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ARTICLE OPEN



Mapping the benefits of nature in cities with the InVEST software

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Natural infrastructure such as parks, forests, street trees, green roofs, and coastal vegetation is central to sustainable urban management. Despite recent progress, it remains challenging for urban decision-makers to incorporate the benefits of natural infrastructure into urban design and planning. Here, we present an approach to support the greening of cities by quantifying and mapping the diverse benefits of natural infrastructure for now and in the future. The approach relies on open-source tools, within the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software, that compute biophysical and socio-economic metrics relevant to a variety of decisions in data-rich or data-scarce contexts. Through three case studies in China, France, and the United States, we show how spatially explicit information about the benefits of nature enhances urban management by improving economic valuation, prioritizing land use change, and promoting inclusive planning and stakeholder dialogue. We discuss limitations of the tools, including modeling uncertainties and a limited suite of output metrics, and propose research directions to mainstream natural infrastructure information in integrated urban management.

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INTRODUCTION

Cities are uniquely positioned to foster a transition to a more sustainable world. They concentrate human and financial resources; a majority of the world's population is urban¹, and about 85% of global GDP is produced in cities². Municipal and sub-national governments control important decisions that directly affect the welfare of their citizens. They are on the front lines of addressing challenges arising from climate change, air and water pollution, flood risk, heat waves, and rapid population growth³.

Investing in nature in cities — “natural infrastructure” here forth — is an important component of making cities more resilient to such challenges. Natural infrastructure is defined as the network of natural and semi-natural elements providing ecological, economic, or social benefits for humans and other species⁴, ranging from urban forests to community gardens, parks to green roofs, and coastal vegetation to riparian corridors. Nature-based solutions relying on natural infrastructure can help to reduce the risk of flooding; attenuate water, noise, and air pollution; mitigate the urban heat island effect, and provide attractive green and blue spaces that promote physical and mental health^{5–8}. Information about how much, where, and to whom investments in natural infrastructure yield benefits can improve urban planning and decision-making and direct limited budgets towards where they can do the most good^{5,9–11}.

Here we present a set of modeling tools to help evaluate the impact of investments in natural infrastructure in cities, implemented within InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)¹². InVEST is a software suite that models the links between nature and the well-being of people, i.e., “ecosystem services” or “nature's contributions to people”¹³. It has been widely used to demonstrate the potential of natural infrastructure investments^{14–16}, including a recent application with a global scope¹⁷. The set of ecosystem services important in urban areas is somewhat different than in rural areas so the new urban tools introduced here address urban cooling to reduce the urban heat island effect, stormwater management, and access to green space in cities. Like the original InVEST software, the new InVEST urban tools are free, open-source, and modular so that users can choose which services to include in the analysis¹². The tools are designed to incorporate spatial information about natural infrastructure's benefits into resilience research and practice.

Alternative commonly-used tools for urban ecosystem service assessment include i-Tree, ARIES (Artificial Intelligence for Ecosystem Services), Costing Nature, and SolVES (Social Values for Ecosystem Services) (see Supplementary Table 1 and associated references¹⁸). Together, these tools have enabled significant advances in measuring the benefits of natural infrastructure in cities around the world. However, to the best of our knowledge, none of these tools can simultaneously assess a large number of urban ecosystem services, operates in cities around the world, and informs a wide variety of urban decision

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contexts (e.g., flood zone planning, climate adaptation, biodiversity conservation, and public health). For example, with its focus on urban trees, i-Tree cannot assess the benefits from green roofs or coastal habitats. Many other tools emerge from research in specific fields and focus on a narrow set of services (e.g., stormwater management). Enabling a comprehensive assessment of services and natural infrastructure is important to further develop the science of urban systems and facilitate a dialogue between researchers and practitioners with different expertise. The InVEST tools support such assessments by allowing for the consideration of more services provided by a diverse type of natural infrastructure (Table 1). As we detail in this paper, the tools are also flexible and broadly applicable (or 'reusable', sensu Hamilton et al.)¹⁹, with dedicated software maintenance, which increases the size of their user community—a critical factor in the uptake of decision-support tools.

With the tremendous advances in globally available spatially explicit data, scientific understanding, and practical applications²⁰—along with a rise in the demand for accessible and actionable assessments—we see an opportunity to build a more integrated, globally applicable approach for natural infrastructure assessment in cities worldwide. The next sections describe the main design elements of the InVEST urban tools that support such an approach and introduce three applications in Shenzhen, China, the Twin Cities, USA, and Paris, France. The case studies represent different spatial scales and decision contexts (economic valuation, land use change prioritization, inclusive regional planning), illustrating the flexibility of the approach, which we discuss, together with its limitations, in the final section.

RESULTS

Diversity of information needs related to nature's benefits in cities

Information about how natural infrastructure generates benefits for urban dwellers can be summarized in three categories: (i) how much of various benefits does natural infrastructure provide, (ii) where does natural infrastructure provide those benefits, and (iii) to whom? Fig. 1c gives examples of questions in each category illustrating the breadth of the decision contexts and associated information needs. Understanding and measuring the benefits of natural infrastructure (how much, where, and to whom) could help local governments choose how to invest. It could also be of use to the private sector, non-governmental and civil society groups, and researchers, who can bring scientific and technological innovation into projects on the ground. The context in which these groups operate and the decisions they face will dictate the types of information that are most useful, including which metrics to use to characterize natural infrastructure. For example, the COVID-19 pandemic increased the focus on mental health and resilience benefits of natural infrastructure²¹.

Reflecting the different decision contexts, models—simplified representations of reality—can be used in three broad ways (Fig. 1b)^{19,22}. First, models can be used for informing on the ground decisions (urban project or policy design), which typically requires quantitative models with relatively low uncertainty. Second, models can be used for exploration—improving understanding of general trends and dynamics of complex systems and inferring general implications of alternative planning options. Finally, models can be used for communication and learning—conveying key insights and facilitating joint understanding. These latter types

Table 1. InVEST urban models and the name of the service, supply, and value metrics.

Model name (Service) ^a	Supply metric	Value metric	Key references
Urban cooling (Local heat mitigation)	Air temperature reduction (degree Celsius)	Work productivity loss (%) Energy (kWh) and cost (\$) savings	76,77
Urban flood risk mitigation (Natural hazard protection)	Extreme weather runoff volume retained (m ³)	Potential avoided damage (\$)	78
Stormwater runoff retention* (Water flow regulation)	Annual stormwater runoff retained (mm/yr) Avoided nutrient load (kg/yr)	Avoided cost of stormwater retention (\$)	78
<i>Carbon sequestration & storage</i> (Global climate regulation)	Carbon stored and sequestered (Mg) on land and in coastal areas (blue carbon)	Economic value of carbon sequestered (\$)	79
<i>Coastal vulnerability reduction</i> (Natural hazard protection)	Vulnerability index based on biophysical and social factors	None	80
<i>Nature-based recreation^b (Recreation and tourism)</i>	Accessible recreation areas (m ²)	Number of photo-user-day (proxy for visitation intensity) Urban green space deficit and surplus (relative to demand)*	81–83
<i>Scenic quality provision (Landscape aesthetic)</i>	Visible natural areas	Visual impact (number of points) and visual quality indices (binned into classes)	84
<i>Crop pollination & honey bee forage (Pollination)</i>	Pollinator habitat quality	Crop yield attributable to pollinators Pollinator abundance as a proxy for biodiversity	85,86
<i>Sediment/Nutrient retention (Erosion/Nutrient regulation)</i>	Sediment/nutrient retained (ton/yr)	None	87,88

^aModules marked with an asterisk (*) are not yet implemented into the InVEST software but have been used by the authors in prototype versions; we expect to make them available soon. Model names in italics denote models that existed in the original InVEST suite and are applicable to both natural/rural and urban landscapes.

^bThis service is assessed via two complementary models: the visitation InVEST model (producing the photo-user-day output) and the greenspace access model (producing the deficit and surplus metrics).

Services follow the terminology proposed by Burkhard et al.⁷⁵ Value metrics are those directly produced by the InVEST models. They do not reflect the most relevant metrics but rather most widely applicable (due to data availability constraints). Detailed model descriptions can be found in the user's manual (Sharp et al.¹²). Additional models will ultimately complement the current urban suite, including mental health, physical activity, noise attenuation, air purification, and urban biodiversity.

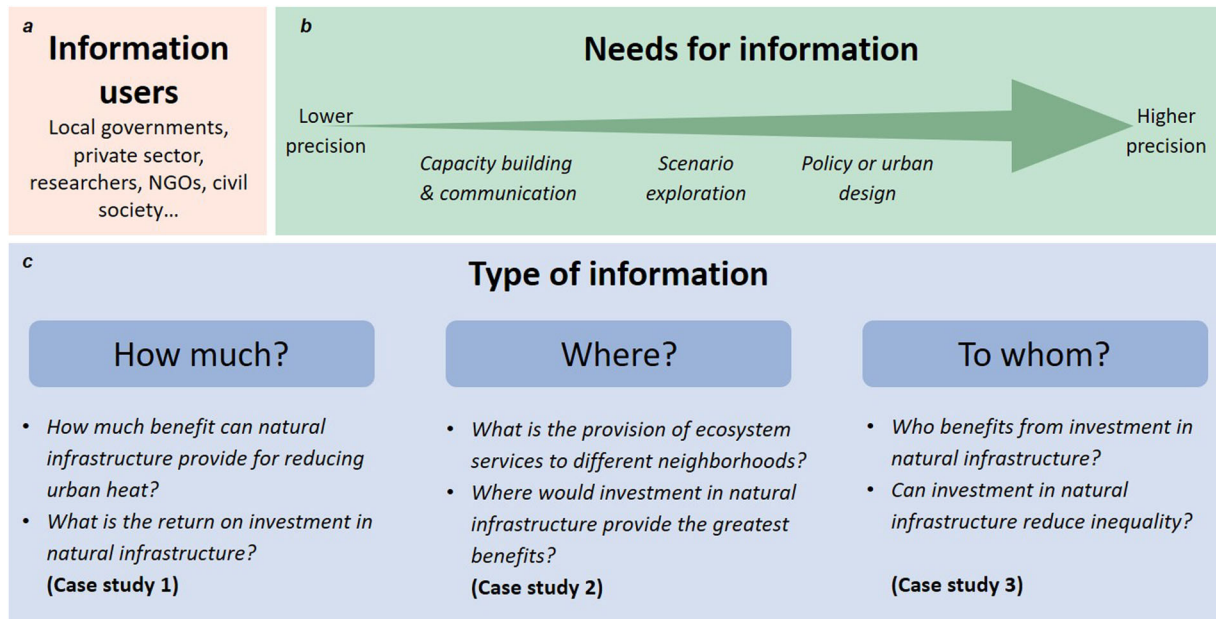


Fig. 1 Diversity of modeling needs for mapping nature's benefits in cities. Modeling tools can address **a** multiple users, **b** varying needs for precision, and **c** different types of information.

of model uses do not typically require the level of precision needed for on-the-ground decisions. The diversity of modeling needs resulting from multiple users, needs, and types (summarized in Fig. 1) requires specific features in the design of modeling tools, which we detail next.

Key design features of InVEST's urban tools

A review of existing urban ecosystem services tools (Supplementary Table 1), types of model use (Fig. 1), and experience with InVEST over the course of more than a decade (Supplementary Methods) point to key features of effective decision support tools: (i) production of metrics supported by sound science that are relevant to policy decisions; (ii) flexibility in the type of decisions, scales, or actions the tools can support; and (iii) free and open-source code that can be applied (and/or modified as necessary) anywhere with easily accessible data. These features, detailed in Supplementary Table 2, guided the development of InVEST models and help to ensure salience, credibility, legitimacy, and accessibility—key features of effective knowledge systems²³ and successful modeling projects¹⁹.

Like the original InVEST models, the urban models introduced in this paper use an “ecosystem service cascade” to describe the flow of services from ecosystems to people^{24,25}. We model two steps: supply (the ecological function creating a potential service), and value (the benefit that individuals or groups of individuals may derive from the service, Table 1). Actual benefits (ecosystem services “flow”²⁶) occur when there is demand for the service. They may be estimated implicitly, by assuming there is demand for this service in the service providing area, or explicitly, by overlaying spatial information on demand. For example, in the flood risk mitigation model, users can choose to represent only the areas that are flood-prone, where reduction of runoff would reduce flood hazard. The nature of ecological functions implies that some models are applicable to any landscape, rural or urban (e.g., carbon sequestration, coastal vulnerability reduction), while we developed others specifically for use in urban environments (e.g., urban cooling, urban flood risk mitigation).

The following three case studies illustrate different decision contexts and modeling purposes: the first case is an example of information for decision-making, focusing on the quantitative

value of natural infrastructure (“how much?”), while the next two are examples of exploratory modeling and social learning, focusing on spatial prioritization (“where?”) and equity analyses (“to whom?”). We use InVEST in combination with other models to illustrate the flexibility of the tool.

Application 1: Assessing the economic benefits of natural infrastructure in Shenzhen, China

Shenzhen, China, is one of the fastest-growing cities in the world with a population that grew from roughly 50,000 in 1980 to over 12 million in 2018. To inform urban planning, the city government of Shenzhen has adopted the use of Gross Ecosystem Product (GEP), a new metric being developed and widely tested in China^{27–30}. GEP calculates the monetary value of the contribution of ecosystems to society to inform investments in ecosystems and to track the performance of policies. Recently, Shenzhen was designated by the central government as the country's first pilot city to use GEP to measure the monetary value of ecosystem services contributed by urban natural infrastructure.

Using a combination of InVEST and bespoke models, we found that natural infrastructure in Shenzhen reduce extreme weather runoff by 187 million m³ (for a 100-yr storm event) (Table 2), conferring benefits of 25 billion USD in avoided costs. Retention of sediment conferred avoided costs of 8.5 million USD for the year 2018. Natural infrastructure reduced the daily air temperature by an average of 3 °C in built-up areas during summer days, which translates into benefits of 71,000 USD/day for the city as a whole. The value of the three services will be combined with the value of other ecosystem services (e.g., air purification, carbon sequestration, water purification) to calculate the total GEP for Shenzhen in 2018. Methods to calculate GEP were shared with government departments as data collection and reporting are becoming part of the standard government operation, with support from the Shenzhen Statistics Bureau. The Shenzhen government expects to use GEP in designing land use plans, assessing management performance of administrative sub-areas, and communicating with citizens about the economic value of local ecosystems. This effort mirrors a global interest in economic valuation of ecosystem services with international institutions promoting natural capital accounting^{31,32}. Often, these efforts are hindered by a lack of

Table 2. Biophysical and economic values for three services in the Shenzhen urban area.

	Flood risk mitigation	Sediment retention	Urban cooling
Biophysical value	187 Mm ³ /yr	3.38 Mton/yr	3 °C/day
Economic value	25 × 10 ⁹ USD/yr	8.5 × 10 ⁶ USD/yr	71,000 USD/day

Services include flood risk mitigation during a 100-yr design storm, sediment retention for the year 2018, and urban cooling in 2018. Economic values can be used to calculate the gross ecological product (see text).

standardized approaches^{33–35} and tools like InVEST could help bridge that gap by providing quantitative information on ecosystem services.

Application 2: Prioritizing land-use change in the Twin Cities, USA

Cities adapt to different needs and pressures as societies and urban priorities change, leading planners and developers to reassess existing land uses. In the Twin Cities (Minneapolis-St. Paul) Metropolitan Area, USA, we explored the impact of potential changes in land use on the provision of benefits across an urban area. In particular, we explored possible transitions of urban golf courses to other types of uses. As golf participation and revenues decline and demand for housing increases, private golf courses see opportunities to sell their land for development^{36,37}. To examine the impact of such decisions, we evaluated ecosystem services provided by golf courses relative to alternative land uses. The methods we used are general and can be applied to any land-use change in urban environments.

InVEST modeling results suggest that the conversion of golf courses to residential areas tends to reduce the supply of ecosystem services, while conversion to city parks would increase the supply (Fig. 2). Compared to residential areas, golf courses provide higher pollinator habitat and lower nutrient export (57% reduction), while providing a slight improvement on cooling for nearby residents. The large reduction in nutrient export comes from the lower density of buildings and pavement compared to the residential landscape, and the assumption that residential areas have similarly intensive land management practices. Residential land use can increase daily mean air temperatures in adjacent lands upwards of 0.1 °C compared to golf courses though the typical increase is small (Fig. 2). The negligible changes in temperature are explained by the similar amount of shade and evapotranspiration in golf courses and residential areas. Conversion to city parks enhances cooling and pollination services and reduces nutrient export (see Supplementary Methods).

Overall, urban green spaces such as parks and to some extent golf courses provide significant ecosystem service benefit relative to residential development. However, these benefits vary by service and by neighborhood within a city, as evidenced by the spread of ecosystem service values relative to golf courses (see boxplots in Fig. 2). Targeted prioritization of urban green space initiatives based on their relative ecosystem service impact can help decision-makers improve the urban environment and the way in which it delivers desired benefits. The approach presented here highlights the consequences of public or private land use decisions, an important driver of urban ecosystem services³⁸. It can be replicated to guide land development decisions such as brownfield redevelopment, urban growth boundaries, and tree-planting initiatives with nationally available data.

Application 3: Regional planning integrating equity metrics in Paris, France

The Ile-de-France region comprises the urban area of Paris in addition to surrounding areas of forest and agriculture. Given the population growth of the metropolitan region, built land use types

in the Ile-de-France region are increasing—having grown from 18% of the area in 1982 to 23% 35 years later. In 2018, we started an evaluation of ecosystem services involving more than 50 stakeholders from 27 institutions, including government agencies (e.g., the regional biodiversity agency (ARB), Metropole du Grand Paris, Institut Paris Région), and NGOs such as *France Nature Environnement* (see details on the IDEFESE project's website³⁹). We examined the impact of land-use change on the value and distribution of ecosystem services to provide recommendations for future master plans.

Using a combination of InVEST and bespoke models, we found that over the past 35 years natural and semi-natural areas shrank by 0.4% in Ile-de-France. Reflecting the decline in natural and semi-natural areas, the supply of seven of eight services generally declined over this period, but at differing rates (Supplementary Fig. 3). The change in ecosystem services ranges from a slight increase (<1% for nutrient retention) to a decline of more than 8% (agricultural potential). We also showed that areas with the lowest access to green space, and areas where green infrastructure investment would reduce inequity only partially overlap (Fig. 3). These results help to visualize and illustrate important equity implications of investing in natural infrastructure. Equity and environmental justice considerations are receiving increasing attention in sustainability research and in cities worldwide^{40,41}. Consideration of spatial justice, in particular, can be mainstreamed by leveraging the potential of geospatial analyses such as those presented here. We note that the present results do not incorporate the demand for ecosystem services, although we are examining this dimension in ongoing research.

DISCUSSION

Incorporating natural infrastructure into urban planning and design can increase benefits from ecosystem services to urban residents, promote biodiversity, and make cities more sustainable. Despite major advances in characterizing the benefits of natural infrastructure within the academic community^{5,42–44}, this understanding typically has not been incorporated into urban planning and decision-making⁴⁵. This gap may be explained in part by the time it takes for science to percolate into standard practice. It may also stem from a lack of transdisciplinary approaches to address urban sustainability issues, leading to calls for better integration of research and practice in urban management^{42,46}. Most importantly, closing the implementation gap requires closer integration of science with practice to remove barriers to nature-based solutions in cities^{47,48} and integrating knowledge from different fields to capture the wide range of benefits (or costs) from nature to people^{6,8}.

We designed the urban tools in InVEST to help close the gap between science and practice. By making information readily available and compelling, easy-to-use tools such as InVEST can support local dialogue between different stakeholders and enable “directed transformations” that enhance resilience in cities⁴⁹. This is achieved by a modular approach (Supplementary Table 2), where InVEST users can choose to model a subset of services, as illustrated in our case studies, or convert InVEST outputs into different metrics (for example, use the temperature reduction to

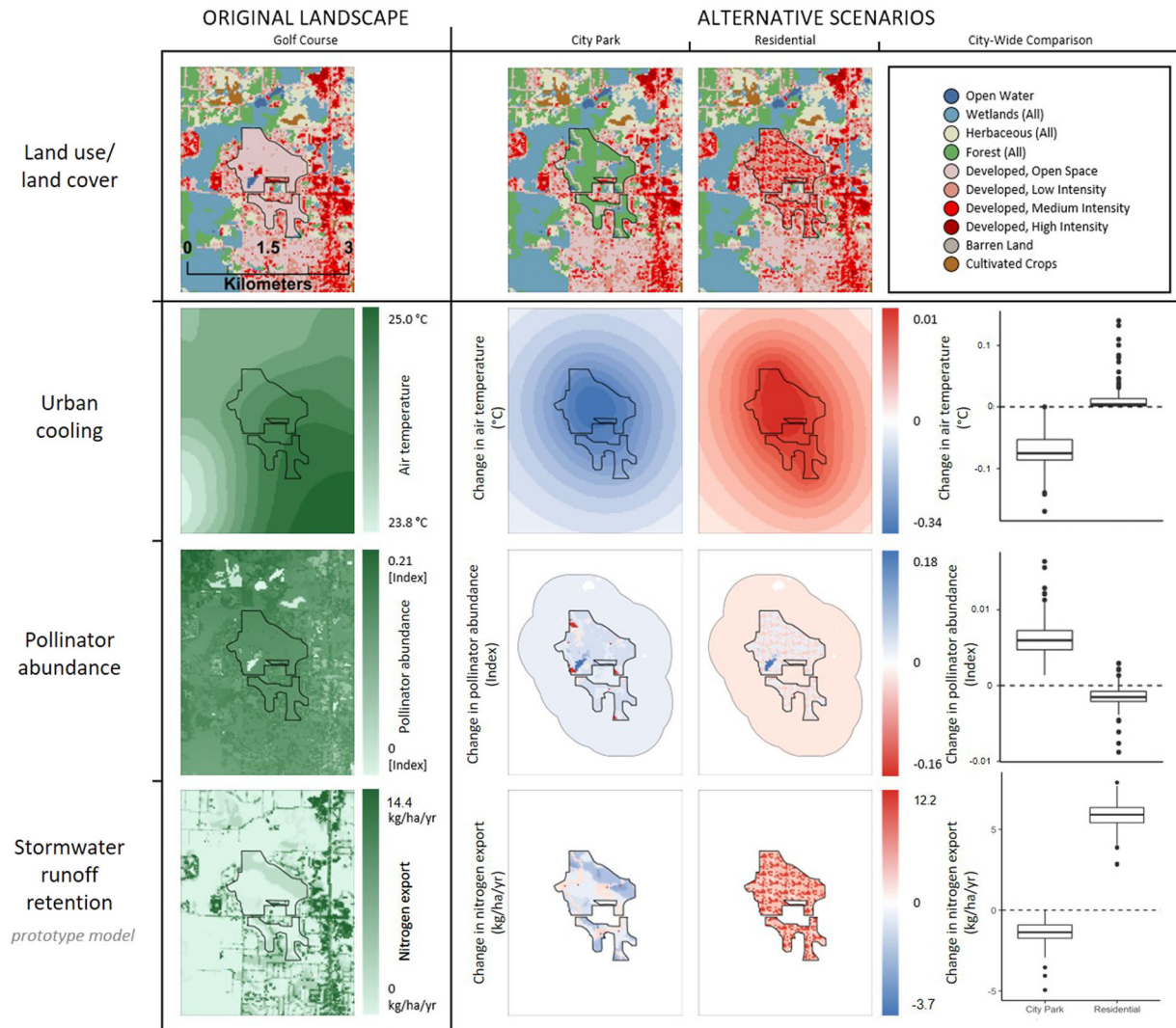


Fig. 2 Ecosystem services provided by golf courses in the Twin Cities (Minneapolis-St Paul) compared with a city park and residential area. Though we modeled golf courses across the metro area, we present maps of ecosystem services on a single golf course parcel as an example of the types of results typical of InVEST models. Boxplots represent the change in an ecosystem service metric relative to a golf course (visualized by the dotted 0 line) for all 135 golf courses analyzed. Boxes represent the interquartile range. Upper (lower) whiskers are the maximum (minimum) values of the data within 1.5 times the interquartile range over (under) the 75th (25th) percentile.

express urban cooling service in metrics of public health⁵⁰. Closing the implementation gap would help produce useable knowledge on the interactions between social, technological, and ecological systems in cities^{5,51}. This is particularly urgent for cities in the Global South, where much of the existing knowledge base is currently inapplicable and where it may be most needed^{5,6,44,52,53}. It is also important to better incorporate equity issues in urban planning^{40,41}, as illustrated in our third case study.

In this paper, we used InVEST to assess eight services, with globally or nationally available data (e.g., national land cover maps), or in combination with local datasets (e.g., natural habitat data in Paris, temperature data in Shenzhen). These case studies complement the few case studies where 'original' InVEST tools had been used in predominantly urban environments^{54,55}. In the Paris case study, InVEST tools were particularly helpful in stakeholder engagement; its accessibility (using readily available data, and producing easy-to-interpret outputs) made it possible to quickly present preliminary results to stakeholders and iterate on goals and outcomes of the projects. In addition, the tools provided information at multiple scales relevant to urban decisions: the Twin Cities case study shows the impact of relatively small

changes in land use (<1 km²) while the Paris and Shenzhen case studies examined patterns at large scales (~10,000 km²). The case studies also demonstrate the use of tools ex post to evaluate changes in land use on benefit flows (Paris) and ex-ante to evaluate potential future alternative plans (Twin Cities).

Although the case studies presented here are in high-income cities with good data, we developed the InVEST urban tools to be applied in any city around the world. This characteristic is important for cities with lower data availability and fewer resources to run complex models⁴⁴. The increasing availability of earth observations globally makes high resolution (e.g., 10 m) environmental data more accessible⁵⁶, which can improve spatial data inputs or model parameters (e.g., capturing tree canopy cover within a residential area, as noted in the Supplementary Discussion of the Twin Cities application). Parsimonious and robust tools like InVEST help empower cities with few resources by enabling relatively simple first steps towards understanding the value of natural infrastructure. Even with cities with few internal resources, such analyses can be supported with the help of multilateral development banks or professional networks like ICLEI (Local Governments for Sustainability) or C40 Cities. Because InVEST has a

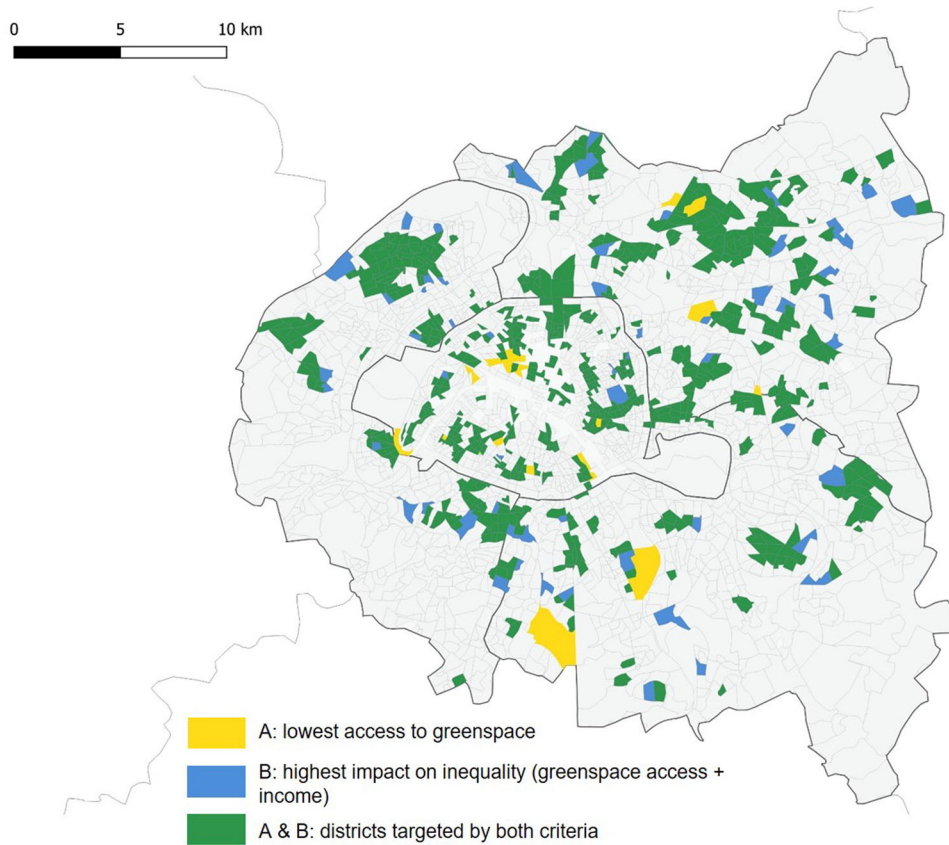


Fig. 3 Priority areas for investing in natural infrastructure in the Paris region, France. Priorities are defined according to two different criteria: lowest access to nature (yellow) and highest impact on inequality, defined by access to green space and income (blue). Green areas represent the overlap between the two selections (see details in Supplementary Methods). While wealthier areas (e.g., within Paris) have lower access to green spaces, investing in natural infrastructure in these areas has a lower impact on reducing inequality.

large user community worldwide, new users of the urban tools will benefit from active support through training programs and the online user community which counts more than 75,000 visitors annually (<https://community.naturalcapitalproject.org/>). In addition, the flexibility and open-source format of the tools also allow for their appropriation and modification by local governments, NGOs, or civil society—making it a resource for community-led initiatives and a tool for enhancing procedural justice. This may be particularly relevant in a post COVID-19 world where the role of natural infrastructure management is recognized and actions at different levels of governance are encouraged to increase^{57,58}.

Beyond local-scale applications in individual cities, recent applications show the potential of InVEST or similar tools for analyses at the global scale, i.e., with low resolution but a high number of cities. The Nature in the Urban Century Assessment⁵⁹, for example, shed light on the impact of future urbanization on biodiversity and using InVEST—the vulnerability of cities to coastal hazards from loss of natural infrastructure. Similarly, Endreny and colleagues used i-Tree to estimate current and potential future ecosystem services from trees in 10 megacities worldwide, illustrating the potential of such global analyses to motivate and accelerate progress towards urban sustainability⁶⁰.

We conclude this discussion by highlighting limitations and future research directions. InVEST provides only one element of the ecosystem knowledge needed to plan cities—that of urban natural infrastructure and the services it provides to people. It does not replace more comprehensive urban planning tools that better capture built infrastructure and multiple socio-economic dimensions^{61,62}, nor can it replace fine-scale (building- or precinct-scale) design tools. InVEST can complement these other tools by

integrating its inputs and outputs in multi-criteria models, a process facilitated by the increasing digitalization of cities⁶³.

InVEST tools are designed to be relatively simple and use readily available data. More specialized state-of-the-art models exist in each discipline (e.g., hydrology, microclimate, coastal engineering), which can be utilized in cases where expertise and data exist. The simplifications in InVEST result from important design constraints related to input and calibration data (limited to those easily accessible from public databases) as well as technical skills and experience of users (our target users are GIS analysts with little modeling experience). Although model simplifications result from deliberate choices, they need to be considered when using the tools, especially if other, more sophisticated, or tailored models are available in a city. Our case studies illustrate such choices where InVEST tools were used in combination with other models (e.g., the urban cooling model used in the Shenzhen case study), which is especially useful when better—or more accepted—models are routinely used (e.g., for urban water management). Specific limitations for each model are provided in the references listed in Table 1.

Exploring future scenarios should incorporate climate change, a dimension that was not incorporated in the case studies above. Most InVEST models have climatic inputs (e.g., annual precipitation in the stormwater model, the temperature in the urban cooling model, etc.), making it relatively easy to explore the impacts not only of changes in management but also of changes in climate on the provisioning of services. Mandle⁶⁴ proposed guidelines on how to incorporate climate change into modeling in InVEST that are applicable to the new urban tools as well. Therefore, each of the three case studies we explored could

include climate scenarios; ongoing work on the Paris case study examines how changes in climate—in addition to changes in land use—might alter trends in ecosystem services³⁹.

Further work can also be done on how to better bridge the science–practice gap, including the use of tools such as InVEST in negotiating and decision-making in cities. Active engagement can not only help to improve information flow to decision-makers but also improve the tools by suggesting new decision-relevant metrics, improving visualization options, among other improvements. The process of introducing and iterating on InVEST results is as important as the final results themselves and substantive literature highlights the benefits of iterating between results of decision-support tools and assumptions^{55,65–68}.

In addition, there are other potential improvements in science and implementation to improve the flow of information about natural infrastructure in cities. Science is advancing on a broad set of potential benefits, such as air quality modeling, and modeling of mental and physical health⁵ that could be incorporated into InVEST. Doing so would broaden the suite of benefits that could be assessed. Improving the linkages to measure of health and wellbeing^{7,69}, along with analyses of the distribution of benefits present another set of frontier issues.

In conclusion, the research approach and tools presented in this paper have the potential to lower the barriers to incorporate the value of urban natural infrastructure into decision-making. By doing so, there is the potential for cities to invest in nature to become more sustainable and to improve the delivery of benefits to current and future urban residents. The nature of urban planning implies myriad decisions about how much and where natural infrastructure should be implemented or protected, and whom it will benefit. The development and application of tools like InVEST can contribute to reducing the gap between research and practice, helping cities around the world plan a more sustainable future for people and nature.

METHODS

Key design features of InVEST's urban models

We reviewed commonly used ecosystem services tools applicable to urban environments (see Supplementary Methods). We listed the ecosystem services and decision contexts that each tool addresses to identify practical gaps that the InVEST tools aim to fill.

Assessing the economic benefits of natural infrastructure in Shenzhen, China

We used InVEST and local empirical data to assess the economic value of three services provided by natural infrastructure – urban flood risk mitigation, sediment retention, and urban cooling – in the urban area of Shenzhen. For each service, we compared scenarios with and without contributions from natural infrastructure. We applied the InVEST urban flood risk mitigation model for a storm with a return period of 100 years. We ran the InVEST sediment retention model to simulate the avoided soil loss in 2018. To represent the value of each of these services in monetary terms, we used avoided costs of building retention infrastructure and dredging sediment (for the stormwater and sediment retention services, respectively, as detailed in Supplementary Methods and Supplementary Fig.1). In addition to modeling with InVEST, we also used an urban cooling model developed by some of the authors based on a statistical relationship between green space and land surface temperature developed for Shenzhen. We computed the associated energy savings of air cooling according to a relationship between electricity consumption and air temperature (see Supplementary Methods).

Prioritizing land-use change in the Twin Cities, USA

We applied the InVEST tool to assess pollinator habitat, urban cooling, and stormwater runoff retention services provided by 135 golf courses relative to alternative land uses in the Twin Cities. Previous work evaluated a broader set of services provided by golf courses using a mix of InVEST and local regression models with local land cover and land use data⁷⁰. Here, we

modeled three services using InVEST and national land cover data and applied a marginal value approach⁷¹ to compare the amount and distribution of benefits provided by each golf course. We compared the services that a park or a residential area would provide at the same location by running the models with the current land use map compared to the alternative land use (Supplementary Fig. 2). Current land use within golf course boundaries was often urban ('Developed, Open space') and ignored the details of vegetation patterns due to relatively coarse resolution (30 m, see Supplementary Methods). Alternative land uses were based on typical patterns found in the city: a mix of predominantly forest and developed open space for city parks, and developed open space and low to high-density development for residential areas (Fig. 2). We assumed that residential areas had intensive landscape management practices (use of fertilizer), similar to golf courses, and did not explicitly consider the effect of irrigation (see discussion in the previous work⁷⁰).

Regional planning integrating equity metrics in Paris, France

We used InVEST and regional data on natural habitat to assess eight ecosystem services in the Ile-de-France region: agricultural potential, groundwater recharge, carbon sequestration and storage, nutrient retention, nature-based recreation, urban flood risk mitigation, urban cooling, and habitat provisioning (to protect natural heritage). Our team selected these services in consultation with the stakeholder group on the basis of their perceived importance and lack of consideration in urban planning documents to-date⁷². To estimate the effect of land use change on ecosystem services, we quantified the natural and semi-natural areas (including forests and open spaces outside developed areas) in both 1982 and 2017 and ran the ecosystem services models for both land use maps. To support equitable urban planning policies and inform where investments in natural infrastructure should be prioritized, we also simulated where increasing access to urban green space would most reduce spatial inequalities. To do so, we identified areas where land conversion to green space would reduce inequalities based on the criteria of access to green space and household income as measures of well-being⁷³, SI. We compared these areas with those targeted by a simpler indicator of access to green space (targeting areas with the lowest amount of green space).

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

DATA AVAILABILITY

The data generated and analyzed during this study are described in the following data record: <https://doi.org/10.6084/m9.figshare.13910660>⁷⁴. The raster files underlying Fig. 2, Table 2 and Supplementary Fig. 1, and the shapefile underlying Fig. 3 in the related manuscript will be shared via institutional file storage and linked via the data record. Interested readers are encouraged to contact the authors for additional information.

CODE AVAILABILITY

Source code for the InVEST software is available at: <https://github.com/natcap/invest>. Additional code used to process results is available on reasonable request.

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AUTHOR CONTRIBUTIONS

All authors contributed to the design of the new InVEST software tools and reviewed and edited the manuscript. Hamel, Guerry, Polasky, Remme, Nootenboom, Janke, Han, and Tardieu wrote the original draft. Sharp, Douglass, Hamel, Nootenboom, Janke, and Han developed the software. Han, Xu, Hamel, Nootenboom, Janke, Lonsdorf, Tardieu, Vigié, Levrel developed the methods for the case studies.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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