

Synergy between Functionality and Ecology in Landscape Design: An Empirical Study on the Optimization of Urban Park Landscape Functional Layout Based on Multi-Source Environmental Data

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ABSTRACT In high-density urban environments, urban parks play a critical role in providing recreational services and ecological benefits. This study proposes a functional layout optimization framework based on multi-source environmental data to achieve coordinated improvement of landscape functionality and ecological performance. Remote sensing imagery, meteorological observations, and field survey data were integrated to establish a functional suitability evaluation system considering both recreational demand and ecological sensitivity. Spatial overlay analysis was employed to identify optimal distributions of functional zones, while ecological network construction was introduced to enhance spatial connectivity among landscape patches. Results indicate that the optimized layout significantly improves accessibility and user comfort while strengthening thermal regulation and biodiversity conservation capabilities. The proposed framework provides a quantitative and data-driven approach for urban green-space planning and offers methodological references for environmental sensing, spatial information analysis, and electromagnetic remote-sensing-assisted landscape assessment.

INDEX TERMS multi-source environmental data, landscape optimization, ecological synergy, environmental sensing, electromagnetic remote sensing

I. INTRODUCTION

AS an integral part of urban green infrastructure, urban parks facilitate recreation, ecological regulation, and cultural services through the strategic deployment of advanced technical materials that enhance structural durability and environmental performance. These engineered material systems provide essential soil stabilization and climate-responsive shading, ensuring that the park's multifunctional roles are supported by a resilient, material-optimized landscape. With the growing speed of urbanization and the continuous impact of climate change, urban park landscape design in recent years has had to fulfill more diverse functional requirements, and ecological environment stability and adaptability are also facing severe tests. How to ensure an efficient organization of recreational functions and sustainable provision of ecosystem services in the limited urban space has emerged as a crucial problem which requires urgent resolution in the field of landscape design. The traditional design of urban parks has tended to emphasize

the visual predominance and spatial form, and the design layout is often based on the experience of the designer or the existing standard model, without a refined reflection on the heterogeneous elements of the site environment. In functional zoning, spatial relationship between activity area, rest space and green space is mostly based on plane composition logic, which can not fully respect the dynamic relationship between microclimate conditions, ecological benefits of vegetation and user behavior needs. This form of design pattern leads to a low actual use of some functional spaces, poor ecological regulating functions, and dichotomy between functionality and ecology. Against this background, this study focuses on optimizing the functional design of urban park landscapes by integrating advanced technical materials with environmental multi-source data to create a unified framework for ecological and structural performance. This approach utilizes high-performance material systems as adaptive landscape components, ensuring that the integration of functionality and ecology is driven by data-

informed material selection. The research is an empirical verification of the effectiveness of functional suitability assessment and ecological network optimization based on environmental data in improving the overall benefits of parks. It focuses on delivering evidence based support of climate-adaptive urban green space design and facilitates the scientific transformation of landscape design methodologies.

II. RELATED WORK

Contemporary landscape design research is undergoing a profound paradigm shift from a single aesthetic orientation to multifunctional collaboration, from empirical description to data-driven, and from static representation to dynamic interaction. In climate-smart landscapes, people manage land use to integrate sustainable production, climate change adaptation and mitigation. Lavorel *et al.* [1] analyzed the impact of fragmentation on multifunctionality and their interaction with land use intensity response. Cortesão and Lenzholzer [2] explored specific applications in urban and landscape design practices. In landscape design, accurate description and communication of spatial visual characteristics are crucial for the design process,

teaching and research. Liu and Nijhuis [3] constructed a design vocabulary system for describing and analyzing the spatial visual characteristics of landscapes. Ye *et al.* [4] conducted a qualitative analysis of the designer's thought process, workflow and creative results in the process of using AI by comparing AI-generated images with traditional hand-drawn sketches. Kim *et al.* [5] explored how to achieve a deep integration of technology and art in landscape design in order to enhance the aesthetic value of space and user experience.

Ak [6] clarified the core principles of ecological landscape design, which together point to creating a landscape that is resilient, low in maintenance costs, and provides multiple benefits to humans and nature. He *et al.* [7] found that the rich natural elements and varied micro-topography of Stanley Park provide a good foundation for creating a multi-sensory experience. Ioannidis *et al.* [8] conducted a cost-benefit analysis of landscape design practices in dam projects, demonstrating its necessity in enhancing the overall value and sustainability of the projects. Im *et al.* [9] explored the feasibility and utility of introducing mixed reality technology into the review stage of special tree landscape design schemes. Huang and Liang [10] used AI algorithms to construct an adaptive landscape design optimization and spatial layout planning method, aiming to realize the paradigm shift from "experience-driven" to "data-algorithm collaboration". This paper aims to couple multi-source environmental data with spatial optimization algorithms to explore the functional layout mode of urban parks that takes into account both recreational service efficiency and ecosystem regulation services, and to provide evidence-based support for the design of high-density urban green spaces under the guidance of climate adaptability.

III. METHODS

A. ACQUISITION AND PREPROCESSING OF MULTI-SOURCE ENVIRONMENTAL DATA

The study carried out preliminary data collection and data preprocessing of multi-source environmental data to build a full data bank of environmental data over the study area. Data sources were high-resolution remote sensing imagery, meteorological station observation, digital elevation model and field survey data. For this, multispectral remote sensing imagery with a spatial resolution of 2 meters was used to extract information on the vegetation cover, the proportion of impermeable surfaces, and water distribution. The image data was radiometric calibration, atmospheric correction and geometric fine correction preprocessing, to remove the sensor errors and atmospheric interference, so as to ensure the accuracy of subsequent analysis. Meteorological data were collected from hourly observation data of 5 automatic weather stations around the study area. The data collection period spanned one year. The observed indicators were air temperature, relative humidity, wind speed and solar radiation intensity. The inverse distance weighted interpolation technique was applied to interpolate the station data in space to create a continuous meteorological element raster layer over the whole study area. The spatial resolution was equally fixed at 5 meters [11,12].

Field surveys and measurements were performed to complement the environmental information that could not be obtained from remote sensing and meteorological data, e.g. vegetation type, soil moisture content, and local micro-topographic features. Measurement points were established using the grid method with a grid spacing of 50 meters and a total of 120 sampling points. At each sampling point vegetation community structure, land cover type and soil moisture content were recorded. Near-surface temperature, humidity and wind speed was measured at the same time with a handheld weather instrument to validate the interpolation of the data.

Multi-source data fusion processing was completed in a GIS platform. All data were projected with a unified coordinate system and spatial resolution, and a spatial database containing six environmental factors, including surface temperature, humidity field, wind speed field, vegetation coverage, impermeability ratio, and terrain slope, was constructed to provide data support for subsequent functional suitability evaluation.

B. CONSTRUCTION AND SPATIAL ANALYSIS OF FUNCTIONAL SUITABILITY EVALUATION INDEX SYSTEM

Based on multi-source environmental data and combined with the typical recreational function requirements and ecological sensitivity characteristics of urban parks, a functional suitability evaluation index system was constructed [13,14]. The study selected three core recreational functions—rest and sightseeing, fitness activities, and parent-child entertainment—as well as three ecosys-

tem regulation functions—thermal environment regulation, runoff control, and biodiversity maintenance—as target types for functional layout optimization. For each type of function, establish the association rules between environmental factors and functional requirements, and determine the evaluation indicators and their weights. The rest and viewing function focuses on environmental comfort and landscape visual quality. Surface temperature, humidity, wind speed and vegetation coverage are selected as evaluation indicators. Areas with low temperature, suitable humidity, gentle wind speed and rich vegetation are more suitable. The fitness activity function focuses on the influence of site openness and microclimate conditions on exercise comfort. The proportion of impermeable surfaces, surface temperature and wind speed are selected as indicators. Areas with a moderate proportion of hard surfaces, not too high temperature and suitable wind speed are more conducive to activities. The parent-child entertainment function emphasizes safety and environmental fun. The terrain slope, vegetation type richness and water proximity are selected as evaluation indicators. Areas with gentle terrain, diverse vegetation and proximity to water are more suitable [15].

The thermal environment regulation function is to focus on the cooling effect of vegetation transpiration and shading effect, and consider the vegetation cover, surface temperature, and surface impermeability as evaluation indicators. Areas which have high vegetation cover, hotter temperatures and higher percentage of impermeable surfaces are suitable for ecological regulation green spaces. The runoff regulation function is focused on surface infiltration and retention capacity (using soil moisture content, topographic slope, and impermeability as an indicator). Areas that have moist soil, low slopes, and a low fraction of impermeable surfaces are favorable for rainwater infiltration and reduction in runoff. The biodiversity maintenance function focuses on the quality of habitats and habitat connectivity potential and utilises the vegetation richness, vegetation cover and proximity to water bodies as indicators for evaluation. Areas which were associated with a high diversity of the vegetation types, high cover, proximity to water bodies possess high ecological value. All indicators were normalized before being imported into the GIS platform to avoid dimensionality influence and to unify the range of balanced economic values between 0 and 1. To ensure the scientific rigor and objectivity of the indicator weights, this study invited a panel of 12 experts from the fields of landscape ecology, urban planning, landscape architecture design, and environmental engineering (including 6 scholars with senior professional titles and 6 senior practicing designers). Through two rounds of Delphi method surveys, judgment matrices for each functional type were constructed based on expert opinions. The analytic hierarchy process (AHP) was used to calculate the indicator weights, and consistency checks were performed on all judgment matrices. The results showed that the consistency ratio (CR) of all judgment matrices was less than 0.1, meeting the consistency requirements and proving the logical

rationality and reliability of the weight assignment results. The suitability evaluation values for each functional type were calculated using a weighted overlay method, resulting in a suitability distribution raster map of the six functional types, which served as the base layer for functional layout optimization.

C. FUNCTIONAL LAYOUT OPTIMIZATION METHOD BASED ON ECOLOGICAL NETWORK

Based on functional suitability assessment, an ecological network construction method is introduced to optimize the spatial layout of functional patches, thereby improving the spatial connectivity and ecological flow continuity between functional patches. The optimization process consists of four steps: functional patch extraction, resistance surface construction, ecological corridor simulation, and layout scheme generation. Functional patch extraction was based on results from suitability assessment. For recreational functional patches (leisure and sightseeing, fitness activities and family entertainment) all patches with a suitability value better than 0.7 were prioritized, along with proximity to existing entrances, paths and service facilities in order to guarantee accessibility and ease of use. For ecological functional patches (thermal environment regulation, runoff control, and biodiversity maintenance), prioritization was done in areas whose suitability value exceeded 0.6 and emphasizes the continuity in patch area and integrity in maintaining the shape of the patch to avoid creating excessive fragment distribution.

Resistance surfaces were made to simulate the ease or difficulty of ecological flow movement between functional patches. Four resistance factors were chosen, namely land cover type, impermeable proportion, road density and intensity of human disturbance. Each factor was given a value according to how obstructed ecological flow was by that factor. Among the different land cover types, forest land with water body showed the lowest resistance whereas hard paved areas and built up land showed highest resistance. Higher impermeable proportions and densities of road also resulted in more resistance. Areas near major activity areas and park roads showed a higher level of human disturbance which translated into a higher level of resistance. The weighted summation of these resistance factors produced a complete resistance surface, which represents the distribution of the ecological flow resistance at various spatial locations within the study area. Ecological corridor simulation is formulated on the basis of a minimum cumulative resistance model to delineate the minimum cost path between functional patches in order to identify potential ecological connectivity channels. Using biodiversity maintenance functional patches as core nodes, the minimum cumulative resistance paths between the core nodes and other ecological and recreational functional patches are calculated as alternative paths for the ecological corridor. Corridor widths are determined ranging from 10 to 15 meters considering resistance levels to provide adequate ecological carrying capacity. Corridor

route selection is adjusted according to the distribution of existing vegetation and topography to refrain from using high-density areas of activity and principal roads, and to make the corridor's feasibility practical.

During the layout scheme generation phase, functional patches and ecological corridors were factored into an optimized functional layout plan. Recreational functional patches were spatially assembled based on suitability levels and service radii keeping in mind that the three types of recreational functions will cover the major activity requirements of the entire park. These functional patches were linked by a park road system. Ecological functional patches and ecological corridors, as a continuous ecological network framework, were formed from north to south through the study area, which linked major patches of woodlands and edges of water bodies, and exist as channels for biological migration and energy movement. To reconcile the potential conflicts between recreational functions and ecological networks, this study conducted synergistic optimization of the two types of functions through spatial overlay analysis in the final layout scheme: the construction of new high-intensity recreational facilities was strictly controlled in the core area of the ecological corridor (i.e., within a 20-meter buffer zone on both sides of the minimum cost path), and only ecological interpretation or rest facilities with minimal environmental disturbance were allowed; while in the outer area of the ecological corridor and in areas with high suitability for recreational functions, a balance between the accessibility of recreational spaces and the connectivity of the ecological network was achieved by setting up vegetation buffer zones and other methods. The optimized plan, while preserving existing high quality vegetation and topographic features, made local adjustments and supplements in the functional spaces to result in a landscape layout that coordinates functionality and ecology.

IV. RESULTS AND DISCUSSION

A. SPATIAL DISTRIBUTION CHARACTERISTICS ANALYSIS OF ENVIRONMENTAL FACTORS

Based on the preprocessing results of multi-source environmental data, the spatial distribution characteristics of six environmental factors in the study area were obtained. Surface temperature distribution exhibited significant spatial heterogeneity, with high-temperature areas concentrated around activity plazas with large hard-paved areas and exposed areas in the shaded areas of buildings, where temperatures were 2.5 to 4.2 degrees Celsius higher than surrounding woodland patches. Areas with high vegetation cover showed significantly lower surface temperatures, with the temperature drop positively correlated with vegetation cover. Humidity distribution was closely related to water bodies and vegetation distribution; relative humidity was higher near major water bodies and dense forest areas than in surrounding open areas, creating a localized humid island effect. Wind speed was significantly affected by topography and building layout; wind speeds were higher in open

activity areas, while wind speeds decreased significantly in dense forests and on the leeward side of buildings, with a maximum wind speed difference of 1.8 meters per second. Vegetation cover distribution was constrained by the existing green space pattern; woodland patches in the central and eastern parts of the study area had higher cover, while the western and southern entrance areas had lower cover due to the concentration of activity areas. The distribution of impermeable surfaces coincides with the locations of garden paths, plazas, and building foundations. Areas with a higher degree of hardening are concentrated on both sides of the main garden path and major activity nodes. The overall terrain has a gentle slope, with local micro-topographical undulations, mainly concentrated in the waterfront area and the terrain modification area formed by earthwork balance.

To visually represent the differences in the distribution of environmental factors in different functional zones, the study selected three typical functional zones: recreation and sightseeing, fitness activities, and ecological regulation. The average values of each environmental factor were statistically analyzed, and the results are shown in Table 1.

The ecological regulation zone, with its high vegetation cover and low hardening rate, creates a significant "cold and humid island" effect, where canopy transpiration and shading jointly drive the synergistic optimization of temperature and humidity. The fitness activity zone, with over 50% hard paving, has low heat capacity and high sensible heat flux. Combined with its open terrain conducive to turbulent exchange, this results in high temperature and strong winds, reflecting the adaptive needs of dynamic activities in an open environment. The rest and viewing area lies between the two, with its relatively high vegetation cover and moderately hard surfaces creating a local microclimate buffer, suitable for static rest. This difference reveals a specific coupling mechanism between functional types and environmental factors in the current layout: ecological patches and activity spaces are complementary and contradictory in terms of thermal environment. However, the encroachment of activity functions on some high-vegetation areas has damaged ecological benefits, reflecting that single-functional zoning neglects the continuity of ecological flow between patches, necessitating functional synergy through ecological network optimization.

B. FUNCTIONAL SUITABILITY ASSESSMENT AND PLAQUE IDENTIFICATION RESULTS

Based on the constructed functional suitability evaluation index system, this study calculated the suitability distribution values for six functional categories and extracted highly suitable areas as the basis for functional patch identification. Highly suitable areas for recreation and sightseeing functions are concentrated in areas

with high vegetation coverage, proximity to water bodies, and slightly undulating terrain, accounting for approximately 18.5% of the study area, and are distributed in patches along the central woodland edges and waterfront

TABLE 1. Statistical analysis of mean environmental factors in typical functional zones

Functional type	Surface temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Vegetation coverage	Impermeable ratio (%)	Topographic slope (°)
Rest and viewing area	28.6	68.3	1.2	0.78	18.5	4.2
Fitness Area	30.2	61.5	1.8	0.42	52.3	2.8
Ecological regulation zone	26.8	73.1	1.9	0.86	8.7	5.1

gentle slopes. Highly suitable areas for fitness activities are concentrated in open areas with a moderate proportion of hard surfaces, suitable wind speeds, and flat terrain, accounting for 14.2% of the area, mainly distributed in the existing activity plazas on both sides of the main park road and surrounding extended areas. Highly suitable areas for family entertainment functions emphasize vegetation diversity and proximity to water bodies, while requiring gentle terrain to ensure activity safety; these highly suitable areas account for 12.8% of the area and are mostly located in gentle slopes with rich vegetation types along the edges of water bodies.

In terms of ecological function, areas with high thermal environment regulation function correspond to regions with high vegetation coverage and a large proportion of impermeable surfaces. These areas are currently mostly at the boundary between dense forests and hard surfaces. The transpiration cooling effect of vegetation can effectively alleviate the intensity of the heat island effect. These areas account for 22.3% of the total area and are relatively scattered. Areas with high runoff regulation function are concentrated in areas with moist soil, gentle slopes, and a low proportion of impermeable surfaces. These are mostly riparian vegetation zones and some depressions, accounting for 16.7% of the total area. They have the potential for rain-water retention and infiltration. Areas with high biodiversity maintenance function are characterized by rich vegetation types, high coverage, and proximity to water bodies. Current forest patches and water body edge areas belong to this category, accounting for 20.4% of the total area. They have good continuity and possess the basic conditions for building an ecological network.

Table 2 presents the mean suitability and number of various functional patches, reflecting the differences in suitability of different functional types under current environmental conditions.

Table 2 shows that the biodiversity maintenance function score has the highest mean suitability score (0.84) and the lowest standard deviation, indicating that currently the ecological conditions of forest patch are relatively stable with low spatial variation of suitability. The thermal environment regulation function has the largest number of patches, but the average patch area is small, reflecting a fragmented distribution at the junction of high vegetation cover and high impermeability to ecological network connections will improve overall suitability. Among the recreational function, mean suitability score for rest and sightseeing is better than fitness activities and family entertainment, but patch area is small and scattered need integrated configuration according

to service radius. The runoff regulation function has mean suitability score of 0.78 and large standard deviation, which means that the soil moisture conditions and topographic conditions of some of the patches are not matched ideally and the suitable areas need to be added in the layout optimization.

C. EVALUATION OF ECOLOGICAL NETWORK CONSTRUCTION AND OPTIMIZATION LAYOUT SCHEME

Based on the model of resistance surface and minimum cumulative resistance, this study simulated the potential ecological corridors between biodiversity maintenance functional patches and integrated the function into a network through the combination of the distribution of other functional patches distribution. Resistance surface analysis revealed that woodland and water bodies had the lowest resistance values whereas hard plazas and the region around main park roads had the highest resistance values. High resistance areas were concentrated mostly in the southern entrance plaza of the study area, the intersection of main park roads, and in and around the area of buildings. The ecological corridor simulation showed there are 15 potential corridors totaling around 4.6 kilometers. These corridors ran mainly along the edges of existing woodland, water slopes and buffer zones with good vegetation cover and they succeeded in connecting the main ecological patches, while taking into consideration the ecological access needs of some of the recreational functional patches. The optimized layout plan increases the number of ecological regulation patches in the existing functional patches with five patches, which are located mainly in the transition area between the area with a high rate of impermeability and existing woodland, which improves the spatial coverage of thermal environment

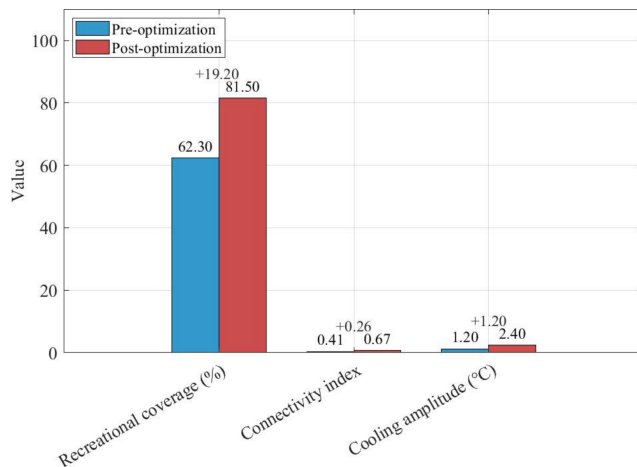
regulation functions. Recreational functional patches are complemented with a service radius of 200 meters to add 8 rest nodes, 6 small fitness areas, and 4 parent-child activity areas which provide balanced coverage of recreational functions for the park. The ecological corridors are situated based on the topography and vegetation conditions, whereby underpasses or expanded areas of vegetation are used to achieve connectivity in areas intersecting roads. Buffer vegetation strips of 10 to 20 meters wide are marked on either side of the corridors, to increase the actual flow efficiency of ecological flow.

To assess the overall benefits of the optimization scheme, three indicators were chosen: functional coverage, ecological connectivity and thermal environment regulation capacity. Comparison of the changes before and after optimization

TABLE 2. Statistics on the suitability of functional type plaques

Functional type	Number of plaques (pieces)	Mean suitability	Suitability Standard Deviation	Total area of the patches (hectares)	Average patch area (hectares)
Rest and sightseeing	twenty four	0.76	0.08	6.28	0.26
Fitness activities	18	0.72	0.11	4.82	0.27
Family entertainment	twenty one	0.74	0.09	4.35	0.21
Thermal environment conditioning	32	0.81	0.07	7.59	0.24
Runoff regulation	26	0.78	0.10	5.68	0.22
Biodiversity maintenance	19	0.84	0.06	6.94	0.37

were done and the results were obtained and presented in Figure 1.

**FIGURE 1.** Comparison of the overall benefits of the functional layout schemes before and after optimization

As shown in Figure 1, the optimized recreational function coverage had increased by 19.2 percentage points, mainly because the newly added functional patches supplement service blind spots and focused more efforts to guarantee that the spatial distribution of various types of recreational functions will be more balanced, which will also enhance the convenience of residents. The connectivity index of ecological patches was increased from 0.41 to 0.67, which indicated the construction of ecological corridors had been successfully increased the functional connections between patches and decreased the fragmentation processes, and thus facilitated the migration of species and energy flow. The temperature reduction in high temperature areas increased from 1.2 degree Celsius to 2.4 degree Celsius, which doubled the thermal environment regulation capacity. The newly added ecological regulation patches and ecological corridors after optimization frankly exerted the vegetation transpiration cooling effect, and made a great contribution to mitigate the local heat island effect.

The optimized scheme has achieved significant results in synergistic effects between functionality and ecology. The layout of recreational functional patches is more scientific, with simultaneous improvements in environmental comfort and accessibility; ecological functional patches are connected by corridors to form a network system, strengthening ecosystem service functions; and complementary and symbiotic relationships are formed among functional patches,

avoiding the spatial fragmentation and ecological benefit loss caused by past single-functional zoning. The results indicate that suitability assessment and ecological network optimization methods based on multi-source environmental data can effectively guide the quantitative adjustment of urban park functional layout, achieving precise matching between functional needs and environmental conditions, and promoting the transformation of landscape design from experience-based to evidence-based.

V. CONCLUSION

This study aims to achieve synergies between functionality and ecology by constructing a framework for optimizing urban park layouts that integrates high-performance systems into the landscape design based on multi-source environmental data. By incorporating engineered materials as essential structural and ecological components, the framework ensures a data-driven optimization of both spatial utility and environmental resilience. Through the spatial analysis of environmental factors, the evaluation of functional suitability and the optimization of ecological network, a layout scheme with balanced performance of both recreational service effectiveness and ecosystem regulation functions can be formed. This methodological framework is ‘city independent’ and has great transferability and scalability. Future research could further integrate dynamic environmental simulation and multi-objective optimization algorithms to investigate the adaptive mechanism of high-performance technical systems within functional layouts, accelerating the development of intelligent and dynamic landscape design. By embedding smart sensors and responsive material structures into these layouts, the framework can more accurately simulate and optimize the long-term temporal variation of urban green spaces.

AUTHOR CONTRIBUTIONS

Conceptualization – Yating Liu and Lingyan Fan; methodology – Yating Liu and Lingyan Fan; investigation – Yating Liu and Lingyan Fan; writing-original draft preparation – Yating Liu and Lingyan Fan. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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