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Review

Models for Assessing Urban Ecosystem Services: Status and Outlooks

Xinyu Ouyang [1] and Xiangyu Luo [1,2,3,*]

[1] College of Life Science, Sichuan University, Chengdu 610065, China; ouyangxinyu0101@outlook.com
[2] Ministry of Education Key Laboratory for Earth System Modelling, Department of Earth System Science, Tsinghua University, Beijing 100084, China
[3] Sichuan Forestry and Grassland Bureau, Chengdu 610081, China
* Correspondence: luoxy17@mails.tsinghua.edu.cn

Abstract: Urban ecosystem services provide many benefits for human beings. Given the dramatic increase of urbanization, maintaining sustainability of cities relies heavily on ecosystem services, and it is crucial for quantifying, managing, and optimizing urban ecosystem services to promote social and ecological sustainable development. This study presents the review of models for assessing urban ecosystem services through gathering the pertinent literatures which were published recent years. The main types of approaches for assessing urban ecosystem services were summarized, and the model simulation approach was detailed. From modelling techniques to the existing models, it was found that a process-based model is, relatively, a better way to detect the mechanism of urban ecological processes and simulate the future dynamic changes of urban ecosystem services. Three key limitations of existing products and frameworks were identified: (1) lacking understanding of multiple urban ecosystem services interactions, (2) ignoring accounting the socioeconomic factors into dynamics of urban ecosystem, and (3) lacking considerations of feedback effects between social system and urban ecosystem. The study concludes with outlooks that a comprehensive social-ecosystem model based on the social-ecological framework is helpful to reveal the relationships and interactions among various urban ecosystem services, and can better assess how human-induced urban growth affects ecosystem services, and better describe the feedback effect between the social environment and urban ecosystem services, as well as dynamically predict the changes of urban ecosystem services under different scenarios in future long time series.

Keywords: urban ecosystem service; assessing; modelling techniques; social-ecosystem

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1. Introduction

Ecosystem provides many benefits for human-beings, and people still rely on ecosystem services even in modern society, with increasingly developed science and technology. These various services provided by the ecosystems were conceived in the 1970s [1,2], and the term "ecosystem services" did not appear formally until 1981 [3]. Early definitions of ecosystem services emphasized that benefits are directly or indirectly provided to humans by natural ecosystem processes and functions [4,5]. In the developing process of the definitions of ecosystem services, the core of definition is always concentrated on the relationship between ecosystem and human wellbeing. As the definition had been developing continuously, both the natural components [6] and ecological phenomenon [7] could be defined as the source of services; meanwhile, all benefits for humans [8] or all contribution to human wellbeing [9] were also considered as ecosystem services.

The urban ecosystem is a complex human-dominated system, involving with many factors and interactions in several fields, such as natural environment, social economy, and culture. Given its complexity and, particularity, the previous definitions of ecosystem, services cannot be well adapted to the studies of urban ecosystem. However, there are relatively few definitions of urban ecosystem services (UES) at present. Bolund and

Hunhammar [10] took the lead in defining urban ecosystem services as those directly and locally generated and related to cities, and highlighted that they are provided by urban ecosystems [7] and their components [11] and consumed by urban residents [12]. In order to avoid the contradictions and deviations of studies on UES, it is critical to well understand the connotations of UES [13]. For the geographical scope, the city mentioned by the definition of UES does not only refer to the city center, but also includes those peri-urban regions relevant to city [14], such as suburbs, towns, and villages. For the structures, urban ecosystem services are generated from natural components, whether those components come from ecological, semi-natural, or artificial structures. For the services, it underlines that urban ecosystem services should be distinguished from those services provides by society [15].

With the rapid development of urbanization, urban populations are rapidly growing and urban areas are constantly increasing. The proportion of the world's urban population has increased from 43% in 1990 to 54% in 2015, and it is expected that nearly 70% of people will live in cities by 2050 [16]. The growing trend is more obvious in China, where the built-up area has tripled from1990 to 2015 [17], with more than 58% of population living there; it is predicted that this number will near 80% in 2050 [16]. Given the dramatic increase of urbanization [18], maintaining sustainability of cities relies heavily on ecosystem services [19], and it is crucial for managing and optimizing urban ecosystem services to promote social and ecological sustainable development [20]. Through the assessment of urban ecosystem services, we can clearly know the ability of urban ecosystem services to mitigate the impact of urban expansion on the structures, functions, and compositions of surrounding natural ecosystems. Additionally, we can also precisely calculate the capacity of urban ecosystem services to provide basic materials and services for urban residents [21]. Based on the precise understanding of urban ecosystem services, the assessment of urban ecosystem services is promoted to be more in line with the urban reality, which can help us make better policies and plan cities [22].

The main approaches for assessing urban ecosystem services can be generally classified into three categories, indicators-based method, valuation-based method, and model simulation [23]. Screening the indicators of UES is not only the key process for indicator-based method, but also an important premise of all approaches. Indicators-based methods experienced the transformation from independent indicators to an indicator system [24,25] for integrating more information into assessment. Though it has been widely used all over the world due to these convertible, operable, and integrable indicators, it is insufficient to reflect the mechanism of changes of UES. The valuation-based method contains three aspects, economic value, social and cultural value, and insurance value [26]. Using indicators and monetized expression, whether applying market prices, conditional value method, or the value transfer to assess the value of UES [27], the valuation-based method makes people intuitively feel the importance of UES and improves people's awareness of natural conservation [28]. However, these methods are relatively subjective and deficient in practical guidance. Studies on modelling urban ecosystem services are increasingly popular with various models emerged one after another. Based on indicators and values, models can systematically assess UES rather than bookkeeping assessment [29]. Model construction is the basis of scenario predictions and multi-objective analysis, while the predictions and analysis are the further applications of model development, as well as a mean to directly apply ecosystem services assessment into urban planning and management. Models are not only convenient tools for integrating assessment into decision-making, but also evaluation methods for future urban ecosystem services.

We reviewed the current studies on the models for assessing urban ecosystem services. Firstly, we summarized the state-of-the-art of models, classified the categories of modelling techniques, and introduced the current progresses and characteristics of modelling. Next, we identified some current products of modelling urban ecosystem services, and compared their advantages and shortages from several perspectives, including structures, parameters, data availability, and model results. Finally, based on the status of models for assessing urban ecosystem services, we identified gaps in our understanding and propose the outlooks of future research on urban social-ecological models.

2. The State of the Art of Urban Ecosystem Models

2.1. Classification of Modelling Techniques for Ecosystem Services

At present, there is a growing understanding of ecosystem services and a growing need to incorporate ecosystem services into policy decisions. It has become a growing trend to integrate urban ecosystem services into policy making, in particular, for a rapidly developing city that is highly dependent on scientific planning and decision-making. Models play an important role in realizing efficient urban ecosystem service assessment and explicit spatial representation, since the research on modelling urban ecosystem services has emerged. In order to apply models to better make urban management strategies and promote urban sustainable development, various modelling techniques and model frameworks have been continuously applied in the urban ecosystem service models. Based on the logic of models, the existing classification of modelling techniques mainly includes correlative models, expert-based models, and process-based models [30].

Correlative models usually use land use types or other ecological parameters to represent the value of ecosystem services based on relationships between ecosystem services and ecological parameters or their statistical correlations [31]. The majority of them often integrate various data, including social and economic data, field survey data, and the attribute data of hydrology, soil, and vegetation, to simulate the value of ecosystem services, and the spatial scopes vary from global to cities. For instance, the Matrix model is a kind of correlative models for quickly mapping ecosystem services by using rows and columns to represent land cover types and ecosystem service classes respectively [32]. de Groot et al. [33] summarized the results of ecosystem services assessment from over 300 cases around the world and derived the global average value. Although correlative models are simple and intuitive, and easy to apply in the preliminary assessment, there are still some limitations. It is difficult to show the characteristics, and temporal and spatial heterogeneity for a specific area, to reflect the scale effects on ecosystem services supply ability of different land cover types, and to illustrate the influence of external changes on the relationship between social system and ecosystem [34,35]. In particular, the correlative model applied in urban areas often has great uncertainty with low credibility and weak applicability, due to such reasons as insufficient data accuracy, high heterogeneity, and effects of external factors.

Assessing urban ecosystem services often involves multiple systems with a high degree of interactions, but the understanding of the complex system often lacks theory and enough data to support; expert-based models are semi-quantitative ways which can simulate and predict it with interdisciplinary knowledge [36]. Social ecological scenarios analysis and Bayesian network are common methods. The former focuses on dynamic change of relationship between ecosystem services and human well-being. Involving driving force of ecological changes into modeling can improve its effectiveness [37] and provide referenced solutions for stakeholders to face the changes in ecosystem services and human well-being. As for future prediction, it is also useful to analyze tradeoffs of multiple ecosystem services and illustrate their relevance to spatial pattern [38]. The latter combines the qualitative probability of experts' prior knowledge with the quantitative relationship of model variables to simulate the flows of ecosystem services. Balbi et al. [39] used the ARIES model to integrate several kinds of data to effectively predict people's dependence on natural resources in rapidly urbanized areas, further demonstrating that expert knowledge can offset data limitation. However, the expression of relationship by semi-quantitative method still exists difficulties in describing the feedback process of ecosystem services, and the lack of clear practical guidance limited their widely usage [40].

Process-based models can establish the flow process of natural capitals and ecosystem services with the understanding of ecosystem functions and biophysical processes [41]. According to the different theories and modeling purposes, it can be divided into specific models and comprehensive models. Specific models are designed for a particular service, and accentuate its responses to externally driven changes, while comprehensive models more concentrate on multiple ecosystem services and aim to analyze their trade-offs and synergies. Compared with the limitations of the former two modeling techniques, process-based models are more applicable to reflect the actual supply of ecosystem services, the feedback interactions of social system and ecosystem, and the objective logical correlation between ecosystem services [29]. In addition, using analysis of sensitivity and uncertainty to calibrate and verify the model results can also increase its credibility. In spite of this, process-based models are relatively difficult to develop and limited in their openness; they still benefit from exploring the mechanism of interactions between human and ecosystem during long-term [42], and can better settle the issues that lack dynamic interactions and feedback mechanisms [43].

2.2. Applications of Process-Based Models in Specific Urban Ecosystem Service

Process-based models were initially derived from the needs of application for forestry, hydrology, agronomy, and edaphology for assessing ecosystem services generated by natural ecosystem. These models mainly focused on the description of vegetation productivity, the carbon cycle, hydrological processes, vegetation dynamics, soil erosions, and other processes, respectively. However, there was little attention paid to urban ecosystems and few studies targeted urban biophysical processes. With the increase of research on urban ecosystem services, these process-based models have also been applied to the practice of urban area, and mainly focus on the regulation services due to their similarity with natural ecosystems.

Various process-based models focus on urban carbon storage and capacity of carbon sequestration. The biome-biogeochemistry (Biome-BGC) model, mainly used for simulating carbon, nitrogen, and water flux, flows of natural ecosystems at large scale [44]. Milesi et al. [45] applied it in urban areas to simulate the potential carbon and water flux of turf grass in the United States under different management situations, and pointed out that the demand for irrigation of urban turf grass is much higher than crops, which lead to the increasing pressure on fresh water for many cities. In addition to large-scale urban studies, Brown et al. [46] applied it in the urban garden of the university of Maryland, simulated the net biome production per unit area per year from 1978 to 2008, and proved its effectiveness in local scale with the comparison with actual calculation. Another large-scale model, Carnegie-Ames-Stanford approach (CASA), is also used in urban areas. For instance, Zhou et al. [47] assessed carbon sequestration in China's Guanzhong–Tianshui economic zone by integrating net primary production (NPP), grain yield, and DMSP/OLS night light data, and quantitatively analyzed the relationship between urbanization and urban ecosystem services. Tripathi et al. [48] used CASA model to simulate the NPP of urban arboretum in India at finer, local scale and studied the capacity of carbon sequestration for artificial forests. In addition, applying biomass models is an easier way to assess the urban carbon storage, but it is worth noting that these biomass models need be corrected to avoid deviation rather than using them directly due to the differences between urban and natural vegetation [49].

Cities are the main sources of air pollution, while urban vegetation provides an air purification service due to its rough surface, which is more beneficial in depositing air pollutants compared to the smooth artificial surface [50]. Most models use pollutant deposition model combined with leaf area index (LAI) of vegetation to calculate the removal capacity of air pollutants [51]. Janhäll [52] summarized the studies on removal of several major air pollutants by urban vegetation, including $PM_{2.5}$, PM_{10}, and ozone, and found that better design and selection of urban vegetation with understanding of pollutant deposition and dispersion had significant impacts on the improvement of urban vegetation air purification services. Specific to urban forests, Bottalico et al. [50] calculated the pollutant removal efficiency of different urban forest types in Florence, Italy, based on high-resolution remote sensing data and field-measured LAI. It was found that the removal efficiency of evergreen broad-leaved forests and coniferous forests was higher than that of other types of forest, and urban forest could contribute 6% to 13% in total to urban air pollution mitigation. Similarly, in the Mediterranean region, Fusaro et al. [53] identified the relative role of urban and peri-urban forests in ameliorating air quality through stomatal uptake of O_3, by using the process-based model Growth of Trees is Limited by Water (GOTILWA+). It was found that the influence of different management practices on urban forest structure will change its ability to remove air pollutants, for example, increasing irrigation in summer can improve the absorption of ozone by trees.

The risk of urban flooding is significantly booming due to the increase of urban impervious surfaces, so that many models used to evaluate water and soil conservation services of natural ecosystem are increasingly applied in urban areas [54]. Marques et al. [55] used a rainfall–runoff model combined with urban planning scheme and decisions of land use conversion to evaluate the value of urban hydrological regulation, and maximize the land use efficiency of urban floods control. Land use changes affect the vulnerability of urban flood risk. Chang et al. [56] assessed the flood risk of different regions in Taiwan with a grid-based, spatial land use change model. It was found that urbanization aggravated the risk of surrounding regions, which was much higher than that of the central city. However, in view of the inner cities, Zölch et al. [57] analyzed the ability of different green infrastructures (trees, green roofs, etc.) of flood prevention by scenario simulation of residential area in Munich, Germany by the MIKE-SHE model. It was found that urban vegetation can effectively mitigate the disturbance in urban hydrological cycle, regulate the surface runoff, and slow down the local rainstorm risk.

2.3. Applications of Modelling Framework in Multiple Urban Ecosystem Services

The current process-based models for specific ecosystem service can be well applied in urban areas, but the evaluation of such single type of urban ecosystem service cannot meet the needs of urban sustainable development. Increasingly more policy decisions rely on the assessment of synergies and tradeoffs of multiple urban ecosystem services. Moreover, using these models in cities still lacks the description of the impact of urban human activities, social environment, and other factors. The comprehensive ecosystem service model frameworks for urban ecosystem have been proposed intensively.

DPSIR (drivers, pressures, the state, impact, and response model of intervention) has been widely used for constructing integrated models, which is a causal framework for describing the human impact on the environment and vice versa [58]. Integrated models concentrated on several key issues, such as interactions of multiple urban ecosystem services, biophysical processes in urban ecosystem, and feedbacks of human activities. Nassl and Löffler [59] coupled DPSIR on ecosystem service cascades, enhanced its presentation of complex causality, and constructed a closed cycle of ecosystem services including social feedback, which can capture more potential interactions. The DPSIR framework is often used to develop natural-based solutions, offers professional perspectives for local municipalities and other policy makers to improve urban resilience to climate change, and has better support for management applications Lafortezza and Sanesi [60]. Currently, DPSIR has been mainly applied in urban wetlands due to its obvious pressure response process. On a small scale, vulnerability assessment of urban wetland integrated the impact of human activities on wetland ecosystem services promotes the development of appropriate management strategies [61]. It was also used to evaluate the ecological benefit improvement in the treatment and restoration process of polluted rivers [62]. While on a larger scale, the modeling of coastal ecosystems in coastal cities also integrates people's demand for urban ecosystem services, such as resource supply, coastal protection, leisure, and entertainment in coastal cities, to quantifies the pressure responses and reflects obvious social and ecological dynamics [63]. Due to the complexity of the socio-ecosystem, DPSIR is also combined with the system dynamic (SD) model to jointly describe the relationship between the ecosystem and human stress. Ingram et al. [64] used this model to simulate the process of social and ecological interactions in Hawaii and found that the local resource management strategy had a great impact on the pressure of the ecosystem, especially the cultural services, and there was an urgent need to develop the strategic deployment of the sustainable development of the ecosystem.

In order to better understand the internal interactions of complex urban ecosystem and the effectiveness of decisions, SD models have been popularly used to promote future sustainable development. SD is predictive tool to simulate the biophysical processes within an environmental system. Xi and Poh [65] established a comprehensive tool with SD and Analytic Hierarchy Process framework to assess the risk of urban flooding in Singapore and support decision making for water resources management. It is argued that the initial proposed strategy cannot mitigate the risk, but desalination and recycled water should be priority measures. Analyzing future landscape change process under scenarios by SD, and simulating the ecosystem service change, it is useful to provide effective decision-making opinions [66]. SD is a holistic framework to examine feedback interactions in socio-ecosystem. Tan et al. [67] established an SD model, which composed of four subsystems, economy, society, environment, and resources, to simulate the performance of urban sustainable development in Beijing with the complex interactions. Lopes and Videira [43] also emphasized that the management of urban ecosystem services is particularly rely on the feedbacks, which supported the identification of the interrelationships among different ecosystem services and provided key indicators for management decisions. SD is also a platform for participatory modeling to involve stakeholders and make them have better understandings. Cavender-Bares et al. [68] built a sustainable SD framework and provide stakeholders with the tool to make decisions by integrating the ecological mechanism, the biophysical tradeoffs and inherent limitations, the preferences and values of stakeholders, and the response to future needs with time changes. Liu et al. [69] used SD and data envelopment analysis (DEA) to analyze the synergy between greening and urbanization in Tianjin. It indicates that greening is the essential pursuit of economic development and provides decision support for sustainable urban development. In settling environmental issues with SD, effective design can be further promoted to achieve more reasonable models, including clarifying the modeling purpose and scope in conceptualization stage, emphasizing the calibration of quantitative relationship and feedback loops and validating in various aspects [70].

Due to the participation of people, social organizations, and government in urban ecosystems, ecological problems often change with agent behaviors, and the feedback effect of human activities on ecosystem services is often affected by policies and behavioral preferences. Involving basic human elements into decision-making process, such as integrated stakeholder perceptions into quantitative simulation through a series of numerical methods, is helpful in solving complex social-ecosystems issues [71]. The change of society, system, individual behaviors, and ecosystem is the key to simulating the evolution of the social-ecosystem [72]. It is necessary to illuminate the complex relationships between humans and the environment in order to better understand and manage urban ecosystem services. Miyasaka et al. [73] established an agent-based model composed of heterogeneous social and ecological components and feedback mechanisms at multiple scales. The model evaluated UES tradeoffs with typical characteristics of the system, such as cross-scales feedback loops, time-delay effects, and threshold changes. The results showed that the policy of returning farmland to forest promoted vegetation and land restoration in the semi-arid areas of northeast China, but caused further land degradation beyond the implementation areas. Agent-based models can help us to understand how cross-scale processes contribute to social-ecosystem, which are often combined with spatial explicit model, land use, and biophysical model and economic drivers to explore the influence of human disturbance and policy adjustment on system results [74]. Although the agent-based model is a powerful tool that can represent the interaction of human actions and ecosystem, it still needs interdisciplinary cooperation to remedy its limits, such as complexity and difficult practicability, and improve the availability of experiential data [75].

3. Comparison of Current Products for Urban Ecosystem Services Modelling

Series of products of process-based model for assessing ecosystem services have been developed under the integrated modeling framework, including InVEST, i-Tree, SolVES, ARIES, MIMES, Envision, EcoMetrix, EcoAIM, etc. Biophysical processes are the basis of these models to quantify ecosystem services. In order to compare the applicability, advantages and limitations of these products in urban ecosystem services assessment, the model structures, data requirements, scope of application, and calculation methodologies are summarized by cases and analyzed by bibliometrics. In accordance with bibliometric, on 3 April 2022, we searched all publications related to urban ecosystem services on the Scopus, Web of Science database and Google Scholar, respectively, using the search terms "'urban' AND 'ecosystem service' OR 'ecosystem services'" in the "Article title, Abstract, Key words" field. After removed duplicates, we further screened the obtained 9074 literatures by "AND" conjunction with "'InVEST model' OR 'InVEST'", "'i-Tree' OR 'iTree'", "SolVES", "ARIES" respectively to compare these four mainstream model products (Figure 1). Since the definition of urban ecosystem services was established in 1974, there has been an increasing number of studies on urban ecosystem services, with the fast growth rate especially after 2015. The share of studies applying these mainstream models is also increasing, gradually expanding from less than 5% before 2013 to about 20% in 2022, which shows the increased importance of model application in urban ecosystem research.

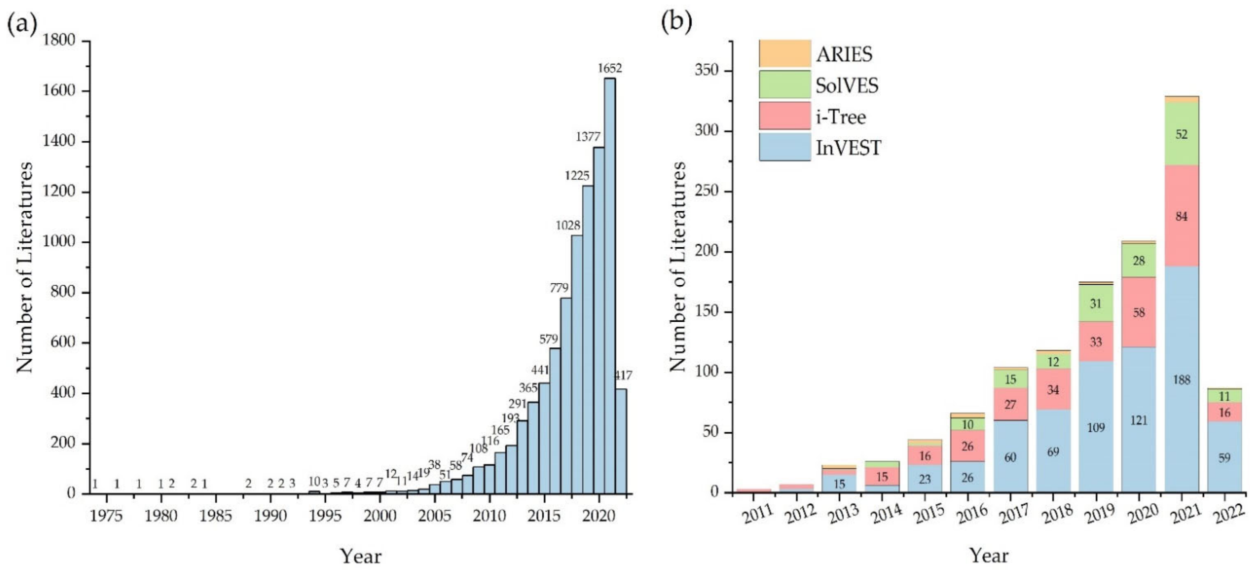

Figure 1. Bibliometrics for research on urban ecosystem services. (**a**) Shows the total number of literatures of urban ecosystem services, and (**b**) shows the number of case studies applied four mainstream models in urban areas.

3.1. InVEST Model

The integrated valuation of ecosystem services and tradeoffs (InVEST) model was developed by Stanford university and TNC natural capital project to support the quantitative evaluation of a variety of ecosystem services through simplified biophysical processes and land use spatial scopes. It is a kind of coupled process-based and correlative model to reflect the impacts of ecosystem structures and functions on the services flow and values. InVEST model (v3.5.0) includes 24 calculation modules and 5 analysis modules [76]. The modules that can be applied in urban areas mainly include Crop production, Carbon, Water yield, Habitat quality, and Recreation (Table 1). The InVEST model can predict the changes of ecosystem services in a certain period with land use changes through the scenario analysis, and display the ecosystem services on the spatial map to support policy making.

Table 1. Comparison of mainstream model products with their attributes.

Name	Type	Module	Calculation Method	Data Requirement	Scale	Remarks
InVEST	Correlative and process-based	Carbon	Carbon density estimation	Land use/land cover map, carbon pool data	Multiple scales: local to national	Latest Version 3.6.0
		Crop production	Percentile or regression	Land use/land cover map, crop table, aggregate result polygon		
		Water yield	Water balance equation	Precipitation, reference evaporation, depth to root restricting layer, plant available water fraction, land use, watersheds, biophysical table and seasonal constant		
		Water purification	Nutrient delivery ratio model	DEM, land use map, nutrient runoff proxy, watersheds, biophysical table, threshold flow accumulation		
		Habitat quality	Spatial distance calculation	Current, baseline and future land cover maps, folder containing threat maps, threats data, accessibility to threats data, sensitivity of land cover types to threats, half-saturation constant		
		Recreation	PUD calculation and regression	Area of Interest map, start and end year		
i-Tree Eco	Process-based	Carbon	Biomass accumulation	*Field data*: Species, canopy, tree cover, tree density, health condition, leaf area, leaf biomass, DBH and other survey information *Species database*: Allometric growth equation for each species *Location database*: City information, hourly pollution data, hourly weather data	Local to individual	Latest Version 6
		Air Quality (including VOC)	Dry deposition model			
		Avoided Runoff	Water balance equation			
		Energy Effects	Cooling effect			
		Structure and value	Proxy evaluation			
ARIES	Expert-based and process-based	Carbon storage and sequestration	Linking process-based models, agent-based models and artificially intelligent engine with multiple criteria ranking algorithm	Land cover map, tree canopy, vegetation types, slope map, soil attributes, population and carbon pool data	Multiple scales: local to national	
		Stormwater regulation		Precipitation, actual evapotranspiration, average runoff, tree canopy, vegetation types, slope map, land use map		
		Water and soil retention		Precipitation, average runoff, average soil losses, soil attributes, tree canopy, vegetation types, land use map		
		Water yield		Precipitation, soil infiltration, actual evapotranspiration, average runoff, vegetation types, slope map, land use map		
		Recreation		Species abundance, DEM, hydrological data, other spatial data for public facilities, population density		
		Aesthetics and neighborhood		Land cover map, distance to city, water quality, road maps, real estate values		
SOLVES	Correlative	Ecosystem Services Social-Values Model	Choosing stakeholders group and determining kernel density surfaces	Environmental data, survey data, other spatial data, social-value allocation amounts	Local to regional	Especially for aesthetics, biodiversity and recreation
		Value Mapping Model	Maxent maximum entropy modeling			
		Value Transfer Mapping Model	Statistical Model generated by Maxent			
MIMES	Process-based	Carbon storage and sequestration	CENTURY/Biome-BGM	*Biosphere*: Genetic kingdom, surface changes, carbon and water limits, etc. *Lithosphere*: Soil attribute, soil features, etc. *Atmosphere*: Climate condition *Hydrology*: Watersheds, hydrological information, etc. *Anthroposphere*: Human capital, built capital, economic production, knowledge and culture preference	Global	
		Storm protection	CLIMBER model		Local	
		Waste treatment	IO models			
		Water supply	WaterGAP		Directional flow related	
		Water regulation/flood protection	IMPACT, IMAGE			
		Nutrient regulation	IMAGE			
		Sediment regulation	Landscape model			
		Raw material and other products	CLUE, Patunxent		In situ	
		Aesthetic/recreation potential	IO model and social network		User movement related	
IMAGE	Process-based	Energy demand and supply	The IMage Energy Regional model (TIMER)	Population, income, energy services, bioenergy production	Global, some module can be applied to regional scale	Latest Version 3.0
		Food consumption and agriculture	Soft-linked agro-economic models MAGNET or alternatively IMPACT	Land, labor, capital and natural resources		
		Emissions	FAIR model	Land cover and land use change, emission inventories		
		Carbon cycle	LPJmL model for productivity	Climate conditions, soil types and assumed technology/management levels.		

Table 1. *Cont.*

Name	Type	Module	Calculation Method	Data Requirement	Scale	Remarks
CITYgreen	Correlative	Water and nutrients	LPJmL model with hydrology model	Irrigated areas, water availability, agricultural water demand and water stress, fertilizer application, wastewater treatment, population	Local scale for small area < 20 acres and city scale for large area > 20 acres	Latest Version 5.4
		Policy	Scenarios simulation	Population, GDP, Trade, and other socioeconomic and policy factors		
		Carbon storage and sequestration Air purification Stormwater regulation Water quality (runoff and contaminant loading) Tree growth	Ecological calculated by Tree canopy GIS layers, and converted into economic value by shadow price or replacement value.	*Spatial data*: Remote sensing images, aerial images, satellite images *Attribute data*: Literature information, field survey for vegetation, buildings, impervious surfaces, etc.		
SAORES	Process-based	Carbon storage	NPP	DEM, soil data, climate data, land use maps	Regional	
		Soil retention	RULS equation			
		Water yield	Budyko curve			
		Grain yield	Potential productivity multiply a natural quality grade index			
ENVISION	Process-based	Carbon sequestration Water yield Food and timber production Nutrient management	Prevalent models	Landscape attributes, biophysical factors, climate data	Local to regional	Latest Version 7
EcoMetrix	Process-based	Provisioning and regulation services	Prevalent models	Landscape attributes, biophysical factors, climate data	Local	
EcoAIM	Correlative and process-based	Provisioning and regulation services	Prevalent models and risk analysis	Landscape attributes, biophysical factors, climate data, management information, preference interviews	Local	

Since 2012, the application of the model in the urban areas has been increased, and the carbon module is the most widely used. Many studies integrated the Carbon module of InVEST model with urban expansion models, such as LUSD [77], CLUE-S [78], and CA [79]. However, there are limitations in the fine simulation in urban areas due to the small number of required parameters and the simplicity of the model. For example, the carbon storage is based on the calculation of carbon density of land use and lacks information about the dynamic process of flow changes and carbon cycle between different carbon pools [80]. Water yield is also a simple estimation based on the water equation, lacking a description of complex hydrological processes [81]. There are differences between the assessment results of habitat quality and the actual biodiversity status, which will affect the decision-making by the simple hypothesis that the positive correlation between habitat quality and biodiversity. Moreover, it is difficult to demonstrate the value of cultural services [82]. As for its application in urban areas, the oversimplified correlation process and inappropriate assumptions affect the accuracy and uncertainty of the results in spite of reducing the model inputs.

3.2. *i-Tree*

i-Tree model is a process-based model for assessing and managing urban forests, which specifically developed by the Forest Service, USDA for cities at a local scale. It quantifies the structure of urban forests and evaluates the urban ecosystem services and disservices based on the investigation of urban forest vegetation. i-Tree is a toolkit including several tools, i-Tree Canopy, i-Tree Landscape, i-Tree Eco, i-Tree Design, and i-Tree Hydro [83]. The i-Tree Eco is widely used for assessing urban ecosystem services generated by community trees. On the basis of field survey data, species database, and location database with city information, i-Tree Eco integrates weather and pollution data to predict future urban forests structure with DBH growth, dead trees, and replantation, and then assess the changes of urban ecosystem services (Table 1).

This model has been widely used in urban forest management at fine scale. Baró et al. [84] used i-Tree Eco to quantify the ecosystem services of green infrastructure and found that the urban forests made large contribution to air pollution purification, but the amount is relatively small compared with urban pollution emission. Kim et al. [85] used i-Tree Eco to quantify the ecosystem services of urban vacant land in Roanoke, Virginia, and clarified the function and value of the forest structure on the vacant lands. Kiss et al. [86] used i-Tree Eco to analyze the carbon sink service and air pollution removal capacity of trees in urban streets and parks in Hungary. Considering the differences in tree conditions and tree species, it was found that completely covered streets and high-density urban forests were not the ideal management methods for optimizing the urban ecosystem services. Using i-Tree Eco model to evaluate the ecosystem services of urban forests, which enhanced the attention of urban forest protection strategies and human wellbeing for urban residents, especially in big cities [87].

The i-Tree model can accurately calculate the ecosystem services supply capacity of urban forests at a fine scale. However, since the model requires large ecological data inputs, such as water, soil, air, and geological information by high-resolution field survey data to support, it is difficult for many regions to carried out similar surveys. Moreover, the parameters adopted by the model are mostly based on the situation in the United States. There comes a paradox that using default values when applied to other regions will lead to increased uncertainty, but further adjustment of parameters will increase the difficulty of application.

3.3. ARIES

The artificial intelligence for ecosystem services (ARIES) model is a coupled expert-based and process-based model developed by the University of Vermont for evaluating ecosystem services through artificial intelligence and semantic modeling. Based on correlation algorithm, spatial data, and other socioeconomic data, the ARIES model combines multi-scale process and Bayesian network to simulate the flow of multiple ecosystem services from the supply area to the beneficial area, and describe the flow processes under the changes of spatial and temporal dynamics [88]. The model introduces the concept of source and sink and simulates the relationships among the regions providing ecosystem services, the regions blocking the flows of ecosystem services and the beneficiaries using ecosystem services in terms of spatial location and quantitative relationship. The services and calculations involved in the model are shown in Table 1.

The ARIES model has been studied in several cases since it was released in 2009, but few cases specifically apply it in urban areas. Bagstad et al. [89] simulated ecosystem services changes in San Pedro river watershed, Arizona, by ARIES model under urban expansion scenario, and the results showed that the landscape will benefit more and more people in the process of urbanization, and the ecosystem services will become more valuable due to the growing demand, though it will cause degradation and losses of ecosystem services. It emphasized that the comprehensive evaluation of ecosystem services should not only focus on ecosystem quality, but also pay more attention to quantify ecosystem service flows, and the ARIES model provides the tool, service path attribute network (span), to evaluating spatial dynamics of ecosystem service flows [89]. Bagstad et al. [90] using the ARIES and SolVES assessed the Wyoming and Colorado national forest of 11 kinds of ecosystem services, identified national forest ecosystem services of hot and cold spots on the urban-rural gradient. The results found that the nearer the distance from the city, the more densely populated places more prone to hot spots, shows the extent of perception of the surrounding forest by urban residents. Zank et al. [91] used the ARIES model to evaluate the impact of two different land use change development programs on natural capital stock and ecosystem service flow, and found that the landscape development reduces its ability to provide ecosystem services but increased the beneficiaries. It emphasized that the impacts of urban form and land use change on urban ecosystem services are different, the tradeoffs among various stakeholders should be taken into account. However, the ARIES model is only applicable to the regions involved in the case study at present, and it needs to be parameterized according to its own situation when applied to other places [81].

3.4. SolVES

The SolVES model is a kind of correlative GIS-based model to assess the social values of ecosystem services based on interviews for preferences of stakeholders, which developed by the United States Geological Survey (USGS) and the Colorado State University. SolVES uses geospatial and tabular data as inputs to three separate models—the Ecosystem Services Social-Values Model, the Value Mapping Model, and the Value Transfer Mapping Model. The first two modules only need at least one raster-based environmental data, while the latter one needs to cooperate with the interview data. SolVES has preset the social value preference for different types of services for 2000 households randomly surveyed at the end of 2004. It can investigate any ecosystem service and quantify its social value, especially for the perceived services such as cultural services [92].

Except for the above mentioned, Bagstad et al. [93] has taken an interest in assessing the perception of the urban forest culture through SolVES, it was rarely applied to urban areas, and only few cases in the last two years. Lin et al. [94] assessed the ecosystem services of Datuan watershed with different protection plans under various levels of urban development. It found that there are significant tradeoffs among urban development, biophysical processes, and social values, and there are spatial overlap and potential synergies between biophysical processes and social value. It helps social ecological planning involving multiple stakeholders. Qin et al. [95] took the Guanzhong-Tianshui economic zone as an example to determine the priority of conservation area under different development and conservation scenarios and chose the most optimized scenario by SolVES taking into account the conservation aesthetics, leisure and entertainment, and other cultural ecosystem services. Sun et al. [96] used SolVES model and tourists' photos to quantify the social values of urban green spaces. Through the exhibition of tourists' photos, the respondents can more easily recall the enjoyed ecosystem services of urban green spaces and have a stronger perception than the traditional questionnaire. Since the SolVES model is mainly aimed at quantification of cultural services, it relies on early investigation of public attitudes and preferences and is more suitable for evaluation in a specific area or small scale. Moreover, in terms of parameter setting, the setting of landscape type parameters is relatively rough, which is difficult to reflect the public perception of different landscape features. Differences between the preset factors and the evaluation area may lead to large errors and uncertainties.

3.5. Other Products

Except for the products mentioned above, some models have also been developed for ecosystem services evaluation and some of them developed based on global ecosystem have the potential to be applied in urban areas, such as MIMES (multi-scale integrated models of ecosystem services) and IMAGE (Table 1). MIMES model aims for determining the stocks and flows of ecosystem services and simulating dynamic of ecosystem services. It divides the earth into five parts, biosphere, atmosphere, hydrosphere, lithosphere, and anthroposphere, to simulate the temporal dynamic of ecosystem services integrating ecological processes, and estimate economic value of ecosystem services by input-output method with anthropogenic actions, natural capital and socioeconomic factors at various scales. It has been well applied in the Albemarle–Pamlico watershed and Massachusetts ocean [97]. Although MIMES has rarely used in urban areas due to the complex model structure and a large number of parameters, it still has a good application prospect. While the IMAGE is a comprehensive integration model of interactions between human and natural systems. It is suitable for large-scale and long-term evaluation of the interaction between human development and natural ecological environment and impacts on ecosystem services [98].

It simulates dynamics of carbon, water, and vegetation based on experts' knowledge and biophysical processes to direct human management actions, and it has been widely used by Millennium Assessment, OECD, and EU to support decision making. The good analysis of uncertainty and the similar ecological processes make the model has a high portability in the cities.

Some GIS-based models are also effective tools for assessing ecosystem services and supporting decision making (Table 1). CITYGreen is an extension tool of ArcView, which is used to calculate the economic values of urban trees or other landscape elements for energy utilization, stormwater control, air purification, carbon sequestration, habitat provision, and other services [99]. Spectral or high-resolution images and survey parameters can be used to build thematic layers to analyze the ecological benefits of urban green space system at different scales. CITYGreen has been used in many applications of urban compact areas, especially in many Chinese cities. However, it still limited to further apply to urban decision making due to the lack of biophysical processes and validation. SAORES (Spatial Assessment and Optimization Tool for Regional Ecosystem Services) is an ecosystem model based on multi-objective optimization algorithm by China [100]. SAORES was originally designed for the optimization of policy and ecological restoration in the loess plateau of China. It enhanced the scenario construction with landscape dynamic processes and integration analysis of multiple ecosystem services tradeoffs, which is suitable for restoration projects but lacks social and economic factors for the application in the cities. ENVISION is also a GIS-based tool for scenario-based community and regional integrated planning and environmental assessments [101]. Based on landscape process models, landscape performance models and multiagent decision models to assess the impact of different development scenarios on ecosystem services [102]. ENVISION is currently mainly used in the United States, it has high requirements for specific local landscape data to applied in other urban areas.

There are also some pay-to-use models led by companies for assessing urban ecosystem services, such as EcoMetrix and EcoAIM (Table 1). EcoMetrix used the physical environment factors from ground survey as the input data for ecological production function to simulate the ecosystem services [103]. EcoMetrix is suitable for small scale or used in combination with other evaluation models for regional simulation [104]. Due to it heavily relying on sophisticated preliminary data, it is mainly used to assist government departments in designing and implementation of ecosystem service protection projects [105]. As EcoAIM (Ecosystem services Asset, Inventory and Management), it is an ecosystem services evaluation model for the environment and health department of enterprises. EcoAIM is a consultant-focused ecosystem services assessment tool that helps in making decisions for development, trading, and ecological restoration, or in providing a methodology for assessing tradeoffs in ecosystem services functions arising from different land or resource management decisions [102]. When considering the impact of ecosystem service functions, EcoAIM more concentrates on the preferences of stakeholders to do the risk analysis.

4. Limitations of Existing Models and Outlooks for Urban Socio-Ecological Models

4.1. Limitations of Existing Models

The quantitative assessment of urban ecosystem services is widely different from most studies on natural ecosystem, due to its needs for combining results with the actual situation to guide the policies making. Therefore, it is required that the research on urban ecosystem services need to make the key issues clear and select a reasonable applicable model as a tool to support better management [106]. At present, there are many related studies in North America, Europe, and China [91,107,108], but few of their results can be directly applied and adopted as the guidance for decision-making, which indicated that there are still some problems in the current research on urban ecosystem services. Firstly, non-material services are difficult to quantify, while these services are important parts of ecosystem services for urban residents [109]. Secondly, there are still large uncertainties in the quantitative results of current research, even the results were simulated by processes-based models [110]. Due to the lack of understanding of the complexity and dynamics among different urban ecosystem services, the contents and results of assessments do not quite meet the needs of practitioners [111]. Finally, on spatial scales, current studies always ignore urban heterogeneity and urban landscape pattern, and their influences on urban ecosystem services [112]. While on the time scales, it can hardly to follow the results of assessment and simulate the future condition precisely without long-term time series dynamic simulation [113]. Mismatches in temporal and spatial scales make those evaluation results hardly feedback to urban designing and planning.

Given the issues mentioned above for research on urban ecosystem services, several pivotal challenges have also been systematic reviewed [14]. Conducting more studies on urban ecosystem services in different regions with different urban development conditions is beneficial for summarizing the mechanism of urban ecosystem services changes from a broader scope. As the studies deepen in urban ecosystem services, it is necessary to emphasize the contribution of socio-economic factors on feedbacks by describing social conditions in the clear range of city. Moreover, integrating various methods and interdisciplinary knowledge, incorporating more comprehensive stakeholder considerations into research, and strengthening the application of different types of data, are presumed to improve the understanding of urban ecosystem services, to transform scientific conclusions into actionable instruction, and to quantitatively determine human well-being [114]. Relevant analysis of urban ecosystem service governance also relies on more quantitative means, and the application of comprehensive models is the key to deal with these challenges [115].

However, from the summary of research on urban ecosystem service models, there are still some limitations. Firstly, existing models still lack understanding of how urban ecosystem provides multiple ecosystem services and know little about the tradeoffs or synergistic interactions among these ecosystem services. Secondly, as for urban ecosystem, social and economic factors will not only affect ecosystem services, but also are influenced by people after enjoying urban ecosystem services. The existing models only consider feedback conceptually rather than in an exact model, because the actual quantification process is still blank. Thirdly, there is a time-lag effect between the changes of ecosystem services and socio-economic factors. It is necessary to predict the future in a long time series under different scenarios to grasp the temporal dynamics of urban ecosystem services, and realize the dynamic evaluation to guide the practical application. Finally, most of current models still focus on ecosystem services in regulating and provisioning, but often ignore the ecosystem services that highly relevant to perception of human wellbeing. It is urgent to call for breakthroughs in quantitative methods to assess these urban ecosystem services, such as biodiversity, habitat quality, recreation, and aesthetics.

4.2. New Perspectives of Socio-Ecosystem for Modelling

Social-ecosystem is a key concept for urban ecosystem research with the integration of social and ecological. The studies related to urban ecosystem services more or less involve urban ecosystem resilience analysis [116,117], urban ecological development sustainability [67], and adaptive ecosystem services governance strategy [118]. However, the social and ecological variables and their feedback cycles are not considered, which is required for the interdisciplinary research with socio-economic status and available tools combined social and ecological data [119]. Urban ecosystem services are not only affected by the characteristics of the ecosystem, but also by the social and economic attributes of urban residents. How to comprehensively consider the interaction between socio-economic factors and ecosystem services is the premise in understanding the change mechanism of urban ecosystem services. Moreover, the change of socio-economic factors can change people's demand for different urban ecosystem services, then alter the level of human wellbeing [20]. The social-ecosystem modeling can provide a new perspective of solution for the current problems in modeling. Based on the social-ecosystem model, stakeholders can manage local ecosystem services through the adaptive natural-based solution, which is the key to promote the innovation of social-ecosystem in urban area [120].

A comprehensive social-ecosystem model is helpful to reveal the relationships and interactions among various urban ecosystem services [121]. The interrelationship among urban ecosystem services needs a comprehensive understanding of the tradeoffs and synergies of different urban ecosystem services from the systematic perspective. These positive or negative relationships are also affected by external socio-economic factors simultaneously. It directly affects whether complete information can be obtained for management decisions by how to understand the mechanism of these influence factors. Evaluation of ecosystem service tradeoffs and synergies requires a more mechanism approach; Dade et al. [122] reviewed literatures to determine the extent of drivers and mechanisms are considered in the assessment of ecosystem services. It was found that only 19% of the assessments clearly identified the drivers and mechanisms when research on ecosystem service relationships was conducted. The assessment should consider more drivers of tradeoffs and synergies, and should adopt more causal reasoning and process-based models to deepen knowledge of mechanism and ensure effective management of ecosystem services. Especially in the current situation that various scales of social-ecosystems are faced with the challenge of sustainable development, better research on urban ecosystem services needs to be fully combined with socioeconomic dynamics and clear relationships among services. In addition, more and more waste, and vacant or underutilized lands are planned to be ecologically restored at present; socio-ecosystem modeling has certain contribution to ecological restoration area by tracking evaluation. The dynamic assessment avoided one-sided consideration of static modeling methods and ignorance of ecosystem services relationships [123].

A comprehensive social-ecosystem model can better describe the feedback effect between the social environment and urban ecosystem services, better assess how human-induced urban growth affects ecosystem services, as well as better understand how ecosystem changes feed back into human society [124]. Pan et al. [125] proposed a comprehensive social-ecosystem modeling framework to identify the interaction between human activities and ecosystem services in large complex urban systems. It coupled the social-ecological process models and policies to expand methodology of assessment by integrating spatial and temporal dynamic and feedback interactions, and spatially measured the potential impact of economic and land use interactions on urban ecosystem services based on scenario analysis. It is obvious that model results will significantly underestimate the impacts of urban ecosystem services on social factors without feedback dynamics. Furthermore, strengthening protection policies can significantly reduce the loss of urban ecosystem services, so as to achieve the reconstruction of land use development pattern, which indicated that the relationships between the ecosystem and society can be promoted by the mutual feedback effects.

A comprehensive social-ecosystem model with socio-economic attributes can be used to dynamically predict the changes of urban ecosystem services under different scenarios in future long time series [126]. In order to understand how social, institutional and economic factors affect the ecosystem services, clarify the impacts on human wellbeing, and incorporate social considerations to support decision-making, it is necessary to consider the urban ecosystem services relationship between supply and demand from a systematic perspective, and understand the dynamics, interactions, and complexity of processes at different scales [127]. However, the destruction and fragmentation of the natural ecosystem caused by human activities will result in the loss of urban ecosystem services with time-delay. The social-ecosystem depends on a series of urban ecosystem services, and the lagging ecological dynamics may affect its long-term sustainability. Lafuite and Loreau [128] studied the delayed ecological feedback and the effect of ecosystem services consumption changes on sustainable development. The results showed that the practices and interactions among social, demographic, and ecological feedbacks control the temporary and long-term dynamics of the entire system. The sustainability of a coupled social-ecosystem highly depends on its long-term ecological dynamics, but current theories of sustainable development have not considered the long-term impact of ecological debt on social-ecosystems [128]. Population growth drives land conversion, which reduces the urban ecosystem services; the social ecosystem will experience excessive population growth and result in environmental crisis when there is time lag in ecological feedback. Integrating population growth, technological invention, and biophysical processes into a dynamic model will provide the threshold of sustainability and prevent the occurrence of environmental crisis [94]. In addition, there are many studies focusing on exploring the temporal dynamics. Rova et al. [129] mixed multiple urban ecosystem services into a single network by using Petri Net to explore the temporal dynamic of urban ecosystem services supply. It prevents repeating inputs to detect potential trends rather than existing static models, and identifies the influences of different driving factors on social ecosystem at the same time. Qiao et al. [130] quantified temporal changes and spatial scale dependence of tradeoffs and synergies of multiple ecosystem services under different urbanization period in Taihu Lake. It was found that the ecosystem service interactions are temporally heterogeneous and depend on spatial scales and the tradeoffs and synergies will also change with time; some tradeoff may change into synergies.

The integration of broad socioeconomic data and multidisciplinary knowledge can contribute to the promotion of immaterial ecosystem services and the quantification of their impact on human wellbeing. Some studies analyzed the vulnerability of social-ecosystem when facing the degradation or losses of ecosystem services to evaluate the impacts on the sense of human wellbeing. For instance, Berrouet et al. [131] analyzed the vulnerability to exposure and risk of various extreme events through the conceptual framework of social-ecosystem, taking into account the differences in socioeconomic characteristics of beneficiaries and their ability to adapt to the new situation of the ecosystem. Ecosystems provide benefits to humans, and, in turn, individuals and groups also highly affect ecosystem structures and functions. The interdependence of human and ecosystem services is critical to the sustainable future of social-ecosystem. Leviston et al. [132] challenged the linear correlation concept of ecosystem health and human wellbeing by using Nexus webs framework. It proposed that the human wellbeing can also affect ecosystem health, and emphasized that exploring the relationship between ecosystem services and human wellbeing, and comprehensively understanding the coupling of social-ecosystem will be conducive to competition in resource management and decision making. In order to understand the relationship between ecosystem services in complex systems also requires us to integrate multidisciplinary knowledge and help us understand by appropriately increasing the complexity of models or assessments [133].

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