



Research Article

From urban scale priorities to local actions: an approach to develop brownfield greening strategies, based on ecosystem services supply and demand

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Abstract

Under rapid urbanisation and climate change, cities urgently need strategies to enhance resilience and sustainability. Transforming brownfields into green spaces has been widely recognised as a nature-based solution (NbS), yet how to integrate this transformation into urban planning to maximise benefits remains unclear. To address the gap, our study proposes a cross-scale approach for brownfield greening (BG) that links urban-scale prioritisation with site-specific greening interventions. By integrating spatially explicit assessments of ecosystem service (ES) supply, demand and supply-demand balance, the approach identifies not only where BG should occur (where to green), but also how tailored interventions can be implemented within sites (how to green). The proposed approach was tested in Tangshan, a typical resource-exhausted city in China, demonstrating how ES assessments can guide both strategic planning and detailed planning of BG. The findings advance the integration of NbS into spatial planning at multiple levels, offering actionable guidance for policy-makers, urban planners and landscape architects. Beyond the case study, the approach also provides insights into

managing land abandonment in shrinking cities worldwide, contributing to more effective and transferable urban greening strategies.

Keywords

brownfield greening, urban planning, ecosystem service, supply and demand assessment, Regeneration Priority, Nature-based Solutions

Introduction

Global urbanisation and climate change have intensified environmental challenges such as urban flooding and biodiversity decline (Hammond et al. 2023). To address these urban challenges, concepts such as ecosystem-based actions and Nature-based Solutions (NbS) have been proposed as cost-effective strategies to leverage ecosystem functions for enhancing ecosystem services (ES) in urbanised areas (Babí Almenar et al. 2021). These approaches emphasise greening interventions as being able to enhance ecological resilience, while cost-effectively providing socio-economic benefits. However, their implementation is often constrained by the limited availability of land within cities, with the primary challenge being where to locate such interventions (Cortinovis et al. 2022, Haase et al. 2014).

Brownfields, which are often underutilised and potentially contaminated sites within cities, offer a valuable opportunity for implementing the above greening approaches. Turning brownfields into green space offers multiple benefits, including improving the living environment, boosting land value and providing various beneficial ecosystem services (ES) for surrounding residents (Bez et al. 2024, De Valck et al. 2019). Brownfield greening (BG) is not a new concept and policies to promote it have been implemented in countries, such as the United States, Canada, Germany and France (De Sousa 2014, Hou et al. 2023). For instance, in France, a national brownfield database and dedicated funding were established in 2022 to actively promote the restoration of these sites (Bez et al. 2024).

In recent years, BG has been increasingly recognised as a Nature-based Solution (NbS), with a primary objective of enhancing ES and addressing pressing urban challenges (Chen and Hashimoto 2025). Given that brownfields are often located close to urban centres where ES demand is typically high, BG offers a unique opportunity to provide critical ES where they are most needed (Cortinovis and Geneletti 2018a, Feng et al. 2023).

As previous research has highlighted, brownfields often do not exist as single entities, but rather form clusters within urban landscapes (Fu et al. 2024, Hou et al. 2023, Rebernik et al. 2023, Preston et al. 2023). Consequently, BG should not be approached as a site-specific intervention alone, but rather as part of a broader, integrative strategy to provide systematic solutions to urban challenges. Therefore, in the context of BG, a coherent and

effective urban planning approach should address two key questions: 'where to green' at the urban scale and 'how to green' at the site scale. The former refers to the strategic prioritisation of suitable BG to yield the greatest benefits for the city, while the latter involves determining how to implement greening on a specific brownfield, including where and what type of NbS should be implemented (Han et al. 2018, Masiero et al. 2022). In the planning practice, the question of 'where to green' is relevant to strategic planning processes, engaging various stakeholders to develop comprehensive strategies for land management (Hersperger et al. 2019). In contrast, 'how to green' is addressed by detailed planning, which is more focused on operational feasibility and site-level implementation. Despite locally specific terminologies, the two levels of 'strategic planning' and 'detailed planning' are common to several countries following different planning traditions.

ES assessments have been widely used in environmental management and urban planning for improving decision-making (Cortinovis and Geneletti 2018b). For example, identifying mismatches between ES supply and demand can help prioritise interventions (Cui et al. 2019) and determine the most suitable NbS in a given location (Longato et al. 2023). In previous applications to BG, some studies have prioritised BG, based on a single ES, such as landscape connectivity, to guide green infrastructure (GI) planning (Wei et al. 2021, Wolff et al. 2023). For example, Wei et al. (2021) ranked the restoration priority of brownfields, based on their contribution to the GI network. However, these studies typically adopt a supply-side perspective focused on a single ES, overlooking the multifunctionality of BG and the crucial role of ES demand. At the site scale, research has mostly focused on how BG can improve ES supply using economic assessment methods (De Valck et al. 2019, Masiero et al. 2022). Overall, existing research has either emphasised urban scale prioritisation without providing follow-up guidance or measures post-greening benefits at the site level without linking back to city-level strategies. This fragmented approach offers little guidance to coherent planning processes and risks of making BG efforts inefficient, hindering the maximisation of benefits in practice.

To address these challenges, this study develops a cross-scale approach that integrates spatially explicit ES assessments to link strategic planning (urban scale) with detailed planning (site scale). The core innovation lies in its operational value for planning practice: the approach not only informs policy-makers on which brownfields should be prioritised, but also guides what NbS should be implemented at the site scale, ensuring the coherence and actionability of BG strategies. This provides a transferable method to maximise ecological benefits under resource constraints in shrinking cities.

Material and methods

The proposed workflow for supporting BG comprises three main steps:

1. Mapping ES supply and demand: Five ES were selected based on the urban planning document and relevant literature: runoff mitigation, urban heat island mitigation, carbon storage, recreation service and habitat quality.

2. Synthesising ES supply and demand: By using the Ecosystem Service Supply and Demand Ratio (ESDR), it can identify mismatches between ES supply and demand (Vignoli et al. 2021).
3. Defining strategies and actions for BG: Multi-criteria analysis (MCA) was used to integrate the five ESDR for generating urban regeneration priorities. Cluster analysis was conducted for site level NbS implementation (Fig. 1).

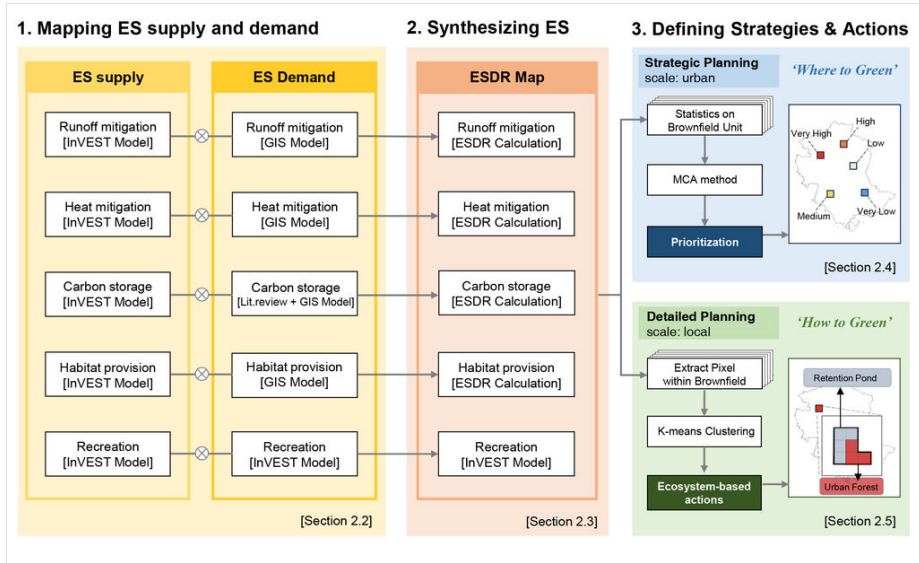


Figure 1.

Workflow illustrating the proposed approach for prioritising brownfield greening at the urban scale and generating ecosystem-based actions at the site scale.

Case study and selection of relevant ecosystem services

The case study selected to test the proposed approach is Tangshan, a large city in the north of China, spanning approximately 14,372 km² with a population of about 7.7 million (Fig. 2(a)). As a typical resource-based city with over 140 years of coal mining and industrial development, numerous brownfields emerged in the city due to industrial transitions and urban transformation. Most of these brownfields require treatment and restoration. To precisely identify existing brownfields in Tangshan, we followed the method proposed by Fu et al. (2024), which combines multi-source data and visual interpretation. The identification process involved three steps:

1. establishing identification rules to standardise the identification process;
2. conducting visual interpretation by examining Point of Interest (POI) data and 2022 remote sensing imagery from Google Earth; and
3. calibrating the results with urban zoning maps and municipal archives.

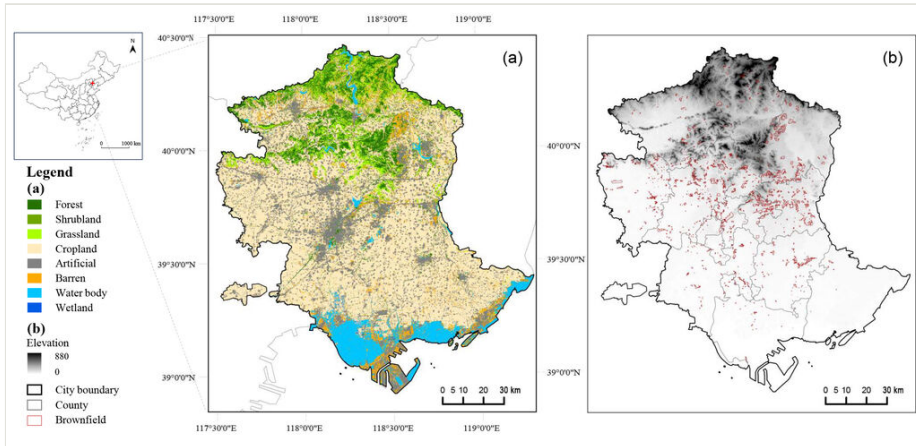


Figure 2.

Case study area: **(a)** Location of Tangshan city and land use; **(b)** the spatial distribution of brownfields. The enclave is not included in the subsequent discussion, as no brownfields were identified in this area.

In all, a total of 1,473 brownfields were identified, covering 317.1 km², around 2% of the city's total land area (Fig. 2(b)). These brownfields are mainly covered by artificial land and bare land, while approximately 9% are vegetated (i.e. forests, grasslands or shrublands). The size of brownfields ranges are very variable, from 955 m² to 17.9 km².

The selection of the five key ES was determined by the local planning goals and the ecological potential of BG. According to the Territorial Spatial Master Planning of Tangshan City (2021-2035), the city aims to achieve carbon neutrality, enhance climate adaptation and promote ecological restoration. Additionally, improving accessible green space for recreation was also set as an important target. Based on previous review, BG has been proven effective in delivering regulating and cultural services that can address the above specific urban challenges (Chen and Hashimoto 2025).

Consequently, five ES were selected to implement this link: runoff mitigation (RM) and urban heat mitigation (HM) were chosen to address climate adaptation; carbon storage (CS) and habitat quality (HQ) were selected to align with the carbon neutrality goal and ecological restoration target; and recreation service (RS) was included to meet the demand for public green spaces in densely populated areas. By integrating these specific ES, BG becomes a core component of Tangshan's spatial planning.

Mapping ecosystem services supply and demand

For the ES assessment, the ES supply was primarily evaluated using the InVEST model to create spatially-explicit ES maps (Sharp et al. 2020). As for the ES demand, we referred to previous studies, utilising data that include population density, statistical records, planning standards and meteorological data. A summary of the InVEST models

and demand indicators is provided in Suppl. material 1, Table A1. The specific mapping methods are detailed in the following sections .

Runoff mitigation

The RM supply was quantified using the InVEST Urban Flood Risk Mitigation model, which estimates pluvial runoff reduction in the analysed area through the runoff retention index (Li et al. 2023, Sharp et al. 2020). The model inputs include a land-cover map, a soil hydrological group map, a table of curve numbers (CN) for each combination of land cover and rainfall depth for the simulated event (Cortinovis et al. 2022). The hydrological soil group data were derived from the global hydrologic soil groups dataset (Ross et al. 2018). The CN was mainly derived from USDA standard values and previous literature (Cortinovis et al. 2022, Leta and Adugna 2024, NRCS 1986). For the rainfall depth, we used the calculation from China Outdoor Drainage Design Code (GB 50014-2021), coupled with the revised rainstorm intensity equation, assuming a flood prevention scenario with a 50-year return period and a 120-minute rainfall duration (more details on methods and data can be found in the Suppl. material 1).

We assessed the demand through the flood risk index (Li et al. 2023), defined as the product of hazard (the intensity of event) and vulnerability (potential damage to people and property). Based on the estimation of the runoff volume, we quantified the demand for flood protection by combining the urban population and buildings at risk on a grid scale.

$$F_r = F_H \times F_V$$

$$F_H = \frac{V_r}{V_T}$$

$$F_V = a \bullet V_p + b \bullet V_b$$

$$V_p = \frac{P}{P_m} \bullet \frac{Q}{Q_m}$$

$$V_b = \frac{B}{B_m} \bullet \frac{Q}{Q_m}$$

where F_r is the flood risk index, F_H is flood hazard and F_V is flood vulnerability. V_r is runoff volume and V_T is total rainstorm precipitation volume. V_p and V_b are population and building vulnerability, respectively and a and b represent the weight of flood vulnerability. This study attributed the weights of 0.6 and 0.4 to population and building, considering more uncertainty from individuals faced with floods (Li et al. 2023). P and B are population and built-up volume and P_m and B_m are the maximum density of

population and built-up volume. Q refers to the runoff depth in the grid, while Q_m is the maximum runoff depth.

Urban heat island mitigation

The HM supply was assessed using the InVEST Urban Cooling Model, which estimates temperature reduction by vegetation (Sharp et al. 2020). The model calculates a heat mitigation index, based on shading, evapotranspiration, albedo and distance from cooling islands (e.g. parks). Specifically, it calculates an index by averaging values of albedo, crop coefficient (evapotranspiration) and canopy coverage (shading) for each land-use class, considering the cooling effects of large green areas on their surroundings. Then, it estimates air temperature by incorporating the heat mitigation index, a rural reference temperature, the urban heat island intensity for the analysed city and the air mixing distance (Cortinovis et al. 2022, Silvia Ronchi et al. 2020). For our study, we set the air blending distance to 550 m (Chung et al. 2024) and the maximum cooling distance to 450 m (Hu et al. 2023). The standard weights recommended by the model developers were applied to map the HM supply. Detailed parameter settings are provided in Suppl. material 1.

The HM demand was defined by hazard and exposure. The hazard indicator represents varying levels of thermal threat to citizens and was quantified with overheated patches, based on Land Surface Temperature (LST) values. The exposure indicator reflects the population distribution. For areas without the population, demand would be set to zero. For LST, we applied the standard deviation zoning method to identify overheated patches and categorised the LST values into five classes: low, relatively low, medium, relatively high and high (Wang et al. 2024). Thresholds were set at 28.7°C, 31.8°C, 38.2°C and 41.4°C, respectively. Values ranging from 1 to 5 were assigned to LST classes, with the highest level of demand (LST_m) set at 5. In our study, a weight of 0.6 was assigned to population and 0.4 to extreme heatwave threats, prioritising population distribution due to the higher uncertainty associated with human vulnerability to heat.

$$HMi = a * \frac{P}{P_m} \bullet b * \frac{LST}{LST_m}$$

Carbon storage

CS supply was assessed using the InVEST Carbon Storage and Sequestration model, which estimates the carbon storage from four carbon pools (Sharp et al. 2020). In our study, we focused on carbon stored in above- and below-ground vegetation and soil organic carbon. The dead organic carbon was excluded because the content is extremely low and difficult to obtain (Yang et al. 2024). For the other three pools, carbon storage values were retrieved from previous studies (Table 5 in Suppl. material 1), focusing especially on those conducted near Tangshan City (He et al. 2023, He et al. 2022, Wu et al. 2024).

We used per capita carbon emissions as a proxy to estimate the demand for carbon storage (González-García et al. 2020). In Tangshan City, the population in 2020 was approximately 7.7 million, with total CO₂ emissions amounting to 310 million tonnes (Ministry of Ecology and Environment of the People's Republic of China 2022). To calculate per capita emissions, we divided the city's total CO₂ emissions by its population, resulting in a per capita CO₂ emission of 40.16 tonnes. Based on the relative atomic weight, we estimated that carbon constitutes approximately 27% of CO₂, which equates to 10.84 tonnes of carbon per capita. We then multiplied the latter per capita value by the population density to generate a spatial explicit carbon emissions map as a proxy for the demand.

Habitat quality

The HQ supply was measured through the InVEST habitat quality model (Sharp et al. 2020, Terrado et al. 2016). Modelling the habitat quality map allows us to identify where ecological conservation should be enforced. We selected agricultural, built-up and barren land as threat sources (Li et al. 2023). The habitat sensitivity table and other key parameters were determined based on previous studies (Bai et al. 2019, Bhagabati et al. 2014, Tang et al. 2020). More detailed information can be found in Suppl. material 1.

Regarding the demand, we followed Shi et al. (2020) and Yang et al. (2024), using the regional average habitat quality as the standard for satisfaction. In our analysis, we utilised the median value to represent the average state due to the skewed data distribution. The formula for calculating habitat quality demand is as follows:

$$HQD = \begin{cases} HQD_{st} - Q_x, & Q_x < HQD_{st} \\ 0, & Q_x \geq HQD_{st} \end{cases}$$

where Q_x represents the supply index of the grid, HQD_{st} is the habitat quality demand standard.

Recreation

The RS supply was mapped using the InVEST Urban Nature Access mode. It estimates nature-based recreation accessibility, based on the location and extent of urban nature, as well as the distribution and density of the population, through the Two-Step Floating Catchment Area method (Liu et al. 2020). The model calculates the supply of urban green spaces on each pixel, considering the area of the green space, the distance from the green space to population grid cells and the population size. For each population pixel, the model aggregates the accessible green space supply from surrounding areas, accounting for distance decay. The result is an estimation of the urban green space accessible to each population pixel, expressed in square metres per person (m²/cap). In our case, we defined forests, shrubs, grasslands as well as waterbodies and wetlands as potential recreational spaces, acknowledging that waterbodies can also provide valuable

nature experiences. Based on local planning documents, a search radius of 500 m was applied.

Regarding the demand, the model adopted a per capita green space target, derived from urban planning standards to represent the ideal amount of green space each person should have access to (Liu et al. 2022). According to the Greenspace System Planning of Tangshan City, the target is set at 18 m² per person (Tangshan Urban Management Bureau 2021). The RS demand map was obtained by multiplying the per capita green space requirement with the population raster.

Synthesising ecosystem service supply and demand

To synthesise the supply and demand, we employed the Ecosystem Service Supply and Demand Ratio (ESDR), a widely used indicator that quantifies the mismatch between supply and demand (Li et al. 2023). Conceptually, the ESDR serves as a diagnostic tool for planners to identify whether a region is in a state of surplus, balance or deficit. The ESDR is calculated as follows. The value of '0' indicates a balanced state. A negative value indicates an ecological deficit, serving as a signal for urgent interventions, while a positive value represents a surplus. For RM, HM, CS and HQ, we used ESDR maps to quantify the mismatch. For RS, the InVEST Urban Nature Access model provides a supply-demand balance map that assesses the balance between the supply of recreational areas and the planning target. Next, we normalised the five ESDR maps by dividing each map by the maximum, scaling all data to the range [-1,1]. This normalisation method ensures that the value '0' remains unchanged while rescaling the five ES maps for comparability.

$$ESDR = \frac{ESS - ESD}{(ESS_{max} + ESD_{max})/2}$$

Defining strategies and actions

Prioritising brownfield greening using ESDR mapping

At the urban scale, we utilised ESDR mapping to prioritise BG interventions. We calculated the average standardised ESDR values for each brownfield site using zonal statistics (Fig. 1), which allowed us to understand its supply-demand balance. The regeneration priority was then determined by the scoring system (Table 1), classifying ESDR values as positive, negative or balanced. Scores from 2 (most urgent) to 0 (least urgent) were assigned to each class. For the balanced state, we defined a range around zero to represent cases where supply and demand are approximately equal, acknowledging that an exact value of '0' is rare.

Since the urban planning document did not specify the relative importance of relevant ES, we treated all ES as equally important and assigned them equal weights. Hence, the

individual maps with the scores were simply summed up to produce a combined prioritisation map for BG.

Table 1.
The Scoring System for Prioritisation. ESDR.X represents the supply and demand ratio for one of the five ES. The coefficient K serves as a scaling factor and is set to 0.1 in our case. The variables p_negative and p_positive are the percentage of negative and positive values, with mean reflecting their average deviation.

ESDR class	Range	Meaning	Scores
Positive	$ESDR.X < -k \cdot p_{negative} \cdot Mean_{negative} $	Supply exceeds demand; no intervention is necessary.	0
Balanced	$-k \cdot p_{negative} \cdot Mean_{negative} \leq ESDR.X \leq k \cdot p_{positive} \cdot Mean_{positive}$	Close to a balanced state; careful management is required to maintain the balance.	1
Negative	$ESDR.X > k \cdot p_{positive} \cdot Mean_{positive}$	Demand exceeds supply; further intervention is needed to enhance ES supply.	2

Spatial clustering to provide information for ecosystem-based interventions

At the local scale, clustering was employed to provide detailed NbS implementation. Specifically, K-means clustering was conducted on the pixel data within brownfield boundaries, revealing the internal heterogeneity of supply-demand mismatches (Fig. 1). To address potential correlations, Principal Component Analysis (PCA) was first performed, selecting the top three components that explained over 85% of the total variance. These PCA-derived components were then used as input for k-means clustering. The optimal number of clusters was determined by combining statistical criteria and interpretational insights (Cortinovis and Geneletti 2020). R was used for PCA and K-means cluster analysis (packages factoextra, cluster and NbClust) (Charrad et al. 2014).

Results

Ecosystem service supply, demand and supply-demand ratios in Tangshan

The assessment of ES supply, demand and ESDR is presented in Fig. 3. In terms of supply, RM and CS supply maps exhibit similar spatial patterns, with high values concentrated in the northern mountainous regions, predominantly covered by forests and shrubs. HM and HQ display similar spatial distributions of low-value areas, primarily in urban built-up and suburban regions. In contrast, RS supply shows a more fragmented pattern, with high-value areas distributed in northern towns and villages near mountains, while low values are concentrated in the urban centre. For ES demand, the five maps reveal similar spatial patterns. Urban built-up areas, especially the centre of the city, exhibit extremely strong demand for all five ES.

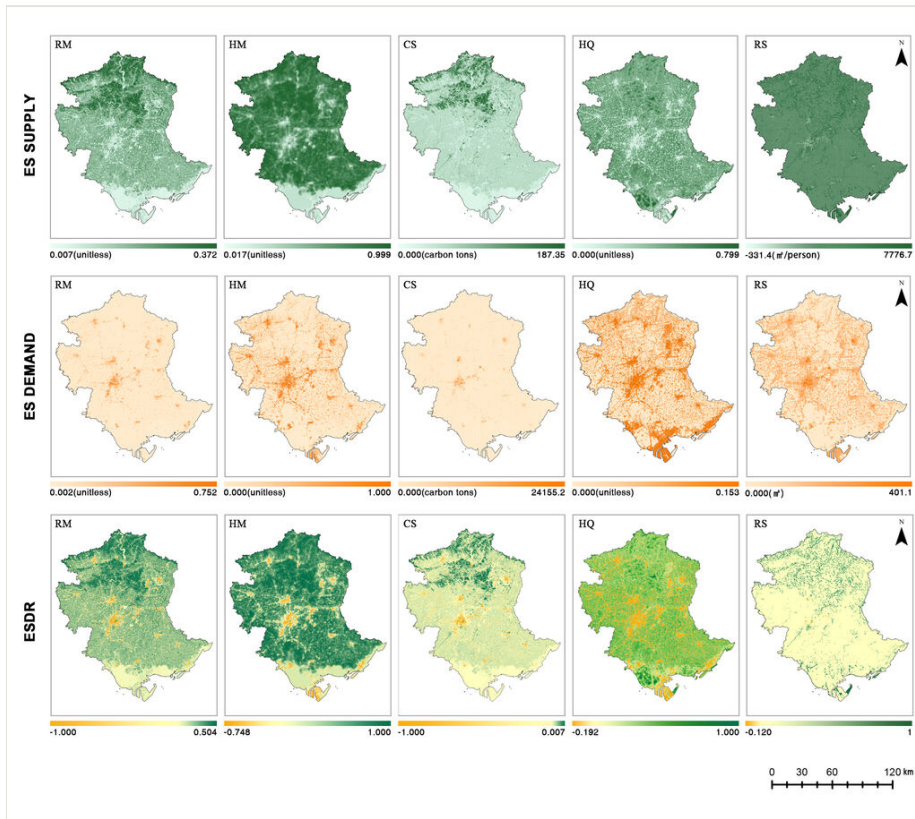


Figure 3.

Maps of ES supply, demand and ESDR. RM = runoff mitigation, HM = heat mitigation, CS = carbon storage, HQ = habitat quality and RS = recreation services. The supply and demand maps for HQ and RS have a spatial resolution of 10 m, while the other ES maps have a resolution of 100 m. All ESDR maps are presented at a 100-m resolution.

The ESDR maps highlight ES imbalances in urban built-up areas, particularly in densely populated central districts, which face significant ES deficits. In contrast, suburban and rural regions show more balanced or surplus status. Surplus areas of RM, CS and HM are concentrated in the northern mountainous regions, while HQ surpluses extend to southern waterbodies and wetlands. For RS, most areas are balanced, with a surplus in northern mountain-adjacent towns and fragmented deficits within central urban areas (Fig. 3).

Priorities for brownfield greening across the city

Brownfields presented great potential in addressing urban challenges in Tangshan. Around two-thirds of brownfields are located in areas with high demand and low supply for carbon storage and habitat provision (Fig. 4). Besides, approximately 25% of brownfields could contribute to mitigating urban runoff and enhancing recreational

services. However, only about 5% of brownfields fall in areas with an unmet demand for microclimate regulation (Fig. 4).

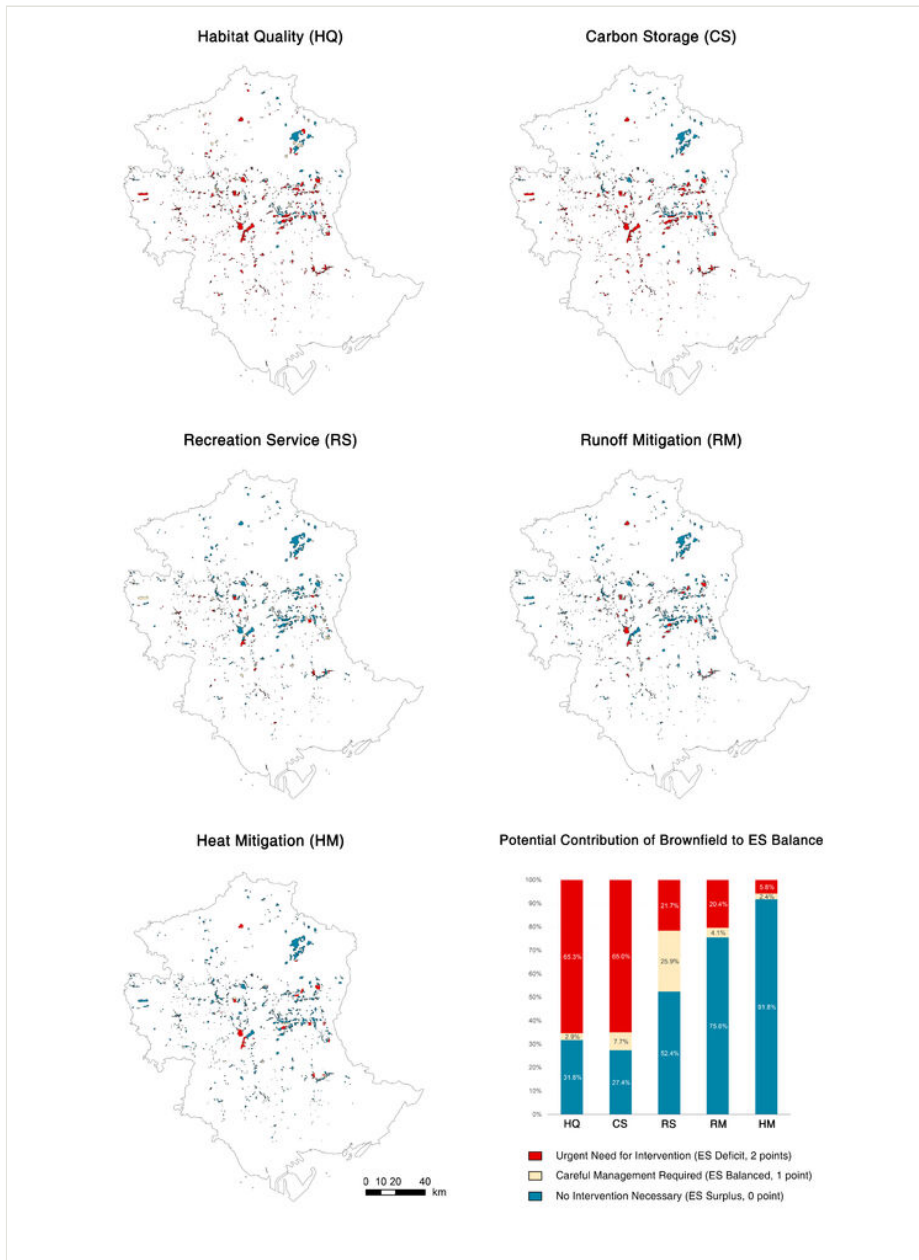


Figure 4. Intervention priority of brownfields, based on the assessment of the ESDR calculated for each ES.

The combined priority map reveals different regeneration urgency across the city (Fig. 5). Based on the natural breaks classification, five categories were generated: very high (8–10), high (6–7), medium (4–5), low (2–3) and very low (0–1) (Fig. 5). The top two tiers of ‘very high’ and ‘high’ scores comprised 431 plots (29.2%), predominantly located in urban centres or peripheries. Conversely, low and very low-priority brownfields included 619 parcels (42%), primarily distributed in suburban and remote natural regions, such as the northern mountainous areas. Overall, nearly one-third of the brownfields exhibit high or very high priority, indicating brownfields that could significantly contribute to balancing urban ES supply and demand by providing more diverse green spaces.

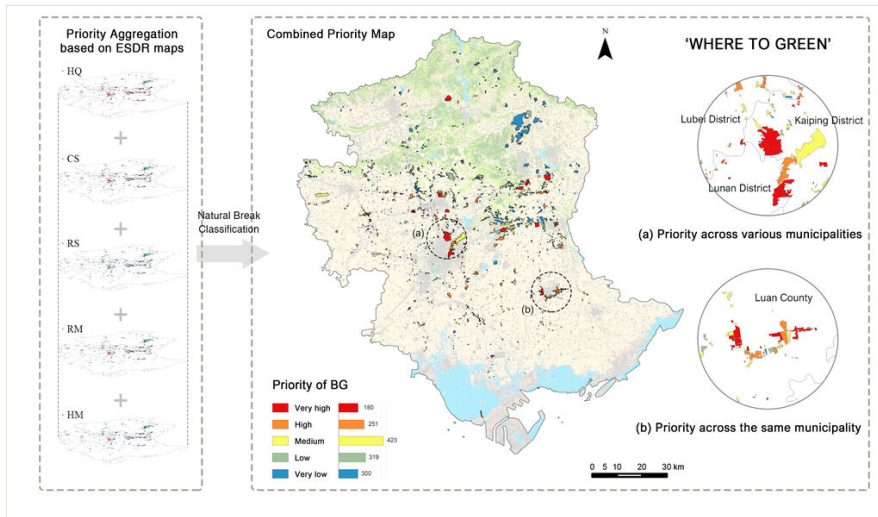


Figure 5.

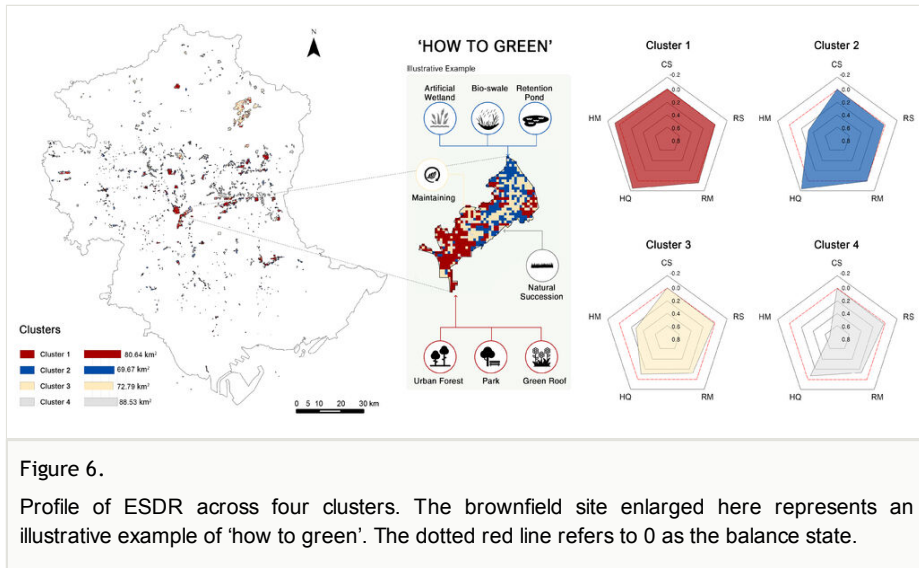
The combined regeneration priority of brownfield greening in Tangshan City.

Identification of suitable ecosystem-based actions for each brownfield site

The analysis identified four distinct clusters of ESDR characteristics within the brownfield sites (Fig. 6). These clusters exhibit unique supply-demand profiles that provide information for detailed ecosystem-based actions, including selecting appropriate NbS types and identifying suitable locations for their implementation. A spider diagram characterises the supply-demand ratio of the analysed ES within each cluster (Fig. 6). The total area of the brownfields included in the clusters has a similar spatial extent, from 69.6 km² of Cluster 2 to 88.5 km² of Cluster 4.

Cluster 1: This cluster covers approximately 80.64 km² and consists of areas where ESDR values are negative for all ES, except for RS. Consequently, comprehensive interventions are needed to enhance ES supply, particularly in CS, HM, HQ and RM. Compared to other clusters, this area has the lowest RS mean value. To address these deficiencies, NbS such as parks, urban forests, bio-swales and green roofs could be implemented to improve multiple ES synergistically.

Cluster 2: This cluster is about 69.67 km², characterised by negative ESDR values for CS, RM and especially HQ. Targeted interventions are needed to strengthen the supply of these ES with particular attention to enhancing habitat provision and rainwater retention. Therefore, NbS, such as artificial wetlands and retention ponds, should be considered.



Cluster 3: This cluster covers around 72.79 km², characterised by relatively high positive ESDR values for most ES, especially HM, HQ and RM. These areas show an ES surplus due to low population density and demand. Therefore, maintaining the existing green spaces would be sufficient to meet the needs of this cluster.

Cluster 4: Similar to Cluster 3, Cluster 4 features an oversupply of ES, but it has notably higher HM ESDR values. In this case, the promotion of natural succession, instead of intentional BG, on the model of the examples presented in Mathey et al. (2018), may be the most suitable approach for these areas.

An illustrative example of the cross-scale brownfield greening approach

Fig. 7 illustrates the application of the cross-scale approach in four representative areas, demonstrating how ES assessments guide both strategic prioritisation and site-specific NbS implementation.

Area A includes two brownfields located in the highly urbanised centre. These brownfields, formerly local steel factories, were abandoned during the industrial shift. These sites are mainly covered by sealed surfaces and disused industrial infrastructure, with very limited green space. Amongst them, one brownfield spans approximately 4.2 km² and is of 'very high' greening priority (score: 10) due to severe deficits across all evaluated ES. The other has a 'medium' priority, despite the two brownfields being close to each other. Compared with the 'medium' priority, the "very high" priority reflects a more

urgent need for interventions to restore the damaged ecosystem and enhance climate resilience within 1-3 years. To guide detailed planning, cluster analysis provided distinct spatial patterns across these sites. The brownfield site with 'very high' priority falls into different clusters. Mostly, they are Cluster 1, which indicates significant ES shortages of all evaluated ES, except for RS. NbS, like de-sealing and revegetating through urban forests can be helpful, as these interventions can address multiple ES deficits simultaneously in a cost-effective manner. Smaller portions fall within Cluster 2 and Cluster 3, each suggesting distinct intervention strategies. Cluster 2 areas highlight the need to enhance habitat quality, runoff mitigation and carbon storage. NbS, such as bioswales, retention ponds, constructed wetlands or rain gardens, could effectively address these deficits. In contrast, areas identified as Cluster 3, characterised by a slight oversupply of ES, require minimal intervention. Here, spontaneous greening or low-maintenance management would be an ideal solution.

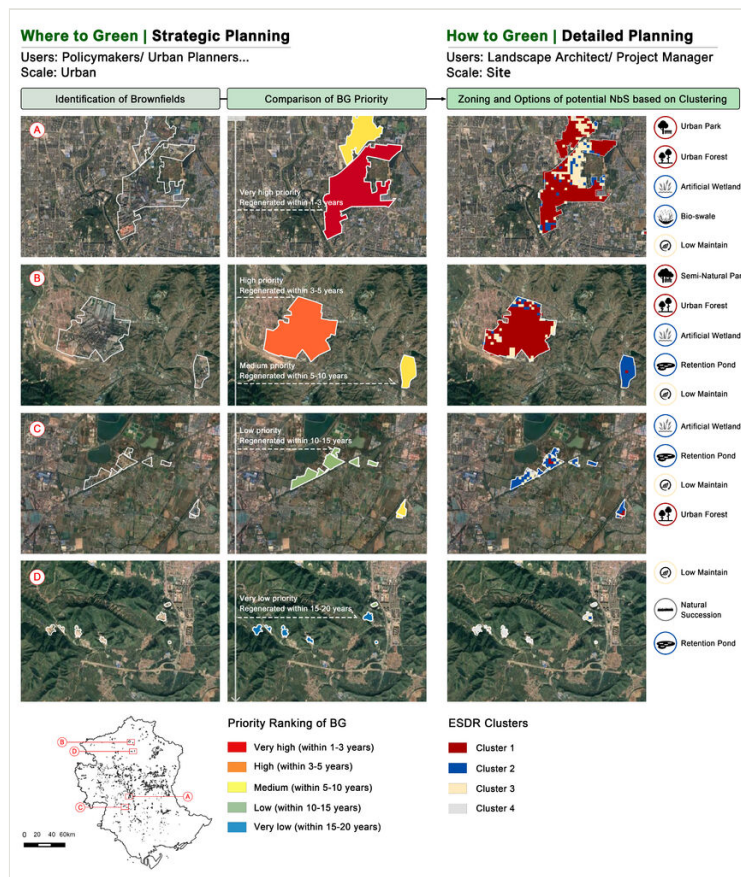


Figure 7.

The four brownfield greening cases (Area A-D) selected to further explain how the methodology could support BG in Tangshan. The last column is illustrative examples of potential NBS based on the clusters.

Area B was selected as a remote town containing two brownfields with differing priorities. The first brownfield is ranked as "high" (score: 8) due to significant ES shortages, except for recreational services. The second site is ranked as a "medium" priority (score: 6), due to limited benefits from interventions in heat mitigation and recreational services. These priority rankings provide local planners with clear guidance on which brownfields should be regenerated first. At the local scale, the "high" priority brownfield is predominantly comprised of Cluster 1, indicating a need for intensive greening interventions to address ES deficits within the brownfield. Conversely, the "medium" priority brownfield is largely covered by Cluster 2, where interventions should emphasise enhancing the ES synergies between runoff mitigation and biodiversity.

In the third example, we examined a series of 'low' priority brownfields along a main traffic route (score: 4). These sites are mainly abandoned parking lots, with some areas spontaneously revegetated by shrubs and trees. As these brownfields are ranked as 'low' priority, their regeneration is less urgent compared to other brownfields, for example, the 'medium' priority brownfield shown in the same sub-window. At the local scale, most of these brownfields fall into Cluster 2, suggesting that efforts should concentrate on improving habitat quality, runoff mitigation and carbon storage within the sites.

The fourth example focuses on mining brownfields located in the northern mountainous outskirts of the city. These sites, averaging 6.5 hectares in size, are predominantly barren or artificial land. Their "very low" priority ranking reflects sufficient existing ES supply to meet local demand, rendering additional interventions unnecessary. Clustering analysis suggests that these areas, dominated by Cluster 4, would benefit most from preserving existing vegetation and allowing spontaneous natural regeneration.

Discussion

Integrating ES information to support decision-making

This study developed a novel approach for supporting BG, based on spatially-explicit mapping of ES supply and demand. In previous ES research, mapping ES mismatches has been recognised as a crucial step in integrating the ES concept into environmental management and decision-making processes (Li et al. 2023, Baró et al. 2015). Our findings aligned with previous studies, revealing a similar spatial pattern of ES mismatches: urbanised areas face severe ES deficits, suburban areas tend to be relatively balanced and natural areas, such as the northern mountainous region in our study, show significant ES surpluses (Chen et al. 2019, González-García et al. 2020, Li et al. 2023). This finding highlights the urgent need for targeted interventions in urbanised areas, particularly in the context of climate change. A key innovation of the study is the focus on brownfields as spatial units for practical change and provides an approach for integrating BG with urban planning. The method streamlines the process from extracting ES goals in urban planning documents to creating BG strategies, which guarantees the continuous use of ES knowledge as a decision-making support.

While previous BG studies have primarily focused on how BG can enhance ES supply, such as air purification and landscape connectivity etc. (Preston et al. 2024, Tinghao et al. 2018, Wei et al. 2021), the potential of BG to address acute urban challenges has been neglected. Although ES demand is easily overlooked in the real-world planning process and documents (Cortinovis and Geneletti 2018b), its integration is essential for more effective decision-making. This integration enables the identification of critical locations where multiple ES mismatches co-exist, thereby addressing specific urban challenges in different areas of the city. In our case, we achieved this through priority ranking and clustering. Brownfields with high priority typically experience more severe ES mismatches and their transformation is expected to significantly improve the imbalance between ES supply and demand. Our analysis revealed that 29% of brownfields have the potential to provide critical ES in high-demand areas. This finding aligns with previous studies indicating that certain brownfields overlap with regions of high ES demand (Feng et al. 2023, Scott et al. 2016). Transforming these brownfields could play a crucial role in enhancing residents' health and well-being by addressing ES deficiencies in urban environments.

The innovation and implications of the proposed approach

While BG is increasingly recognised as a NbS, effective pathways to integrate it into urban planning remain unclear. This study addresses this critical gap by developing a dual-scale framework that systematically guides both 'where to green' and 'how to green'. The innovation of the research lies in the integration of these two scales and its contribution to planning practice. By bridging the traditional silo between strategic planning and site-level implementation, this framework transforms ES assessments into actionable strategies, ensuring that BG interventions are not only strategically prioritised, but also matched with specific NbS types to address site-level deficits. This facilitates the holistic implementation of BG and delivers comprehensive guidance for relevant stakeholders.

The dual scale approach offers a distinct advantage over single-scale assessments. At the urban scale, the multi-criteria analysis (MCA) enables rapid screening, allowing policy-makers to efficiently identify key sites for regeneration (Ahmad et al. 2019, Fu et al. 2024). At the site scale, the clustering provides a "magnifying glass" for fine-scale NbS implementation tailored to the specific brownfield site. Unlike previous studies that often stopped at prioritisation (Cortinovis and Geneletti 2018a, Shanshan et al. 2019, Wei et al. 2021), our approach extends the workflow to actionable prescriptions, linking sites to NbS types documented in previous studies. For example, the form of an 'urban forest' can take inspiration from projects in Leipzig, Germany (Rink and Schmidt 2021). This dual approach provides urban planners, policy-makers and other stakeholders with clear, actionable insights for strategic prioritisation and effective on-the-ground implementation. It contributes to the broader discussion on integrating NbS into spatial planning across both strategic and detailed local levels. In doing so, it also addresses the lack of NbS studies that consider multifunctionality and link management measures to physical units (Goličnik Marušić et al. 2023, Li et al. 2025).

Furthermore, this method can also have implications for managing abandoned spaces in shrinking cities beyond traditional industrial brownfields. In Germany and Japan, many houses have been abandoned due to population decline (Kim et al. 2018, Mallach et al. 2017). In a megacity like Tokyo, a recent regulation has been passed regarding the reuse of abandoned housing, which must be registered within three years (Tokyo Legal Affairs Bureau 2024). Otherwise, the property may be designated for public use. Similar to the “right sizing” strategies proposed in shrinking U.S. cities (Schilling and Logan 2008), which emphasise greening strategies of where and how interventions should be made, our approach provides a dual-scale approach that clarifies both aspects and can be applied across contexts.

Limitations and future research

This study has certain limitations regarding the mapping of ES supply and demand. In the quantitative assessment of ES demand, some datasets were used as inputs for multiple demand indicators due to data availability. For instance, population density was incorporated into several demand indicators, including CS, HM, RM and RC. While we addressed it through the PCA analysis in the clustering process, future research could integrate a broader range of socio-economic data, such as age distribution and economic status of population, to provide more detailed and targeted ES management recommendations. Regarding ES supply mapping, the InVEST models, which have been widely used in research and planning applications, were applied. However, certain limitations remain due to model constraints and input data. For instance, in the case of RM, we relied on a global soil database, which may have led to the loss of localised soil characteristics, potentially affecting the accuracy of the simulation (Li et al. 2023). For HM, the cooling capacity index was derived from empirical settings, based on previous studies, which may introduce uncertainties when applied to different urban contexts (Hu et al. 2023). Therefore, more detailed, on-the-ground data are still needed for validation and further analyses.

Regarding the cross-scale prioritisation method, prior to aggregation, ESDR values were classified into three priority levels, based on the degree of supply-demand mismatch. This threshold-based classification acts as a non-linear filter, ensuring that higher priority scores are driven by significant deficits. Subsequently, we employed an MCA approach, utilising the linear aggregation of discrete scores to identify regeneration hotspots. The primary strength of this approach lies in its transparency and communicability, which are essential for informing non-expert policy-makers about areas with co-occurring deficits. Crucially, it is important to clarify that this metric assesses the current state of urgency rather than predicting the future ecological impact of regeneration. However, we acknowledge that this model relies on the assumption that different ES are substitutable in the context of urgency assessment, which simplifies the complex, non-linear synergies and trade-offs between ES (Cortinovis 2020). While this simplification is necessary for strategic screening at the urban scale, the actual ecological benefits after regeneration will depend on the specific site-scale solutions and their interactions. Additionally, regarding the definition of priority scores, we adopted a simplified statistical method that

determines the balance state based on data distribution (Table 1). Alternative methods, such as quartile or standard deviation thresholds, could also be applied depending on specific analytical needs.

Finally, we acknowledge that our analysis does not incorporate the temporal perspective. The primary focus of our study was to develop a transferable, cross-scale approach for guiding brownfield greening and we were concerned that adding the temporal dimension might have increased complexity, undermining the applicability of the approach. However, in real-world applications, brownfield greening projects are implemented sequentially, leading to dynamic changes in ES supply and demand, particularly when two brownfields are close to each other. Future research should explore dynamic regeneration processes to better assess the long-term impacts of implementation and enhance the adaptability of planning strategies.

Policy implications and implementation feasibility

The implementation feasibility of this approach is reinforced by the specific land-management context in China. With land being primarily state or collectively owned, the government plays a dominant role in facilitating land acquisition and regeneration process (Sun et al. 2022). Driven by a strong will to promote urban transformation and improve the quality of life, spatial planning policies serve as powerful tools for brownfield redevelopment (Cheng et al. 2011). Consequently, the priority map generated in this study can serve as a direct reference for municipal authorities to allocate resources efficiently.

However, these spatial findings should be seen as support to decision-making rather than a rigid direction. While BG can address urgent ES imbalances and bring multiple benefits, it could also trigger potential conflicts, such as green gentrification (Ali et al. 2020). Mitigating these risks requires active stakeholder participation, i.e. involving communities, developers and government to jointly discuss priorities and specific NbS implementation (Rizzo et al. 2015). This participatory process helps balance the direct costs of remediation with broader social benefits, promoting successful project delivery (Hou et al. 2023). Additionally, potential conflicts between residual contamination and recreation services require careful consideration, as soil contamination can be hidden and NbS may not be suitable for heavily polluted brownfields (Pecina et al. 2021). Therefore, strict environmental impact assessments and long-term monitoring are critical.

Conclusions

Transforming brownfields into green spaces has been widely recognised as an important strategy for promoting urban sustainability and resilience. This study proposes a cross-scale approach that integrates ES supply and demand to support brownfield greening, providing practical guidance for urban planners and policy-makers. By prioritising brownfields at the urban scale and identifying targeted ecosystem-based actions at the local scale through cluster analysis, the approach bridges the gap between broad-scale

decision-making and site-specific implementation. The findings underscore the role of brownfield greening in addressing ES imbalances in urbanised areas, contributing to more equitable and sustainable urban transformation.

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Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary material

Suppl. material 1: Supplementary material 1 [doi](#)

Authors: Buke Chen

Data type: docx

Brief description: This file summarises the data sources for ES mapping methods and provides a detailed explanation of the methods and parameters for ES mapping.

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