Sustainability Science
https://doi.org/10.1007/s11625-022-01180-5

CASE REPORT

Ecological performance standards for regenerative urban design

Janine Benyus[1] · Jamie Dwyer[1] · Sara El-Sayed[2,3] · Samantha Hayes[4] · Dayna Baumeister[1,2] · Clint A. Penick[3,5]

Received: 28 September 2020 / Accepted: 16 May 2022
© The Author(s), under exclusive licence to Springer Japan KK, part of Springer Nature 2022

Abstract
Ecosystem services encompass the tangible human benefits that ecosystems provide. Past efforts to maintain ecosystem services have focused on conserving and rehabilitating natural ecosystems, but there is growing consensus that the built environment must contribute these services as well. The field of regenerative design seeks to create infrastructure that contributes to and enhances local ecosystems, but a key challenge has been the development of baseline standards that reflect ecosystem health as opposed to business-as-usual design. To address this challenge, we draw on work by Biomimicry 3.8 and project partners to outline a framework for ecological performance standards (EPS) that can be applied to regenerative projects. While current sustainability frameworks quantify negative impacts of proposed designs and seek to reduce those impacts, EPS specifies positive-impact performance standards based on local ecosystems. The EPS process involves four steps: (1) identifying a local reference ecosystem, (2) quantifying ecosystem services at the reference ecosystem to develop EPS metrics, (3) designing to meet or exceed EPS metrics at the building site, and (4) implementing and assessing the proposed design. We outline these steps in detail and provide three case studies that highlight implementation successes and challenges at the city, development, and building scale.

Keywords Ecosystem services · Regenerative design · Green building · Biomimicry · Ecosystem metrics · Sustainable architecture

Introduction

The livability of cities is entirely dependent on ecosystem services—benefits that include climate regulation, atmospheric cleansing, water storage and purification, pollination, soil building, and nutrient cycling (Boyd and Banzhaf 2007; Costanza et al. 1997; Fisher et al. 2009). These services are largely provided by ecosystems outside of cities, but there is increasing acknowledgment that cities must begin to provide ecosystem services themselves to maintain healthy drinking water, clean air, and stable ecological communities (Bolund and Hunhammar 1999; Elmqvist et al. 2015; Pickett and Cadenasso 2008; Tratalos et al. 2007). To achieve the sustainable development goals outlined by the United Nations (Lu et al. 2015), cities must contribute to ecosystem services provided by healthy, local ecosystems. Buildings, infrastructure, and surrounding ecosystems should work together to contribute to annual per hectare goals for clean air, clean water, healthy soil, sequestered carbon, nutrients cycled, erosion reduced,heat reduced, and biodiversity supported.

Incorporating ecosystem services into urban infrastructure is a central focus of regenerative design, which seeks to move beyond damage reduction and towards built environments that deliver positive benefits (Cole 2012; El-Sayed and Cloutier 2022; Lyle 1996; Mang and Reed 2015). A challenge for regenerative design is the development of standards that translate ecosystem performance into metrics that apply directly to the built environment (Pedersen Zari 2012). Current green building standards, such as LEED and

Handled by Christopher Ives, University of Nottingham, United Kingdom.

✉ Clint A. Penick
cpenick1@kennesaw.edu

[1] Biomimicry 3.8, Missoula, MT 59802, USA

[2] The Biomimicry Center, Arizona State University, Tempe, AZ 85287, USA

[3] The Global Institute of Sustainability and Innovation, Arizona State University, Tempe, AZ 85287, USA

[4] Cities Research Institute, Griffith University, Nathan, QLD 4111, Australia

[5] Department of Ecology, Evolution, and Organismal Biology, Kennesaw State University, Kennesaw, GA 30144, USA

Published online: 05 August 2022

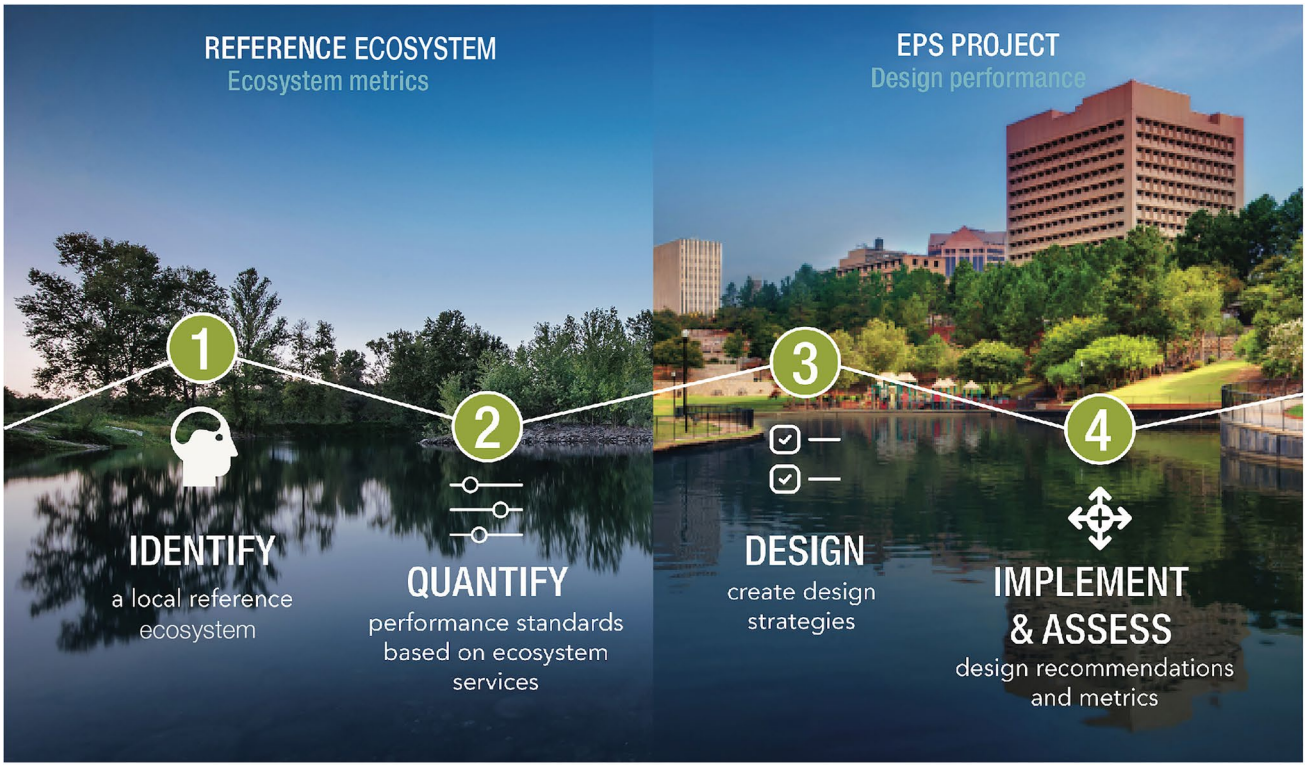

Fig. 1 Design process for EPS projects from beginning of design phase to implementation and assessment. The process begins with identifying a local reference ecosystem to quantifying ecosystem services. Those ecosystem services are then translated into EPS metrics and design strategies that apply directly to the building sector. The design must then incorporate elements to meet or exceed those metrics, and the final design will be assessed to determine how well those metrics were met (copyright Biomimicry 3.8)

Net-Zero, have been vital for reducing the negative impacts of buildings and infrastructure on the environment (Berardi 2012; Marszal et al. 2011; Zuo and Zhao 2014), but they do not require positive, contributive performance. Built environment sustainability frameworks typically begin by assessing the negative impacts of business-as-usual design and then set targets to reduce those impacts. For projects that seek to create or enhance local ecosystem services, current standards do not provide an adequate baseline (Olgyay and Herdt 2004; Pedersen Zari 2018).

To deliver projects that are truly regenerative, we outline an approach to define baseline sustainability goals based on how a native healthy ecosystem would operate on that site, which we term Positive Performance or ecological performance standards (EPS). This approach was developed through more than a decade of work by Biomimicry 3.8 (B3.8), a US-based nature-inspired consultancy, and their project partners (Table S1). EPS translates functions and services generated by local ecosystems into tangible design targets for the building sector (e.g., kilograms of carbon sequestered per km^2, pounds/year of airborne particulate matter removed, etc.). The EPS approach is biomimetic in nature by creating goals based on the performance abilities of local ecosystems in which cities are embedded (Benyus 1997; Pedersen Zari 2018). Some technologies for achieving goals of EPS already exist, including bio-swales, green roofs, carbon-sequestering cement, shading structures, pollinator corridors, architecture that provides biodiversity support (habitecture), and wetland-assisted water purification (Oberndorfer et al. 2007; Pataki et al. 2011). While these technologies are not new, when used in combination with EPS, they can support urban development—buildings, infrastructure, and landscaping—that provides many of the ecosystem services delivered by a healthy ecosystem.

EPS methodology

EPS requires collaboration among urban planners, ecologists, architects, engineers, designers, and operations and maintenance teams to develop and design for ecosystem services. Through the work of B3.8 and others (Pedersen Zari 2018; Stack 2014), a general framework for EPS has emerged with four steps that include (1) identifying a local reference ecosystem, (2) quantifying ecosystem services to develop EPS metrics, (3) designing to meet or exceed those metrics, and (4) implementing and assessing the proposed design (Fig. 1). These steps bridge work between those who

collect ecosystem metrics and those who develop design interventions to meet or exceed EPS metrics and implement those strategies on site.

(1) Identifying a local reference ecosystem

Choosing a local reference ecosystem (or ecosystems) requires an understanding of which native ecosystem types the site would support if undisturbed. Within the context of EPS, a reference ecosystem is an existing, relatively intact and healthy site used to establish baseline EPS values. In most cases, this means identifying protected conservation areas or wildlife preserves located in the same region as the project site. In past projects, we have used national parks, forest preserves, and even the planned building site if the ecosystem present is relatively intact (see Table S1). A building site may be composed of multiple ecosystems (e.g., a mix of broadleaf forests, grasslands, and wetlands), in which case each ecosystem should be assessed independently for the ecosystem services that they provide.

EPS prioritizes using existing ecosystems for a reference, but for a select number of cities, such as New York and San Francisco, researchers have digitally recreated historical ecosystems that existed in these places prior to intense human modification (Brastow 2006; Sanderson 2009). Historical data can provide useful insights, but they do not necessarily replace the need for identifying an extant reference ecosystem. For one, historical ecosystems may have existed under different climate scenarios or water regimes than those present at the site currently, which could lead to a mismatch in EPS metrics for current climate conditions. In addition, a site visit to an extant ecosystem gives design teams a tangible goal to design towards as well as organismal and ecosystem models for biomimetic design interventions that cannot be accomplished using historical data alone. For these reasons, current ecosystems serve as better models to derive EPS metrics and serve as inspiration under current climate conditions.

Contemporary challenges facing cities, such as climate change and the urban heat island effect, should also influence decisions in choosing a local reference ecosystem. If the current climate of a site is not considered when choosing a local reference ecosystem, there could be mismatches between proposed solutions based on the ecosystem and the reality on the ground. For example, native plants that might have once thrived at a specific site may no longer be a good choice given current climate conditions, industrial shading, or altered soil chemistry. And while we have tended to focus on native ecosystems in our past EPS projects, there has been wider recognition of the importance of novel ecosystems in conservation planning (Clement 2020; Hobbs et al. 2009; Seastedt et al. 2008). Novel ecosystems have been influenced either directly or indirectly by human activity, which may include lands impacted through historical agriculture or novel species communities composed of introduced species. Some novel ecosystems may even hold significant cultural value and may be prioritized for restoration on site. It is, therefore, up to the research team to decide which aspects of an ecosystem to emulate, and for specific sites, novel ecosystems may be useful for collecting baseline values.

(2) Quantifying ecosystem services to develop EPS metrics

Once a reference ecosystem has been selected, the next step is to quantify ecosystem services provided in that system. The services humans receive from ecosystems are often divided into four categories (Reid et al. 2005): provisioning services (e.g., food, fuel, and medicines), regulation services (e.g., pollination, climate regulation), supporting services (e.g., soil formation, solar energy), and cultural services (e.g., recreation, artistic inspiration). Multiple categorization schemes for ecosystem services exist (Carpenter et al. 2009; Gunton et al. 2017), and recent efforts have argued for expanding the ecosystem services framework to include benefits to ecosystems that may or may not have direct human benefits (e.g., maintaining biodiversity Mace et al. 2012; Polishchuk and Rauschmayer 2012). Therefore, it is up to the project team to identify the key ecosystem metrics to prioritize for a project or specific site.

The overarching goal of EPS is to create metrics for infrastructure projects that match or exceed ecosystem services provided in a reference ecosystem, but single projects are unlikely to produce all ecosystem services (Pedersen Zari 2012; Rainey et al. 2015). The project team must, therefore, determine which ecosystem services to prioritize, and in cases when there is uncertainty about the capacity of a design solution to deliver the desired ecosystem services, the precautionary decision is to prioritize retaining actual ecosystems. Different ecosystem services, at a minimum, should be emphasized based on the ecosystem in which a project is embedded. Desert environments, for example, might prioritize water provisioning, while erosion regulation may be more important in coastal areas. The selection of ecosystem services to prioritize will also depend on stakeholder needs, budget, and other project constraints. It is, therefore, important to work with project partners to understand the trade-offs associated with prioritizing one category of ecosystem services over another.

A combination of quantitative and qualitative metrics may be necessary to assess ecosystem services in a reference ecosystem. To develop quantitative metrics, a growing number of tools are available to aid in the collection of ecosystem services on site (reviewed in Bagstad et al. 2013).

These tools use a variety of spatial data for model input, then provide an estimate of the site's ability to generate ecosystem services. B3.8 and partners have used two of these tools to aid the development of EPS metrics: the InVEST tool (Integrated Valuation of Ecosystem Services and Trade-offs) by the Natural Capital Project, and the ESII tool (Ecosystem Services Identification & Inventory) and additional algorithms by EcoMetrix Solutions Group. InVEST uses a GIS interface to map and value the goods and services at a given site (Tallis et al. 2010), and it allows users to model ecosystem changes and quantify the effects on biophysical (e.g., kilograms of carbon sequestered) and economic (e.g., net value of sequestered carbon) aspects of landscape performance. InVEST has the capability to create a wide range of models for different use-case scenarios, including carbon capture, water purification, habitat quality, pollination, scenic quality, urban cooling, and urban flood risk mitigation among many others. For InVEST and similar tools, some basic skills in GIS or programming are required, while the ESII tool is designed as an iPad app and web interface that can be used by non-specialists after minimal training. ESII facilitates on-site collection of ecosystem attributes and provides estimated values for ecosystem services that include erosion regulation, flood mitigation, noise attenuation, and a range of air and water quality metrics (for detailed metrics, see Table S2). The user inputs estimated qualitative and quantitative units measured on site (e.g., percent canopy cover, percent ground cover, land slope, etc.), which are used to calculate scoring curves to estimate a site's ecosystem services using non-monetary, service-specific metrics (Bagstad et al. 2013; Snell 2016).

While tools like InVEST and ESII allow practitioners to gather quantitative metrics for many ecosystem services on site, other ecosystem services are more difficult to quantify. For example, aesthetic and cultural services may require qualitative metrics to capture reference ecosystem values that can be incorporated into EPS (Plieninger et al. 2013; Schirpke et al. 2016; Van Berkel et al. 2018). In addition, biodiversity support is one of the more difficult ecosystem services to measure. Full-scale biodiversity surveys (e.g., David 2005) are outside the scope of most projects, though a literature review can reveal information about native plants and animals on site, keystone species, threatened species, and threats to biodiversity (e.g., invasive species). Teams can also assess habitat features that provide habitat support (e.g., nesting habitat, nurse logs, food resources, etc.), conduct limited surveys using digital tools for plant identification, such as iNaturalist (Unger et al. 2021), and leverage on-site biodiversity information that is gathered through an environmental impact assessment (Mandelik et al. 2005). In addition, there are numerous metrics that can allow teams to assess resources for target species, including habitat suitability models and population viability metrics that can be used to assess the likelihood that a proposed design will improve the probability of the species persisting on site (Garrard et al. 2018).

Beyond collecting data for the creation of EPS performance goals, a site visit also provides an immersive experience for the design team in a functioning ecosystem. Site visits to planned building locations are already a well-established component of the early design process, and a site visit to a reference ecosystem provides similar advantages. Teams can observe ecological processes at work in reference ecosystems, aided by having a knowledgeable biomimicry professional, ecologist, or land manager on site. Reference ecosystems contain a diversity of organisms that have adapted to similar climatic, physical, and ecological conditions as those required at the planned building site. Using biomimicry design methods, these organisms can serve as inspiration for place-based design interventions that help meet EPS goals during the design phase (Hayes et al. 2020). Site visits with a local guide may also educate the team about components of the environment that have cultural significance, which can be incorporated into the design process as well.

Finally, the same measurement process should also occur at the development site to assess the level of ecosystem services, if any, that are provided. The measurement of ecosystem services provided at the development site allows the team to identify the performance gap between the current site and the reference site, which may be large depending on the level of previous development. While the choice of which metrics to prioritize may differ among projects due to stakeholder needs and feasibility, the comparison of metrics between the reference ecosystem and development site should be consistent. In the best-case scenario, detailed measurements of ecosystem services on site will allow for precise comparisons, but qualitative metrics can still be useful when the same criteria are applied across sites.

(3) Designing to meet or exceed EPS metrics

Once EPS metrics have been selected and the performance gap has been quantified, the third step is to develop design strategies to meet or exceed EPS goals. The biggest impact EPS can have is often during the initial stage of the design process when site selection occurs. EPS metrics can be used to assess which areas on site should be prioritized for preservation or whether a new site should be chosen entirely. Although EPS methodology is not the same as ecological restoration, where the goal is to restore native ecosystems (Palmer et al. 2016), these two approaches can work synergistically to maximize on-site production of ecosystem services. Given that it is unlikely that even the most sustainable design interventions will restore all ecosystem services provided by a healthy native ecosystem

(Rainey et al. 2015), it is important to prioritize restoration of functioning ecosystems to the extent possible.

At the start of the design phase, a series of questions must be considered: At what scale will implementation take place (e.g., building, district, or city)? What are the economic constraints? What are the social requirements for the project (e.g., employee satisfaction, social equity)? Could the project provide opportunities for local green jobs and business start-ups? Recent projects in restoration ecology and conservation biology have applied tools from decision science to develop formal procedures for reaching consensus among multiple stakeholders (Marcot et al. 2012; Martinez-Harms et al. 2015). This approach follows a multistep process that can fit within the EPS framework to identify key metrics of ecosystem performance, define alternative management actions and evaluate the consequences of those actions, assess trade-offs, and finally make a decision on which course of action to follow.

To aid in decision-making, B3.8 and partners have used the InVEST tool to build alternate scenarios so that design teams can compare how various approaches will affect ecosystem services provided. This helps clients and stakeholders prioritize which design interventions best accomplish EPS goals given budget or other constraints. While it is theoretically possible to propose design interventions that exceed EPS goals, we have yet to see this situation in either models or reality. However, it is important to note that EPS metrics should not be limiting, and there are likely cases where EPS goals may be exceeded by proposed design interventions for specific ecosystem services, especially as technologies improve. It is also important that EPS projects take into account future environmental challenges to cities, such as those posed by climate change (Hughes et al. 2020). For example, a building site that uses a temperate grassland as a reference ecosystem will still need to include design interventions that mitigate extreme temperatures, such as including constructed shade structures or landscaping with shade trees that may or may not be part of the identified reference ecosystem.

As mentioned above, there are already a number of design interventions that can be deployed to meet or exceed EPS goals (Fig. 2). For example, the integration of bioswales, permeable pavement, and rainwater capture systems can be used to limit stormwater runoff and erosion (Li et al. 2019). Other common design interventions may include composting toilets (Anand and Apul 2014), green and blue-green roofs (Droz et al. 2021; Francis and Jensen 2017; Oberndorfer et al. 2007), carbon-sequestering cement (Gupta et al. 2018), and energy-efficient electrical and mechanical equipment (see Fig. 2 and Tables S1 and S2 for additional examples). It is up to the design team to decide which technologies and design approaches to integrate into the proposed plan and/or to develop novel, nature-inspired design interventions to achieve the goals set by EPS.

To recreate the functions of a reference ecosystem, EPS projects must also provide habitat to support biodiversity. Landscaping with native plants is a common practice in regenerative design, and there is growing support for efforts that seek to incorporate animal habitat features into urban design plans (Apfelbeck et al. 2020). Garrard et al. (2018) have distilled ecosystem features that provide biodiversity support into five principles that can be applied to urban design: maintain and introduce habitat, facilitate dispersal, minimize threats and anthropogenic disturbances, facilitate natural ecological processes, and improve potential for positive human–nature interactions. The incorporation of these features into a proposed design is likely to benefit a wide range of native species. Furthermore, consideration should also be given to how the site is connected to other potential habitat through natural and constructed corridors that allow plant and animal dispersal (Hostetler et al. 2011; Peng et al. 2017).

(4) Implementation and assessment

The final step of an EPS project is implementation and assessment. Implementation involves the construction of a proposed project, and may take place as short-, medium-, and long-term interventions based on the budget and scale of a project. EPS guidelines can, therefore, serve as long-term targets for planners to build towards as they implement new construction or retrofit existing structures. A clear assessment strategy allows operation teams to monitor their progress towards closing the performance gap and meeting EPS goals. For corporations and communities, measuring the positive ecosystem services being generated by a site is an opportunity to celebrate how close they are to performing like a healthy native ecosystem, or as B3.8 says: "to being functionally indistinguishable from the wildland next door." To achieve these goals, the final design will need a combination of habitat restoration and design interventions.

Case studies

B3.8's methodology for EPS evolved through a series of pilot projects working with public and private clients at the building, development, and city scales. Among the nine EPS projects B3.8 has worked on (Table S1), we highlight three case studies below (Table 1). These cases were chosen because they span our earliest application of EPS (Lavasa) through our most recent completed project (Factory as Forest). Within each case study, we highlight our methodology and call out challenges that we encountered along the way. Our methodology has evolved over the course of a

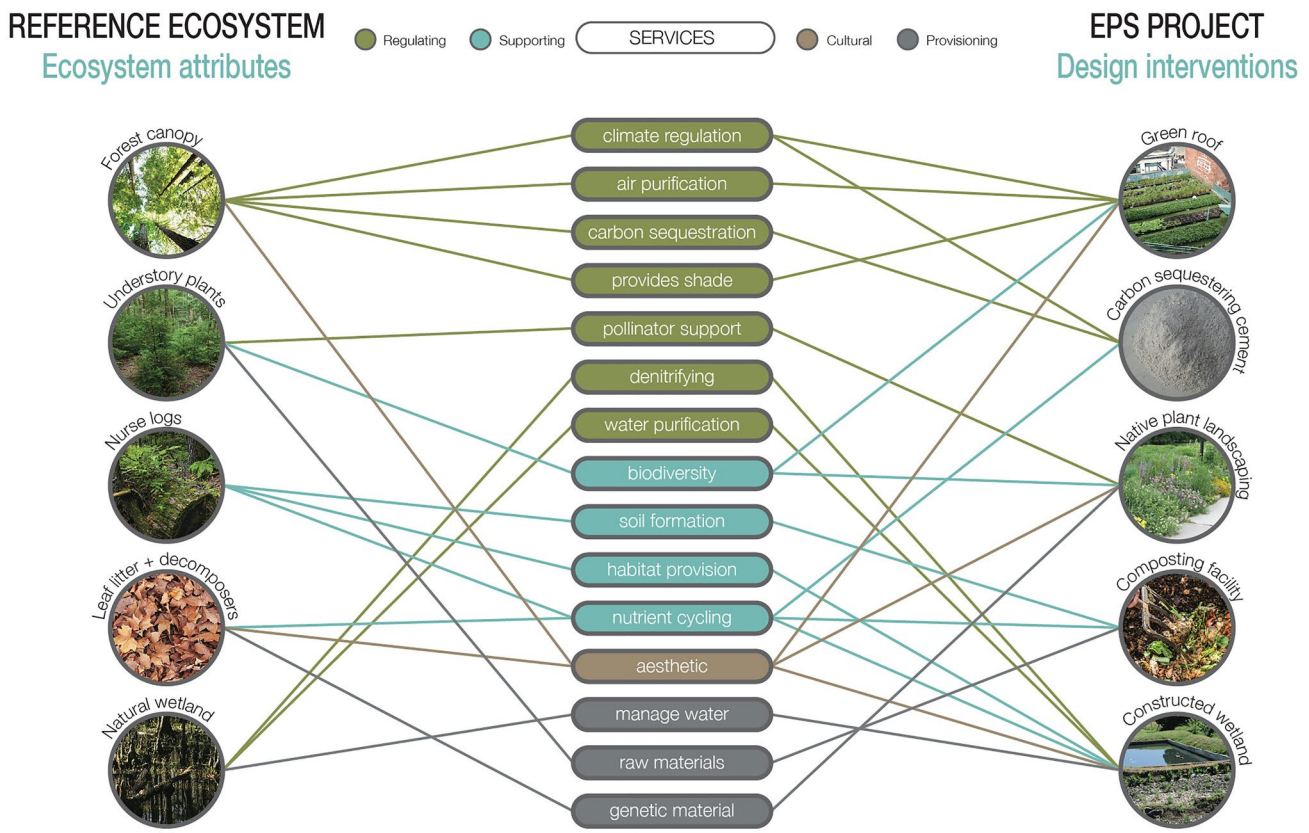

Fig. 2 Comparison of ecosystem services provided by reference ecosystems and proposed EPS design interventions for the Factory as a Forest project in Georgia, USA. An oak–hickory–pine forest served as the reference ecosystem, and services focused on air quality, water performance, and nutrient cycling

decade—and continues to evolve with each new project—and we point out specific examples where the adoption of new strategies has improved our application of EPS.

Lavasa, India: development master plan (2008–2009)

The first pilot of EPS was conducted in collaboration with the architecture firm HOK to create a development master plan for Lavasa, a private, planned development built around the shores of Dasve Lake outside of Pune, India. Lavasa was conceived as an "eco-city" to be built for up to 200,000 residents in the Western Ghats, one of 25 global biodiversity hotspots (Myers et al. 2000) and a UNESCO World Heritage Site. An initial goal of the project was to create a sustainable development that followed an environmental management plan focused on water conservation, rainwater management, and biodiversity support (Datta 2012).

Prior to development, most of the land on site had forest cover, though significant portions were degraded as a result of hundreds of years of grazing and cultivation. The construction of Lavasa required clearing some forest at proposed build sites, and EPS was used to help restore ecosystem services that were being provided by the existing ecosystem. For this reason, the in-tact forest surrounding the site—a subtropical, moist, broadleaf forest—was identified as the local reference ecosystem. This forest included several untouched sacred groves (forest patches dedicated to specific deities and protected by local communities) that were visited by B3.8 and HOK during multiple site visits. B3.8 also conducted a literature review on the ecosystem type, which was used to identify relevant ecological dynamics and specify EPS metrics. Conducting a full literature review was an arduous process, and it became clear that a full assessment of the site would not be feasible using published literature alone—a recurring challenge for each EPS project. We were still able to glean unique characteristics about the site that were incorporated into the design plan, including an erosion-reduction design that mimicked the impacts of the forest canopy during monsoon season (Wang 2006).

In this first pilot, over 20 critical ecosystem service metrics were identified, but these were quickly deemed too complex by the clients and builders, a lesson that we learned for future projects. Beginning at Lavasa, the team grouped EPS metrics into simple categories that aligned

Table 1 EPS case studies

Location	Years	Reference ecosystem(s)	Tools used	EPS categories
Lavasa, Maharashtra, India	2008–2009	Subtropical, moist, broadleaf forest	Peer-reviewed journal articles Site visits	"Water"—water retention, evapotranspiration "Light"—climate-regulating albedo "Earth"—nutrient cycling, decomposition rates, erosion management "Biodiversity"—habitat support
Durban, KwaZulu-Natal, South Africa	2014	Kwazulu Natal-Cape coastal forests Southern Africa mangroves	Peer-reviewed journal articles InVEST B3.8's Life's Principles	Water yield (mm^3) Flood index (%) Carbon storage (tC) Sediment yield (t/year) Nitrogen and phosphorus export (kg/year)
LaGrange /West Point, Georgia, United States	2016–present	Oak–hickory–pine forest	Peer-reviewed journal articles Site visits ESII tool	Water—watershed consumptive use, runoff rate, evapotranspiration rate, infiltration, total suspended solids (TSS) removal/concentration Atmosphere—mean summer surface temperature, ground-level ozone threshold, particulate matter removal, atmospheric CO_2 Carbon cycle—carbon sequestration Soil—soil depth, soil organic matter, nutrient recycling Habitat and biodiversity—habitat enhancement, non-native invasive species, view quality, natural light enhancement

with client goals, which were represented as "water" (water retention and evapotranspiration), "light" (climate-regulating albedo), "earth" (nutrient cycling, decomposition rates, and erosion management), and "biodiversity" (habitat support). These contained nearly all of the original 20 metrics we developed, but grouping them into easy-to-understand categories improved communication with the clients and builders. Without the aid of assessment tools, it was outside of the scope of this project to directly measure precise metrics on site. As such, baseline values of each metric were estimated using ecological literature, and proposed design interventions were qualitatively ranked as meeting, falling below, or exceeding baselines.

Ultimately, these metrics guided the design of the development master plan by HOK, which received three awards from the American Society of Landscape Architects. Notable interventions included in the master plan were roof designs that enhanced evaporation, road modifications to address erosion challenges, and increased buffer zones along intermittent waterfalls (*nalas*). Due to the scope of the project and limited feasibility, we did not directly measure biodiversity on site, though the proposed design included restoration of 70% of deforested land on site to provide biodiversity support, which included land previously cleared for agriculture and areas that would need to be cleared for construction. Wherever feasible, we recommended protecting existing forest, as forest restoration projects take significant time before ecosystem services fully return (Lamb 2018). For that reason, protection of natural ecosystems should be prioritized whenever feasible.

Lavasa was the first application of EPS to a large-scale project by B3.8, and it revealed several challenges that needed to be addressed in future projects, namely finding assessment tools to quickly estimate ecosystem services and to evaluate proposed designs. Lavasa also highlighted the synergistic benefits of a site visit with the design team, which led to bio-inspired solutions incorporated into the design plan, such as a polymer product that stiffens soil to create the same stabilizing effect as a cliff swallow mixing saliva with mud to create a mortar that adheres their nests to buildings. These lessons were carried over into subsequent projects.

Durban, South Africa: resilient development plan (2014)

B3.8 joined a consortium working with the government of Durban, South Africa—one of the first international cities to be included in the 100 Resilient Cities Program (Sutherland et al. 2019)—to create a development plan that did not compromise ecological integrity or biodiversity of the building site. An initial challenge encountered during the first three EPS projects was quantifying ecosystem metrics in values that would permit benchmarking of proposed design interventions against measured baselines. For Lavasa, we estimated EPS metrics using ecological literature and then developed a qualitative ranking system for comparing proposed design interventions to baseline values. For the Durban project, B3.8 used the InVEST tool to quantitatively model ecological performance of the current ecosystem and compare across proposed design interventions.

The planned development at Durban was largely under sugarcane cultivation, so the team identified two reference ecosystems outside the proposed building site: (1) Southern Africa mangroves, and (2) Kwazulu Natal-Cape coastal forest, a subtropical moist broadleaf forest that represents the southernmost distribution for tropical forest in Africa with a high number of endemic species. Two reference ecosystems were chosen because both forest types would have been present on site prior to sugarcane cultivation, and the loss of natural mangrove habitat was a major concern for the site. In particular, risk assessment models of Durban identified that water yield and flood attenuation were the ecosystem services most at risk in the development area so these metrics were prioritized when generating EPS metrics.

Working at the proposed building site and reference habitats, the B3.8 team generated EPS metrics using the InVEST tool to model current performance (sugarcane fields), historical performance prior to cultivation based on reference ecosystems, and business-as-usual performance options. EPS metrics were used to develop high-level design principles informing the resilience framework focusing on carbon storage (tC), water yield (mm^3), flood index (%), sediment yield (t/year), and nitrogen and phosphorus export (kg/year). The high-level principles and proposed design solutions included four Life's Principles taken from the work of B3.8: (1) adapt to changing conditions, (2) integrate development with growth, (3) be locally attuned and responsive, and (4) be resource and energy efficient (Baumeister et al. 2013). For example, under "Adapt to Changing Conditions," the team suggested designing villages with decentralized networks for water, energy, wastewater, and food production to embody resilience through diversifying how these services are supplied and ensuring functional redundancy. Another design recommendation from this work included rehabilitating wetlands and estuaries under sugarcane cultivation to restore ecosystem services lost during the transition to agriculture. Using InVEST to estimate ecosystem services provided by the sugarcane fields relative to those expected from a partially restored ecosystem predicted that this would increase water yield by 3–10% and carbon storage by two-fold. In addition to restoration efforts, the plan included infrastructure inspired by mangrove trees to provide storm surge protection where mangroves would not be present. The Durban project identified the utility of tools like InVEST to aid in the collection of EPS data and for alternative scenario planning, but the scale of the project remained a challenge for implementation. Ultimately, we developed a plan that would allow decision-makers to roll out proposed design interventions in stages to prioritize main concerns, such as water management.

Interface, Inc.: factory as a forest (2015–2020)

The Factory as a Forest project was piloted over multiple locations in Australia and the United States for Interface, Inc., a global manufacturer of commercial flooring. Compared to the case studies described above, the Factory as a Forest project was deployed on a smaller scale (a factory), which allowed for stronger integration of EPS into the design plan. In addition, sustainability had been a long-term priority for Interface, whose vision and mission statements refer to "cherishing nature, restoring the environment, and maximizing the satisfaction of all stakeholders" (Stubbs and Cocklin 2008). EPS was selected as a methodology to help Interface achieve its sustainability objectives as well as build and retrofit factories that would promote the health, safety, and well-being of its employees. Thus, the development team considered both ecological and social metrics for the application of EPS to Interface factory and headquarters projects.

Focusing on the existing factory site in LaGrange, Georgia (USA), B3.8 collaborated with Terrapin Bright Green to measure baseline metrics from the existing facility to compare with EPS metrics from the reference ecosystem (Table S3). The factory was located in an oak–hickory–pine forest in the southern piedmont region of Georgia. In addition to a site visit to the intact forests surrounding the factory, the initial quantification of performance metrics for the LaGrange site was conducted through analysis of ecological literature as in previous projects. This approach, while thorough, was time-consuming and had a significant administrative burden. In ongoing work at LaGrange, B3.8 partnered with EcoMetrix Solutions Group to apply the ESII tool, an open-access tablet-based field application, to develop performance goals on site. The ESII tool improved efficiency of obtaining the ecosystem performance metrics, and tools of this nature will arguably be integral to scaling the EPS approach across industries and locations. After inputting on

site landscape features into the ESII app, the model provided a range of quantitative metrics, including air particulate matter removal (lbs/year), British thermal unit reduction provided by shade (BTU/h), total suspended solids removal in water systems (mg/l), water provisioning (gallons), water quantity runoff (gallons/min), as well as others that were primarily related to air and water quality, temperature, and erosion control.

Because Interface had initiated a strategic focus on water and carbon storage across their company, those metrics were given the highest priority. Terrapin Bright Green compiled a range of potential design solutions to reduce the performance gap, including carbon sequestration in mass timbers, and water harvest and storage interventions. The Interface team invested approximately $3 million USD in design interventions aimed at reducing the gap between the reference ecosystem EPS metrics and the performance of their sites. The implementation phase of this project is ongoing, and design interventions are planned to be rolled out in stages to meet short-, medium-, and long-term goals. Application of the ESII tool allowed for better quantitative metrics collected on site from the reference habitat than previous metrics, and compared to other EPS projects, the collaboration between the EPS team and Interface has lasted long enough to see beyond the design phase and into implementation and assessment. Interface's manufacturing facility at LaGrange employs more than 1000 people, and internal surveys during the EPS process revealed that employees were highly engaged with learning about their local ecosystems, and the fact that the company was using this information to create a better work environment proved to be a large driver for employee support (Mathew 2018).

Conclusions

The EPS projects completed to date have demonstrated both the feasibility and interest in incorporating ecosystem services metrics into regenerative design. Cross-sector engagement will be necessary to continue piloting EPS and to establish policies and programs for broader adoption of the methodology. Success will also depend on broader integration of EPS and similar conservation strategies to improve ecosystems at the landscape scale. In addition to buildings and sites, the authors see potential to bring the EPS methodology to agriculture, forestry, transportation corridors, homes, and schoolyards. Factories as Forests programs could expand into "Backyards as Forests," "Campuses as Forests" (currently in progress with Appalachian State University), "Highway Easements as Forests," "Neighborhoods as Forests," etc., accomplishing regeneration of lands in an incremental fashion.

We have identified two notable lessons from past projects to help implementation of EPS in the future. First, we found that it is important to work with major stakeholders from the beginning to determine the EPS metrics of interest. If EPS metrics do not align with the goals of the project team or a company's mission, then those metrics are less likely to be incorporated into the final design. These may include a mix of quantitative and qualitative goals, as well as complementary social goals. These metrics must align with overall project performance goals, and the earlier in the process that alignment is achieved the better. For example, determining that a planned development site should be elsewhere within a mixed habitat parcel to maximize ecosystem performance potential is best identified before a master plan is finalized. Second, tools that allow practitioners to easily collect ecosystem metrics on site, such as ESII, provide quantitative metrics that are near impossible to glean from literature reviews or without substantial on-the-ground research efforts when those tools are lacking. Further improvements in these tools, as well as alternate scenario planning features in tools like InVEST, will help streamline EPS procedures in the future.

Moving ahead, we see multiple opportunities to accelerate the implementation of EPS. There is a need for increased collaboration between ecologists and built environment professionals to identify, design, and evaluate methods for delivering ecosystem services through built environment design (see Pedersen Zari and Hecht 2020). Practitioners also need to further develop ecosystem services modeling tools that support conversion to building-specific metrics that allow designers to evaluate how well their designs meet EPS goals. Ideally, these are available as early in the process as possible. Beyond the scientific challenges of creating verifiable models of ecosystem services, many questions remain about how various design interventions will work synergistically over time to produce positive ecosystem services. Numerous long-term case studies with sufficient measurement protocols will be essential. And finally, practitioners must document EPS pilot projects and case studies, such as those shared above, to inform a set of best practices that comprise design for ecosystem services. This can be challenging for projects that are delivered for private clients, for which project details may be confidential. Pushing for more openness about project details, successes, and failures will be required so that practitioners can share best practices with the broader community. Project outcomes, if shared, could eventually create a global 'atlas' of ecosystem services metrics, performance targets, and biomimetic design interventions that would streamline EPS adoption.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-022-01180-5.

Acknowledgements We thank all participants of the Generous Cities Summit and the organizing staff in the Biomimicry Center, which includes Prasad Boradkar, Heidi Fisher, Mary Kivioja, Olaya Valeria Reyes, Nathan Carmichael, and Channing Schoneberger. We also thank our collaborators from EPS case studies presented above, including HOK, Biomimicry South Africa, Interface, Terrapin Bright Green, EcoMetrix Solutions Group, VMDO, and Green Schools National Network.

Author contributions The concepts presented in this paper emerged from the work of B3.8 and discussions at the Generous Cities Summit at Arizona State University in 2018. JB, JD, and DB led the work at B3.8 developing the EPS framework and applying it in the case studies described above. SE, SH, DB, and CP organized the Generous Cities Summit and synthesized outcomes to generate the initial manuscript. All authors participated in the writing and editing of the final manuscript.

Declarations

Conflict of interest JB, JD, and DB work for Biomimicry 3.8, a consulting firm that led EPS work presented in the pilot projects section. SE, SH, and CP have no conflicts of interest to declare.

References

Anand CK, Apul DS (2014) Composting toilets as a sustainable alternative to urban sanitation—a review. Waste Manage 34:329–343
Apfelbeck B et al (2020) Designing wildlife-inclusive cities that support human-animal co-existence. Landsc Urban Plan 200:103817
Bagstad KJ, Semmens DJ, Waage S, Winthrop R (2013) A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosyst Serv 5:27–39
Baumeister D, Tocke R, Dwyer J, Ritter S, Benyus J (2013) Biomimicry resource handbook: a seed bank of knowledge and best practices, vol 3. Biomimicry 3.8, Missoula
Benyus JM (1997) Biomimicry: innovation inspired by nature. HarperCollins, New York
Berardi U (2012) Sustainability assessment in the construction sector: rating systems and rated buildings. Sustain Dev 20:411–424
Bolund P, Hunhammar S (1999) Ecosystem services in urban areas. Ecol Econ 29:293–301
Boyd J, Banzhaf S (2007) What are ecosystem services? The need for standardized environmental accounting units. Ecol Econ 63:616–626
Brastow P (2006) Nature in the city. Earth Island J 21:21–21
Carpenter SR et al (2009) Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc Natl Acad Sci 106:1305–1312
Clement S (2020) Governing the Anthropocene: novel ecosystems, transformation and environmental policy. Palgrave Macmillan, London
Cole RJ (2012) Transitioning from green to regenerative design. Build Res Inf 40:39–53
Costanza R et al (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260
Datta A (2012) India's ecocity? Environment, Urbanisation, and mobility in the making of Lavasa. Environ Plan C 30:982–996
David H (2005) Handbook of biodiversity methods: survey, evaluation and monitoring. Cambridge University Press
Droz AG, Coffman RR, Fulton TG, Blackwood CB (2021) Moving beyond habitat analogs: optimizing green roofs for a balance of ecosystem services. Ecol Eng 173:106422
Elmqvist T et al (2015) Benefits of restoring ecosystem services in urban areas. Curr Opin Environ Sustain 14:101–108
El-Sayed S, Cloutier S (2022) Weaving disciplines to conceptualize a regenerative food system. J Agric Food Syst Community Dev 11:23–51. https://doi.org/10.5304/jafscd.2022.112.003
Fisher B, Turner RK, Morling P (2009) Defining and classifying ecosystem services for decision making. Ecol Econ 68:643–653
Francis LFM, Jensen MB (2017) Benefits of green roofs: a systematic review of the evidence for three ecosystem services. Urban For Urban Green 28:167–176
Garrard GE, Williams NS, Mata L, Thomas J, Bekessy SA (2018) Biodiversity sensitive urban design. Conserv Lett 11:e12411
Gunton RM et al (2017) Beyond ecosystem services: valuing the invaluable. Trends Ecol Evol 32:249–257
Gupta S, Kua HW, Low CY (2018) Use of biochar as carbon sequestering additive in cement mortar. Cement Concr Compos 87:110–129
Hayes S, Desha C, Baumeister D (2020) Learning from nature–biomimicry innovation to support infrastructure sustainability and resilience. Technol Forecast Soc Change 161:120287
Hobbs RJ, Higgs E, Harris JA (2009) Novel ecosystems: implications for conservation and restoration. Trends Ecol Evol 24:599–605
Hostetler M, Allen W, Meurk C (2011) Conserving urban biodiversity? Creating green infrastructure is only the first step. Landsc Urban Plan 100:369–371
Hughes S, Chu EK, Mason SG (2020) Climate change in cities: innovations in multi-level governance. Springer, Cham
Lamb D (2018) Undertaking large-scale forest restoration to generate ecosystem services. Restor Ecol 26:657–666
Li C, Peng C, Chiang P-C, Cai Y, Wang X, Yang Z (2019) Mechanisms and applications of green infrastructure practices for stormwater control: a review. J Hydrol 568:626–637
Lu Y, Nakicenovic N, Visbeck M, Stevance A-S (2015) Policy: five priorities for the UN sustainable development goals. Nature 520:432–433
Lyle JT (1996) Regenerative design for sustainable development. Wiley, New York
Mace GM, Norris K, Fitter AH (2012) Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol Evol 27:19–26
Mandelik Y, Dayan T, Feitelson E (2005) Planning for biodiversity: the role of ecological impact assessment. Conserv Biol 19:1254–1261
Mang P, Reed B (2015) The nature of positive. Build Res Inf 43:7–10
Marcot BG et al (2012) Recent advances in applying decision science to managing national forests. For Ecol Manage 285:123–132
Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, Napolitano A (2011) Zero energy building—a review of definitions and calculation methodologies. Energy Build 43:971–979
Martinez-Harms MJ, Bryan BA, Balvanera P, Law EA, Rhodes JR, Possingham HP, Wilson KA (2015) Making decisions for managing ecosystem services. Biol Cons 184:229–238
Mathew M (2018) Factory as a forest: reimagining facilities as ecosystems. https://blog.interface.com/factory-forest-reimagining-facilities-ecosystems/
Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858
Oberndorfer E et al (2007) Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience 57:823–833
Olgyay V, Herdt J (2004) The application of ecosystems services criteria for green building assessment. Sol Energy 77:389–398
Palmer MA, Zedler JB, Falk DA (2016) Foundations of restoration ecology. Island Press, Washington
Pataki DE et al (2011) Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Front Ecol Environ 9:27–36

Pedersen Zari M (2012) Ecosystem services analysis for the design of regenerative built environments. Build Res Inf 40:54–64
Pedersen Zari M (2018) Regenerative urban design and ecosystem biomimicry. Routledge, New York
Pedersen Zari M, Hecht K (2020) Biomimicry for regenerative built environments: mapping design strategies for producing ecosystem services. Biomimetics 5:18
Peng J, Zhao H, Liu Y (2017) Urban ecological corridors construction: a review. Acta Ecol Sin 37:23–30
Pickett ST, Cadenasso ML (2008) Linking ecological and built components of urban mosaics: an open cycle of ecological design. J Ecol 96:8–12
Plieninger T, Dijks S, Oteros-Rozas E, Bieling C (2013) Assessing, mapping, and quantifying cultural ecosystem services at community level. Land Use Policy 33:118–129
Polishchuk Y, Rauschmayer F (2012) Beyond "benefits"? Looking at ecosystem services through the capability approach. Ecol Econ 81:103–111
Rainey HJ, Pollard EH, Dutson G, Ekstrom JM, Livingstone SR, Temple HJ, Pilgrim JD (2015) A review of corporate goals of no net loss and net positive impact on biodiversity. Oryx 49:232–238
Reid WV et al (2005) Ecosystems and human well-being-synthesis: a report of the millennium ecosystem assessment. Island Press, Washington
Sanderson EW (2009) Mannahatta: a natural history of New York City. Abrams, New York
Schirpke U, Timmermann F, Tappeiner U, Tasser E (2016) Cultural ecosystem services of mountain regions: modelling the aesthetic value. Ecol Indic 69:78–90
Seastedt TR, Hobbs RJ, Suding KN (2008) Management of novel ecosystems: are novel approaches required? Front Ecol Environ 6:547–553
Snell M (2016) Review of ecosystem services valuation tools. Prepared for Frenchman Bay Partners. https://frenchmanbaypartners.org/wp-content/uploads/2016/09/Review-of-Ecosystem-Services-Valuation-Tools.pdf
Stack K (2014) The origin of ecological performance standards as applied to the built environment. State University of New York College of Environmental Science and Forestry
Stubbs W, Cocklin C (2008) An ecological modernist interpretation of sustainability: the case of Interface Inc. Bus Strateg Environ 17:512–523
Sutherland C, Roberts D, Douwes J (2019) Constructing resilience at three scales: the 100 Resilient Cities programme, Durban's resilience journey and water resilience in the Palmiet Catchment. Hum Geogr 12:33–49
Tallis H et al (2010) InVEST 1.004 beta user's guide. The natural capital project. Stanford University
Tratalos J, Fuller RA, Warren PH, Davies RG, Gaston KJ (2007) Urban form, biodiversity potential and ecosystem services. Landsc Urban Plan 83:308–317
Unger S, Rollins M, Tietz A, Dumais H (2021) iNaturalist as an engaging tool for identifying organisms in outdoor activities. J Biol Educ 55:537–547. https://doi.org/10.1080/00219266.2020.1739114
Van Berkel DB et al (2018) Quantifying the visual-sensory landscape qualities that contribute to cultural ecosystem services using social media and LiDAR. Ecosyst Serv 31:326–335
Wang B (2006) The asian monsoon. Springer Science & Business Media
Zuo J, Zhao Z-Y (2014) Green building research–current status and future agenda: a review. Renew Sustain Energy Rev 30:271–281

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.