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Understanding the contribution of ecosystem services to urban metabolism assessments: An integrated framework

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A B S T R A C T

The growing evidence-base demonstrating that cities are responsible for accelerated natural-resource erosion and the exacerbated impacts of atmospheric emissions on climate change suggest the need for more systemic resource-use mitigation strategies at the urban scale. Nowadays, ecosystem service analysis provides an extensive reservoir of techniques and strategies to optimize the metabolism of cities through enhanced resource cycling and emission abatement. However, this reservoir is largely untapped in urban metabolism research despite substantial progress in ecosystem service knowledge and classification. In response to this knowledge gap, in this article we propose an integrated urban metabolism and ecosystem service framework to extend Economy-Wide Material Flow Analysis (EW-MFA). The framework utilizes "Pressures", "Drivers" and "State" indicators to describe the relationships between anthropogenic and natural systems. A set of indicators was compiled from previous urban metabolism and ecosystem service studies to provide a shared and adaptable set of assessment categories across the two areas to jointly measure ecosystem services and resource flows. Through the proposed framework, interdependencies and causal relationships between ecosystem service assessment and EW-MFA flow categories can be identified. The focus of the paper is on elaborating the conceptual foundations of the framework and its analytical characteristics.

1. Introduction

The increasing urbanization of rural areas, along with the accelerated rate of population growth globally (Tobergte & Curtis, 2016; United Nations, 2018), reflect the numerous environmental changes that have occurred on the planet in the last century (Ahmed et al., 2020; Sarkodie, 2018; Satterthwaite, 2005). Cities rely on materials and energy to conduct their regular activities, but the rate of resource use keeps increasing, to unprecedented levels (United Nations, 2018), outpacing the global biological capacity and causing adverse effects to environmental systems (Ekins et al., 2017; Schandl et al., 2018; UNEP, 2013). Hence, one of the main challenges confronting sustainability science is to reduce the current rate of resource consumption and resource intensity of urban areas. Understanding the processes that take place in cities is a first step toward overcoming these challenges. The Urban Metabolism (UM) field is tailored to this purpose since its overarching goal is to assess the interaction between natural environments and anthropogenic systems, including urban areas (Bai, 2016; Kennedy et al., 2011). For the last 30 years, other approaches to tackle the increasing depletion of natural resources have built on the growing evidence base on Ecosystem Services (ES), a concept developed in ecological economics (Costanza et al., 1991). ES are the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being (Costanza et al., 2017). These contributions take the form of material and energy provision (i.e. "provisioning ES"), the regulation of essential ecological processes (i.e. "regulating ES"), non-material benefits such as recreation and cultural identity (i.e. "cultural ES"), and the indirect processes necessary to support all types of ES (i.e. "supporting ES") (Braat & De Groot, 2012; De Groot et al., 2002).

The application of this concept in an urban context can leverage more efficient management of natural resources and the abatement of Greenhouse Gas (GHG) emissions resulting from cities' energy and material demands (Keeler et al., 2019; Perrotti & Stremke, 2020). It has also provided a different perspective for policy and urban planning applications, such as the implementation of Nature-based Solutions (Babí Almenar et al., 2021; Nesshöver et al., 2017), which suggests that the cross-fertilization with ES research can foster the implementation of UM

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knowledge in practice (Newell et al., 2019; Perrotti & Iuorio, 2019; Winker et al., 2018).

While sharing a common purpose of understanding interconnections between natural and anthropogenic systems to attain long-term sustainable development, the UM and ES fields differ substantially in terms of their use of concepts, assessment methods, analytical tools and models. The ES concept was initially used separately in environmental economics and ecosystem ecology, with the primary goal of highlighting how biodiversity loss has a direct impact on ecological functions that provide services for people's well-being (Braat & De Groot, 2012; Gómez-Baggethun et al., 2010). In the 1980s, ecological economics was established as a discipline bridging research gaps across the two fields while linking to other disciplines (e.g. psychology, political science, and earth system sciences) and professional practice; it made ES a key element of its research agenda (Costanza et al., 2017). Furthermore, Economy-Wide Material Flow Analysis (EW-MFA), one of the most common UM models describing the biophysical foundations of a system's economy through consideration of aggregated material and energy flows (Eurostat, 2001), excludes in-boundary activities and internal dynamics associated with resource consumption, limiting the possibility to capture the complexities of urban systems (Huang et al., 2018; Voskamp et al., 2020).

The goal of this study is to develop a novel framework that incorporates ES assessment into EW-MFA and consider interdependencies and trade-offs between ES and material and energy flows. The framework is based on a systemic approach, where each flow can be modeled dynamically while considering mutual influences, spatio-temporal variations and causal relationships. Furthermore, the framework includes a set of indicators describing a range of biophysical and socioeconomic conditions, which can modulate the framework application based on specific characteristics of local contexts.

The paper is structured as follows. The Background section examines previous research on the conceptual aspects between UM and ES studies as well as the motivation for suggesting the integration of the two fields and exploring the potential of ES to counterbalance EW-MFA flows. The Method and Materials section presents the methodological approach and assumptions behind the framework development. Finally, in Results and Discussion, first, the framework structure and features are presented; then, methodological challenges, significance and opportunities for application in case studies are discussed.

2. Background

2.1. Urban metabolism and ecosystem services

Urban Metabolism (UM) is an interdisciplinary research field integrating several disciplines, each with its own particular methodologies, scopes and implications (Broto et al., 2012; Dijst et al., 2018). UM methods aim to assess the processes and activities underpinning resource demand and waste generation in cities based on an understanding of the interaction and influence cities have on other socioeconomic systems and the environment. Contributions to UM research come from a variety of fields of study including industrial ecology (IE), urban ecology (UE), ecological economics, political ecology and political-industrial ecology (Perrotti, 2020; Wachsmuth, 2012). Among these fields, the UM line of research in IE stands out in terms of the number of empirical investigations (Li & Kwan, 2018; Tang et al., 2021; Wang et al., 2021). The most common UM definition used by industrial ecologists is the "total sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007). As this definition shows, UM studies in IE are mainly concerned with the quantification of resource flows and the optimization of resource use. Material Flow Analysis (MFA) is a family of methods commonly employed in UM which allows the classification and quantification of material flows within the boundary of a defined system (Brunner & Rechberger, 2016), such as a nation, a region or an urban area.

Given the variety of assessment methods available in literature, we conducted a review to determine an appropriate UM assessment approach for the framework proposed in this article. The review of UM methods consisted of the search for, and selection of, 44 case studies using three search strategies: a search via Scopus, snowball method, and screening of review articles. **(Supplementary Table S1)**. The studies were classified in terms of accounting model, inflow and outflow indicators, spatial and temporal scope. In all the studies examined, the EW-MFA method (Eurostat, 2001) is the most consistent in terms of flow categories and had the highest number of case studies. Initially designed for nationwide analysis, the EW-MFA has become a foundation for UM studies in the European Union and has been adapted to city and regional levels including, for example, Lisbon (Rosado et al., 2014), Cape Town (Hoekman & von Blottnitz, 2017), Amsterdam (Voskamp et al., 2017), Rennes and Le Mans (Bahers et al., 2019), Stockholm (Papageorgiou et al., 2020), and regions in European countries (Bianchi et al., 2020). All material flows required for the establishment, operation, and maintenance of socioeconomic biophysical stocks are quantified by EW-MFA (Mayer et al., 2016). Domestic extraction (DE) is defined as the sum total of all materials extracted from the environment that enter the socioeconomic system; waste and emission outputs that are disposed in the environment are considered as domestic processed outputs (DPO) (Fig. 1).

The integration of UM accounting and the ES concept can provide an alternative to overcome the aforementioned UM methodological hurdles and improve the way urban systems are modeled. Ecosystem Services arise from interactions of the natural capital (i.e. the world's stock of natural resources) with the human capital (people), the social capital (societies), and the built capital (infrastructure), which result in benefits that contribute to human well-being (Costanza et al., 2014). A number of ES classification systems are currently available in the literature, for example, the Millennium Ecosystem Assessment (2005), the classification provided by The Economics of Ecosystems and Biodiversity (TEEB) (Kumar, 2010), and the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2010). The main characteristics of these and other ES classification systems have been studied in detail by La Notte et al. (2017), and McDonough et al. (2017) and lie outside the scope of this article.

CICES was elaborated for the European Environment Agency with the final purpose of mapping ES in the European Union, where an organized record of ES was needed (Haines-Young & Potschin, 2012). A characteristic of CICES is the hierarchy among categories used to classify the ES, including "sections", "divisions", "groups" and "classes" (from larger to smaller scopes). This hierarchy enables ecological assessments to be developed at an appropriate level of depth based on available data. Moreover, it provides a more detailed classification for ES that also includes biotic and abiotic outputs of ecosystems such as renewable energy, which are not considered in other classification systems. For this reason, CICES was used as a baseline for the accounting of ES in the integrated framework we propose. Moreover, CICES has become the official ES classification system adopted by the EU, following its implementation in the MAES project (Mapping and Assessment of Ecosystems and their Services), an overarching ES assessment initiative in Europe (Maes et al., 2011, 2013, 2016).

2.2. How can ES contribute directly and indirectly to UM flows? A review of current studies

In order to build a comprehensive knowledge of the integration between UM accounting methods, particularly EW-MFA, and ES assessments, a review of studies that incorporate both concepts was conducted. For this purpose, a Scopus search was performed using quantitative and qualitative criteria. Initially, a database of publications was generated using the following search string: TITLE-ABS-KEY ("urban metabolism" OR "metabolism of cities" AND "ecosystem

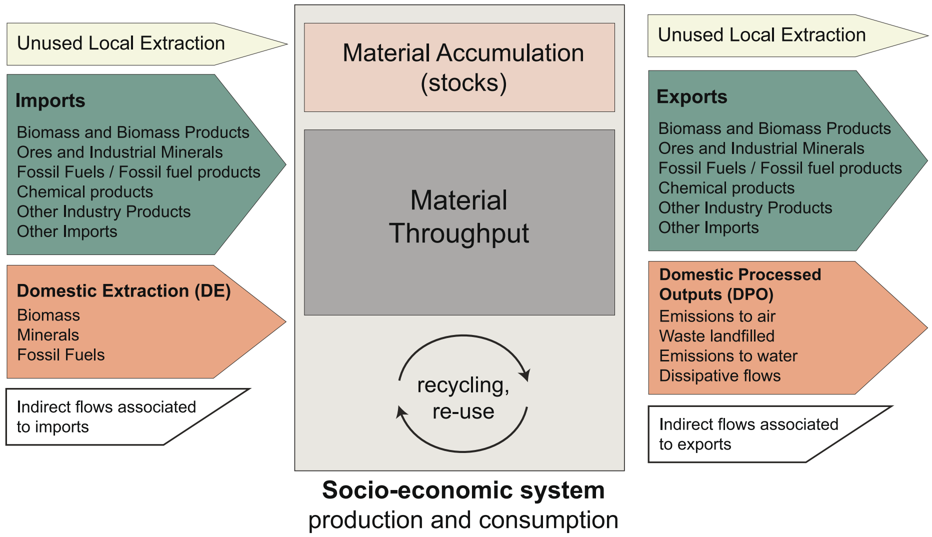

Fig. 1. EW-MFA scheme. Balancing items in the inflows and outflows are defined to have a closed material balance. After Eurostat (2018).

service*"), only articles in English were selected. Two themes could be found within the 15 document results in the search. The first theme is concerned with commonalities between UM and ES concepts and assessments, as well as opportunities for integrating analytical frameworks. For example, Pincetl (2012) argues in favor of the viability of coupling of urban ES and UM, where industrial ecology methods can complement ecological science. Perrotti and Stremke (2020) further advance the integration of ES in UM by reviewing empirical studies where urban ES provided by green infrastructure can influence the outcomes of material and energy flow accounting in urban areas. Furthermore, Elliot and colleagues (2019) elaborated a review of empirical UM studies that intersect with the ES research field, and introduced different modeling approaches targeted at overcoming methodological gaps (e.g. spatio-temporal dynamics and cause-effect relationships). The second set of articles examines research in which the ES(s) studied are also classified as a resource flow and so fall under the purview of an UM assessment. Kane and Erickson (2007) investigate cities' reliance on non-marketed ES, namely, provision of water from regional watersheds. The authors argue, based on a case study, that UM is a valuable instrument for determining water demands and, as a result, for establishing compensations to watershed communities for the provision of ES. Van Leeuwen and colleagues (2012) discuss indicators from a diverse set of methodologies such as UM and ES assessments to develop a strategy for integrated urban water management. Langemeyer et al. (2021) propose the inclusion of urban agriculture in urban planning, considering the benefits and externalities of its implementation in cities. Dal Bo Zanon et al. (2017) evaluate the potential of using nutrient waste and carbon emissions to cultivate algae, food and biofuel in areas near to delta and coastal cities. Finally, Elliot and colleagues (2020) provide an assessment of GHG emissions in Lisbon, and the potential of urban forests to sequester carbon emissions in cities, a regulating ES.

The remaining studies utilize an UM approach that integrates ES into a resource assessment; however, the UM methods used by the aforementioned authors are not the same as in the framework proposed in this article (EW-MFA and provisioning and regulating ES). Pietta and Tononi (2021), for example, contribute to the Urban Political Ecology approach to UM by taking into account human-nature linkages in cities and combining them with cultural ES to assess a set of socio-cultural values of urban parks. Beck & Villarroel Walker (2013) investigate the notion of nexus security, which they define as the interconnections between water, food, and energy flows, as well as urban resilience. Furthermore, Viglia and colleagues (2018) evaluate the environmental performance of five Italian cities using Cumulative Energy Demand (CED) and Emergy Accounting (EMA), to quantify the energy embodied in Provisioning ES in terms of solar emjoules. Furthermore, some studies utilize the UM method or the ES concept but not both; thus, they were not considered in the review. Metzger et al. (2016) conducted an UM assessment of three cities in the US; however, they only mention ES to emphasize that its degradation is an environmental issue. Mörtberg et al. (2013) assessed ES using a landscape ecological model (LEAM) in a Swedish city; however, here "UM" refers mainly to a variety of approaches to model urban systems. Furthermore, Inostroza (2014) presented "Technomass" as a new indicator to characterize stock accumulations in an UM assessment and utilized this indicator in a Colombian case study; but the paper contains no clear reference to ES assessments, whether it be provisioning or regulating ES.

The 16 articles provided insights into the integration of ES assessment and the UM approach, conceptually and through the assessment of certain UM flows and ES services that are intrinsically similar. However, the number of articles available was deemed insufficient to provide a thorough examination of both concepts. As a result, a more in-depth review of the literature dealing with the ES concept in urban environments was conducted using text-analysis metrics. The first step consisted of a Scopus search using the following Boolean string: TITLE-ABS-KEY ["ecosystem service*" AND ("city" OR "cities" OR "urban")], also limited to English-language documents. This search retrieved 5209 documents. Since the extensiveness of the document search mad it difficult to conduct a thorough screening, the content of the Titles, Keywords and Abstracts in all results were analyzed using Natural Language Processing (NLP) and Text Mining (TM). A set of two text-analysis metrics (frequency and log-likelihood) were used to characterize those words or keywords that are relevant to ES research. A detailed description of the text-analysis process can be found in the **Supplementary Document S2**.

In total, 82 terms were selected and included in the string search along with the term "urban metabolism" or "metabolism of cities" (**Supplementary Document S2**). A total of 565 results were retrieved, which were further screened through their abstract and selected using the following two criteria:

1) The article focuses on the assessment of at least one ES among those classified in CICES (Haines-Young & Potschin, 2010), TEEB (Kumar, 2010) and MA (Millennium Ecosystem Assessment, 2005), including both ES that correspond directly to physical flows in EW-MFA (Provisioning ES) and ES that offset physical flows in EW-MFA (regulating ES). Despite not being included in the standard EW-MFA, water provisioning and wastewater flows are among the physical flows to be considered when assessing ES as part of the UM,

given their significant impact on the urban economy (Voskamp et al. 2017). Supporting and cultural ES were not included in the review since their assessment requires a different, multilayered modeling approach (Maes et al., 2012) which differs substantially from the one used in our framework development (cf. Method and Materials section).

2) The ES(s) identified in the article is/are assessed using primary data from a case study, and is/are located inside the administrative boundaries of the urban area (e.g. urban agriculture, carbon sequestration in urban areas).

A total of 57 papers resulted from this streamlined search. The results of the Scopus search provide evidence of the integration of UM and ES assessments since there are provisioning and regulating ES that can be characterized as EW-MFA flows (Table 1). Moreover, there is also evidence that ES can generate offsets of EW-MFA flows. The results are described as follows.

A significant portion of these studies (16 out of the total) develop an analysis of the water cycle or quantify water flows in an urban context. For example, this includes studies that developed an extended EW-MFA including water inputs and outputs (Voskamp et al., 2017), other UM methods (Ngo & Pataki, 2007), a mass-balance framework for water-flow classification (Kenway et al., 2011), and the assessment of rain-water from collection systems in buildings (Morales-Pinzón et al., 2015; Winker et al., 2018).

A set of articles deals with the provision of biomass as food within a city from the implementation of urban agriculture (LeGrand et al., 2014; Rufí-Salís et al., 2020; Wielemaker et al., 2018), recovery of food waste as energy (electricity, biogas, heat and biofuel) (Chaker et al., 2021), energy from grazed crops sourced from urban and *peri*-urban areas (Saha

Table 1
Results of the Scopus search: Case studies of provisioning and regulating ES assessments that can be characterized as EW-MFA categories of flows.

Category of EW-MFA (Eurostat, 2018)	Ecosystem Service				Empirical Studies
	CICES (Group)*	CICES (Class)*	MA	TEEB	
Crops (excluding fodder crops) (MF 1.1)	Cultivated terrestrial plants for nutrition, materials or energy	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	Food	Food	Barles, 2009; Cadenasso & Pickett, 2013; Caputo et al., 2021; Leduc & Van Kann, 2013; LeGrand et al., 2014; Rufí-Salís et al., 2020, 2021; Wielemaker et al., 2018
Crop residues (used), fodder crops and grazed biomass (MF 1.2)	Cultivated and wild terrestrial plants for nutrition, materials or energy	Cultivated and wild plants (including fungi, algae) grown as a source of energy	Fiber, timber, ornamental, biochemical	Raw materials, medicinal resources	Bahers et al., 2019; Chaker et al., 2021; Forkes, 2007; Islam, 2017; Leduc & Van Kann, 2013; Sarralde et al., 2011
Waste for final treatment and disposal (MF 6)	Cultivated and wild terrestrial plants for nutrition, materials or energy	Fibers and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)	Fiber, timber, ornamental, biochemical	Raw materials, medicinal resources	Chaker et al., 2021; Saha & Eckelman, 2015; Sarralde et al., 2011
Biomass (MF 1)	Cultivated aquatic plants for nutrition, materials or energy	Fibers and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials)	Fiber, timber, ornamental, biochemical	Raw materials, medicinal resources	Dal Bo Zanon et al., 2017; Villarroel Walker et al., 2017
Organic fertilizer (Manure) (MF 7.4.1), Emissions to Water (MF 7.3)	Reared animals for nutrition, materials or energy	Fibers and other materials from reared animals for direct use or processing (excluding genetic materials)	Fiber, timber, Ornamental, Biochemical	Raw materials, medicinal resources	Barles, 2007; Cui et al., 2015; Kenway et al., 2011a; Villarroel Walker et al., 2017; Wielemaker et al., 2020; Wielemaker et al., 2018
Fossil energy materials/carriers (MF 4) (Offset), Emissions to Water (MF 7.3)	Reared animals for nutrition, materials or energy	Animals reared to provide energy (including mechanical)	Fiber, timber, ornamental, biochemical	Raw materials, medicinal resources	Pearce & Chertow, 2017; van der Hoek et al., 2017
Nitrogen (MF 7.3.1), Phosphorus (MF 7.3.2)	Regulation of soil quality	Decomposition and fixing processes and their effect on soil quality	Soil formation (supporting service)	Maintenance of soil fertility	Firmansyah et al., 2017; Villarroel Walker et al., 2017
Emissions to air (Offset) (MF 7.1)	Atmospheric composition and conditions	Regulation of chemical composition of atmosphere and oceans	Atmospheric regulation	Climate regulation	Blecic et al., 2011; Chrysoulakis et al., 2013; Elliot et al., 2018; Kellett et al., 2013; Laureti et al., 2018; Li et al., 2018; Penazzi et al., 2019; Xia et al., 2018; Xia et al., 2019; Zhang et al., 2015
Fossil energy materials/carriers (MF 4), (Offset),	Atmospheric composition and conditions	Regulation of temperature and humidity, including ventilation and transpiration	Atmospheric regulation	Climate regulation	Kenway et al., 2011; Mitraka et al., 2014
Fossil energy materials/carriers (MF 4), (Offset)	Non-mineral substances or ecosystem properties used for nutrition, materials or energy	Solar energy	–	–	Rúa et al., 2020; Sarralde et al., 2011; Zara et al., 2017
No identified EW-MFA category **	Surface/ground water used for nutrition, materials or energy	Surface, ground (and subsurface) water for drinking; Surface and ground water used as a material (non-drinking purposes)	Water	Water	Burn et al., 2012; Hermanowicz and Asano, 1999; Ngo and Pataki, 2008; Niza et al., 2016; Paul et al., 2018; Pauleit and Duhme, 2000; Russo and Buonocore, 2014; Thériault and Laroche, 2009; Villaroel Walker et al., 2012; Villaroel Walker and Beck, 2012; Voskamp et al., 2017; Sahely et al., 2003

*Group and class of ecosystems are part of the hierarchical scheme of CICES. Class is a more detailed classification of ES, and Group represents a broader category (Group is composed of several classes).

** Water flows are not accounted for in EW-MFA. They have been included in our literature view due to their impact on the economy of the studied system. Moreover, they are not considered in the TEEB or MA, reason for which CICES was used in our study.

& Eckelman, 2015; Sarralde et al., 2011) and timber from urban forests as a construction material (Kampelmann, 2021). The ability of urban green spaces (parks and forests) and trees to absorb carbon and reduce emissions is another example of biomass-based regulating ES in the city (Chrysoulakis et al., 2013; Elliot et al., 2018; Kellett et al., 2013; Penazzi et al., 2019; Zhang et al., 2015) Moreover, urban trees and forests have the capacity to provide a cooling effect and reduce the Urban Heat Island (UHI) effect (Kenway et al., 2011; Mitraka et al., 2014), which can reduce the energy demand for cooling in buildings (Santamouris et al., 2015).

Another group of articles deals with the reuse of wastewater as fertilizer nutrient (Barles, 2007; Cui et al., 2015; Wielemaker et al., 2020; Wielemaker et al., 2018) and as biomass-to-energy processes (Pearce & Chertow, 2017; van der Hoek et al., 2017). Another regulating ES found in the search is the soil fixation of nutrients such as nitrogen from agricultural practices, as studied by Firmansyah et al., 2017 and Villarroel Walker et al., 2017. Similarly, solar energy in cities has the capacity to reduce the demand for energy from fossil fuels; therefore studies that quantify solar PV energy potential within urban areas have also been included among the analyzed physical flows (Rúa et al., 2020; Sarralde et al., 2011; Zara et al., 2017).

3. Method and materials

In this article, we propose an analytical framework that incorporates ES assessment into the EW-MFA method. Unlike previously developed UM methods, this framework is suited to the inclusion of a broad set of ES based on the CICES classification and it characterizes the relationship between the natural capital and the social capital. For that purpose, we 1) examined definitions and methods for assessing UM and ES in order to synthesize current knowledge and 2) designed an assessment framework that also addresses key challenges presented in urban system modeling. The first step involved a literature review of UM case studies that used flow-based models, and a review of ES classification systems and assessment methods. Details about the review were presented in the Background section above. CICES was the classification selected since it is compatible with the categorization of flows underpinning the EW-MFA (cf. Table 1). Further details on the reasons for selecting CICES were presented in the Background section.

3.1. Review of ES assessment methods

In the current literature, several modeling approaches aim to identify, characterize, quantify, and value ES, their processes and functions. These approaches can be classified in three types: biophysical, socio-cultural, and economic valuation assessments (Burkhard & Maes, 2017; Harrison et al., 2018). Moreover, there are also multi-ecosystem assessment tools which cover more than one type of approach: InVEST (Sharp et al., 2016), Aries (Villa et al., 2014), ESTIMAP (Zulian et al., 2014), TESSA (Peh et al., 2013) and MIMES (Boumans et al., 2015). We will focus only on biophysical assessments since they quantify ES supply flows, which are relevant for this research. Based on the literature review described in the previous section, we selected 34 ES from the total 90 ES classified in CICES, of which 30 are Provisioning ES, and 4 are regulating ES. **Supplementary Table S3** provides the detailed list of the ES that were considered in the framework development.

In the assessment of ES supply, two types of ES have been identified: ES that are material and energy flows and ES that create changes or offset the flows. The first type of ES is easily compatible with the EW-MFA structure, because many UM flows, such as materials, biomass, energy, and water, are Provisioning ES. The assessment of offsets, on the other hand, is a more difficult task because it requires the use of proxies or additional calculations.

For some provisioning services (e.g. cultivated crops, reared animals, aquaculture animals and plants) the information on availability generally comes from official databases, statistics and surveys. Furthermore, approaches to biophysical assessment of ES encompass physical modeling of specific flows. These approaches include: hydrological models such as SWAT (Cong et al., 2020; Frizzle et al., 2021) and SUWMBA (Moravej et al., 2021) that assess water supply flows; crop productivity models (Lecerf et al., 2019; Mueller et al., 2012) that quantify agriculture production, transport; fate models for nutrients flows analysis (N,P) (Lusk et al., 2017; Shultz et al., 2018); and the assessment of photovoltaic potential to quantify solar energy generation (an abiotic ES following CICES, Bazán et al., 2018; Singh & Banerjee, 2015). Finally, the Bayesian belief networks model (BBN) (Bicking et al., 2019; Dang et al., 2019) offers an alternate way of incorporating expert knowledge in the assessment of factors influencing ES Supply when empirical evidence is not available.

UM flow offsets are mainly generated by regulating ES. Among the models that assess the sequestration of air pollutants (emissions) by vegetation are the UFORE model (Riondato et al., 2020; Selmi et al., 2016), based on remote sensing data (Bottalico et al., 2017) and spatial resolution sensors (Marando et al., 2016). These models calculate the dry deposition of pollutants (CO, NO_2, SO_2 and O_3) in urban vegetation. Furthermore, the sequestration of carbon by trees, shrubs and urban vegetation can be assessed using biophysical characteristics of trees such as biomass equations and growth capacity (Nowak et al., 2013, 2016), and using Light Detection and Ranging (LiDAR) data to quantify forest features and growth (Zhao & Sander, 2015). The InVEST tool provides a model for calculating the reduction of energy demand in buildings by estimating the temperature reduction in urban areas due to the cooling effect from vegetation (regulating ES) (Bartesaghi Koc et al., 2018; Zardo et al., 2017).

3.2. Indicators

In our research, the relationship between natural capital and social capital is characterized through the analysis of five factors and their interrelationships: *Pressure, State, Driver, Supply,* and *Demand* (Fig. 2). *Pressures* refer to anthropogenic activities that may have a negative impact and affect the *State* of ecosystems. They can be classified in three types: land-use change, nutrient content (emissions or substances) that affect the health of the ecosystem, and the overuse and exhaustion of resources (Lu et al., 2019; Müller & Burkhard, 2012). *State* defines the physical, chemical and biological conditions of the ecosystem that allow the maintaining of its capacity to deliver the service (Maes, 2014; Müller & Burkhard, 2012). *Drivers* are essential conditions and material needs that propel change in the demand for natural resources from social, human and built capital (Müller & Burkhard, 2012), and can be categorized as economic, demographic or cultural (Dijst et al., 2018). Finally, *Supply* describes goods and services provided by the ecosystem to the beneficiaries (social capital)*; Demand* is defined by the material requirements, ecosystem goods and services used by the beneficiary (social capital) (Bakshi et al., 2015; Burkhard et al., 2012). The

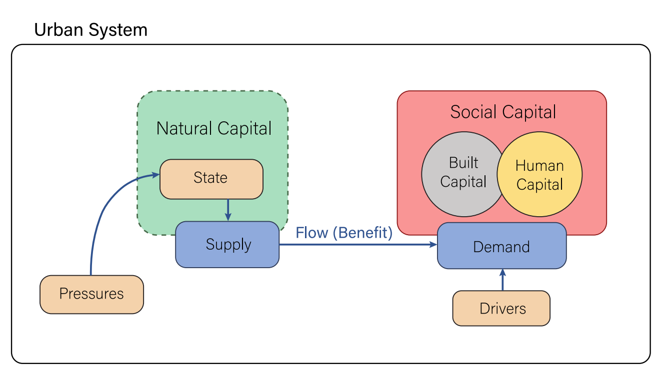

Fig. 2. Conceptual scheme behind the development of the proposed integrated ES and UM framework.

interaction between social and natural capital illustrated in Fig. 2 is meant to occur within an urban context, delimited by the administrative boundaries of a city. Although natural capital and its factors can be external to urban boundaries (e.g. the supply of food or fossil fuels and pressure associated with it), in this research, the factors illustrated in Fig. 2 are intended to be analyzed within the urban system.

The factors Pressure, State and Supply aim to interpret and characterize the interactions between an ecosystem's ecological processes and components, as well as the services they provide (Braat & de Groot, 2012; Oesterwind et al., 2016). ES research has focused mostly on the potential of ecological functions or biophysical elements to provide an ES (Supply) (Burkhard et al., 2012; Yu et al., 2021), while inclusion of demand from beneficiaries and stakeholders in ES assessments has been scarce (Peng et al., 2020; Syrbe & Grunewald, 2017; Wei et al., 2017). However, there is an increasing realization that the inclusion of ES demand is important for an integrated ES assessment because it provides more significant insights in terms of natural and social capital synergies and supply–demand interactions (Peng et al., 2020; Tao et al., 2018; Yu et al., 2021). Moreover, Drivers in our conceptual scheme refer to those factors that influence resource use and demand. This reflects the growing interest in IE not only to quantify biophysical flows but to also to analyze the driving factors that affect these flows (He & Myers, 2021; Li et al., 2021; Voskamp et al., 2020). **Supplementary Table S3** illustrates the interaction between the five factors and a set of indicators associated with them, which can be selected according to the context of the case study to be assessed. A sample collection of two ES from the **Supplementary Table S3** is available in the Table 2 each representing one type of ES considered relevant to the purpose of our integrated framework: Provisioning ("Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes") and Regulating ES ("Regulation of temperature and humidity, including ventilation and transpiration").

In addition, Fig. 3 describes the links among factors for the Provisioning ES "Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes", which exemplifies the application of our conceptual scheme. Land-use change (Pressure) is expressed in spatial units (ha, m^2) and along with the crop yield (State), expressed in ton/ha, it can decrease agriculture production (Provisioning ES Supply), expressed in mass units (ton). Demand describes the needs of the urban population and is expressed as mass of food consumed in t or ton/cap.

The State indicators are characterized in two types: the first refers to indicators that describe the health of the ecosystem (soil quality, soil attributes, crop diversity and fragmentation), the second is the capacity to supply an ES in a spatial unit (crop yield). The linkage between State and Supply will depend on the type of indicator selected; however, their interactions are represented by linear relationships as further discussed in section 5. For example, an excess of nutrients causes a reduction of total agricultural output and water quality, while reduction of forest area causes a reduction in total timber output (Cosyns et al., 2020; Favero et al., 2020; Kulkarni & Goswami, 2019; Valani et al., 2021).

The Pressure-State linkage is represented by an "if-then" cause: if a Pressure indicator increases, the capacity of the ecosystem to provide a good or service (State indicator) decreases in a given period. There are three types of Pressures (Drobnik et al., 2018; Gomes et al., 2021; Lu et al., 2019): land-use change, nutrient loads, and resource depletion. The effect of land-use change over a period of time is expressed in spatial units (m2, ha); therefore, the change of a State indicator S caused by the effect of a Pressure will be expressed as the difference between the State in time t and time $t + 1$ (Eq. (1)).

$$S_t - S_{t+1} = \Delta S \tag{1}$$

Where ΔS refers to the effects of the pressure indicators in a time t (years, months, etc.). Moreover, the two other types of Pressures (nutrient loads and resource depletion) affect the state of the ecosystem in terms of a linear relationship. Thus, the effects of a Pressure in a time t can be represented with a ratio p, where S is the state indicators in a time t (Eq. (2)). Moreover, in order to standardize pressure assessments, we will introduce Eq. (2). into Eq. (1) to represent changes in the state of the ecosystem over a span of time (Eq. (3)).

$$\frac{S_{t+1}}{S_t} = p_i \tag{2}$$

$$S_t(1 - p_i) = \Delta S \tag{3}$$

The change of demand over time is defined by the Drivers, which can be of a socioeconomic or physical nature (He et al., 2021; Luo et al., 2021; Shen et al., 2021).

4. Results

Fig. 4 illustrates the structure of the integrated UM-ES assessment framework , which uses the EW-MFA as a baseline. Material and energy inputs and outputs to the system (Domestic Extraction, Imports, Domestic Outputs and Exports) are accounted for based on the conceptual structure in Fig. 2. The EW-MFA category flows are presented on the sides of the framework (Fig. 4), the colored categories indicate that there is a contribution from an ES, the arrows show the type of contribution, whether direct (unbroken lines), or offsets (dotted lines). The relations among the factors (Pressures, State, Supply, Demand and Drivers) illustrated in Fig. 2 can be expressed by means of the indicators listed in the **Supplementary Table S3** and the models presented in the Method section. This process applies for each EW-MFA flow.

A relevant modeling approach to describe the factors and its interactions in the assessment framework is System Dynamics (SD).This approach has been used in both UM assessments (Elliot et al., 2018; Huang et al., 2018) and ES studies (Pouso et al., 2019; Ravar et al., 2020; Sušnik et al., 2021). SD is the simulation of a dynamic feedback system that analyzes structures, functions, and dynamic behavior (Winz et al., 2009). Founded in systems thinking and control theory (Richardson, 1991), SD is an environmental modeling method used in management decisions for socio-ecological systems. It provides a collection of conceptual and quantitative tools for modeling, analyzing, and simulating the complex feedback and non-linear interactions between the constituents of a system (Bayer, 2004; Richardson, 1991). The characterization of the model's complexities is defined by a network of cause-effect and feedback loops with State variables represented by "stocks" and the rate of change in stocks represented by "flows" (Bala et al., 2016). Moreover, SD models, unlike other similar methods, are used to replicate dynamic behavior across time rather than looking for steady-state solutions. SD modeling can be used to quantify flows over time, considering feedbacks and trade-offs between indicators.

Application of the SD modeling in the framework can be described by using water flows in the city of Lima, Peru as an example. The ES class from CICES that corresponds to this flow is the abiotic Provisioning ES "Ground and Surface Water used for nutrition, materials or energy". The application of the conceptual scheme (Fig. 2) to the case of Lima is illustrated in Fig. 5. Lima is the capital of Peru, a city of almost 10 million people, the largest in the country (El Peruano, 2021). Water is a critical resource since the city is located in a desert, and previous natural disasters have shown the city's vulnerability and water management issues (Vázquez-Rowe et al., 2017). The Pressure, State, Supply, Demand and Driver factors and their indicators in Fig. 2 can be used to feed the SD modeling and to assess change in water flows over time. In this example, State indicators are Groundwater levels, and Water flow per water body. Lima relies primarily on two rivers: the Rimac River (providing 80% of the total water production) and the Chillon River (8% of the water production), the rest is provided by groundwater wells distributed around the city (SEDAPAL, 2014). Pressure can be identified as climate change, whose indicators are changes in precipitation, temperature, runoff and groundwater level, which affect water supply conditions. Water flow per water body (rivers) and groundwater levels provide the indicator for the Supply factor. Total abstraction of water provides an indicator for the Demand factor, which can also be

Table 2
Sample of indicators collection for Pressure, State, Supply, Driver and Demand.

Section	Group	Class	Pressure Indicators	State Indicators	Supply Indicators (Ecosystem Services)	Demand Indicators	Drivers
Provisioning (Biotic)	Cultivated terrestrial plants for nutrition, materials or energy	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	Intensification/Extensification and CCI Farming Intensity – Spatialization Pesticides risk Gross Nutrients Balance - Land annually taken for built up areas per person Soil sealing Climate change	Soil Quality (AEI) Composite agri-environmental soil quality index: Soil organic carbon, Soil pH (pH), Bulk soil density (kg/m3), Soil Organic Matter in arable land General Ecosystem Attributes Grassland habitat fragmentation, Landscape fragmentation index, Crop diversity. Production of agro-ecosystems, area of cropland, agricultural limits for soil, Average agricultural yield	Agriculture production (ton/year; euro/year) Net primary production (ton C; kJ) Harvested crops (ton) The ratio of gross output value of agriculture to GDP (%)	Food demand per capita (ton, ton/year) Annual food consumption per capita (ton, ton/year) Consumption of agricultural products (ton, ton/year) Animal fodder use (ton, ton/year)	Economic (level of economic development, economic specialization, crises, economic growth, changes in GDP) Demographic (Population growth, population size) Technological (conversion efficiency) Geographical (Land Use Change, land use intensity) Environmental (Climate change, climate conditions, HDD)
Regulation & Maintenance (Biotic)	Atmospheric composition and conditions	Regulation of temperature and humidity, including ventilation and transpiration	Degradation of *peri*-urban and urban forests Frequency of fires, burnt area, drought stress Land use change: Urbanization of surrounding areas, Isolation of forest patches gradually surrounded by densely built-up areas/road construction. Soil quality: Damage to soil due to the high intensity of traffic, pollution (Litter)	Radiation temperature of land surface (°C) Number of inhabitants per area (number/ha) Artificial area per inhabitant (m2/person) Length of the road network per area (km/ha) Percentage of built-up area (%) Weighted Urban Proliferation (Urban Permeation Units/m2) Imperviousness (%)	Cooling Effect (ΔT) Humidity index Tree cooling potential (°C) Evapotranspiration (mm)	Urban Heat Island (ΔT)	Drought frequency Vulnerability to heat Population density (as a proxy of city size) Generation of anthropogenic heat Cooling Degree Days Land Use Change Thermal Comfort: (Behavioral and socio-demographic variables (occupancy rates, thermostat settings) Physical characteristics of the building (Heating systems, house typology, building efficiency)

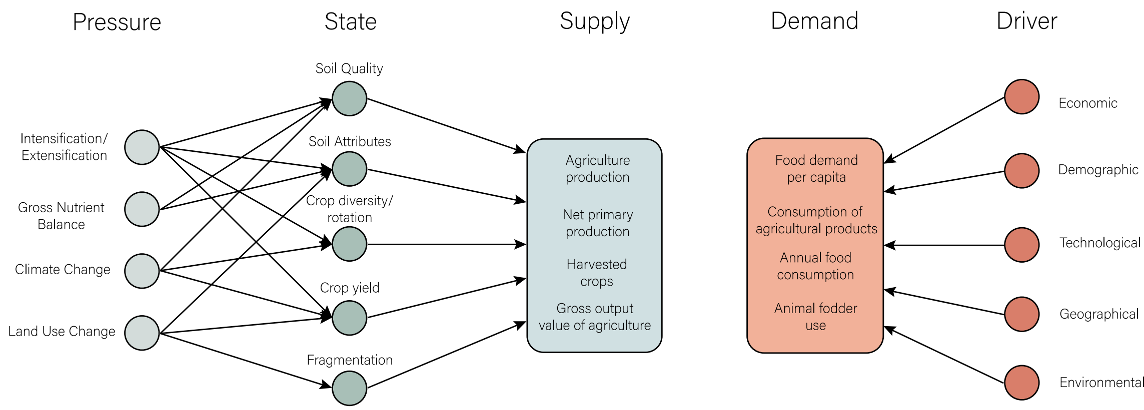

Fig. 3. Relationships among factors of the conceptual scheme for Provisioning ES "Cultivated terrestrial plants grown for nutritional purposes" (based on the CICES classification).

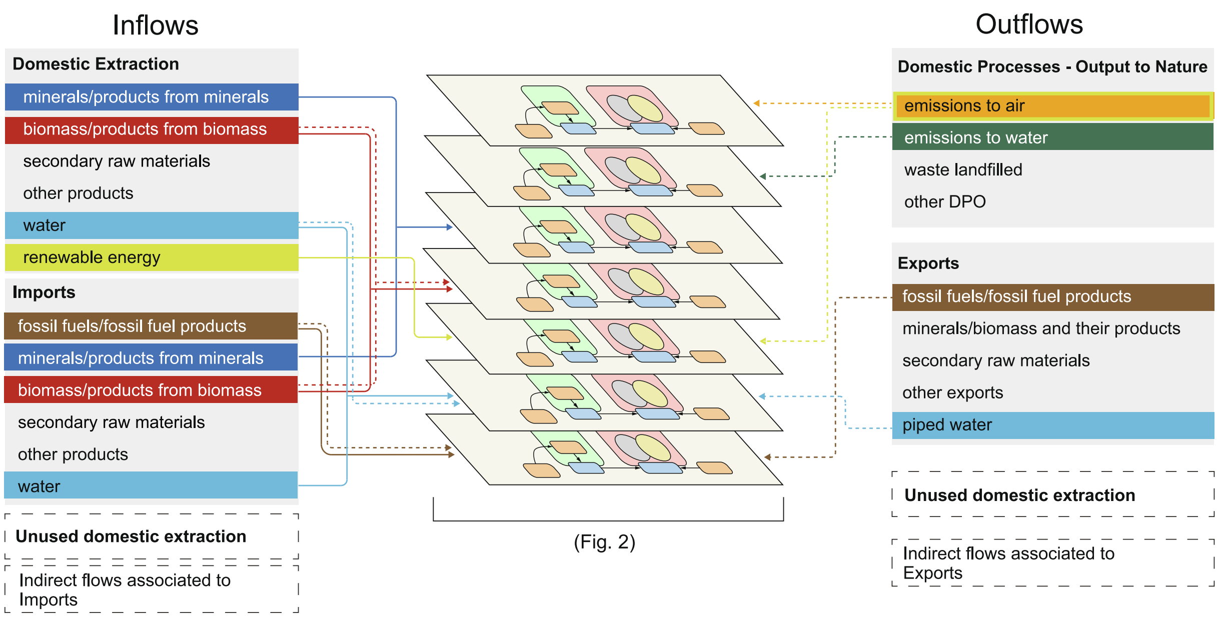

Fig. 4. Overview of the integrated UM-ES framework. On both sides the categories of the EW-MFA are provided, and the ES in UM are highlighted in color; the arrows describe the type of flow assessed using the conceptual scheme (layers in the center). The unbroken lines refer to the direct contribution of ES flows, the dotted lines refer to an offset of flows from ES.

represented in per capita values (SEDAPAL, 2013). Official projections (Municipalidad Metropolitana de Lima, 2010) for growth population estimations, changes in water flows due to climate change, and reduction of groundwater levels due to urbanization can be used to quantify the ES supply and demand flows for an estimated time period. Finally, since Lima is a growing city, the Drivers are represented in spatial and demographic terms (El Peruano, 2021; Ministerio de Vivienda, 2012).

The application of the conceptual scheme (Fig. 2) of the provisioning ES in System Dynamics modelling is shown in Fig. 5. The mechanisms for the provision of water to the city are related to the State and Pressure indicators. Regional climate models predict that precipitation and temperature changes will be exacerbated due to climate change – a Pressure indicator – affecting the water supply of coastal areas, including the city of Lima (Urrutia & Vuille, 2009). The stock and flow model shown in Fig. 5 illustrates the collection of water in four sub-catchments that correspond to three basins: Lurin, Rimac and Chillon. Moreover, water flows in both the Rimac and Chillon rivers fluctuate seasonally; the highest water discharge occurs in the months of January and February and the lowest in the months of July and August (Schütze et al., 2019). Moreover, the groundwater outflow is defined by the amount of abstracted water in the 407 operational wells distributed throughout the city. The stock is the accumulation of inflows and outflows. In the model structure, the stocks are represented by the Water Treatment Plants (WTP), sub-catchments that define the state of the river, and the groundwater wells. Water collection and distribution reflect inflows and outflows, whereas the WTP sub-model accounts for losses due to evaporation and decantation processes. Water availability is the sum of the outflows from the three WTP and the groundwater outflow. The model assembles the main driving factors of water demand: Population, Income and GDP per capita. These are suitable indicators to describe Drivers influencing change in water abstraction and demand over time. Furthermore, a detailed description of the variables used in the assessment are shown in Table 3.

5. Discussion

The UM field is constantly working to enhance accounting models and processes (Cui, 2018; Tang et al., 2021). The framework presented in this article contributes to progress in the field by proposing an expanded and enhanced UM accounting method expressing the role of

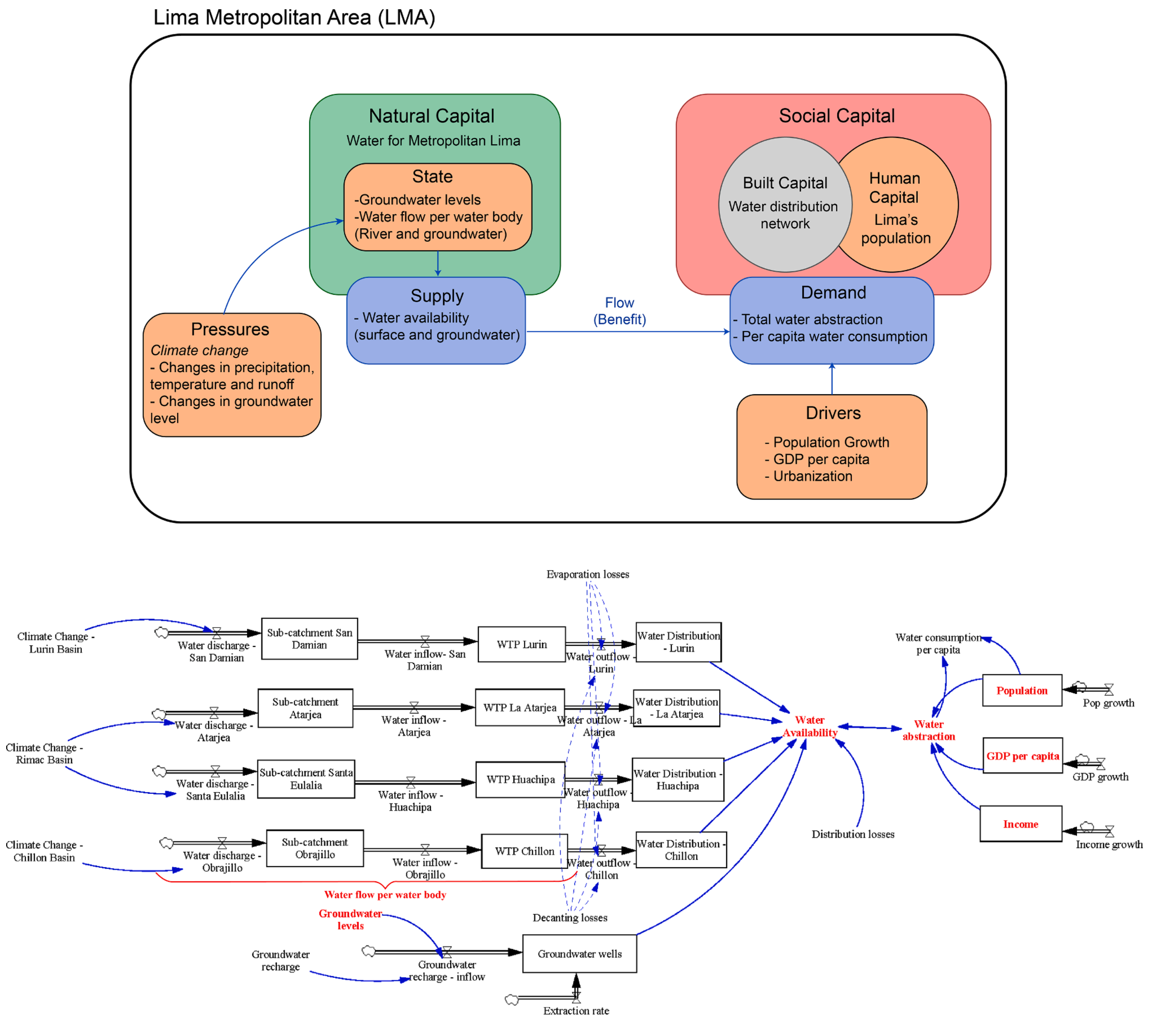

Fig. 5. Conceptual scheme applied to the assessment of water provision in metropolitan Lima (Top). Application to the Conceptual model of System Dynamics: Stock and Flow diagram (Bottom).

natural capital into material flow accounting in urban areas. The integration of ES assessments into the EW-MFA accounting model permits the inclusion of ecological processes that are normally mapped through UE methods. Moreover, our framework considers features of the biological and ecological functions and processes of the natural capital in an urban context by including factors such as Pressure and State, but also considers the social capital and its characteristic processes (Drivers). The framework also advances the UM research agenda by allowing the assessment of processes inside the system and contributing to overcoming the "black box" conundrum, which has been largely criticized in UM literature (Elliot et al., 2019; Perrotti, 2020; Yeow and Cheah, 2019). The integrated framework can guide the development of temporally dynamic assessments describing system internal processes through SD modeling based on the description of feedback loops among the five factors and their indicators.

However, this framework faces some challenges. The framework claims linearity in the relationships between indicators. This does not entirely reflect how ES interact, since the Pressure, State and Driver indicators influence Supply and Demand flows dynamically and have more complexity in the spatial and temporal dimensions. The structure of the assessment framework is layered, meaning that each flow is assessed separately, which limits the possibility of accounting for trade-offs between ES. Moreover, the dynamic nature of the model will depend on data availability for each flow. This means that the framework is data intensive and there is the possibility that information will not be available for all flows in a case study. Finally, due to the complexity of the factors involved in the assessment framework, communicating the results of the model to policymakers and stakeholders becomes a more complicated task; however, this opens the possibility of using tools such as interactive and spatially explicit visualization schemes that would translate the outputs of the model for a broader audience.

One of the ways the framework can be evaluated is through participatory approaches involving different communities of knowledge, in this case, policy and industry stakeholders. Participatory testing processes can enhance the transfer and sharing of UM and ES knowledge in a collaborative learning environment, while highlighting the consequences of solutions for decision making and policy (Perrotti, 2019). Knowledge transfer is increasingly being viewed as an iterative cycle, where the learning process is mutual rather than a linear science-to-policy approach (Ugolini et al., 2018). Moreover, the intervention of the stakeholder in the design and production of the framework can lead to more adaptable and functional frameworks (Dijst et al., 2018). Thus,

Table 3
Variables utilized in the SD model: "Ground and Surface Water used for nutrition, materials or energy" for Lima Metropolitan Area.

Variable Name	Unit of measure	Description of Indicator
Climate Change – Lurin Basin	m^3/month	Describes the change of water flow (discharge) in the basin of Lurin, Rimac and Chillon. Projections of future discharge due to climate change are assessed using statistical downscaling of HadGEM2 models of scenarios of RCP (4.5 and 8.5) (Astorayme & Gutiérrez, 2017)
Climate Change – Rimac Basin	m^3/month	
Climate Change – Chillon Basin	m^3/month	
Sub Catchment – San Damian	m^3/s	Measurement of water that passes through before its processed by the Water Treatment Plants in the three basins: Lurin, Rimac and Chillon. Water inflow.
Sub Catchment – Santa Eulalia	m^3/s	
Sub Catchment – Atarjea	m^3/s	
Sub Catchment – Obrajillo	m^3/s	
WTP La Atarjea	m^3	Stock of surface water that is processed for human consumption
WTP Lurin	m^3	
WTP Chillon	m^3	
Water distribution - La Atarjea	m^3/s	Total processed water that is distributed to the LMA
Water distribution - Lurin	m^3/s	
Water distribution - Chillon	m^3/s	
Groundwater recharge	m^3/year	Replenishment rate of underground aquifers
Groundwater wells	m^3	Total stock of ground water for human consumption
Population	hab	The total population in LMA
GDP per capita	Soles[1]/hab	Gross domestic product per habitant in LMA
Income	Soles/hab	Family income per capita

[1] Soles is the Peruvian currency.

we suggest the implementation of iterative testing (e.g. engagement workshops) to assess how the use of the framework can provide a body of knowledge for more comprehensive resource management strategies in an urban context. Moreover, the knowledge transfer must be transparent and accessible; consequently, the use of interactive and spatially explicit visualization diagrams (e.g. Sankey diagrams, maps) as a common language is beneficial in reaching broader audiences, actors and stakeholders. The use of interactive and spatially explicit data for knowledge transfer to stakeholders has proven effective across various case studies (Canedoli et al., 2017; Otero Peña et al., 2022; Safford et al., 2017; Vukomanovic et al., 2019).

6. Conclusions and outlook

The objective of this paper is to present a novel framework that integrates UM and ES assessments. In particular, it provides an extension of the EW-MFA method, linking the assessment of ES under the CICES classification by using five factors that describe the interrelationships between natural and social capital. From this perspective, this framework is an attempt to open methodological pathways into an in-depth examination of the role of natural capital in conventional approaches of resource demand assessments at the urban scale.

Understanding the end goals of both fields emphasizes the importance of developing new methods that integrate multidisciplinary perspectives pertaining to urban science. In order to determine the suitable modeling method for this research, a review of UM studies was performed. Moreover, a bibliometric analysis was conducted with a focus on ES case studies that overlap with the UM method. The few studies that integrate both UM and ES concepts mostly propose modeling alternatives and conceptual insights; however, we also identified case studies where ES can be characterized as EW-MFA flows, which indicates that there is scarce cross-integration but also potential opportunities to narrow this methodological gap.

The construction of the integrated assessment framework was guided by a conceptual scheme. This structure proposes five factors (Pressure, State, Supply, Demand and Drivers) to illustrate interactions between natural and social capital. Furthermore, based on the bibliometric analysis, we selected a set of ES that influence the results of the assessment of the EW-MFA method in two ways: by direct contribution to material and energy flows (mainly Provisioning ES), and the offset of some of these flows (regulating ES). A set of indicators was collected for each factor, in order to amplify the potential linkages between factors.

As a result, the proposed assessment framework consists of a layered structure that involves the influence of ES assessment in the EW-MFA method. Therefore, it is an adaptable scheme offering a palette of indicators and whose application can be undertaken according to the information available in each case study. We propose System Dynamics as a modeling method to quantify the relationships between factors, this method allows the development of temporally dynamic assessments and predictive forecasting. An example of the application of this framework was created for the case of water flows in the city of Lima, Peru. The findings of this framework could raise awareness of the value of nature in anthropogenic-dominated contexts and increase the integration of ES in urban planning.

There are potential opportunities for further research. The assessment framework provides a systemic approach for the analysis of material and energy flows in an urban context; however, it fails to address the exchange and trade-offs between flows. Furthermore, the complexity of the potential outcomes of the framework makes communication with policy and planning stakeholders challenging. Future research should include the testing of the framework using participatory, feedback-based approaches in order to determine how relevant is to policy. Overcoming these challenges will provide valuable outcomes from the integration and cross-fertilization of the different disciplines, coalescing around the analysis of urban systems. This remains an essential precondition to frame the transition toward more sustainable urban development.

CRediT authorship contribution statement

Úrsula Cárdenas-Mamani: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Writing – original draft. **Daniela Perrotti:** Conceptualization, Supervision, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.108593.

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