

Review

# Pathways to Modelling Ecosystem Services within an Urban Metabolism Framework

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**Abstract:** Urbanisation poses new and complex sustainability challenges. Socio-economic activities drive material and energy flows in cities that influence the health of ecosystems inside and outside the urban system. Recent studies suggest that these flows, under the urban metabolism (UM) metaphor, can be extended to encompass the assessment of urban ecosystem services (UES). Advancing UM approaches to assess UES may be a valuable solution to these arising sustainability challenges, which can support urban planning decisions. This paper critically reviews UM literature related to the UES concept and identifies approaches that may allow or improve the assessment of UES within UM frameworks. We selected from the UM literature 42 studies that encompass UES aspects, and analysed them on the following key investigation themes: temporal information, spatial information, system boundary aspects and cross-scale indicators. The analysis showed that UES are rarely acknowledged in UM literature, and that existing UM approaches have limited capacity to capture the complexity of spatio-temporal and multi-scale information underpinning UES, which has hampered the implementation of operational decision support systems so far. We use these results to identify and illustrate pathways towards a UM-UES modelling approach. Our review suggests that cause–effect dynamics should be integrated with the UM framework, based on spatially-specific social, economic and ecological data. System dynamics can inform on the causal relationships underpinning UES in cities and, therefore, can help moving towards a knowledge base tool to support urban planners in addressing urban challenges.

**Keywords:** urban metabolism; socio-ecological impacts; spatio-temporal dynamics; multiscale; sustainability; ecosystem services

## 1. Introduction

Increasing urbanisation of the growing global population forces new and increasingly complex challenges into the urban system. The United Nations predict world population to soar from the current 7.6 billion to 9.8 billion by 2050 and 11.2 billion by 2100 [1]. Simultaneously, reports around the rapid influx of countryfolk to urban centres, increasing from 50% globally to 68% by 2050 [2], bringing

with them demands for marketed goods and services such as materials and energy, and demands for non-marketed services related to ecosystem functions. However, the demand for marketed goods and services is not without consequences and making them available (extracting raw materials, processing them, transporting, using the products and discarding them) inevitably has impacts on the environment. In particular, this can degrade the geobiophysical components and processes of an ecosystem that underpin the biological cycles, and the services they provide.

Ecosystem services (ES) are the ecosystem-supplied goods and services that benefit humans in the forms of provisioning services (e.g., food yield), regulating services (e.g., climate, water and nutrient cycles) and cultural services (e.g., aesthetic and healthful nature interactions) [3]. Thus, it becomes necessary to understand how urbanisation can be channelled to consolidate and mobilise behaviours and decisions at the urban level to reduce humanity's effect on ecosystems' capacities to supply ES at global and local levels. However, there is still little knowledge on the magnitude, drivers and effects of interregional ES flows, especially for regulating and cultural ES [4].

In this research, we focus on the increasing urbanisation, so it follows that we pay attention to the ES supplied to cities, and impacted by urban activities [5]. Accordingly, we draw the reader's attention to the concept of urban ecosystem services (UES)—the subset of ES that supply benefits within the urban system [6]. This includes both locally specific ES (e.g., flood protection) and global ES that are nonetheless relevant to urban liveability, such as global climate regulation.

In anticipation of the rising social and ecological demands concentrated in cities, it is necessary to quantify the cause–effect relationships between elements of the urban system, such as material and energy flows, and their impact on ecosystem functionality. This will enable society to make more socially and ecologically conscientious decisions today for the needs of tomorrow by providing pathways that allow cities to tackle not only urban, but also global sustainability development goals [7]. To this end, the implementation and use of tools capable of modelling and assessing the relationships between elements within the urban system will be key to support the development of policies oriented to preserve the supply of UES.

Several assessment methods and coupled, integrated, hybrid methods have been proposed to measure and trace the social and environmental impacts associated with the flow of materials and energy. For example, these include life cycle assessment (LCA) [8], mass balance [9], emergy analysis [10], cost-benefit analysis [11] and multi-criteria decision assessment [12]. Some of these can be adapted to suit the urban level [13]. Moreover, many of these assessment methods sit under the umbrella metaphor of urban metabolism (UM). UM is used to describe the material, energy, social and economic flows ('metabolic flows') through the urban system [14]. The term was coined by Karl Marx [15] and later brought to popularity by Wolman [16] and has since opened up a large research domain linking the disciplines of engineering, political ecology and political economy, industrial ecology, social ecology and ecological economics [17–20]. We define UM as the metaphor for the stock and flow of socio-ecological resources circulating in and through the urban system. As Wolman (1965) suggested, this helps understanding the complex dynamics and interdependencies between urban environments and their surroundings (i.e., ecosystems). Therefore, UM may be a suitable assessment framework that can be expanded to elucidate the valorisation of ES.

UM models usually assess the flow of physical quantities of water [21], materials [22], food [23], chemical elements, solar emergy joules [24], and various energy units [25]. Some of these metabolic flows can also be used to assess and model ES [26] thus creating an opportunity to connect the relatively newer concept of UES to UM assessment methods [17,27–29]. Furthermore, there have been compelling appeals for UM research to expand its scope towards the holistic assessment of various new levels, including ES [17,30–35]. In fact, urban planning of phenomena/structures capable of generating UES may bring opportunities to enhance the resilience and ecological functioning of urban systems [36]. This leads us to question how the ES concept can be integrated into an UM-based method to allow a better assessment of UES.

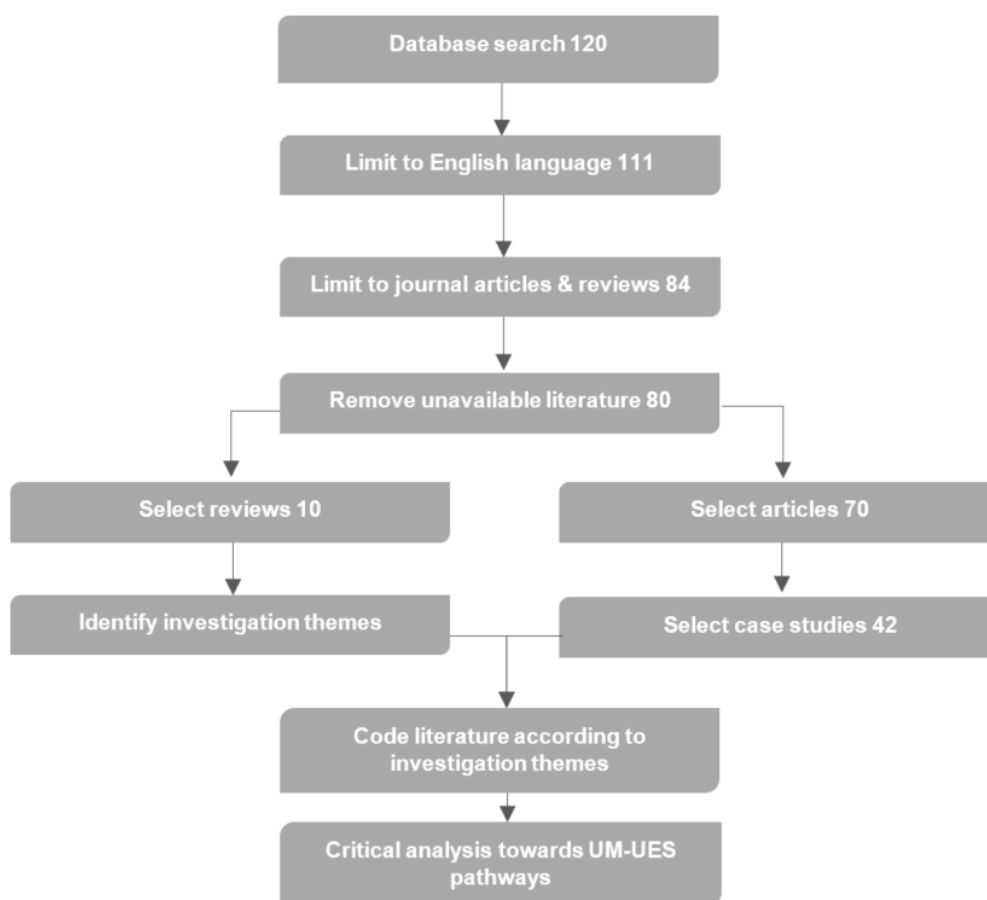
Several ES indicators are implicitly assessed by UM methods. Urban Material/Energy Flow Analysis (MEFA) traces the flow of products that do not use ES nomenclature, but are nonetheless equivalent to many provisioning ES. In the UM community, yields of provisioning ES correspond to raw materials/resources. For example, the stock and flow of energy, water, food and material provisions are traditional metabolic flows while also being the physical exploits of ES. In general, we can use MEFA, mass balance, or emergy analysis for the quantification of provisioning ES. However, it may be more challenging to use these UM methodological bases for the quantification of regulating and cultural ES. Burkhard and Maes [37] suggest that for these latter groups of ES, simple measurement of stocks and flows are not enough, but a more complex modelling approach is needed. Subsequently, we pose the following research questions to be explored in this paper:

What are the steps needed to include UES assessments within an UM modelling framework, and what are the relevant key methodological issues that such a UM-UES paradigm may enhance or resolve?

We believe these questions can be addressed by exploring the viability of creating an integrated UM-UES modelling approach. This approach may add to the completeness and representativeness of these two currently distinct concepts and foster the development of an integrated urban sustainability analysis method. To this end, the first objective of this paper is to critically review UM literature that encompasses the ES concept and identify the approaches that may allow or improve the integration of UES assessment. This can provide a relevant scientific background, methodological knowledge and research evidence to address the second objective of this study, which is to define pathways towards an integrated UM method enabling a quantitative assessment of UES.

## 2. Methodology

We performed a database search focusing on UM studies that intersect with the ES research field. We narrowed down the list of selected papers through a sequence of filters and assessed the results according to a set of key investigation themes. These filters are depicted in Figure 1 and together with the investigation themes are explained in more detail in the following sub-sections. Later, the information found in the literature was used to outline pathways towards a holistic integrated UMUES modelling framework. We identified these pathways by investigating which types of information in UM case studies could be used to incorporate assessment of UES. Thereafter we investigated the types of UM analytical tools that were used to model with ES-related information.



**Figure 1.** Representation of critical review method and number of literature items at each step.

### 2.1. Database Search

We searched for literature limiting the selection of literature to journal papers that had a focus on UM-based methods allowing the incorporation of UES. We experimented with several combinations of UM and UES search strings with the aim of revealing literature that embodies the UM metaphor and assesses ES, ecosystem health or ecosystem functioning. However, ES approaches are sometimes referred to with varying and ambiguous nomenclature, hence the inclusion of alternative wording. With the emphasis on expanding the UM metaphor to encapsulate an assessment of ES, we searched for literature with UM as the subject, and refined this to the subset of UM literature that referred to ES. This subset was identified by including several alternative words related to ES based on the string used in the review of Luederitz, et al. [6]. We used the following string to search the SCOPUS database on 19th November 2018. The SCOPUS database was used instead of other databases (such as Web of Science) because of the superior number of journals covered, as pointed out by previous research in this field, e.g., Aghaei Chadegani, et al. [38].

(TITLE-ABS-KEY (“urban metabolism” AND (“ecosystem” OR “ecosystem servic\*” OR “ecosystem functio\*” OR (provisioning AND ecosyste\*) OR (regulating AND ecosyste\*) OR (cultural AND ecosyste\*) OR (supporting AND ecosyste\*) OR (habitat AND ecosyste\*))))

This search yielded 120 literature items. These were limited to English language papers published in journals, following the process in Figure 1. The remaining 80 papers were split into reviews and articles. Only the full text of the 70 remaining research articles were reviewed for relevancy to the

research question. If the papers answered positively the following two questions, they were considered relevant to the scope of our research:

- (1) Did the study demonstrate its contribution using a case study?
- (2) Did the case study assess social or ecological metabolic stocks and flows that belong to the ES concept?

We found only 42 literature items within the original 120 that satisfied these criteria. This was the final set of literature used in the following review, and they are tabulated in Supplementary Information—Literature table.

## 2.2. Key Investigation Themes

We conducted a scoping review in order to identify the key investigation themes by which to review the 42 literature items, as defined by Tricco, et al. [39]. Considering our research questions, these themes were identified in the conclusions and future research opportunities of UM review papers. Of the 10 identified reviews (see Figure 1) we excluded six papers that were less focused on the methodological advancements of UM, but instead related to complementary aspects and applications such as network analysis. We filled this gap by cross-referencing the remaining literature. We identified and included an additional six relevant scoping review papers: Kennedy, et al. [35], Pincetl, et al. [31], Pincetl [17], Zhang [34], Zhang, et al. [40] and Beloin-Saint-Pierre, et al. [32]. The final 10 review papers and the future directions they highlighted are summarised in Supplementary Information—Scoping review. The resulting themes are described in Table 1.

**Table 1.** Key investigation themes revealed from the scoping review. An explanation of the themes is given in Supplementary Information—Scoping review.

Theme	Description
Suitability for ecosystem services (ES) assessment	Which ES were mapped, measured, or estimated? If they were not, were the metabolic flows relatable to any ES?
Temporal detail	Did the model provide forecasts for future scenario analysis, and if so, is the model dynamic in the sense that system elements can evolve over the model run?
Spatial detail	Was the urban system spatially specific, or was the system considered as a single spatial unit?
Multi-level	How was the urban system boundary defined? Was the boundary defined by political jurisdiction, functional urban area, metropolitan area, community, or a combination of geographic levels?
Cross-scale integration	Were social, ecological and economic scales considered (e.g., coupled human and natural systems; CHANS)? Where relationships between elements from different scales acknowledged?

Temporal and spatial detail, multi-level analysis, and linking across elements in the system are the primary themes found in the scoping review, which address known limitations of state-of-the-art UM methods, and may help to understand how the UM-UES framework could be modelled. Temporal detail is important to understand how future UES supplies will be influenced over time [41]. Spatial detail is important because ES are often linked to land use/land cover meaning that the supply of ES varies over space [42,43]. Interregional flows are important because many UES have their origins outside the urban system or are causally linked to processes outside the urban system [37,44]. Therefore, taking a multi-level approach is important to account for those interregional flows that transcend the boundary of the urban system. Finally, cross-scale integration is important to consider because ES is an economics concept about the linkages between human scales and ecological scales [45–47]. As these scales are interacting when humans enjoy the benefits of ES, it follows that an UM-UES assessment approach should acknowledge the CHANS. As these types of information may require specific model approaches, we also recorded which methods were used in each case study. Later, these results are

described in Section 3, and in Section 4 we discuss and propose pathways to modelling UES by way of an integrated UM modelling framework.

### 3. Results

This section shows how the UM literature items performed against ES suitability, the remaining four key investigation themes (information complexity) followed by which model types were used to deal with the various types of information (model complexity). The results for each study are shown in brief in Table 2, and fully in Supplementary Information—Literature table.

**Table 2.** Urban metabolism (UM) literature according to ES suitability, the four investigation themes, and associated model complexity.

UM Literature Item Citation	Metabolic Flows Indicators Measured/Described	ES Suitability			Investigation Themes				Model Complexity			
		Provisioning	Regulating	Cultural	Temporal Detail	Spatial Detail	Multi-Level	Cross-Scale Integration	Network Analysis	Energy Analysis	Life Cycle Thinking	Systems Thinking/System Dynamics
Metzger, et al. [48]	Water, food, energy, wastes	✓	✓	✗	✓	✗	✓	✗	✗	✗	✗	✗
Huang, et al. [49]	Emergy (sej)	✓	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗
Conke and Ferreira [50]	Materials, energy, water	✓	✓	✗	✓	✗	✗	✓	✗	✗	✗	✗
Cui, et al. [51]	Phosphorous	✓	✓	✗	✓	✗	✗	✓	✗	✗	✗	✗
Zhang, et al. [52]	Consumption intensity	✓	✓	✗	✓	✗	✗	✗	✓	✗	✓	✗
Zhang, et al. [53]	Nitrogen	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗
Lin, et al. [54]	Carbon, nitrogen, phosphorous	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓
Forkes [55]	Nitrogen	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗
Liu, et al. [56]	Water	✓	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓
Chrysoulakis, et al. [57]	Energy, water, carbon (especially), and socio-economic indicators	✓	✓	✗	✗	✓	✗	✓	✗	✗	✗	✗
Garcia-Montiel, et al. [23]	Water, food, waste, energy	✓	✓	✗	✗	✓	✗	✓	✗	✗	✗	✗
Pauleit and Duhme [58]	Energy, water, carbon dioxide	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
Villarroel Walker and Beck [59]	Carbon, nitrogen, phosphorous, and water	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
Dal Bo Zanon, et al. [60]	Nitrogen and phosphorous	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗
Viglia, et al. [24]	Emergy (sej)	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗
Kennedy, et al. [61]	Water, SO <sub>2</sub> , NO <sub>x</sub> , volatile organic compounds, and particulate matter	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Firmansyah, et al. [62]	Nitrogen and phosphorous	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Yang, et al. [63]	Emergy (sej) indices	✓	✗	✗	✓	✓	✓	✓	✗	✓	✗	✗
Fragkou, et al. [64]	Water	✓	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗
Zhang, et al. [65]	Materials, energy, water, labour	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
Leduc and Van Kann [66]	Energy	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗
Lei, et al. [67]	Mass, energy, emergy	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
Mörtberg, et al. [68]	Biodiversity/habitat fragmentation	✗	✓	✗	✓	✓	✓	✗	✓	✗	✗	✓
Lookingbill, et al. [69]	Nitrogen and water	✗	✓	✗	✓	✓	✓	✗	✗	✗	✗	✓
Lin, et al. [70]	Nitrogen and phosphorous	✗	✓	✗	✓	✗	✓	✗	✗	✗	✗	✓
VandeWeghe and Kennedy [71]	Carbon dioxide	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
Thomson and Newman [72]	Food, fuel, energy	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
Zhang, et al. [73]	Energy and carbon dioxide	✗	✓	✗	✗	✗	✓	✓	✗	✗	✓	✗
Chen and Chen [74]	Carbon dioxide	✗	✓	✗	✗	✗	✗	✓	✓	✗	✓	✗

Table 2. Cont.

UM Literature Item Citation	Metabolic Flows Indicators Measured/Described	ES Suitability		Investigation Themes				Model Complexity				
		Provisioning	Regulating	Cultural	Temporal Detail	Spatial Detail	Multi-Level	Cross-Scale Integration	Network Analysis	Emergy Analysis	Life Cycle Thinking	Systems Thinking/System Dynamics
Wen, et al. [75]	Ammonia, ammonium, and NO <sub>x</sub>	X	✓	X	X	X	X	X	X	X	✓	X
Huang and Chen [76]	Emergy (sej)	X	X	X	✓	✓	✓	X	✓	X	✓	X
Lu, et al. [77]	Human time and Land Use	X	X	X	✓	✓	✓	✓	X	X	X	X
Tan, et al. [78]	Relationship indicators	X	X	X	✓	✓	X	X	✓	X	X	X
Wang, et al. [79]	Energy and labour	X	X	X	✓	X	✓	✓	X	X	X	X
Sun, et al. [80]	Emergy (sej)	X	X	X	✓	X	X	✓	X	✓	X	X
Han, et al. [81]	Energy, economic labour productivity, human activity	X	X	X	✓	X	X	✓	X	X	X	X
Wu, et al. [82]	Emergy (sej)	X	X	X	✓	X	X	✓	X	X	X	X
Zhang, et al. [83]	Ecological hierarchy index	X	X	X	✓	X	X	X	✓	X	✓	X
Li, et al. [27]	Energy, materials, mutualism index	X	X	X	✓	X	X	X	✓	X	X	X
Zhang, et al. [84]	Emergy (sej)	X	X	X	✓	X	X	X	X	✓	X	X
Zhang, et al. [85]	Socioeconomic and ecological indices	X	X	X	X	X	X	✓	X	X	X	X
Zhang, et al. [25]	Energy	X	X	X	X	X	X	X	✓	X	X	X

Green = identified in that study (red = not identified). See Supplementary Information—Literature table for full results.

### 3.1. UM Suitability for Integration of ES

None of the case studies explicitly assessed ES. However, several studies used metabolic flows that could be used as proxy ES indicators. Twenty-two case studies exhibited some link to provisioning services, and 25 were linked to regulating services, while no study was found to have a link with cultural services. For example, several of the case studies that traced water stock and flow may be relevant for the assessment of water-related ES supplies [64]. Similarly, the case studies that measured biomass stocks and flows are relevant for assessing food, materials, and bioenergy provisions [60]. We identified UM case studies that are relevant for assessing nutrient cycle regulation (in particular, carbon, nitrogen and phosphorous) [51,54,70]. Table 3 shows the UM stocks and flows we identified in the 42 case studies which we deemed relevant to assessing ES, and supporting literature demonstrating how these UM indicators have already been used or discussed as proxy ES indicators. In addition to cultural ES, other ES (such as pollination) are missing from this table because no case study traced correspondingly relevant metabolic stocks or flows.

Twelve of the case studies were not related to ES assessment. Instead, these 12 case studies calculated indices or indicators relating to network relationships [25,78], human activity [77,81] and emergy indicators [76,80,82,84]. These types of UM performance index are useful insofar as they reveal the dominant socio-economic patterns relating to material and energy flows, but we did not find these indices suitable for assessing the supply of any ES. This is because they did not contain links between MEFA and socio-ecological impacts. From this point on, we discuss the results of the 30 case studies that were found to be relevant for ES assessments. Table 4 highlights these case studies tabulated by ES group and the investigation themes they addressed. This table shows that key investigation themes such as temporal and spatial information as well as cross-scale integration were very common among those UM case studies that related to ES-relevant metabolic stocks and flows.

The case studies that were relevant for assessing ES (Table 3) are shown grouped by provisioning and regulating ES in Table 4 according to the key investigation themes, and the modelling approaches they used. Cultural ES are not shown because none were identified in the literature.

**Table 3.** Urban metabolic flows and their related ES.

Metabolic Stock/Flow	Related Ecosystem Services	Example Reference of This Metabolic Flow as an ES Indicator
Nitrogen	Nutrient cycling	Burgin, et al. [86], Herzig, et al. [87], Jones, et al. [88]
Phosphorous	Nutrient cycling	de Groot, et al. [89]
Carbon	Food/material provision, nutrient cycling, soil formation	Power [90], Maes, et al. [91]
Carbon dioxide	Global climate regulation, air quality maintenance	de Groot, et al. [89], Dobbs, et al. [92]
Water	Water provision, water regulation, climate regulation	Grizzetti, et al. [93], de Groot, et al. [89]
Food	Food provision/cultivated crops	Orsini, et al. [94], Calvet-Mir, et al. [95]
Biomass	Food/material/energy provision	Maes, et al. [91]
Particulate matter	Local climate regulation/filtering dust particles	Dobbs, et al. [92]
Land use/cover	Habitat regulation, genetic diversity regulation	Nelson, et al. [96], Foley, et al. [97]

**Table 4.** Key investigation themes linked to ES. Percentage values count only the 30 cases in which ES were identified.

Investigation Themes	Provisioning ES	Regulating ES	Provisioning and Regulating ES
Temporal detail	37% (11)	37% (11)	27% (8)
Spatial detail	27% (8)	30% (9)	17% (5)
Multi-level	13% (4)	20% (6)	7% (2)
Cross-scale integration	30% (9)	27% (8)	20% (6)
Total	73% (22)	83% (25)	53% (16)

### 3.2. Temporal Detail

Temporal detail was the most relevant type of information for UM-UES integration. Fourteen of the 30 case studies had some consideration of time dependency while the remaining 16 cases used only a single temporal datum. Of these 14 temporal case studies, 11 were suitable for assessing provisioning ES and 11 suitable for assessing regulating services. Eight were suitable for assessing both provisioning and regulating ES. The temporal detail most common was historic time-series (e.g., [51,52]). This essentially meant multiple independent snapshots of the UM. Four cases went further and considered dynamic links between temporal data points [54,68]. Mörtberg, et al. [68] used a land use change model (LEAM; Deal and Schunk [98]) to simulate future habitats to assess biodiversity potential. Lin, et al. [54] assessed 20 years of historic data to calibrate a ten-year forecast of carbon, nitrogen and phosphorous stocks and flows using system dynamics modelling. These two studies demonstrate the potential usefulness of applying system dynamics (SD) to complex urban ecosystems by predicting results over time. However, Mörtberg, et al. [68] and Lin, et al. [54] considered limited types of UM indicators (biodiversity and soil nutrients respectively) thus limiting the completeness and complexity of such SD forecasts.

### 3.3. Spatial Detail

Spatial detail was identified in 12 cases. This was relevant for eight cases that related to provisioning services and nine cases that related to regulating services. The most common type of spatial detail was the use of land use/land cover maps to disaggregate and spatially link geographically separate stocks and flows or infrastructure. VandeWeghe and Kennedy [71] described a method by which emissions can be linked to geographic information and thus mapped. Pauleit and Duhme [58] used geographic information systems to assess surface water infiltration based on land surface media.



This enabled spatially explicit analysis of surface water flows. Chrysoulakis, et al. [57] developed and applied the BRIDGE method for urban sustainability assessments that is spatially explicit and capable of measuring energy, water and material flows that can be related to several UES. Mörtberg, et al. [68] and Lookingbill, et al. [69] were the cases in which both spatial and temporal dynamics were considered, especially the former. The remaining 18 case studies did not consider spatial information, meaning the system was considered as a black box unable to reveal any information about where the stocks and flows occurred.

### 3.4. Multi-Level

Geographic boundaries varied between the case studies. While five of the ten scoping review papers suggested taking a multi-level approach to system boundaries, only eight case studies assessed metabolic flows at multiple geographic levels. Three of these eight compared distinct areas [48,60,64]. Zhang, et al. [73] used a nested hierarchical approach whereby they assessed the carbon dioxide emissions of the city built-up area and the encompassing supporting area. Lookingbill, et al. [69] considered two levels; the urban system and a watershed that partially overlap and their boundaries are subject to change because of their exchanges. The cases with multiple geographic levels were not typically as relevant to ES compared to spatial or temporal details although this may be due to the general complexity of modelling UM across spatial levels rather than the relevance to ES.

### 3.5. Cross-Scale Integration

Cross-scale integration refers to the assessment of parameters from more than one sustainability pillar. This means assessing impacts at more than once scale or using elements of one scale to draw conclusions about impacts at different scales, (i.e., socio-ecological or economic-ecological metabolic elements), often referred to as CHANS. Eleven case studies considered metabolic flows that only related to social and or economic elements. The remaining 19 cases assessed traditional material-energy metabolic flows such as water, carbon, and nitrogen. Of the 11 integrated assessment cases, nine were relevant to provisioning services and eight were relevant to regulating services.

### 3.6. Model Complexity

During the literature review, we identified five main UM model types in the 30 studies. Variations of the traditional MEFA were used in 16 studies. The remaining 14 cases made use of LCA, SD, emergy analysis and ecological network analysis (ENA). Interestingly, but not surprisingly, some of these modelling frameworks were more adept at assessing certain types of metabolic flows, and therefore, more promising for assessing certain UES. Table 5 shows the frequency of modelling type for each investigation theme.

**Table 5.** UM modelling approaches used per investigation theme. ENA: ecological network analysis.

Modelling Approaches	Temporal Detail	Spatial Detail	Multi-Level	Cross-Scale Integration
Network analysis/ENA	3	1	1	1
Emergy	3	1	1	1
Life cycle thinking	1	0	1	2
Systems thinking/system dynamics	4	3	3	1

Network models, especially ENA models, have been popularised in the UM field Zhang, et al. [25,99]. Network analysis methods were used in six of the 30 studies demonstrating suitability for ES. The network method involves defining each urban activity sector as a node and the material or energy flow between two nodes as a path. This enables the model to describe urban activities in terms of demand centres and is used to show competition intensity of nodes [52] and ecological hierarchy [100]. Network analysis was especially useful for considering temporal detail, albeit only

in longitudinal studies. In the reviewed papers, network models were applied to study the UM for distinct years in three studies.

Emergy models assessed material and energy flows using the concept of “transformity” as a multiplier to convert all flow units into the uniform solar emergy joules (seJ). Six studies use emergy models, two of which were combined with statistical methods: Logarithmic Mean Divisia Index [80] and Principal Component Analysis [82]. In spite of some research streams within the emergy synthesis community linking emergy and ES, the reviewed literature did not focus on this relationship, hampering a deeper interpretation of the meaning of seJ in the context of the UM-UES metaphor. Emergy models, like network analysis, were mostly applied to longitudinal studies.

Life-cycle-based approaches were rarely used in the reviewed literature in spite of this being an established method. Life-cycle thinking was employed twice in studies that assess elements across different scales [73,74]. The study by Chen and Chen [74] used an ENA method that acknowledged different stages of metabolic flows comparable to life-cycle stages.

We identified two integrated decision support models in the case studies: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM; Giampietro and Mayumi [14]) and LEAM [98]. Four studies we reviewed used the MuSIASEM approach [77,79,101,102] while LEAM was used only once. Studies that used MuSIASEM placed stronger emphasis on CHANS by assessing labour and wealth alongside material and energy flows, but these were not found to be relevant for assessing ES. The MuSIASEM tool can deliver forecasts but does not allow for dynamic modelling. LEAM, however, is capable of SD forecasting for land use classes [98,103] which can inform ES supplies [104]. SD forecasting was also used in the case of Lin, et al. [54] by coupling with MEFA. This study did link multiple indicators in a SD way; however, there was no consideration of CHANS. The cases of Lookingbill, et al. [69], Lin, et al. [70] and Liu, et al. [56] also applied systems thinking but did not extend the method to forecast results. In general, these modelling types have different strengths when it comes to assessing ES and some more than others.

It is worth mentioning that, outside the relatively small set of UM studies analysed in this paper, the literature considering the links between ES and these modelling approaches is vast. Research that links ES assessments with network/emergy analyses, life-cycle-based approaches and integrated decision support models, but not addressing specifically on UM issues, already exist exterior to the umbrella of the UM metaphor. An additional investigation of these large bodies of literature, which were out of scope in the present work, might ideally contribute to inspire future research on how to address the modelling of UES using the modelling approaches listed in Table 5.

#### 4. Discussion

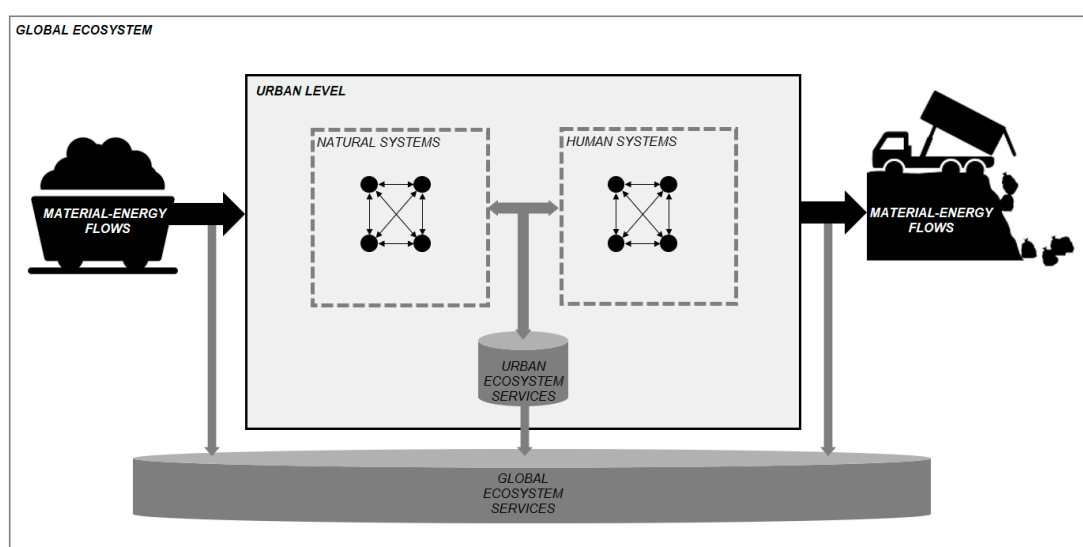
The main message we could retrieve from the above analysis of key investigation themes is that a critical gap exists between state-of-the-art UM assessment methods and their application to assessing UES. In fact, the reviewed literature did not even suggest the linkage between UM and UES. We have seen that some modelling frameworks are favoured for different types of information: spatial, temporal, different levels and scales, and the dynamics between them. All the cases we reviewed do not capture the full complexity of the UM stocks and flows, but between these various approaches some strengths can be drawn.

In the next sections, we inspect and discuss the main causes underlying the omission of UES assessments in the reviewed UM case studies and underlying models, emphasising on the potential assets for further improvement of the UM-UES framework. Based on these strengths and weaknesses of those cases we go on to propose pathways towards an advanced integrated UM-UES modelling framework, including which methodological aspects should be incorporated and which have lower priority.

#### 4.1. Modelling Complex Information

Spatio-temporal details are a major part of the complexity of urban systems, and the methods for integration of these details in UM approaches remain an open research question [32,56]. Urban activities, and therefore the metabolic flows, occur in heterogeneous spatial patterns [105,106]. While we found studies that addressed either spatial heterogeneity or considered temporal evolution, only one study simulated future spatio-temporal patterns by implementing the dynamic land use change model LEAM [68].

Accounting for spatio-temporal heterogeneity requires additional data complexity. Using static spatial information only provides snapshots of the spatial patterns. In contrast, dynamic land use models are useful for predicting some ES supplies, but not all UES are so directly linked to land use [107]. For example, supply of climate regulation is global regardless of the land use and origin of greenhouse gas emissions [108]. However, understanding how these patterns change in relation to material-energy stocks and flows and their impact on the supply of ES requires a detailed database of historical land use maps from which those spatio-temporal dynamics may be revealed, calibrated and validated [47,109]. Land use and land cover maps (e.g., Urban Atlas; Montero, et al. [110]) can be used to estimate physical qualities (e.g., as surface type and imperviousness, tree cover), and as proxies to spatially disaggregate material-energy stocks and flows (e.g., construction materials in urban fabric) [110]. In this case, data should be disaggregated to a spatial unit of measurement to capture the spatial patterns. For example, the space within the urban boundary may be subdivided into spatial units each described by a matrix of material and energy flow data specific to that spatial unit. These data can provide the information for measuring UES indicators for that spatial unit [104,111]. This is illustrated in Figure 2, which represents the multi-level system in terms of a foreground urban level nested within a background global ecosystem. The background level serves as source and sink of resources and emissions, while the urban level houses the socio-economic demands for those resource flows. In doing so, the urban system causes impacts to the supply of ES, both within the urban level (the UES), but also the ES at the non-urban level. Those UES are linked to spatial units. Black stocks and flows represent the aspects of the UM metaphor which are already exercised in state-of-the-art methods. That is, the material-energy inputs and outputs, and the disaggregation within the subsystem by ENA or spatial information. The grey lines and icons represent exchanges between human and natural systems, which are currently missing in state-of-the-art UM methods, and necessary for the advancement to a holistic UM-UES integrated model.



**Figure 2.** Multi-level UM system and its resource flows influencing urban ecosystem services (UES) supplies.

Among the strengths of using such an approach is the opportunity to represent spatially relevant patterns at high resolution and eventually quantify and map UES and their values according to well-established modelling tools for the ES community [96]. The individual models case studies found in this literature review are apparently not sufficient to cope with these aims, however, so an appropriate integrated modelling framework is needed to support the data complexity.

#### 4.2. Methodological Bases

We saw in Section 3.6 that material-energy flow analysis, emergy analysis, network analysis, system dynamics, and life cycle approaches were used to illuminate and reveal different aspects of the urban complexity. Some of these model types may be especially relevant for advancing a UM-UES modelling framework thereof.

To understand the link between urban activities and associated socio-ecological impacts the data should capture both the direct and indirect impacts (embodied along the life cycle of a material) [86]. This requires taking a life cycle thinking approach when defining the system boundary of material and energy flows whose life cycle impacts transcended the urban level [33,112]. Data that only deal with impacts at the urban level can give limited results by missing the impacts on ES supplies up and downstream in the life cycle of material-energy flows. This was the purpose of Goldstein, et al. [113] developing the UM-LCA, from which it was concluded that embodied impacts associated with urban metabolic flows in fact are not trivial in the calculation of urban environmental footprints.

While this model focused on the environmental impacts typically considered in LCA, it could also be useful to inform the socio-ecological aspects of an UM. Embodied impacts can be measured with, for example, environmentally extended multi-regional input-output tables [114]. However, the disaggregation of economic sectors into the necessary granularity of the urban scales (e.g., to specific material flows) involves assumptions and increases uncertainty. Many of the ENA models described in Section 3 used input–output data that are mostly available at the city level in China. European cities rarely have city level input–output data tables available. Some studies have been done on the factorisation of city-specific data from national level input–output (IO) tables. A hybrid method for constructing regional (e.g., city-level) IO tables is described by Miller and Blair [115]. This may provide the best solution for using IO data to capture those embodied impacts. Alternatively, other life-cycle inventories based on bottom-up data collection are available for specific regions, especially in Europe. However, in the case where city-specific life cycle inventory data are not available there would be associated with applying one city’s data to fill the gaps of another. In this case, IO tables seem to offer the more attractive option due to their methodological consistency and replicability across cities and nations. IO and multi-regional IO tables can also inform the socio-economic flows entering and leaving the urban system. However, as the relationships between socio-economic elements in the urban system should not be assumed as linear, additional information is needed to link these flows to UES [116]. These data should be collected on a city-specific basis and validated by (and calibrated to) observed historical time-series data to understand their potentially emergent properties [116,117].

#### 4.3. Linking Elements of the Urban System

CHANS is an important characteristic of urban systems [44,47,118]. Understanding the interactions between elements in the urban system, especially the CHANS, is a recurrent theme in urban systems modelling [20,30,31]. While it is not yet well-adopted in most UM studies, strong cases have been made for including related aspects such political and social ecologies in the UM framework [17,20].

One of the models assessed in the literature review—MuSIASEM—was designed to model urban systems considering CHANS [119]. However, MuSIASEM is not a dynamic forecasting model meaning it does not reveal the self-organising and emergent relationships borne of the complex internal urban dynamics [116]. Modelling the urban system without considering those causal relationships thus limits the representativeness of information pertaining to spatio-temporal dynamics [120–122]. In contrast, SD modelling takes causal relationships into consideration and equates them by a system

of difference equations. For example, the MIMES (Multiscale Integrated Models of Ecosystem Services) is a modelling approach that models ES linked to CHANS across scales, but it is not based on UM stocks and flows [123]. However, based on the findings in this review the tailored UM-UES framework should also be based on SD. This is supported by the conclusions of Beloin-Saint-Pierre, et al. [32]. SD modelling frameworks can represent UES in spatio-temporally specific detail across multiple levels and acknowledges the role of the relationships between system elements [124–130]. Existing attempts based on the MIMES suggest that new models may be specifically tailored for the network UM framework to track physical flows as influencers of ES supply to include aspects of urban material-energy flows [123,131,132]. Combining these attributes—spatially explicit, multi-level, life cycle information and dynamic cause–effects integrated across social, economic and ecological—can provide a detailed holistic representation of the complex urban dynamics [133].

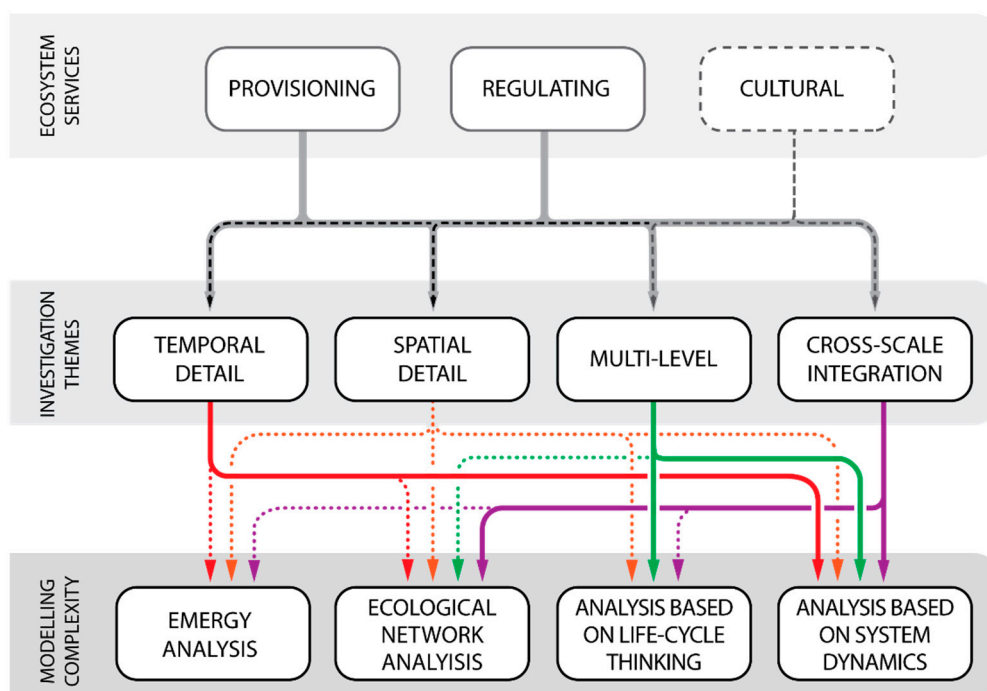
Network analysis is another fundamental piece of knowledge capable of linking elements of the UM system [32,99] that was used in many studies reviewed in this paper [53]. Network nodes usually represent economic sectors while materials, water, energy, and waste flows are transferred between nodes, represented by network edges. This method is a useful way to measure the distribution of material-energy flows to specific nodes or sector and therefore the competition between different sectors for those resources [134]. Network analysis can also be linked to spatial information (e.g., land use maps) as demonstrated by Leduc and Van Kann [66], and can be used with CHANS to model relationships between ecosystems and political economy [135], to address for instance the sociological issues raised by Pincetl [17]. Network analysis has been applied to trophic webs [136] and increasingly to other aspects of ecology [99]. How to quantify UES according to network models for UM thus opens another room for further research and development. Incorporating network analysis in modelling ecosystems can further facilitate the linkage from UM flows to CHANS [125].

#### 4.4. Pathways Towards UM-UES Assessments

Our results showed that the UM metaphor, subject to some reorientation and increased modelling complexity, has the potential to assess provisioning and regulating UES, thus strengthening the socio-ecological capabilities of UM. However, in our review we saw no convergence towards measuring and mapping cultural UES. The UM assessments we reviewed considered various geobiophysical flows and derived socio-economic indicators, but the educational, intrinsic, spiritual or recreational phenomena were not assessed. These types of cultural ES are not so obviously connected to resource flows, and so it is not surprising that the UM community, which has historically dealt with water, energy, material and economic indicators, does not yet intersect with this dimension of ES research. Even in the ES research field, assessment of cultural ES is an open question [137,138]. This may be because cultural UES are generally more difficult to conceive of in physical quantities [137]. Proposals to measure and map cultural ES tend to focus around variables such as accessibility to and visitation of natural structures [95,139]. As we have seen, these evaluations share little in common with state-of-the-art UM methods. However, we did encounter UM case studies that used survey and participatory methods [62]. This type of UM assessment may hold the key to incorporating cultural services in a comprehensive integrated UM-UES model. Studies focusing on the advancement of cultural UES assessments emphasise the need to take a systematic CHANS approach using social science tools such as participatory mapping, structured interviews, and linking these to spatial information [138,140,141]

Most importantly, our review identified links between the types of information deemed relevant to assessing and predicting UES, and the modelling tools being used in UM research. That is, to model and predict spatio-temporal changes in UES that relate to UM stocks and flows, models must respect the cause–effect relations of CHANS, embodied life cycle impacts of material and energy stocks and flows, and spatio-temporal information. Therefore, the integration of SD, ENA, and LCA modelling approaches must be considered in the evolution of the UM-UES models. The proposed set of pathways (Figure 3) shows our results on investigation themes relate to assessing provisioning, regulating and cultural UES using the UM metaphor. Figure 3 is composed of three layers: ES (what we want to

model), investigation themes (information the models should incorporate), and modelling complexity (the types of models that may be needed). Lines representing dependencies link these layers.



**Figure 3.** Potential pathways for modelling the UM-UES framework.

The top and middle layers, representing ES and investigation themes, are connected by solid lines or dashed lines. Solid lines represent an investigation theme as necessary for the assessment of the connected ES group. Dashed lines stemming from cultural ES are connections that were not identified in the literature albeit may have potential to be developed. This is consistent with current research on cultural ES, which generally points to a lack of cultural ES assessments due to the need for spatially specific information, interregional (i.e., multi-level) flows and integrated modelling across social and ecological scales [4,140].

The layers representing investigation themes (middle) and modelling complexity (bottom) are connected by solid lines or dotted lines. Solid lines represent prioritisation of the modelling approach to cope with the data detail associated with that investigation theme based on the literature we reviewed. Dotted lines represent links that are possible but that are not a priority (i.e., the modelling approach has the capacity to deal with that data type, but the investigation theme is out of the scope of the model).

These pathways emphasise the importance of integrated analysis based on SD, life cycle thinking and ENA in order to assess provisioning, regulating and cultural UES in a comprehensive, integrated methodological framework. Each of these modelling frameworks resolve the current gaps in UM capability to assess UES, while increasing the demands on information complexity. Linking these modelling approaches such that the benefits of each remain useful and coherent may be challenging. However, outside the UM and ES communities, efforts are already underway to link aspects of these approaches [99,133,142]. For example, Onat, et al. [143] have already forged a way to weave the non-linearity of system elements into a life-cycle sustainability approach.

## 5. Conclusions

This paper intends to mark the way towards a novel modelling approach to incorporate the assessment of urban ecosystem services (UES) in the framework of UM models. Our results showed that the UM metaphor, subject to some reorientation and increased modelling complexity, has the

potential to assess provisioning and regulating UES, thus strengthening the socio-ecological capabilities of UM.

The number of both urban metabolism (UM) and urban ecosystem services (UES)-related studies have increased rapidly in recent years. However, there are still few inter- and trans-disciplinary examples in the literature exploring how they may be integrated as an UES modelling tool. Moreover, the reviewed UM literature has invariably limited scope of cross-scale integration. These state-of-the-art UM studies largely focus on ‘opening’ the UM modelling box by coupling one investigative theme at a time among temporal, spatial and multi-level factors. In this regard, no study demonstrated a holistic UM-UES approach, and while many studies assessed metabolic flows that could easily be linked to UES, the scope of those studies were not comprehensive in modelling coupled human-nature systems (CHANS) in an integrated manner. Overpassing the interactions between elements in the urban system limit the model’s ability to acknowledge and reveal complex and internal system dynamics. If too few elements are considered, the results may not be robust and this can generate burden shifting, whereby results may show positive trends in one aspect while the negative trends in another aspect may go unaccounted. Avoiding this requires a holistic, integrated and systematic modelling approach.

Considering this identified gap, we propose new pathways to address the UM paradigm with potential to support an UES assessment approach. These pathways address the key investigative themes such as spatio-temporal details and multi-level and cross-scale integrations. This model borrows the concept of CHANS as a basis from which to develop a more advanced UM method. System dynamics (SD) modelling is well suited to deal with CHANS. Additionally, our results showed that SD enabled for predictive forecasting at multiple geographic levels making use of spatially explicit information and landscape metrics. This may allow for the simultaneous incorporation of multi-level and spatio-temporal, and life-cycle information, as well as a systemic picture about the dynamic cause–effect relationships among the model variables that link the UM to its potential consequences in the supply of UES.

These enrichments to the contemporary UM framework are anticipated to better inform urban planners on the long run consequences of deploying sustainability interventions with the goal of meeting urban and global sustainability challenges. In this way a SD modelling approach could capture the spatio-temporal dynamics that so many UM reviews have highlighted as current methodological shortcomings. Incorporating life cycle thinking can also capture the metabolic flows occurring outside the urban system, such as resource extraction and end of life processes. These life cycle stages may add valuable information to the assessment of non-urban ES supplies that are, nonetheless, causally tied to the socio-economic activities within the UM system. In this way, an integrated UM-UES framework with SD and life cycle thinking may have the potential to assess and predict future UES and ES supplies linked to spatial information at multiple geographic levels.

Future research also opens new and interesting questions about the application of integrated modelling for urban planning decision support. Among others, we foresee this model quantitatively assessing the value of nature-based solutions to support sustainable urban planning. More specifically, we intend the identification of these methodological pathways to serve as a benchmark for future development of tools capable to address sustainable development goals such as sustainable cities, water, climate, human equity, and biodiversity. We expect this to aid in the design of sustainable cities and more comprehensive evaluation of urban systems quantifying the gains and losses of multiple UES supplies associated with metabolic flows.

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**Author Contributions:** T.E. established the aim and research question, conducted the literature review, and wrote the manuscript. J.B.A., wrote paragraphs in the introduction and discussion as well as reviewing the manuscript and illustrating Figure 3. S.N. and V.P. supervised and supported the conceptual development of the research and reviewed draft versions of the manuscript. B.R. defined the research project and identified the research agenda within which this paper was written, in addition to contributing paragraphs throughout the manuscript and reviewing the overall coherency.

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## Abbreviations

BRIDGE	sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism [57]
CHANS	coupled human and natural systems
ENA	ecological network analysis
ES	ecosystem services
IO	input-output
LEAM	Land use Evolution and impact Assessment Model [98]
LCA	life cycle assessment
MEFA	material-energy flow analysis
MIMES	Multiscale Integrated Models of Ecosystem Services [123]
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism [14]
SD	system dynamics
seJ	solar emeryg Joules
UES	urban ecosystem services
UM	urban metabolism

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