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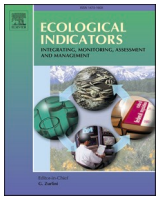
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A coupling framework for assessing spatial inequities in regional provisioning ecosystem services and designing rooftop greening interventions: A case study of South Holland Province, Netherlands

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ABSTRACT

Urbanization often produces mismatches between where ecosystem services are supplied and where people demand them, leading to pronounced service deficits in dense urban cores. Yet planners still lack integrative tools that can both diagnose these spatial inequities and directly inform targeted interventions. This paper develops a cross-scale framework that couples regional ecosystem service assessment with microscale greening design to mitigate inequities in provisioning ecosystem services. Using South Holland Province (Netherlands) as a case, we construct a Per Capita Provisioning Services Index (PSI) that links ecosystem service supply to population distribution and define "ecosystem service poverty" as areas falling into the lowest PSI class. Local spatial statistics (Getis–Ord G*) are then applied to identify statistically significant "coldspots" of ecosystem service poverty, contrasted with peripheral service "hotspots." A six-dimensional performance matrix (food, water, energy, soil support and nutrients, habitat support, and cooling) is used to characterize coldspot types, revealing, for example, zones dominated by habitat and climate regulation deficits versus areas facing multi-dimensional shortages. Three-dimensional building data and explicit physical thresholds are subsequently used to identify suitable rooftops for greening in each coldspot type, and to match rooftop typologies with differentiated intervention strategies. The results demonstrate how targeted green roof configurations can respond to distinct local needs. By bridging macro-scale diagnosis and micro-scale design, the framework offers a transferable technical pathway for addressing ecosystem service poverty and advancing spatially just urban sustainability planning.

1. Introduction

Since the acceleration of industrialization in the 19th century, global urbanization has occurred in distinct stages (Davis, 2015). As urbanization in developed countries approaches saturation, urban agglomerations have undergone structural reorganization, characterized by a paradigm shift from monocentric population concentration to a more balanced polycentric distribution (Liu and Wang, 2016). This redistribution eases pressure on some city centers but creates complex spatial effects on the environment. As cities spread and reorganize, they alter regional biogeochemical cycles through land-use change (Johnson and Munshi-South, 2017). Notably, urbanization-driven environmental homogenization is affecting ecological gradients between urban and non-urban habitats, resulting in spatial differentiation patterns exhibiting significant threshold effects (Groffman et al., 2014). This context provides a critical backdrop for dynamic assessment of ecosystem services at the regional scale, particularly in response to rapid structural transformations of urban agglomerations. As a key indicator reflecting the coupling degree of human-environment systems, the spatiotemporal heterogeneity of ecosystem services effectively reveals the cascading impacts of urban expansion on ecological environments and human well-being (Su et al., 2012a, 2012b; Peng et al., 2015; Ouyang et al., 2021).

According to the Millennium Ecosystem Assessment framework, ecosystem services are categorized into four fundamental types: provisioning services (food, freshwater), regulating services (climate regulation, flood control), supporting services (soil formation, biodiversity), and cultural services (aesthetic value, recreational space) (Dominati et al., 2010; Millennium Ecosystem Assessment, 2005). Provisioning services are particularly vulnerable to spatial declines because they directly support basic human needs. Such deficits can exacerbate ecological risks such as environmental injustice and reduced urban

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resilience, ultimately affecting human well-being (Feng et al., 2021; Du Toit et al., 2018; Syrbe and Walz, 2012). Such mismatches raise concerns of environmental justice, as underserved urban populations suffer from 'ecosystem service poverty' (Wolch et al., 2014). Currently, the enhancement of ecosystem services primarily relies on traditional land use planning tools (Lautenbach et al., 2011; Fu et al., 2015). However, these conventional approaches face two key challenges in spatially heterogeneous regions. First, high-density urban areas experience severe limitations in service provision capacity due to soil sealing and shrinking green space; Second, despite the resources redundancy of rural areas, ecosystem services suffer from supply–demand mismatches owing to low population densities (Haase et al., 2014). This spatial differentiation means that traditional land use regulation cannot fully alleviate ecosystem service deficits in dense urban cores in the short term (Tan et al., 2021a, 2021b).

Cross-scale spatial coordination is increasingly emphasized to meet ecosystem service demands across regions via supply–demand matching. Green roofs alleviate supply bottlenecks caused by soil sealing and enhance overall urban environmental quality through multifunctional ecosystem services (Francis and Jensen, 2017). Numerous empirical studies have demonstrated that green roofs contribute to urban food provision, climate regulation, stormwater management, and biodiversity support (Walters and Stoelzle Midden, 2018; Nguyen et al., 2021). This vertical ecological technology can improve provisioning ecosystem services via multiple mechanisms (Russo et al., 2017), including generating new urban food sources (Orsini et al., 2014), reducing building cooling loads and mitigating urban heat island effects (Susca, 2019; Wang et al., 2022a, 2022b), lowering flood peaks and improving runoff water quality (Vijayaraghavan, 2016) and enhancing urban biodiversity (Minor et al., 2018; Frisk and Hanslin, 2025). Additionally, emerging photovoltaic green roof hybrid systems can contribute to energy supply by increasing solar panel efficiency (Chemisana and Lamnatou, 2014a). These benefits show that green roofs have substantial potential to serve as critical links between microscale interventions and macro scale ecosystem service supply.

The integration of spatial data with machine learning has emerged as a vital approach for assessing and diagnosing ecosystem services, which enhances evaluation accuracy and spatial resolution toward precise matching between supply and demand (Zhang et al., 2023; Sun and Scanlon, 2019). For example, Vrebos et al. (2020) develop the regional decision support tool ECOPLAN-SE using detailed local data to simulate 18 ecosystem services and assess land use change impacts on service provision. Similarly, Nyelele et al. (2023) use social media photographs and a random forest model to predict the spatial distribution of recreational services by vegetation cover and topography. Langemeyer et al. (2020a) identify that dense residential and industrial areas in Barcelona have the most urgent demand for heat regulation and habitat services through expert-weighted multi-criteria spatial analysis. Venter et al. (2021) develop a participatory decision support tool to simulate spatial decisions based on the importance of temperature regulation, stormwater mitigation, and habitat connectivity. Based on these foundations, selecting appropriate tools to participate in the identification, assessment, and diagnosis workflow is essential when bridging micro-level interventions with regional objectives.

In summary, the current body of research provides a rich theoretical foundation and practical cases for ecosystem services delivered through green roofs, especially for provisioning services (Droz et al., 2021; Evans et al., 2022). These advances broaden international perspectives and highlight future opportunities for innovations in cross-scale coupling and supply–demand alignment. Despite progress in ecosystem service assessment and green roof functionality, systematic research integrating regional-scale provisioning services with micro-scale interventions remains limited. There is a lack of comprehensive multi-source data integration methods to accurately identify ecosystem service depletion hotspots and to develop differentiated intervention strategies. Moreover, current green roof deployment often relies on empirical judgment rather than quantitative analysis to regional ecological demands. To address this gap, we propose the core question: How can the spatial imbalance of provisioning ecosystem services in urban regions be precisely identified, and how can suitability-based rooftop greening interventions be designed to achieve equitable ecosystem service allocation and cross-scale spatial optimization?

To answer this, we develop an integrated framework combining principal component analysis (PCA), spatial clustering, and rooftop screening in an end-to-end process from regional assessment to intervention design. By synthesizing multidimensional provisioning service indicators, we quantitatively characterize the "invisible poverty" of ecosystem services (i.e., severe unmet needs in urbanized areas) and elucidate the spatial supply–demand balance (Peng and Jim, 2015; Wolch et al., 2014). Subsequently, after identifying coldspots (clusters of significantly low per-capita service supply), we assess deficits across service dimensions using a six-axis provisioning ecosystem service performance matrix (a radar-chart representation of six provisioning scores). These pathways emphasize data-driven decision making with explicit spatial analysis (Manso et al., 2021). By applying physical suitability criteria, we then identify target rooftops and propose corresponding intervention strategies tailored to each coldspot type. Theoretically, this study shifts ecosystem service assessment from aggregate quantification to a spatial equity perspective. Practically, it offers a quantifiable spatial intervention toolbox for densely urbanized cities. This research fills a key gap by linking regional-scale service supply–demand assessment with micro-scale green infrastructure interventions, providing methodological support for refined urban ecological planning.

2. Materials and methods

This study employs a systematic approach that progresses from assessment to identification and then intervention, gradually shifting focus from the regional scale to rooftop micro-spaces. This closed-loop framework aims to promote equitable ecosystem service allocation and cross-scale spatial optimization (Fig. 1).

2.1. Study area and data sources

2.1.1. Characteristics of the study area

This study selects the Zuid-Holland province (51.9°N, 4.5°E) in the Netherlands as the empirical study area (Fig. 2). This region (3308 km^2, 7.5 million population) has a three-tiered gradient: a dense urban core (Rotterdam–The Hague) with >5000 persons/km^2 and low green cover, a transitional belt of mixed towns (e.g., Delft, Leiden) with moderate density and green space, and a rural periphery ("Green Heart" and wetlands) supplying most of the province's food and biodiversity CBS (Statistics Netherlands), 2023; KNMI (Royal Netherlands Meteorological Institute), 2022. South Holland thus exemplifies contrasting service supply-demand patterns and is well-suited for our framework.

We also make explicit the boundary conditions under which the proposed framework is expected to perform as intended, so that its scope of application is not overstated. The approach is most informative in regions characterized by a pronounced spatial gradient in the supply–demand balance of provisioning services where per-capita deficits are spatially differentiated and local clustering of hotspots and coldspots is statistically detectable. In morphologically homogeneous cities with limited internal supply–demand contrast, the Getis–Ord G* step may identify few significant clusters, and the diagnostic value of the PSI is correspondingly reduced. Likewise, in data-scarce contexts, including many rapidly urbanizing cities in the Global South where authoritative high-resolution layers and 3D building data (here CBS, PDOK, BRO, and BAG 3D) are unavailable, both the resolution of the PSI and the reliability of the rooftop screening would decline. Application beyond the present setting therefore requires recalibration of the indicator set, classification thresholds, and rooftop screening criteria to local data

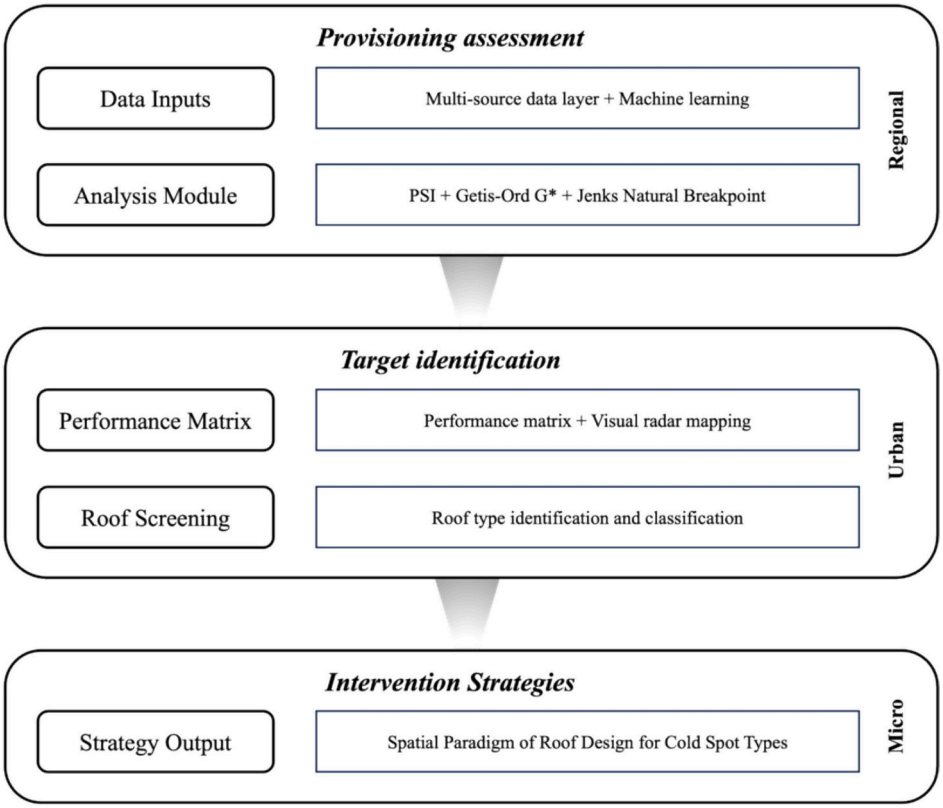


Fig. 1. Research workflow.

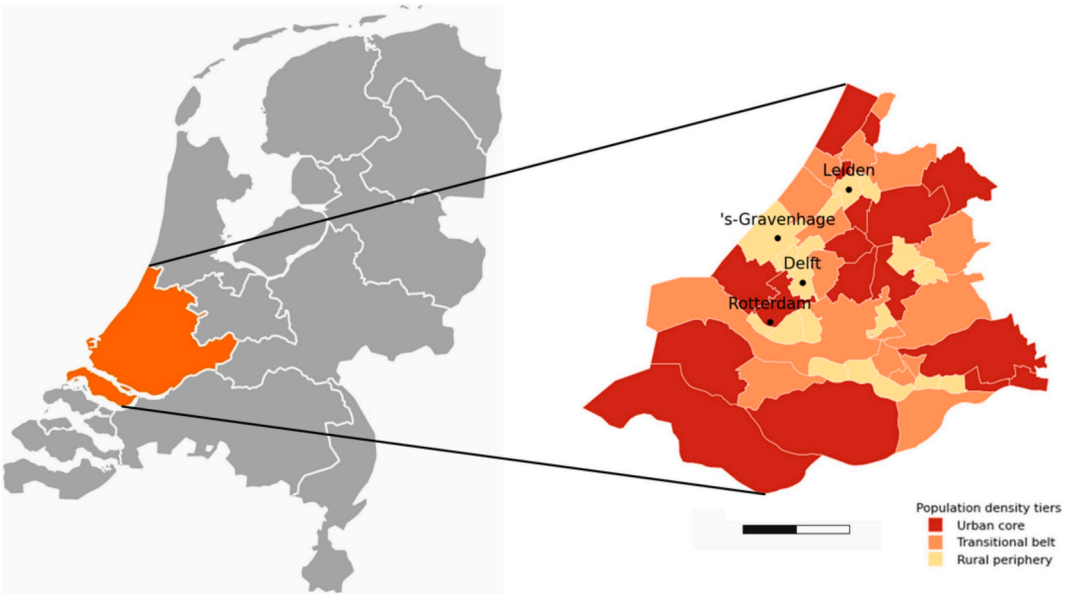


Fig. 2. Location of the study area and the three-tier urban–rural gradient in South Holland.

availability and built-form typologies. These boundary conditions are revisited in the discussion of research limitations and future directions.

2.1.2. Provisioning ecosystem services dimensions and data collection

This study expands the scope of provisioning ecosystem services into six major dimensions (see Table 1), all closely related to the functional attributes of green roofs. This classification not only encompasses the direct provision of material resources but also integrates supporting ecological processes (e.g., soil health) and regulating functions (e.g., temperature control), providing a more comprehensive characterization of urban provisioning service resilience (Peng and Jim, 2015). Specifically, these dimensions include food provision, water supply, energy supply, soil support and nutrient provisioning, habitat (biodiversity) support, and cooling services. Firstly, food provision represents one of the core material provisioning services supplied by agricultural production. Urban green roofs can contribute to enhancing local food self-sufficiency (Sanyé-Mengual et al., 2015). Secondly, water provisioning encompasses both supply and regulation. Green roofs retain and delay

Table 1
Indicator system for provisioning ecosystem services used in this study, including service dimensions, indicator data layers, sources, and directional correction for each indicator.

Data Category	Data Name	Data Source	Directional Correction
Food Provisioning	Food Crop Yield	CBS + PDOK	Positive (+)
	Commercial Crops	CBS + PDOK	Positive (+)
Water Provisioning	Groundwater Volume	PDOK	Positive (+)
	Surface Water Volume	PDOK	Positive (+)
	Annual Precipitation	KNMI	Positive (+)
Energy Provisioning	Solar Energy	CBS + PDOK	Positive (+)
	Wind Energy	ERA5 + PDOK	Positive (+)
Soil Support & Nutrient Supply	Land Subsidence Risk	PDOK	Negative (−)
	Soil Nutrients	BRO + PDOK	Positive (+)
Biodiversity Provisioning	Bee Distribution	PDOK	Positive (+)
	Habitat Distribution	PDOK	Positive (+)
Cooling Provisioning	Urban Heat Island Effect	PDOK	Negative (−)
Population Distribution	Population	CBS + PDOK	–
Building Attributes	Rooftop Information	BAG 3D	–

Higher values for indicators marked "Positive (+)" indicate greater provisioning of that service, whereas higher values for indicators marked "Negative (−)" indicate lower provisioning (i.e., greater ecosystem service deficit).

stormwater runoff, contributing to urban water recharge and mitigating peak runoff events (Vijayaraghavan, 2016). Thirdly, energy provisioning plays a vital role in urban sustainability. Green infrastructure can contribute clean energy through rooftop photovoltaic systems and wind energy installations (Chemisana and Lamnatou, 2014a). Fourthly, soil support and nutrient provisioning reflect the foundational services soils provide to ecosystems. In urban contexts, green roofs function as an extension of ground-level soil, facilitating organic matter cycling and nutrient replenishment (Dominati et al., 2010). Fifthly, habitat support refers to the capacity to provide refugia for biodiversity, a critical aspect for assessing provisioning service resilience. Green roofs offer novel habitats for plants and pollinators enhancing urban biodiversity (Madre et al., 2014; Williams et al., 2014). Finally, cooling services represent the ecosystem's role in regulating urban microclimate. Vegetation transpiration effectively lowers building surface temperatures that can alleviate urban heat island effects (Wang et al., 2022a, 2022b). Together, these six provisioning service indicators form the foundation for evaluating the spatial patterns of urban provisioning services in this study. For each dimension, we select data layers from regional/national sources. All spatial layers are resampled to a 100 m grid. Additionally, population and geographic data for the study region are obtained from official Dutch sources. For example, Statistics Netherlands (CBS) reports a total population of about 17.94 million on 1 January 2024, rising to approximately 18.04 million by 1 January 2025.

Auxiliary spatial data used in the analysis (not treated as provisioning ES indicators) include population distribution (CBS; PDOK) and building/rooftop attributes (BAG 3D).

2.2. Data standardization and calculation of the provisioning ecosystem services per capita index

We standardize all indicators to ensure comparability. First, variables with negative ecological implications are transformed to align with the overall positive directionality of ecosystem service evaluation:

$$Z_i'(p) = \max(X_i) - X_i(p)$$

where $Z_i'(p)$ is the standardized value, $X_i(p)$ is the original value, and $\max(X_i)$ is the maximum value of indicator i. This approach unifies all indicators into a positive polarity (larger values indicate better provisioning capacity) (Huang et al., 2015).

Secondly, Z-score standardization is applied to the indicator values that are uniformly positive:

$$Z_i(p) = \frac{X_i(p) - \mu_i}{\sigma_i}$$

Where μ_i and σ_i are the mean and standard deviation of indicator i, respectively. If σ_i is 0, then $Z_i(p)$ is 0. This supports the integration of heterogeneous data from multiple sources (Li and Wu, 2020).

For service dimensions containing multiple sub-indicators (e.g. water supply, biodiversity, etc.), the first principal component is extracted using Principal Component Analysis (PCA) and the weights are determined by their loading coefficients:

$$\omega_j = \frac{|a_j|}{\sum_{k=1}^{n} |a_k|}$$

where a_j is the absolute value of the loading coefficient of the first principal component corresponding to sub-indicator j. The weights of the sub-indicators can be determined objectively by this method (Jolliffe and Cadima, 2016).

The level of integrated provisioning ecosystem service is calculated for each raster cell after negative processing, Z-score normalization and PCA assignment:

$$Composite(p) = \sum_{j=1}^{n} w_j * Z_j(p)$$

The population density data is further combined to calculate the provisioning ecosystem services per capita index (PSI) for each cell:

$$PSI_i(p) = \frac{Composite(p)}{\max(Pop(p), 0.1)}$$

where $Pop(p)$ is the population density of raster cell p. Taking the lower limit of 0.1 in the denominator avoids division by zero and reduces the amplifying effect of very low population areas on PSI values (Su et al., 2020). Thus, PSI integrates ecological provision with human demand, explicitly incorporating social equity by weighting services per person. Additional socio-economic variables (e.g., income, green space access) could be incorporated into the denominator in future work to further refine equity considerations (Sanchez and Reames, 2019).

To clarify the incremental contribution of the Provisioning Service Index (PSI), it is helpful to contrast it with existing frameworks. The methodological novelty of the PSI does not stem from its individual statistical operations; techniques like PCA-derived weighting, Z-score standardization, and population normalization are already well-established. Instead, its innovation lies in how these operations are integrated into a spatially explicit, equity-oriented diagnostic framework.

Traditional composite indices typically aggregate values per unit area (e.g., service value per km^2) to describe absolute supply, while supply–demand ratios match service budgets at coarse administrative levels. The PSI departs from these approaches in three key ways. First, it couples a multidimensional provisioning composite with fine-grained population data at a 100 m grid scale, shifting the focus to strict per-capita equity. Second, it defines "ecosystem service poverty" based on the lowest PSI class, translating a continuous index into an actionable policy category. Finally, the framework is fully interoperable with downstream local spatial statistics and micro-scale rooftop screening. Consequently, the same index that diagnoses regional inequities can directly drive targeted local interventions. Ultimately, the true

contribution of the PSI is not any single computational step, but this cohesive, diagnosis-to-intervention workflow.

2.3. Diagnosis of spatial imbalances

To identify the spatial heterogeneity of provisioning ecosystem services in urban areas, we first apply Jenks natural breaks classification to the PSI distribution to delineate meaningful service levels. This method highlights intrinsic data structures by minimizing within-class variance (Jenks, 1967), resulting in four provisioning service zones: very high (value = 3), high (value = 2), low (value = 1), and very low (value = 0). This classification offers a quantitative basis for interpreting spatial service deficits and surpluses, supporting subsequent prioritization of interventions (Coulston and Riitters, 2021).

While Jenks natural breaks classification effectively optimizes within-class homogeneity, its breakpoints are data-dependent. They can vary across software implementations and are not always perfectly reproducible. To verify that our four-class structure was not a mere artifact of this method, we performed a sensitivity analysis using equal-interval and quantile classifications as benchmarks. The lowest class (the "ecosystem service poverty" zone) is of primary importance here, as it dictates all subsequent coldspot identification and local targeting. Therefore, we assessed robustness by measuring the spatial agreement of this specific class across all three schemes. This validation relied on the proportion of overlapping grid cells (intersection over union) and pixel-level Cohen's kappa.

We further employ the Getis-Ord G* local spatial autocorrelation method (Ord and Getis, 1995) to detect localized clusters of high and low PSI values. By constructing a distance-based spatial weight matrix, this approach identifies statistically significant hotspots and coldspots that reflect the interaction of population density, land cover, and ecological conditions. In dense urban cores with high populations and degraded ecosystems, service coldspots tend to cluster, indicating significant service deficits. Conversely, sparse and ecologically intact peripheral areas often exhibit service hotspots, representing high-value clusters.

2.4. Provisioning ecosystem service performance matrix and radar mapping construction

After identifying significant coldspot areas from the PSI, we evaluate the performance of these service-deficient regions across each ecosystem service dimension to guide targeted intervention classification. To achieve this, we develop a provisioning ecosystem service performance matrix and visualize it using radar charts. To ensure matrix stability and comparability, we apply a three-step processing approach: standardization, outlier clipping, and normalization mapping.

$$z_{ik} = \frac{x_{ik} - \mu_k}{\sigma_k}$$

$$z'_{ik} = \min(2, \max(-2, z_{ik}))$$

$s_{ik} = \frac{z'_{ik}+2}{4}$, $s_{ik} \in [0,1]$.where x_{ik}denotes the raw mean value of the i cold spot cluster on the supply ecological service indicator k, and μ_k and σ_k are the mean and standard deviation of this service dimension among all cold spot clusters, respectively. Then, considering the possible existence of outliers with extreme deviations from the mean, we crop all z_{ik} into the interval [−2,2] to suppress the excessive influence of individual outliers. Finally, the cropped z'_{ik} values are uniformly mapped to the interval [0,1] to form a uniform ecological service performance score s_{ik}.

Instead of the conventional ±3 criterion, which encloses approximately 99.7% of a normal distribution, we adopted a ±2 standard-deviation truncation threshold. This decision was driven by the small-sample nature of our radar matrix. Because the matrix is computed across only seven coldspot clusters, a ±3 bound would rarely be reached in practice. Consequently, it would fail to protect the [0, 1] rescaling from the disproportionate influence of a single extreme outlier.

In contrast, a ±2 bound retains roughly 95% of values under a normal assumption while effectively tempering such extremes. This constraint preserves the comparative legibility of the radar profiles, whose purpose is to contrast relative deficits rather than map absolute distributional tails. Crucially, this clipping operation is monotonic. It preserves the ordinal ranking of all clusters within the interval, compressing only the scores beyond ±2. Indeed, out of the 42 cluster–dimension combinations (seven clusters × six service dimensions), only 3 cases exceeded ±2, and the largest observed value was $|z| = 2.29$, just below the theoretical ceiling of $\sqrt{6} \approx 2.45$. In no instance did this truncation alter a coldspot's assignment to its functional deficit type. Thus, the threshold shapes only the visual scaling of the radar charts, leaving the substantive typology intact.

Following the processing steps, each coldspot area obtains a relative performance score matrix across six categories of ecosystem services. These score matrices are visualized as hexagonal radar charts to intuitively present the provisioning structure and shortcomings of each coldspot region.

2.5. Roof identification and screening

To accurately identify target rooftop spaces within coldspot areas, this study designs an automated screening workflow based on spatial attribute constraints. This method integrates the official Dutch three-dimensional building database (BAG 3D) with geospatial analysis tools (Geopandas and Rasterio) and applies rigorous selection criteria tailored to rooftop urban agriculture. We refer to several Dutch and international standards for rooftop urban agriculture to select roofs. Roofs with slopes less than 15° are considered suitable for mixed green infrastructure on commercial and residential buildings (Dutch Standards Institute, 2018; Van der Hoeven et al., 2020). Previous studies indicate that rooftops ranging from 100 to 500 m^2 optimize energy output, support commercial urban agriculture, and form pollinator migration corridors (Chemisana and Lamnatou, 2014b; Orsini et al., 2014; Madre et al., 2014). Buildings under 30 m in height are suitable for large-scale green roofs (Aboelata, 2021). For orientation, south-facing roofs (135°–225°) exhibit higher solar potential, while west-facing roofs require reinforcement to mitigate high wind speeds KNMI (Royal Netherlands Meteorological Institute), 2022; Dutch Wind Energy Association (NWEA), 2021. Regarding materials, concrete flat roofs offer the best static load capacity and dynamic tolerance (NEN 6702, 2018).

Then, Python automation scripts are utilized to sequentially screen candidate rooftops. Compared to Roofpedia, which employs deep learning models such as convolutional neural networks (CNN) for multi-class rooftop classification (e.g., green roofs and solar roofs) (Tan et al., 2021a, 2021b), this study specifically targets provisioning ecosystem service with an emphasis on urban agriculture. Urban agriculture rooftops demand precise and explicit criteria on attributes like area, slope, and orientation. Thus, machine learning classification results may lack necessary transparency and accuracy. Consequently, this study adopts a spatial attribute threshold method supported by explicit literature, ensuring precise rooftop identification, interpretability, and operational feasibility for practical interventions.

We evaluated the reliability of the automated screening using two complementary approaches. First, we tested screening selectivity as an internal baseline. Out of 29,148 candidate buildings intersecting the coldspot areas, only 121 (0.4%) satisfied all four primary criteria simultaneously (slope$< 15^{\circ}$, footprint 100–500 m^2, height $< 30\ m$, and south-facing orientation 135–225°). This stringent cumulative filtering eliminated 99.6% of candidates. By eliminating 99.6% of candidates, the procedure keeps the risk of false positives (Type I, or commission, errors) low. These results show that the screening protocol is discriminating rather than permissive. Second, we conducted a threshold

sensitivity analysis by applying a more conservative parameter set to the same pool (slope $< 10^{\circ}$, footprint 150–400 m^2, height $< 25\,m$, and orientation 150–210°). Among the 121 previously selected rooftops, 30 survived these tighter thresholds, yielding a 24.8% intersection over union (IoU). This indicates that while a quarter of the identified pool represents a high-confidence core, the remaining three-quarters operate within the flexible margins of the primary thresholds.

Despite these validation steps, certain residual limitations warrant acknowledgement. First, because the BAG 3D model generalizes roof geometry, derived slopes and footprints may deviate from actual as-built conditions, particularly for complex or stepped surfaces. Second, temporal mismatches can occur between the building database and real-time conditions due to recent retrofits or demolitions. Finally, our framework relies strictly on spatial and morphological attributes; it cannot capture structural load-bearing capacity, which ultimately dictates whether a roof can support a greening intervention. Consequently, these results function as a strategic macro-prioritization for planning-level targeting. They do not offer a parcel-level guarantee, and site-specific engineering and ownership audits remain essential before implementation. Following this methodology, we next present the key results of the spatial service assessment and rooftop intervention analysis.

3. Results

3.1. Spatial patterns of PSI for provisioning ecosystem services

The calculated PSI map shows clear spatial imbalance (Fig. 3). Urbanized areas, particularly Rotterdam and The Hague, show low PSI values. Some zones fall below −0.5 that indicates a marked decline in ecological resource availability amid high population density. These regions experience extensive land sealing, severe reduction of agricultural lands and natural ecological patches, and a sustained degradation of provisioning ecosystem service capacity. In contrast, agricultural zones and wetland conservation areas display relatively high PSI values, reaching up to 1.57 serving as dominant providers of ecosystem services. These areas possess intact ecological foundations and lower population burdens. Additionally, certain low-density residential zones in the northern province show moderate to high PSI levels suggesting the existence of ecological service buffers in urban peripheries.

Overall, the spatial distribution of PSI reveals significant gradient differentiation by the spatial mismatch between population distribution and ecosystem provisioning configuration. High PSI regions are predominantly located in ecologically intact and less developed peripheral zones, whereas low PSI areas coincide with high-intensity urban land use and extensive underground development. These patterns underscore the challenges urbanization poses to equitable ecosystem service provision. This approach diagnoses service 'coldspots' and categorizes them into functional types and immediately translates each type into targeted greening strategies.

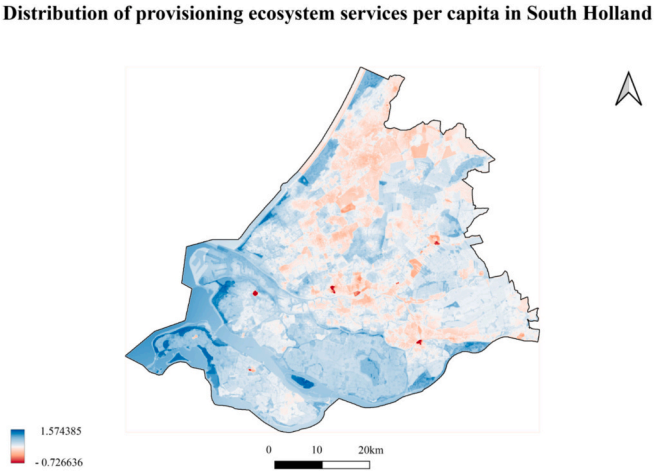


Fig. 3. Spatial distribution of the PSI in South Holland.

3.2. Spatial inequality and hotspot–coldspot identification of provisioning ecosystem services at the regional scale

To classify the provisioning service capacity levels across the region, we apply the Jenks natural breaks classification method to spatially grade PSI values (Fig. 4a). The results delineate four distinct service zones: very low-level areas are predominantly concentrated in urban built-up cores, forming large contiguous patches that align closely with previously identified coldspots. In contrast, very high-level zones are primarily located in ecological conservation areas and low-density agricultural lands, illustrating a typical "peripheral surplus" pattern in provisioning services. Intermediate-level zones largely cover satellite towns and urban–rural transition belts, where service supply and demand remain relatively balanced yet susceptible to gradient fluctuations.

Our sensitivity analysis confirms that the delineation of the lowest PSI class is robust across data-adaptive classification schemes. The "ecosystem service poverty" zone identified by the Jenks method overlapped with the quantile-derived class by 80.4% (intersection over union), achieving a pixel-level Cohen's kappa of 0.860. This confirms

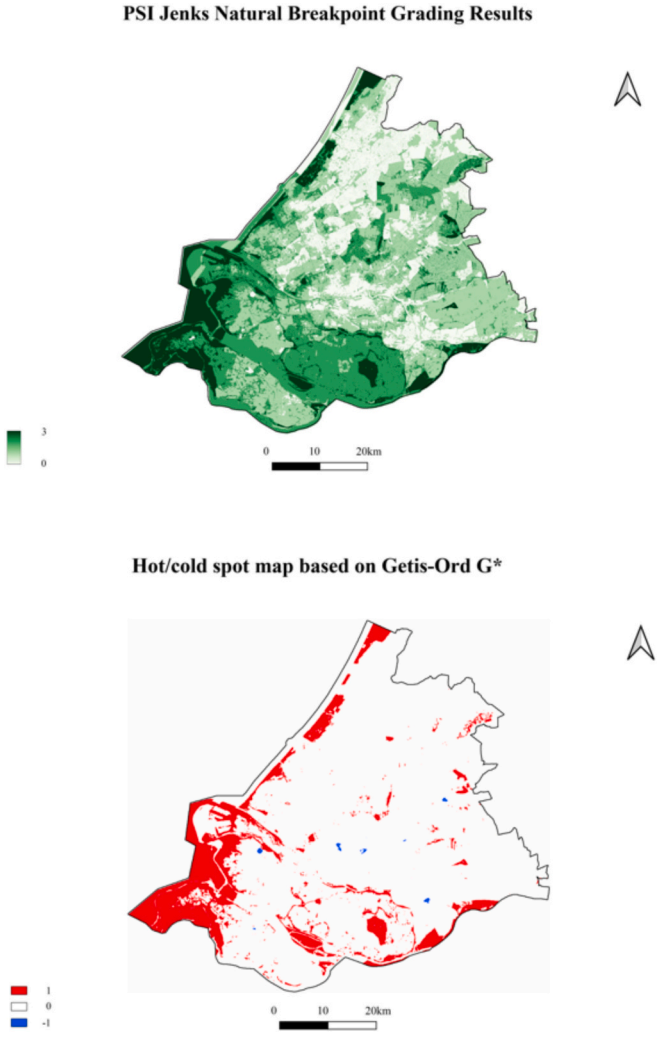


Fig. 4. Spatial inequality analysis of PSI using Jenks natural breaks (a) and Getis-Ord G* (b).

strong agreement between the two distribution-sensitive methods.

Conversely, the near-zero overlap between the Jenks and equal-interval schemes (IoU = 0.1%, k = 0.001) is informative rather than problematic. This sharp divergence reflects the strongly right-skewed PSI distribution of South Holland. While all Jenks and quantile breakpoints naturally fall within the positive range of [0.33, 1.61], the rigid equal-interval scheme assigns its lowest tier to the interval [−2.11, −0.87]. Crucially, this negative range is virtually empty in our observed dataset. Rather than undermining our framework, this divergence highlights why standard equal-interval partitioning is inappropriate for skewed environmental data, further justifying our choice of Jenks natural breaks. Consequently, the stable spatial footprint of urban-core coldspots across both data-adaptive methods proves that downstream target areas are structurally real and not an artifact of the algorithm. Detailed maps and agreement matrices are available in Supplementary Table S1 and Fig. S1.

Building on this classified framework, we further employed the Getis-Ord G* method to detect statistically significant spatial clustering in per capita provisioning ecosystem services (Fig. 4b). The analysis reveals a continuous band of significant coldspot clusters concentrated in the urban core, particularly along the Rotterdam–The Hague corridor and its densely built-up surroundings. These areas not only exhibit low PSI values but also lack high-value buffers at the neighborhood scale. Conversely, significant hotspots are distributed across the ecological periphery and agriculturally intensive southern regions, indicating strong local clustering of high values and pronounced positive spatial spillover effects in ecosystem service provision.

3.3. Intervention typology of coldspot areas guided by deficiencies in provisioning ecosystem services

Building upon the identification of regional coldspots, this study constructs a six-dimensional ecosystem service performance scoring matrix to elucidate the structural deficiencies of provisioning services. The matrix encompasses key indicators including food provision, water supply, energy supply, soil support and nutrient provisioning, habitat support, and cooling capacity (Fig. 5). This framework not only captures the overall provisioning capacity but also reveals structural disparities across specific service dimensions.

We calculate the standardized scoring and conduct radar chart analysis of seven representative coldspot regions (Fig. 6). We identify significant heterogeneity in ecosystem service performance, which further clustered into several distinct functional types. The first category is termed as environmental regulation-weakened type (areas a, e, and f). It exhibits systemic weakness in habitat connectivity, soil support, and temperature regulation with area f showing the lowest levels across all three indicators. The second category is named basic resource-constrained type (area b). This is characterized by pronounced deficits in water and soil provisioning, reflecting limitations in fundamental ecological material flows. The third category is multifunctionally deficient type (area d). It displays consistently low provisioning across most service indicators except for soil and temperature support, indicating a

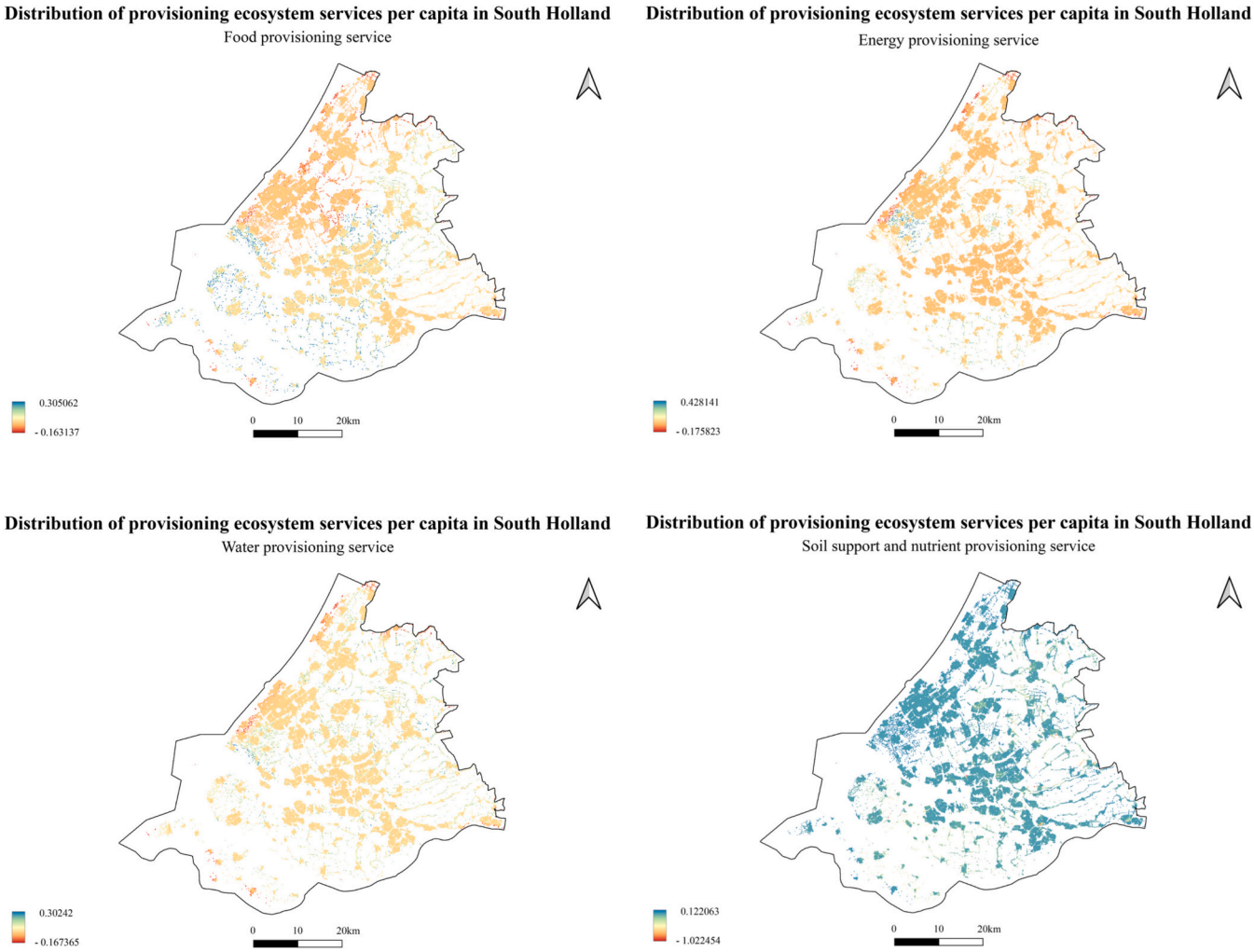


Fig. 5. Component-wise PSI distribution across six ecosystem service dimensions.

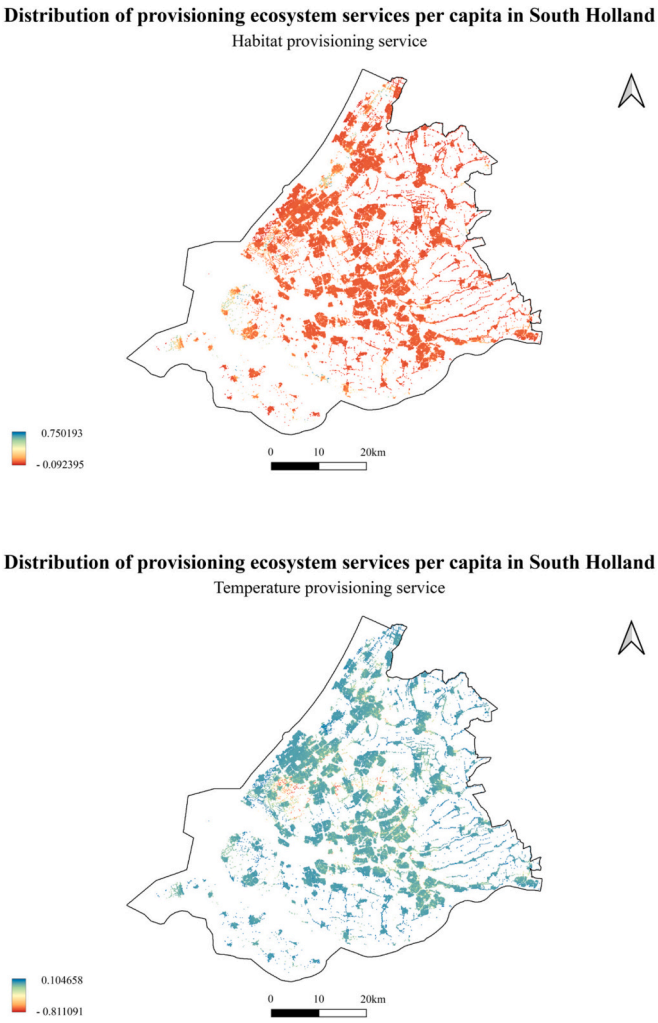


Fig. 5. (*continued*).

generalized ecosystem service disadvantage. Additionally, two marginal coldspot types are observed. Area c is classified as relatively balanced with minor provisioning gaps which shows generally even performance except for slight shortfalls in food and energy provision. Area g is identified as food-specific deficient type. It is marked by a singular and prominent deficit in food provision. This functional classification explicitly links service dimension performance with targeted intervention strategies. Together, it offers a theoretical basis and practical reference for differentiated urban greening planning and precise utilization of rooftop spaces.

3.4. Rooftop identification and screening results: Spatial response mechanisms of functional deficits

After identifying the types of ecosystem service deficits in coldspot regions, this study conducts rooftop identification and screening to enable precise intervention design. Target rooftops with greening potential differ markedly in spatial structure from one coldspot area to the next (Fig. 7). This pattern closely matches the corresponding service-deficit types.

Table 2 systematically summarizes the building morphology and rooftop resource conditions for five types of ecosystem service coldspot regions and proposes differentiated intervention strategies accordingly. Environmental function weakening areas are suitable for deploying transpiration vegetation and ecological habitat modules to achieve microclimate regulation and habitat restoration. Basic resource-limited zones emphasize rainwater harvesting and energy efficiency improvements to compensate for resource shortfalls. Multi-dimensional function-deficient areas are appropriate for combined green infrastructure experiments. Marginal coldspots are better suited for participatory and low-threshold green roof designs. Together, these links form a service-to-space-to-intervention pathway. A service deficit points to a spatial cluster, and that cluster points to the rooftops best able to address it. An ecological diagnosis thus becomes a concrete spatial target. The same logic also shifts green-infrastructure planning away from simply adding more green space and toward placing each intervention where its function is most needed.

4. Discussion

4.1. Paradigm innovation focused on regional provisioning ecosystem service spatial inequality and urban microscale regulation

In summary, this study reveals pronounced core–periphery disparities in provisioning ecosystem services and identifies targeted rooftop interventions for deficit areas. Theoretically, this research reconstructs and interlinks two core concepts. Firstly, it redefines ecosystem service poverty from a macroscopic supply deficit to a spatial structural inequality. Secondly, it conceptualizes coldspots as dynamic targets characterized by functional deficiencies, distributional imbalance mechanisms, and spatial priorities. Notably, ecosystem service deficit areas do not necessarily coincide with green space scarcity zones but

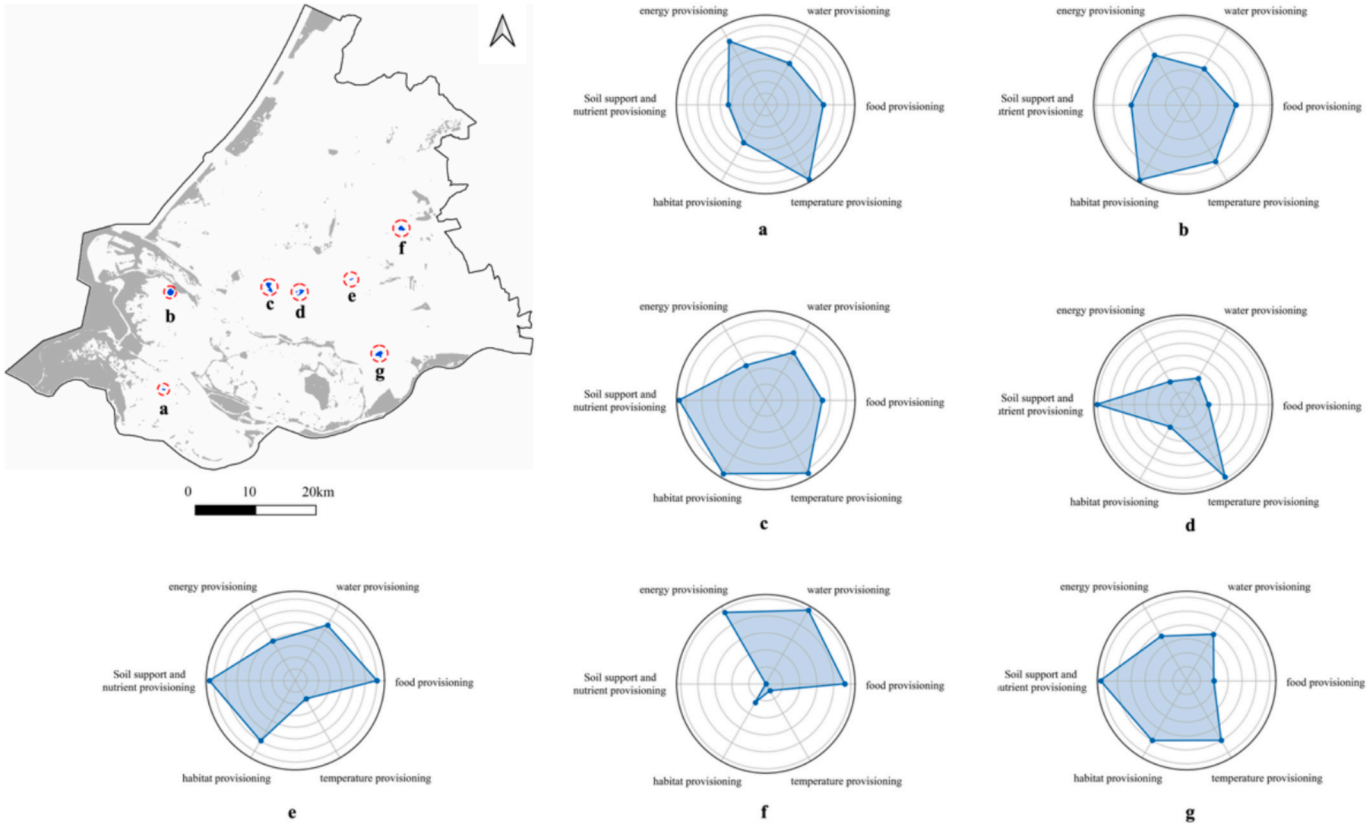


Fig. 6. Ecological service performance profiles of seven coldspot clusters.

rather reflect an asymmetry between actual population burden and spatial service allocation. This asymmetry provides a theoretical basis for understanding why certain urban areas may exhibit inadequate ecosystem services despite high green coverage. This phenomenon shifts urban spatial interventions from "how much green" to "who uses the green" and "why green is used" (Meerow and Newell, 2019).

Methodologically, this study analyzes the role of green roofs in mitigating the lack of service functions in high-density urban core areas, which reflects their positive impact through their ubiquity and functional adaptability. High-density urban cores predominantly function as coldspot areas of ecosystem services and exhibit pronounced geographic disparities (Kabisch et al., 2016). These findings resonate with contemporary discourse emphasizing accessibility, distribution, and fairness of ecosystem services (Schwarz et al., 2021). The study also demonstrates that green roofs are critical leverage points for reducing provisioning-service deficits in urban cores. This theoretical perspective effectively addresses the limitations of focusing on aggregate ecosystem service quantification while overlooking the integration of spatial structure and microscale interventions. We believe this study can facilitate a paradigm shift from macroscopic supply analysis toward cross-scale spatial regulation.

4.2. Constructing a ternary coupling mechanism of service–space–intervention identification

To address the critical bottleneck in urban ecosystem service assessment from diagnostic outcomes into actionable intervention strategies, this study proposes an integrated ternary framework that couples service function identification, spatial structure analysis, and intervention suitability screening. In the first phase, we develop the PSI that spatially couples regional provisioning ecosystem services capacity with population density to identify structural mismatches in ecological resource allocation. By integrating equity considerations with spatial explicitness, the PSI provides an objective basis for prioritizing interventions.

Spatial heterogeneity and clustering of ecosystem services are analyzed using Getis-Ord Gi* local spatial autocorrelation alongside Jenks natural breaks classification. This combined approach enhances statistical robustness with hierarchical stratification and offers a structurally transparent logic for spatial intervention planning (Kroll et al., 2012). For targeted intervention, rooftop resources are identified via a spatial attribute threshold method. Compared to more complex techniques such as deep learning or semantic segmentation, this method ensures greater transparency, controllability, and policy relevance particularly suitable for optimizing green infrastructure in medium-density built environments (Zhang et al., 2020).

Furthermore, based on six key ecosystem service indicators, radar charts are constructed to classify typical coldspots regions into functional types. This service-structure typology operationalizes the concept of ecosystem service bundles at the micro-scale to shift green infrastructure design from generalized aggregation to functionally targeted intervention (Raudsepp-Hearne et al., 2010). Overall, the ternary framework developed here overcomes fragmentation in spatial identification and generic targeting in ecosystem service governance. This study offers a cross-scalar, replicable, and locally adaptable pathway for ecological renewal in urban microsites (Syrbe and Walz, 2012).

4.3. A spatial transformation pathway from ecological diagnosis to implementable interventions

The core practical contribution of this study lies in proposing and validating an integrated pathway that links spatial diagnosis of ecosystem services with targeted rooftop intervention design. While previous research has focused primarily on evaluating isolated benefits of green roofs (Berardi, 2016), a systematic spatial diagnostic logic often leaves a gap between problem identification and precise intervention.

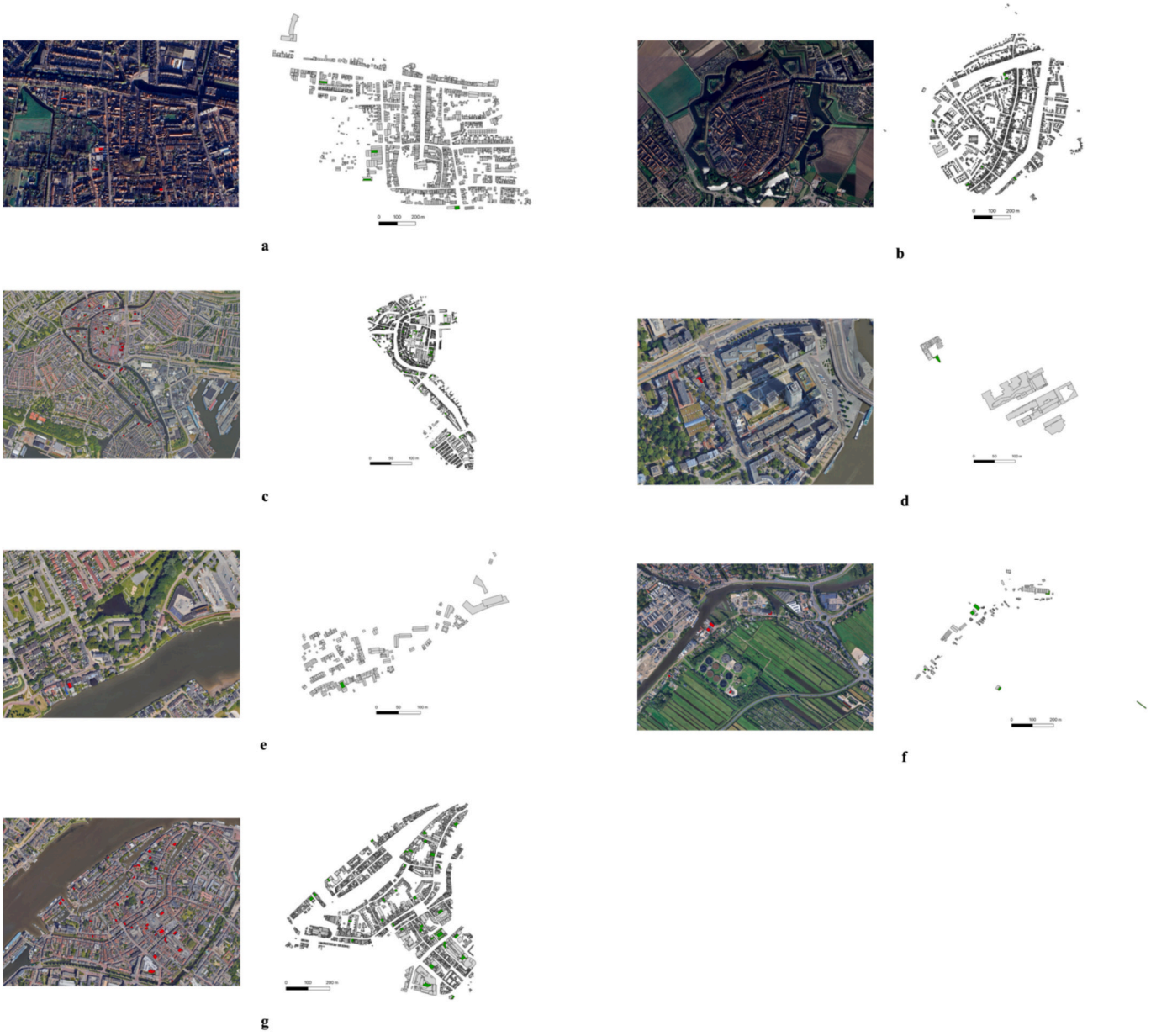


Fig. 7. Rooftop suitability analysis and morphological context of PSI coldspot regions.

By integrating the PSI spatial distribution, coldspot service profiles, and rooftop morphology patterns, we develop five tailored rooftop greening strategies aligning with a specific coldspot typology to address distinct functional gaps and leverage locally available rooftop resources. This approach ensures functional specificity and spatial adaptability while enhancing the reliability and logical coherence of the results (Fig. 8). The five proposed intervention types are structured as follows:

Type 1: Weakened environmental functions type focuses on deploying vegetation with high evapotranspiration rates to enhance microclimate regulation and biodiversity in dense urban cores. A representative example is the DakAkker rooftop farm in Rotterdam, which integrates urban agriculture and pollinator habitats to improve local microclimate and ecological connectivity (Sustainable Urban Delta, 2026). This approach aligns with the role of vegetated rooftops in mitigating urban overheating and promoting biodiversity (Santamouris et al., 2020).

Type 2: Constrained basic resources type emphasizes the integration of rainwater harvesting and energy-efficient systems to mitigate critical deficits such as water scarcity and energy limitations. Singapore's Marina Barrage exemplifies this model and incorporates green roofs with comprehensive stormwater and energy management (Urban Land Institute, 2016). This echoes earlier findings on the multifunctionality of green roofs for water retention and energy efficiency (Vijayaraghavan, 2016).

Type 3: Multi-dimensional function missing type integrates diverse ecological components such as edible landscaping, renewable energy generation, and biodiversity corridors, which are suitable for holistic ecological improvements on large institutional and commercial rooftops. The Brooklyn Grange farm in New York City demonstrates this multifunctional approach to combine food production, stormwater management, biodiversity enhancement, and heat mitigation (Bon Appétit, 2016). These functions are in line with studies on rooftop agriculture's ecological and provisioning potential (Orsini et al., 2014).

Type 4: Marginal I type adopts participatory greening interventions specifically designed for densely populated neighborhoods with limited rooftop availability. Berlin's Prinzessinnengarten illustrates how participatory greening can support both ecosystem services and community inclusion (Urban Green-Blue Grids, 2026). The effectiveness of

Table 2
Typological classification of cold spot areas based on ecosystem service performance.

Type	Representative Area(s)	Ecosystem Service Performance Characteristics	Building and Rooftop Resource Characteristics
Environmental Function Weakening	Areas a, e, f	Systematic deficiencies in regulating services including habitat connectivity, soil support, and temperature regulation; particularly severe in area f.	Predominantly low-rise, densely packed residential buildings with small roof spacing and uniform orientation, forming localized ecological cold islands and green connectivity networks.
Basic Resource Limitation	Area b	Significant deficits in water and soil provisioning, limiting the allocation of basic ecological materials.	Complex and diverse building typologies, including older residences and commercial facilities; rooftops are scattered but collectively substantial.
Multi-dimensional Functional Deficiency	Area d	Generally low provisioning across all service indicators except soil and temperature, indicating widespread ecosystem service disadvantages.	Sparse rooftop distribution with larger individual roof sizes and stable structural integrity.
Marginal Coldspot Type I	Area c	Overall balanced ecosystem services but slight deficits in food and energy provisioning.	Predominantly small- to medium-sized residential rooftops with high community accessibility.
Marginal Coldspot Type II	Area g	Primarily characterized by a singular shortfall in food provisioning.	Small- to medium-sized residential rooftops with low technological thresholds.

such participatory models is supported by research on community gardening as a route to urban green-space production and social inclusion (Rosol, 2012).

Type 5: Marginal II type involves community-operated rooftop agricultural modules, emphasizing edible plants and localized food production ideal for small residential areas. Copenhagen's ØsterGRO project illustrates this model by successfully creating a community-supported rooftop farm and providing local organic produce and serving as an educational and communal resource (Danish Architecture Center, 2026). This model echoes findings on the role of rooftop gardens in sustainable urban food systems (Sanyé-Mengual et al., 2015).

These patterns provide explicit functional and spatial guidance to enable context-sensitive implementation that avoids one-size-fits-all solutions and improves the efficiency of green infrastructure under resource constraints (Zölch et al., 2016). This spatial prioritization mechanism is critically important for supporting practical urban ecological restoration in terms of fiscal budgeting, spatial coordination, and policy implementation, particularly applicable to existing building renovations and ecological upgrades in historic urban areas (Langemeyer et al., 2020b).

Furthermore, the proposed interventions incorporate participatory and modular design principles, emphasizing an "ecological–social" coupling approach. For areas with relatively complete service structures but localized deficits (e.g., food or temperature), community-based greening or edible landscape modules are prioritized which not only enhance ecosystem functions but also promote public acceptance and sustained stewardship. This dual consideration of ecological efficacy and social embedding has been shown to significantly improve the long-term stability and policy acceptance of green infrastructure (Frantzeskaki et al., 2019). In short, the design-pattern system works on two levels. It is a practical toolkit for spatial design and policy, and it is a template for deploying green roofs in a way that is both standardized and locally adapted.

4.4. Research limitations and future directions

While this study establishes a ternary framework, several aspects of the methodology present opportunities for refinement in future research. First, the current indicator system focuses primarily on provisioning services due to their direct relevance to green roof functions, yet it does not incorporate supporting, regulating or cultural services. This limits a holistic understanding of ecosystem benefits. Future studies should integrate indicators from these underrepresented dimensions to

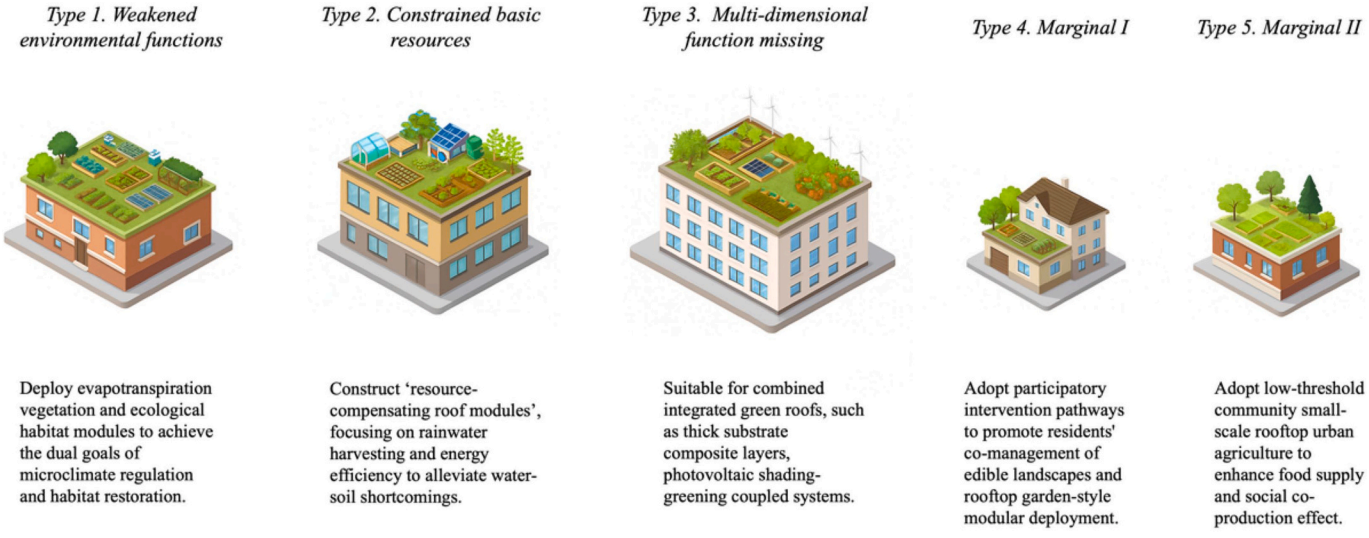


Fig. 8. Green roof design paradigm based on supplying ecosystem service cold spot areas (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

support more multidimensional ecological intervention logic (Chan et al., 2012). Second, although the analysis benefits from high-resolution spatial data, the transferability of the approach remains constrained in data-scarce contexts such as developing regions. Supplementing model inputs with street-level imagery and crowdsourced geographic data could improve universality and support cross-city application (Neset et al., 2016). Third, while physical criteria underpin the current assessment of intervention feasibility, key socioeconomic drivers are not systematically incorporated, despite their critical influence in real-world implementation (Kabisch and Haase, 2014). Future work should develop a composite "ecological–social" feasibility framework to better align intervention planning with institutional and societal contexts. Finally, the present methodology is static in nature and does not account for temporal dynamics in ecosystem services or post-intervention ecological trajectories. Integrating system dynamics modeling or multi-scenario simulation in future research could help assess nonlinear benefits over time and support more adaptive, forward-looking spatial planning of green infrastructure (Baró et al., 2016).

5. Conclusion

This study confronts the challenge of spatial imbalance in provisioning ecosystem services by developing a comprehensive, cross-scale analytical framework. By integrating ecosystem service assessment, spatial clustering diagnosis, functional deficit analysis, and intervention matching, we create a closed-loop process that starts with identifying problems and ends with proposing solutions. Applying this framework in South Holland province demonstrates its utility. We introduce the Per Capita Services Index to map provisioning service supply relative to population, revealing clear patterns of "have" and "have-not" areas. Using local spatial statistics and classification, we systematically identify clusters of service-deficient neighborhoods (coldspots) and discern different types of deficits within those areas. Urban core areas are shown to suffer compounded shortages (simultaneous lack of food, water, and climate regulation services under high population pressure), whereas certain fringe areas have more specific limitations. Based on these findings, we propose a typology of coldspot areas to distinguish five functional deficit types and provide a targeted model for ecological restoration interventions.

Furthermore, by combining three-dimensional building data with feasibility criteria, we establish a rooftop identification and screening mechanism to connect each deficit area with tangible greening opportunities. This ensures that our analysis does not remain abstract, but directly informs where and how to act. Coupling the coldspot typologies with on-site physical characteristics, we formulate five intervention paradigms. For instance, environmental function weakening areas are addressed with transpiring vegetation and habitat modules, while basic resource limitation areas receive rainwater harvesting and energy-efficiency roofs. This explicit matching of intervention to deficit represents a novel operational approach and closes the gap between ecosystem service assessment and urban design implementation. In essence, the research provides a blueprint for how cities can go from recognizing where ecosystem service poverty exists to executing what greening measures are needed as a linkage.

CRediT authorship contribution statement

Yu Huan: Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Steffen Nijhuis:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Nico Tillie:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Yu Huan reports financial support was provided by CSC. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.115151.

Data availability

Data will be made available on request.

References

Aboelata, A., 2021. Assessment of green roof benefits on buildings' energy-saving by cooling outdoor spaces in different urban densities in arid cities. Energy 219, 119514.

Baró, F., Gómez-Baggethun, E., Haase, D., Frantzeskaki, N., 2016. Mismatches between ecosystem services supply and demand in urban areas: a quantitative assessment in five European cities. Ecol. Indic. 63, 146–158. https://doi.org/10.1016/j.ecolind.2015.11.057.

Berardi, U., 2016. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. Energ. Buildings 121, 217–229. https://doi.org/10.1016/j.enbuild.2016.03.021.

Bon Appétit, 2016. The Work of a Farmer: Making New York City Greener. August 4, Retrieved from. https://www.bonappetit.com/people/article/work-farmer-making-new-york-city-greener.

CBS (Statistics Netherlands), 2023. Population statistics – spatial data. Statistics Netherlands. https://www.cbs.nl/en-gb/figures/detail/37296eng. Retrieved from.

Chan, K.M.A., Satterfield, T., Goldstein, J., 2012. Rethinking ecosystem services to better address and navigate cultural values. Ecol. Econ. 74, 8–18. https://doi.org/10.1016/j.ecolecon.2011.11.011.

Chemisana, D., Lamnatou, C., 2014a. Photovoltaic-green roofs: an experimental evaluation of system performance. Appl. Energy 119, 246–256.

Chemisana, D., Lamnatou, C., 2014b. Photovoltaic-green roofs: a life cycle assessment approach with emphasis on warm months of Mediterranean climate. Energy Convers. Manag. 88, 63–71.

Coulston, J.W., Riitters, K.H., 2021. A global comparison of methods for classifying ecosystem service spatial patterns. Landsc. Ecol. 36 (4), 1123–1143.

Danish Architecture Center, 2026. ØsterGRO: Rooftop Farm Above the Concrete. Retrieved from. https://dac.dk/en/knowledgebase/architecture/oestergro-rooftop-farm-above-the-concrete/.

Davis, K., 2015. The urbanization of the human population. In: The City Reader. Routledge, pp. 43–53.

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol. Econ. 69 (9), 1858–1868.

Droz, A.G., Coffman, R.R., Fulton, T.G., Blackwood, C.B., 2021. Moving beyond habitat analogs: optimizing green roofs for a balance of ecosystem services. Ecol. Eng. 173, 106422.

Du Toit, M.J., Cilliers, S.S., Dallimer, M., Goddard, M., Guenat, S., Cornelius, S.F., 2018. Urban green infrastructure and ecosystem services in sub-Saharan Africa. Landsc. Urban Plan. 180, 249–261.

Dutch Standards Institute, 2018. NEN 6702: Technical requirements for building structures (NEN 6702).

Dutch Wind Energy Association (NWEA), 2021. Wind energy in the Netherlands: Annual overview 2021. NWEA. https://nedzero.nl/en. Retrieved from.

Evans, D.L., Falagán, N., Hardman, C.A., Kourmpetli, S., Liu, L., Mead, B.R., Davies, J.A. C., 2022. Ecosystem service delivery by urban agriculture and green infrastructure – a systematic review. Ecosyst. Serv. 54, 101405.

Feng, H., Squires, V.R., Wu, J., 2021. Ecosystem services provisioning, urban growth and the rural–urban interface: a case study from China. Land 10 (4), 337.

Francis, L.F.M., Jensen, M.B., 2017. Benefits of green roofs: a systematic review of the evidence for three ecosystem services. Urban For. Urban Green. 28, 167–176.

Frantzeskaki, N., van Steenbergen, F., Stedman, R.C., 2019. Urban resilience: a framework for empowering cities in face of environmental challenges. Cities 92, 176–185. https://doi.org/10.1016/j.cities.2019.04.009.

Frisk, C.A., Hanslin, H.M., 2025. Optimizing plant species composition of green roofs for ecological functionality and biodiversity conservation. Urban Ecosyst. 28 (2), 12.

Fu, B., Zhang, L., Xu, Z., Zhao, Y., Wei, Y., Skinner, D., 2015. Ecosystem services in changing land use. J. Soils Sediments 15, 833–843.

Groffman, P.M., Cavender-Bares, J., Bettez, N.D., Grove, J.M., Hall, S.J., Heffernan, J.B., Steele, M.K., 2014. Ecological homogenization of urban USA. Front. Ecol. Environ. 12 (1), 74–81.

Haase, D., Haase, A., Rink, D., 2014. Conceptualizing the nexus between urban shrinkage and ecosystem services. Landsc. Urban Plan. 132, 159–169.
Huang, J., Lu, X.X., Sellers, J.M., 2015. A global comparative analysis of urban form metrics for assessing sustainability goals. Environ. Res. Lett. 10 (2), 024002.
Jenks, G.F., 1967. The data model concept in statistical mapping. In: International Yearbook of Cartography, 7, pp. 186–190.
Johnson, M.T., Munshi-South, J., 2017. Evolution of life in urban environments. Science 358 (6363), eaam8327.
Jolliffe, I.T., Cadima, J., 2016. Principal component analysis: a review and recent developments. Phil. Trans. R. Soc. A 374 (2065), 20150202.
Kabisch, N., Haase, D., 2014. Green justice or just green? Provision of urban green spaces in Berlin, Germany. Landsc. Urban Plan. 122, 129–139.
Kabisch, N., Qureshi, S., Haase, D., 2016. Human–environment interactions in urban green spaces—a systematic review of contemporary issues and prospects for future research. Environ. Impact Assess. Rev. 50, 25–34.
KNMI (Royal Netherlands Meteorological Institute), 2022. Climate data Netherlands. KNMI Data Platform. https://english.knmidata.nl. Retrieved from.
Kroll, F., Müller, F., Haase, D., Fohrer, N., 2012. Rural–urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29 (3), 521–535.
Langemeyer, J., Baró, F., Roebeling, P., Gómez-Baggethun, E., 2020a. Contrasting values of cultural ecosystem services in urban areas: the case of park users in Barcelona, Spain. Ecosyst. Serv. 43, 101091. https://doi.org/10.1016/j.ecoser.2020.101091.
Langemeyer, J., Wedgwood, D., McPhearson, T., Baró, F., Madsen, A.L., Barton, D.N., 2020b. Creating urban green infrastructure where it is needed: a spatial ecosystem service–based decision analysis of green roofs in Barcelona. Sci. Total Environ. 707, 135487.
Lautenbach, S., Kugel, C., Lausch, A., Seppelt, R., 2011. Analysis of historic changes in regional ecosystem service provisioning using land use data. Ecol. Indic. 11 (2), 676–687.
Li, W., Wu, C., 2020. Spatial standardization of multi-source geospatial data for urban ecosystem service assessment. Ecol. Indic. 115, 106382.
Liu, X., Wang, M., 2016. How polycentric is urban China and why? A case study of 318 cities. Land. Urban Plan. 151, 10–20. https://doi.org/10.1016/j.landurbplan.2016.03.007.
Madre, F., Vergnes, A., Machon, N., Clergeau, P., 2014. Green roofs as habitats for wild plant species in urban landscapes: first insights from a large-scale sampling. Landsc. Urban Plan. 122, 100–107.
Manso, M., Teotónio, I., Silva, C.M., Cruz, C.O., 2021. Green roof and green wall benefits and costs: a review of the quantitative evidence. Renew. Sust. Energ. Rev. 135, 110111.
Meerow, S., Newell, J.P., 2019. Urban resilience for whom, what, when, where, and why? Urban Geogr. 40 (3), 309–329. https://doi.org/10.1080/02723638.2016.1206395.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being, vol. 5. Island Press.
Minor, E.S., Anderson, E.C., Belaire, J.A., Garfinkel, M., Smith, A.D., 2018. Urban green infrastructures and ecological networks for urban biodiversity conservation. In: Lips, D.J. (Ed.), Urban Biodiversity, pp. 186–199.
NEN 6702, 2018. Technical Requirements for Building Structures. Dutch Standards Institute.
Neset, T.S.S., Cordell, D., Moosavi, S., Andersson, L., 2016. Local phosphorus flows and urban agriculture in the food–water–energy nexus: case studies from three global cities. Resour. Conserv. Recycl. 102, 26–38. https://doi.org/10.1016/j.resconrec.2015.06.020.
Nguyen, C.N., Muttil, N., Tariq, M.A.U.R., Ng, A.W., 2021. Quantifying the benefits and ecosystem services provided by green roofs: a review. Water 14 (1), 68.
Nyelele, C., Keske, C., Chung, M.G., Guo, H., Egoh, B.N., 2023. Using social media data and machine learning to map recreational ecosystem services. Ecol. Indic. 154, 110606.
Ord, J.K., Getis, A., 1995. Local spatial autocorrelation statistics: distributional issues and an application. Geogr. Anal. 27 (4), 286–306.
Orsini, F., Gasperi, D., Marchetti, L., Piovene, C., Draghetti, S., Ramazzotti, S., Gianquinto, G., 2014. Exploring the production capacity of rooftop gardens (RTGs) in urban agriculture: the potential impact on food and nutrition security, biodiversity and other ecosystem services in the city of Bologna. Food Secur. 6 (6), 781–792.
Ouyang, X., Tang, L., Wei, X., Li, Y., 2021. Spatial interaction between urbanization and ecosystem services in Chinese urban agglomerations. Land Use Policy 109, 105587.
Peng, L.L., Jim, C.Y., 2015. Economic evaluation of green-roof environmental benefits in the context of climate change: the case of Hong Kong. Urban For. Urban Green. 14 (3), 554–561.
Peng, J., Liu, Y., Wu, J., Lv, H., Hu, X., 2015. Linking ecosystem services and landscape patterns to assess urban ecosystem health: a case study in Shenzhen City, China. Landsc. Urban Plan. 143, 56–68.
Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. 107 (11), 5242–5247. https://doi.org/10.1073/pnas.0907284107.
Rosol, M., 2012. Community volunteering as neoliberal strategy? Green space production in Berlin. Antipode 44 (1), 239–257.
Russo, A., Escobedo, F.J., Cirella, G.T., Zerbe, S., 2017. Edible green infrastructure: an approach and review of provisioning ecosystem services and disservices in urban environments. Agric. Ecosyst. Environ. 242, 53–66.
Sanchez, L., Reames, T.G., 2019. Cooling Detroit: A socio-spatial analysis of equity in green roofs as an urban heat island mitigation strategy. Urban Forestry & Urban Greening 44, 126331. https://doi.org/10.1016/j.ufug.2019.04.014.
Santamouris, M., Osmond, P., Paolini, R., 2020. Recent progress on urban overheating and heat island research: integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with global climate change. Energ. Buildings 207, 109482.
Sanyé-Mengual, E., Orsini, F., Oliver-Solà, J., Rieradevall, J., Montero, J.I., Gianquinto, G., 2015. Techniques and crops for efficient rooftop gardens in Bologna, Italy. Agron. Sustain. Dev. 35 (4), 1477–1488.
Schwarz, N., Haase, D., Elmqvist, T., 2021. Understanding the spatial structure of ecosystem services in urban areas: integrating landscape metrics and machine learning. Landsc. Urban Plan. 206, 103978. https://doi.org/10.1016/j.landurbplan.2020.103978.
Su, C.H., Fu, B.J., He, C.S., Lü, Y.H., 2012a. Variation of ecosystem services and human activities: a case study in the Yanhe watershed of China. Acta Oecol. 44, 46–57.
Su, S., Xiao, R., Jiang, Z., Zhang, Y., 2012b. Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. Appl. Geogr. 34, 295–305.
Su, S., Pi, J., Wan, C., Li, H., Xiao, R., Li, B., 2020. Categorizing social vulnerability patterns in Chinese coastal cities. Ocean Coast. Manag. 185, 105056.
Sun, A.Y., Scanlon, B.R., 2019. How can big data and machine learning benefit environment and water management: a survey of methods, applications, and future directions. Environ. Res. Lett. 14 (7), 073001.
Susca, T., 2019. Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. Build. Environ. 162, 106273.
Sustainable Urban Delta, 2026. DakAkker: This 1000 m^2 Urban Rooftop Farm Shows the Sky is the Limit. Retrieved from. https://sustainableurbandelta.com/dakakker-rotterdam-rooftop-farm/.
Syrbe, R.U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services: providing, benefiting and connecting areas and landscape metrics. Ecol. Indic. 21, 80–88.
Tan, P.Y., Sia, A., Lai, Y.H., 2021a. Roofpedia: automatic mapping of green and solar roofs for an open roofscape registry and evaluation of urban sustainability. Landsc. Urban Plan. 214, 104167.
Tan, P.Y., Sia, A., Ng, E., 2021b. Roofpedia: a synthetic mapping framework for rooftop greening potential assessment. Urban For. Urban Green. 63, 127223.
Urban Green-Blue Grids, 2026. Prinzessinnengarten, Berlin. Retrieved from. https://urbangreenbluegrids.com/projects/prinzessinnengarten-berlin/.
Urban Land Institute, 2016. Marina Barrage, Singapore. Retrieved from. https://casestudies.uli.org/wp-content/uploads/2016/06/Marina-Barrage.pdf.
Van der Hoeven, F., Wandl, A., van Timmeren, A., 2020. Spatial analysis of green roof potential in Rotterdam: a GIS-based approach. Sustain. Cities Soc. 53, 101936.
Venter, Z.S., Barton, D.N., Martinez-Izquierdo, L., Langemeyer, J., Baró, F., McPhearson, T., 2021. Interactive spatial planning of urban green infrastructure – retrofitting green roofs where ecosystem services are most needed in Oslo. Ecosyst. Serv. 50, 101314.
Vijayaraghavan, K., 2016. Green roofs: a critical review on the role of components, benefits, limitations and trends. Renew. Sust. Energ. Rev. 57, 740–752.
Vrebos, D., Staes, J., Broekx, S., De Nocker, L., Gabriels, K., Hermy, M., Meire, P., 2020. Facilitating spatially-explicit assessments of ecosystem service delivery to support land use planning. One Ecosyst. 5, e50540.
Walters, S.A., Stoelzle Midden, K., 2018. Sustainability of urban agriculture: vegetable production on green roofs. Agriculture 8 (11), 168.
Wang, X., Li, H., Sodoudi, S., 2022a. The effectiveness of cool and green roofs in mitigating urban heat island and improving human thermal comfort. Build. Environ. 217, 109082.
Wang, Y., Akbari, H., Berardi, U., 2022b. Cooling the cities: a systematic analysis of green roof and wall technologies in urban heat island mitigation. Energ. Buildings 254, 111567.
Williams, N.S., Lundholm, J., MacIvor, J.S., 2014. Do green roofs help urban biodiversity conservation? J. Appl. Ecol. 51 (6), 1643–1650.
Wolch, J.R., Byrne, J., Newell, J.P., 2014. Urban green space, public health, and environmental justice: the challenge of making cities "just green enough.". Landsc. Urban Plan. 125, 234–244.
Zhang, C., Wang, K., Yue, Y., Qi, X., Zhang, M., 2023. Assessing regional ecosystem conditions using geospatial techniques—a review. Sensors 23 (8), 4101.
Zhang, X., Zhong, T., Feng, X., Wang, K., 2020. Estimation of the relationship between urban vegetation configuration and land surface temperature with remote sensing. J. Environ. Manage. 351–361.
Zölch, T., Maderspacher, J., Wamsler, C., Pauleit, S., 2016. Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. Urban Forest. Urban Green. 20, 305–316. https://doi.org/10.1016/j.ufug.2016.09.011.