suggestions included adding sun and rain shelters, quiet resting areas, and cultural and educational zones (Sun et al. 2013, p. 63), as well as improving the wayfinding system to help visitors navigate the large park (Li et al. 2020, p. 69).

3.1.5 Social successes and lessons

The BOFP has clearly become a place for people by design. A decade of statistics about park visits and usage speak to the park's enduring popularity, thanks to its good accessibility and inclusive services. The park affords visitors intimate sensory experiences with nature, provides facilities for various recreational and fitness activities and offers well-designed sites for social gatherings. It has become a sanctuary for urban dwellers to seek relief from high-density living's congestion, crowdedness, and undesirable environmental qualities. Empirical studies have shed light on the substantial health benefits to park users, as well as the influence of regular park usage on shaping a healthy lifestyle. The educational and learning opportunities afforded by interactions with nature or the park's programs will continue to enlighten a stronger sense of ecological awareness and cultivate civic pride among the public.

The reviewed studies offered various critiques primarily related to the park's functional flaws and management issues. People's desires, for example, for greater capacities for recreational facilities and services and better maintenance and service qualities, reflected the critical underinvestment in public engagement since the early design stage, as well as the operational dilemma of public parks exclusively funded by the government. Top-down (as opposed to participatory) environmental governance practices and the tight construction timetable precluded meaningful public participation vital for understanding societal needs and preferences that could have better informed the initial design. The lack of an adaptive management mechanism, associated with the common financing dilemma for large-scale public parks in China, prevented swift design and management refinements in response to public feedback after construction. The nature of the park as a *public* amenity, with promised free access to all, strictly excluded all forms of private financing. To date, how to adequately fund large parks to ensure both social equity and excellent functionality and aesthetics remains a national dilemma to be solved with determination, creativity, and a long-term vision.

3.2 Environmental performance

3.2.1 Water

The park's water conservation, water quality enhancement, and flood mitigation benefits have been well documented in the literature. First, regarding water conservation, LAF CSI evaluated that the use of reclaimed water to irrigate and recharge water bodies reduced annual potable water use by 950,000 m^3 (Dvorak et al. 2012, methods pp. 1 and 3), equivalent to 31,600 residents' annual consumption, saving 2.85 million RMB (~$0.45 million) of water fees. Zhao and Deng (2014, p. 24) reported that, during 2007–2008, the stormwater reuse system collected 13,210 m^3 of stormwater per year to be reused for irrigation and street or plaza sweeping.

Second, the constructed wetland system has shown efficacy in water quality treatment and provided valuable lessons to other water-deprived cities as they experimented with similar technologies. Xie et al. (2012, p. 106) assessed the circulated water from Aohai in 2008 and found an efficient removal of BOD5 (biological oxygen demand, − 59%), CODcr (common chemical oxygen demand, − 40%), NH_4^+–N (− 11%), NO_3^-–N (− 39%), TN (total nitrogen, − 20%), TP (total phosphorus, − 44%), OP (orthophosphorus, − 49%) and Chlorophyll *a* (− 52%). This enabled the effluent to meet the State Environmental Protection Agency's surface water quality standards, with the caveat of dissatisfying nitrogen removal efficiency. A survey of park users then also showed that 98.1% of the 371 respondents favored the construction of the wetland (Xie et al. 2012, p. 106). Over time, however, eutrophication did occur in 2010, likely due to the accumulation of nitrogen and phosphate, the shallow water depth, and low flow velocity (Zhou et al. 2017, p. 4). The park then implemented remedial actions, including algal removal, aquatic planting, adding beneficial microorganisms, and establishing a monitoring network. Zhou et al. (2017, pp. 5–7)'s monitoring in 2013–2014 revealed significant TN and TP reduction and no further eutrophication, recommending continuous monitoring and careful management of harvested aquatic plant materials to maintain the water quality treatment performance. Lastly, a park user willingness to pay (WTP) study (He et al. 2010, p. 788) indicated that the mean WTP of the 489 participants for the wetland's aesthetic, recreational, and educational values was 160.23 RMB (~$24.5) per household per year over 20 years—in the medium to high range compared to similar studies.

Third, the stormwater treatment system infiltrated most surface runoff while sufficiently treating its water quality. Monitoring at the stormwater outfalls during 2007–2008 indicated the system reduced 84.8% (36,0468 m^3) of the park's total runoff, out of which 347,258 m^3 (96%) was infiltrated or lost to evapotranspiration, and 13,210 m^3 (4%) was reused (Zhao and Deng 2014, p. 24). Regarding responses to torrential summer storms, the system retained the entire 563 mm of rainfall during June–September 2008, with the largest storm being 101 mm deep (Zhang 2009, p. 21). The LAF CSI study also reported that the park survived a 50-year storm in 2011, while nearby areas outside of the park's drainage boundary suffered severe flooding (Dvorak et al. 2012, sustainable features section). Concerning water quality, Zhou (2010, pp. 120–121) tested water samples from stormwater percolation wells and underground cisterns in Aug. 2009 for pH, COD, BOD, colority, turbidity, and SS (suspended solids). Except for SS and colority that occasionally violated the standards, all other parameters met the criteria for irrigation reuse, eliminating the need for expensive, additional filtration devices. By the end of 2008, experience gained from constructing BOFP's stormwater system was applied to over 10 other stormwater reuse projects (totaling 50 hm^2) in Beijing (Deng et al. 2008, p. 100).

While the above studies demonstrated the efficacy of the water system leading to or shortly after the Olympics, few studies followed up about the park's recent performance. Because both the constructed wetland and stormwater system require constant upkeep to ensure that they continue to function in the long-term, it is critical to report recent monitoring outcomes, evaluate maintenance needs, and identify remedial actions if necessary.

3.2.2 Habitat

Although a comprehensive habitat assessment remains absent, a few studies that surveyed the BOFP's vegetation and wildlife provided insight into how the ecosystem has evolved. Due to the urgency to complete the construction before the Olympics and difficulty sourcing enough native plant materials from local nurseries, the original near-nature planting plans were not fully implemented. A construction as-built survey was not conducted, making it challenging to precisely evaluate vegetation succession. During 2010–2011, Yu et al. (2012, p. 646) recorded 295 vascular plant species belonging to 75 families and 203 genera, 60.7% (179 spp.) of which were native. Of all the native species, 43.6% (78 spp.) were planted, whereas the rest (56%, 101 spp.) spontaneously settled into the park. Li et al. (2019, p. 160) specifically studied spontaneous vegetation in 2015 and recorded 102 species belonging to 28 families and 79 genera, 80.4% of which were native—a much higher percentage than the 60.7% of the park as a whole. Compared to the 47% and 45.2% native percentages previously reported by Zhao et al. (2010, p. 195) and Wang et al. (2007, p. 4030) for Beijing's built-up areas and the city as a whole, respectively, BOFP has a higher native species percentage, especially from its spontaneous vegetation. The rushed construction process lowered the ecological value of the plantings,

revealing the need to elevate the entire green industry to better support ecological designs. Li's research also informed how future designs could strategically take advantage of spontaneous vegetation to enhance native biodiversity (Li et al. 2019, pp. 164–165).

As a bird watching hotspot, BOFP has been the subject of many studies investigating bird population dynamics and habitat relations, although surveys of other wildlife remained sparse. The most recent report by Nature's Friends Birdwatching Club (2020) recorded 160 bird species of 19 orders and 51 families in the south park with diverse aquatic and upland habitat types during March–December 2020. Twenty-five of those species are protected at the international or national level; thirteen were observed for the first time in the south park. Bao et al. (2015, pp. 187–189) recorded 46 species in the north park in winter and spring of 2013, out of which 31 (67.4%) are protected species at the national or municipal level, including one exclusive to China, the *Parus venustulus*. Zhang (2015, p. IV) also reported that 51.5% of the 66 species observed during 2013–2015 were protected species, adding to the evidence that BOFP has played a vital role in supporting species struggling to thrive in highly urbanized areas. Regarding other wildlife, THUPDI conducted four wildlife surveys in 2016 to fill in this research gap and recorded 56 resident bird, 13 fish, 2 amphibian, 1 mammal, and over 70 insect species.

The vegetation and wildlife research above offered valuable design and management lessons to inform future habitat design in dense cities. We highlight a few as follows. First, a more intentional division of zones to separate public recreation from wildlife protection is necessary to reduce human disturbance. Topographical variations could effectively achieve such separation even in heavily-used recreational areas, as observed in the south park with the human-made hills. Second, patch size and the diversity of habitat types significantly influence overall biodiversity, with the highest observed within and around water bodies and large patches, particularly the wetlands. Third, diverse ecosystems are naturally messy, conflicting with the needs of management to reduce fire hazards and maintain a neat appearance for public approval. Finally, cultivated plant materials should be discouraged due to their higher insect repellent capability that could influence the entire food web.

3.2.3 Air quality, energy, and carbon

Due to their close relationship with public health, the air quality improvement and urban heat island (UHI) mitigation effects of BOFP have gained higher scholarly attention than the energy and carbon impacts coarsely quantified in a few studies. Regarding air quality, Pan et al. (2012, p. 49) measured the concentration of negative air ions (NAI) in BOFP for five years (2005–2010). They found a substantial improvement in NAI concentration after the construction of BOFP. He et al. (2016, pp. 306–307) measured the airborne particulate matter PM2.5 and PM10 on a hazy day on the three arterials around BOFP and found that once the forested buffer width exceeded 20 m, significant reductions of PM2.5 and PM10 occurred, especially for the most polluted road. For example, the PM2.5 level dropped from 784 $\mu g/m^3$ on the Fifth Ring Road to 221 $\mu g/m^3$ 20 m into the park. Additionally, Hu (2009, p. IV) used the CITYgreen software and estimated that the forests could absorb ~ 37,795 kg of O_3, 12,686 kg of SO_2, 19,584 kg of NO_2, 35,052 kg of particulate matter, and reduce 4191 kg of CO, saving $0.28 million in potential CO treatment expenses.

In terms of UHI mitigation effects, Kuang et al. (2020, p. 10) found an apparent cooling effect by the park during summer. The air temperature in a dense-grass lawn area interspersed with trees in the north park was, on average, 0.7–0.9 °C lower than that measured in a surrounding residential compound. Amani-Beni et al. (2019, p. 4) mapped the land surface temperature (LST) patterns for the 5 km buffer zone of BOFP, showing lower LSTs in the park than its surroundings (Fig. 11). The large size of the park and the spatial relationship among the green patches were prime factors in the cooling effect, with tree canopies and water bodies as the most effective land cover types to mitigate UHI. Generally, the park's cooling effect decreased, at a rate of ~ 0.15 °C/km, as the distance away from the park boundary increased.

Regarding the energy and carbon effects, LAF CSI estimated 83,000 kWh of electricity generation per year from the solar panels at the park's south gate, equivalent to ~ $6375 annual cost-saving and enough to meet the annual needs of 227 Beijing residents (Dvorak et al. 2012, methods p. 2). The carbon flux monitoring station installed in BOFP in 2010 estimated that the forests sequestered 3,060 and 4,545 metric tons of CO_2 annually in 2012 and 2013 (Yu 2014, p. 51), respectively, equivalent to removing 600–891 passenger vehicles off the road.

3.2.4 Environmental successes and lessons

The post-construction monitoring and assessments have provided solid evidence for a thriving novel ecosystem in BOFP. Ecological science and technology, supported by McHarg's approach of multi-aspect site analyses, allowed nature's functions and processes to play out to the full extent. The several "firsts" of its kind in a large public park, i.e., the self-sustaining water system involving stormwater infiltration, collection and reuse, and comprehensive employment of green energy technologies and solutions for park facilities, have proven effective in achieving critical ecological services to the community at large. Ecological planning and design helped create an expansive network of wildlife

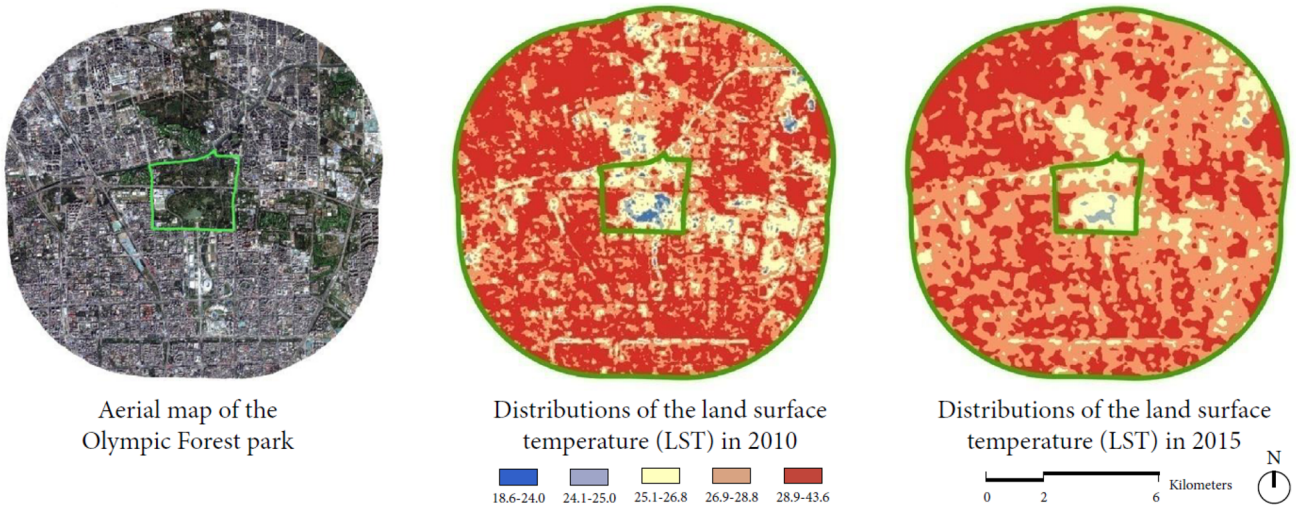

Fig. 11 Distribution of land surface temperature in BOFP and surrounding areas in 2010 and 2015. Adapted from Amani-Beni et al. (2019)

habitats within the city. The approaches of nurturing and utilizing nature have made BOFP an integral part of Beijing's ecological infrastructure.

While the studies above offered invaluable insights to inform future design, operation, and maintenance, significant gaps in research and practice remain to be addressed, and means to sustaining long-term performance assessments need to be developed. For example, the efficacy of the first-ever eco-bridge in enhancing habitat connectivity has not yet been assessed, creating difficulties for broader implementation of eco-bridge practices. Besides, the solid waste recycling and reuse system have been out of operation, likely due to the lack of in-house technical expertise, undermining the original goal of demonstrating advanced ecological technologies. Moreover, as previously mentioned, follow-up studies on the water systems' recent performances are necessary to ensure their long-term functionality. As elsewhere, post-occupancy evaluation (POE) has not become an integral part of the landscape design process in China due to many good reasons such as lack of funding, time, and interdisciplinary expertise. A better forum for collaboration—one that involves the governments, universities, professional firms, and citizens, new professional standards requiring POE as project deliverables, and various incentives such as grants and rewards are all potential strategies to boost research and evaluation activity.

4 The next decade forward

More than ten years after its construction, the BOFP has successfully transformed 680 hectares of land in the capital city into a place fondly labeled as a green treasure. One of the largest public parks ever created in urban China, the BOFP has manifested a successful fusion of quintessence from both the western and eastern landscape fields. It adopts landscape design elements inspired by the Olmsteds and implements modern landscape construction technologies informed by ecological science. More importantly, anchoring itself at the northern end of the urban central axis, the park strengthens its cultural value by taking on the Chinese Shan-Shui landscape layout and integrating into its design many elements of cultural significance. Highly accessible to the public and offering a wide range of recreational and social facilities, the BOFP charms residents and visitors to Beijing.

The significance of the BOFP lies in not only the enormous benefits it has generated for the city but also its influence on the practices of landscape-making and development. Its high performance as a social amenity and ecological infrastructure has demonstrated the value of merging science, technology, and culture through interdisciplinary collaboration. The collaboration also took place among government agencies, which ultimately enabled the park to become an integral part of many regional systems such as the hazard evacuation and regional ecological corridor systems. It has become a norm for major landscape projects undertaken in China to enlist planners and allied design professionals, urban and ecological scientists, and engineers into planning and design teams. Many players in the public sector are more willing to overcome institutional fragmentation in those projects, thanks to the BOFP's successful experiences and outcomes.

The BOFP exemplifies a transformative place-making strategy that holds inspiration to cities and regions experiencing rapid, high-density urbanization. The conventional approaches, such as those practiced in China for long and often, have been to focus on the built output for economic efficiency while ignoring the environmental impacts. The

BOFP's achievements in translating ecological value to economic and social value have helped shift that mindset. Leveraging well-designed and multi-functional urban open spaces as catalysts to foster environmental restoration in compact cities is a feasible and promising pathway for sustainable urban development. While offsetting the negative physical and psychological impacts of high-density living, these open spaces can integrate green, blue, and grey infrastructure to provide multiple ecosystem services, which often translate into land value increase in their vicinity, as well as cost savings by harnessing nature-based solutions. Many cities in China are implementing this open space-anchored approach to high-density urban redevelopment, especially in areas where lack of planning or poor planning in the past has resulted in low environmental quality.

Problems undoubtedly exist for the BOFP. The underinvestment in public participation in both design and operation has left room for improvements in many aspects. An adaptive management mechanism based on participatory environmental governance needs to be established to obtain public feedback and identify critical design and operational refinements on a regular basis. As elsewhere, sustaining long-term, continuous performance assessment to guide the park's operation and maintenance remains a primary challenge. Multiple strategies will need to be explored simultaneously to build better forums for collaboration, establish new professional standards, and create strong incentives for research. Last but not least, developing innovative financing solutions to ensure both social equity and outstanding park performance will require close collaborations among governmental agencies, private sectors, and grass-root communities. These issues, although rooted in circumstances beyond the scope of landscape planning and design, need to be addressed to ensure the park's long-term success.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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