Article

Incorporating Metabolic Thinking into Regional Planning: The Case of the Sierra Calderona Strategic Plan

Juanjo Galan [1],* and Daniela Perrotti [2]

[1] Department of Architecture, Aalto University, 02150 Espoo, Finland; E-Mail: Juanjo.galan@aalto.fi
[2] Université Catholique de Louvain, 1348 Louvain-la-Neuve, Belgium; E-Mail: daniela.perrotti@uclouvain.be

* Corresponding author

Abstract
A metabolic study of the South-Eastern part of the Calderona Mountain Range (Sierra Calderona) was developed in 2014 as a part of the Sierra Calderona Strategic Plan (SCSP). The goal of the study was to define strategies to optimise materials and energy flows in the region and, thereby, enhance the sustainability of the entire regional system. Due to its location on the outskirts of the Metropolitan Area of Valencia, Sierra Calderona presents most of the metabolic challenges and potentials that characterise peri-urban areas, giving the SCSP case a wider and transferable interest. After introducing the scope, rationale, and research questions, the article first summarises the main theoretical and methodological frameworks underpinning the integration of metabolic studies in regional and urban planning. Following our literature review, the article focuses on the way in which the metabolic analyses were inputted and informed the different phases and outcomes of the SCSP: analysis and diagnosis, regional objectives and strategies, landscape and land-use plan, sectoral plans and pilot projects. This approach was based on the combination of complementary analytical methods such as material and energy flow accounting and Ecological Footprint Analysis. Additionally, the article reflects on how new conceptual tools such as the Functional Metabolic Areas were used in the SCSP in order to operate in a complex spatial system and to generate a regional metabolic model. Subsequently, the main contributions and shortcomings of the use of metabolic inputs in the SCSP are discussed by comparing the metabolic assessment approach adopted in the SCSP with available models and methods. Finally, our conclusions suggest potential improvements and future lines of research on a two-way implication between urban metabolism research and regional and urban planning practice.

1. Introduction

1.1. The Scope of the Article

This article positions itself within the growing body of literature advocating the need for better integration of urban metabolism (UM) thinking and, more specifically, UM assessment methods, in spatial planning (e.g.,

Ibañez & Katsikis, 2014; Li & Kwan, 2018; Perrotti & Stremke, 2018). In line with one of the most cited definition of UM in industrial ecology (Kennedy, Cuddihy, & Engel-Yan, 2007), in this article we refer to UM as the multiple socio-technical processes by which cities or—in the case of our study—regions gather, transform, and use biotic and abiotic resources, and expel waste, to ensure their functioning.

An increasing number of UM review articles nowadays discusses the extent to which a metabolic perspective is essential for spatial planners to understand the natural and anthropogenic processes underpinning the spatial and temporal transformations of human environments (e.g., Cui, 2018; Dijst et al., 2018; Zhang, Yang, & Yu, 2015). The success recently enjoyed by the UM research field results from a growing consensus in the wide "urban sustainability" scientific community that deeper knowledge of the material and energy inputs and outputs of urban systems can contribute to their sustainable and resilient maintenance and growth (Beloin-Saint-Pierre et al., 2017). The transition from a "linear" UM (i.e., based on the assumption of a limitless supply of resources from the hinterland and high amounts of expelled waste) towards a more "circular" metabolism has been identified as a condition to achieve a more sustainable development of urban systems since the early stages of industrial ecology (Girardet, 1992). More recently, this hypothesis has been further explored and developed throughout a wide range of case studies across the globe, based on evidence that cities lie at the beginning and at the end of many production-consumption chains and material waste paths.

The question of how UM assessment methods can be used and incorporated into spatial planning is a recurring topic in UM scientific literature nowadays. The considerable progress made in the UM research field in the early 2000s (Cui, 2018) has not always resulted in a large exploration of the UM applicability in planning. Until very recently, only a limited number of published studies specifically addressed this aspect of UM research. One of the first and most cited journal articles discussing applications of UM studies (282 citations in Scopus at the time this article was written) was published in 2011 (Kennedy, Pincetl, & Bunje, 2011). The article reports only three applications in urban planning, of which one book (Oswald & Baccini, 2003), one master's thesis (Quinn, 2007, later expanded in a PhD thesis; see Quinn, 2012), and one set of three journal articles that refer to the same case study (Codoban & Kennedy, 2008; Engel-Yan, Kennedy, Saiz, & Pressnail, 2005; Kennedy et al., 2007).

This trend has rapidly changed over the last five to seven years. Since 2011, UM research initiatives and published works specifically exploring applications of metabolic studies in spatial planning have gained momentum. According to Scopus data, 103 journal articles containing "urban metabolism" and "planning" in the abstract, title, or keywords have been published in English between the beginning of 2011 and September 2018 (date at which the search was conducted), whereas only 26 journal articles were published between 1994 and 2010. Moreover, at least two interdisciplinary research projects within the European Community's Seventh Framework Programme (EU-FP7) have been concluded and published to date on the link between UM and urban planning (Chrysoulakis, de Castro, & Moors, 2015; Davoudi & Sturzaker, 2017).

1.2. Goals, Research Questions, Research Method, and Article Structure

This article makes a twofold contribution to the growing body of research on UM applications in spatial planning. First, within the broad spectrum of spatial planning disciplines, it focuses specifically on regional planning and aims at clarifying the benefit of incorporating UM thinking and UM assessment methods in the development of planning orientations and documents at the regional level. In this article, regional planning is understood as being concerned primarily with the sustainable distribution of land uses and activities in a geographical scope including different land/use and landscape patterns. This definition is in line with the one proposed by Glasson and Marshall (2007), who argue that the primary objective of regional planning is to inform the distribution of new activities and developments, leaving a flexible interpretation of both the limits of the region and the timescale. To achieve this goal, we will discuss a recent case study, the Sierra Calderona Strategic Plan (SCSP; Galan, 2014b). SCSP is an integrated plan for the sustainable development of the Sierra Calderona informed by two complementary UM assessment methods: material and energy flow accounting and the calculation of the ecological footprints (EFs) associated with users' and inhabitants' lifestyles. The combination of these two UM methods in the same plan arguably reinforces the validity of the Sierra Calderona case to illustrate a possible way through which regional planning can be informed by UM studies. Although planning might have always been about integration (Glasson & Marshall, 2007), for the purpose of this article, the concept of "integrated planning" places special emphasis on the interaction between different activities, land uses, and agencies in contrast to classic zoning or to sectoral planning, traditionally concerned with one particular activity or land use.

Secondly, through the discussion of the UM approaches and main outputs of the SCSP, the article addresses a series of challenges that can emerge from the application of UM methods in real-world regional planning practice (e.g., quantitative versus qualitative research approaches, availability of datasets). This allows discussing the main limitations of the two UM assessment methods used in the SCSP in terms of the translation of UM knowledge into planning strategies. Although based only on the Sierra Calderona example, our conclusions can provide insights and recommendations for UM researchers to better respond to practitioners' needs and policy requirements.

In synthesis, the article addresses the following research questions through a critical analysis of the UM approach adopted in the SCSP and its outputs:

1. How can the results of UM studies be incorporated into integrated regional planning?
2. Which UM assessment methods can facilitate this incorporation and what are the main limitations

of current UM methods to better inform regional planning?

From a methodological perspective, we develop a single case study research (Yin, 2014), in which critical analysis of the SCSP is used as a means to explore our two research questions and to draw conclusions that could be generalised to similar case studies. In fact, as discussed throughout the article, the Sierra Calderona represents a prototypical example of many natural areas located at the limits of urban agglomerations, which, by being often exposed to the same pressures and challenges, are susceptible to share similar strategic solutions. Moreover, the critical analysis is conducted with a double embedded perspective (research and practice), as the corresponding author was also involved in the development of the SCSP, in collaboration with the local authorities (Municipalities of Náquera, Serra, Olocau, Marines, and Gátova).

The article is structured as follows. In Section 2 we firstly elaborate on the specific contributions and potential of UM methods to inform regional planning, beyond the traditional focus of UM research on urban planning and the study of strictly-speaking "urban" systems (i.e., based on cities' administrative boundaries). Secondly, we present a brief review of the two main UM methods used in the SCSP, considering their potential and limitations in regional planning.

In Section 3, the UM methods, planning challenges, and solutions proposed in the SCSP are discussed, as well as the challenges emerging from the use of UM methods in regional planning. The SCSP builds on some broadly accepted assumptions found in UM literature (e.g., benefits resulting from increasing circular cycling in urban/regional systems, and from reducing consumption levels and resource-intensity without affecting people's well-being). In addition, the SCSP assumes as a fact the beneficial effect of dense and multifunctional urban fabrics in the levels of consumption of water and energy in different types of urban fabrics in the Valencian Region (Lloret, 2013). In addition, section 3 illustrates the way in which UM concepts and assessment methods were integrated into the SCSP, the studied metabolic flows (water, waste, and energy) and the use of EFs as a tool to assess the metabolic performance of individuals and communities. Finally, section 3 explains how the metabolic inputs informed the development of strategies, sectoral plans, and one pilot project, by making use of operational units named Functional Metabolic Areas (FMAs). Through the article, FMA is proposed as a key concept that can facilitate the incorporation of UM methods into regional planning practice.

Section 4 elaborates on the answers to the proposed research questions by discussing the main contributions and shortcomings of the use of metabolic inputs in the SCSP, and by suggesting potential improvements. This discussion is based on a critical comparison between the available theoretical and methodological frameworks and the work developed in the SCSP. Additionally, questions for future research on a two-way implication between UM theory and models and planning disciplines are presented.

Given its scope and goals, the article may be of interest to three main readership profiles. Regional and urban planners will find an example of how UM methods can inform planning and design processes. UM researchers will be introduced to a recent example of how regional planners have engaged with resource accounting methods and related shortcomings when it comes to their use in daily practice. Finally, local and regional authorities will be provided with an overview of the potential and limitations of combining spatial planning and UM tools into decision-making processes.

2. Background

2.1. Regional versus Urban Scopes in Metabolic Studies and Planning

The unclear limits of the urban phenomena, as well as the high connection between urban areas with their surrounding and the metabolic processes taking place in regional mosaics, suggest the relevance of adding regional scopes to the integration of metabolic studies in planning (Baccini & Brunner, 2012).

In this article, we argue that the introduction of the regional scale can open new directions of inquiry for metabolic studies by exploring the interactions between urban and non-urban systems and by incorporating a wider palette of land uses. Thus, a regional perspective can further enhance the UM research agenda by working across (at least) three levels. Firstly, the differences between areas ascribed within the same land-use can provide the opportunity to identify how morphological and functional variations affect metabolic behaviours. This idea is supported by several authors (e.g., Alberti, 2005; Ferrão & Fernandez, 2013) who advocate the need for further research into the effect of diverse land uses and the urban physical form on the resource intensity of urban settlements; the same may apply to other land-use categories (e.g., agricultural or infrastructural areas). Secondly, a regional perspective can allow for the identification of areas with similar or distinctive metabolic patterns. This can lead to a more systematic metabolic characterisation and modelling of a region or complex spatial system. Thirdly, the comparison between the resource demand and provision from areas with distinct metabolic patterns can offer a deeper understanding of the current and potential metabolic interactions between different areas within the same region, and therefore inform more resource-efficient spatial, land use, and sectoral planning and policies.

Following this reasoning, a regional metabolic model for the Sierra Calderona was proposed, based on the interactions between different spatial subsystems. This approach advances previous studies' suggestions of classifying "spatial types" according to their metabolic per-

formance (see city types in Ferrão & Fernandez, 2013) and offers an alternative to the definition of regional metabolic models based on metabolic activities (see the use of "nourish", "clean", "reside & work", and "transport & communicate" activities in the METALAND model by Baccini & Brunner, 2012).

2.2. UM Assessment Methods

Within the broad range of UM disciplinary strands, related modelling, and conceptual frameworks (Castán Broto, Allen, & Rapoport, 2012; Wachsmuth, 2012), in this article we focus only on the two assessment methods which were used in the SCSP: material and energy flow accounting and the calculation of the EFs associated with the material/energy consumption of different types or user/inhabitant profiles. Both methods originated within industrial ecology, which, in quantitative terms, represents the most influential research path in UM studies (Newell & Cousins, 2014). Although different in scope and utilised metrics, both flow accounting and EF calculation are relevant to the regional focus that is adopted in this article.

The mass-balance method Material Flow Analysis (MFA) is the most used input-output method for material and energy flow accounting in urban systems (Cui, 2018). Similarly to other industrial ecology's UM methods, MFA is based on an understanding of the city as an individual open system embedded into the wider earth system and whose metabolism is the result of the interactions between different sub-systems. MFA was firstly introduced in the late 1960s by Ayres and Kneese (1969), further implemented in the 1990s (Baccini & Brunner, 2012; Bringezu, 1997), and then formalised by the Statistical Office of the European Community in the early 2000s (Eurostat, 2001). The Eurostat's MFA was initially designed as a flow accounting method at the scale of national economies. Hammer, Giljum, Bargigli and Hinterberger (2003) adapted the Eurostat's method to the scale of urban regions, and the validity of the regional MFA was demonstrated through a study of the metropolitan region of Hamburg. Since then, the regional MFA has been used as a basis in the study of several urban systems since the late 2000s and in the 2010s (e.g., Bahers, Barles, & Durand, 2018; Barles, 2009; Niza, Rosado, & Ferrão, 2009; Voskamp et al., 2017). The application to the regional scale by Hammer et al. (2003) as well as the increasing popularity of MFA in UM urban and regional case studies worldwide (Cui, 2018; Newell & Cousins, 2014) suggest that the use of MFA can favour the incorporation of UM methods in regional planning.

Among the several methods used to calculate the EFs of urban populations, Ecological Footprint Analysis (EFA; Wackernagel, Kitzes, Moran, Goldfinger, & Thomas, 2006) represents to date the most widely used methodology in published scientific literature. EFA was initially designed as a tool to measure if and to what extent the outputs of human economic activities can be supported by the regenerative capacity of the biosphere (Rees, 1992). Footprints can be assessed on different spatial scales, from economic activities performed by the entire population of the planet, down to those within urban systems or even individual dwellings. The standardised unit used to measure EFs is global hectares, namely hectares adjusted to represent the average yield of all bioproductive areas on Earth (Monfreda, Wackernagel, & Deumling, 2004). One global hectare is understood as one hectare of biologically productive space, which is calculated based on the average productivity across the planet in a given year. The fundamental hypothesis behind the use of EFA in UM assessment frameworks is that most of the flows that sustain the metabolism of an urban/regional/national system can be associated with the biologically productive area that is required for their generation or maintenance (Wackernagel et al., 2006). Despite its high level of aggregation and subsequent limitations when aiming at assessing the magnitude of metabolic flows, EFA can be considered as a valuable and intuitive tool to link metabolic thinking with planning, decision-making processes, and policy-making (Ferrão & Fernandez, 2013)

In this article, we argue that both MFA and EFA provide useful results that can improve spatial planners' understanding of the metabolic functioning of a region and, if incorporated in the spatial planning process, can facilitate the elaboration of planning strategies aiming at achieving an optimised metabolism of regions.

3. Case Study: The SCSP

3.1. Contents and Structure of the SCSP

The SCSP (Galan, 2014b) was developed during the years 2013–2014 in five municipalities (Serra, Náquera, Olocau, Marines y Gátova) located in the outskirts of the Metropolitan Area of Valencia (Figure 1), in the southeastern part of the Sierra Calderona. The SCSP covers a surface of 200km^2 with a permanent population of 13,000 people that reaches 40,000 people in the high season. A significant part of this area is included in the Sierra Calderona Natural Park (49%) and an additional 30% in its buffer area.

In general, the whole SCSP aimed to integrate environmental, cultural, social, economic, and urban planning, as well as to guide decision-making processes and the development or updating of local plans (Planes Generales de Ordenacion Urbana). In the Spanish and Valencian jurisdiction, local plans are the statutory instruments that define the spatial evolution of municipalities. The drafting of the SCSP was informed and driven by the analysis of social, cultural, sustainability, and economic factors, and was supported by a participatory process.

As displayed in Figure 2, the plan included three main chapters. The first chapter consisted of a multi-layered analysis and diagnosis. The second chapter defined a set of regional objectives and strategies based on the same layers used in the first chapter. Finally, the third chapter
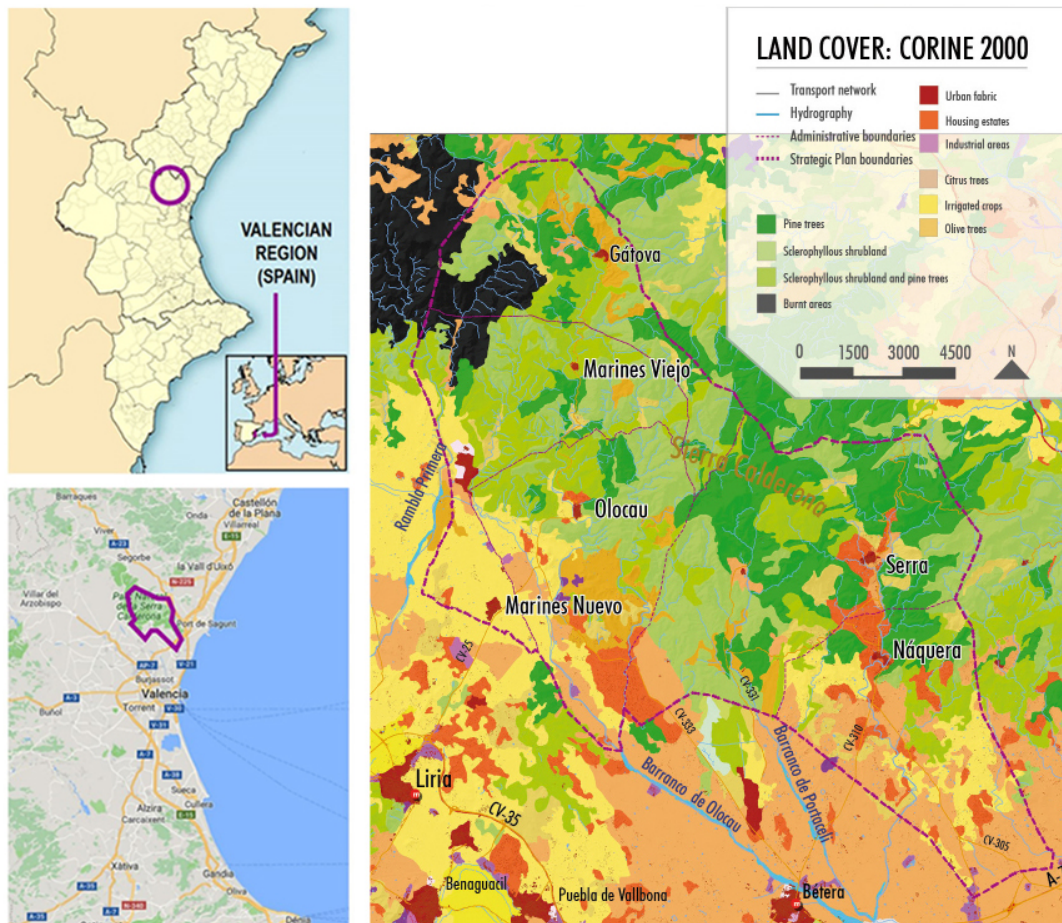
Figure 1. Location and land covers in the SCSP (municipalities of Serra, Náquera, Marines, Olocau and Gátova, SPAIN). Source: CITMA (Galan, 2014b, 2018).

included one landscape and land-use plan, nine sectoral plans, and eighteen pilot studies and projects. Throughout the three chapters, analysis of landscape, sustainability, socioeconomic processes, and their associated metabolic flows were used to support planning.

3.2. Metabolic Approaches and Concepts in the SCSP

As discussed in the previous section, one of the key challenges in UM studies is to incorporate UM results into planning processes, using UM knowledge to better express the drivers behind the socio-economic functioning of the planned system or territory. Moreover, the study of the mutual interactions between metabolic flows and the spatial distribution of land use and cover types has recently emerged as a rich line of research in metabolic studies (Zhang, 2013). In the SCSP, an instrumental approach to UM knowledge was used, meaning that the focus was mainly on the contribution of UM studies regarding sustainable regional planning.

In the SCPS, the study of metabolic flows was organised according to a set of spatial units or subsystems that in this article are formalised and presented as FMAs. These FMAs are proposed as a tool to facilitate the study of complex metabolic systems, such as regions or metropolitan areas, in which the different components of the land-use mosaic have distinctive metabolic behaviours or performances.

FMAs might be associated with land uses as well as to specific characteristics influencing the metabolic functioning of those land uses, such as "density" in urban areas or "cultivation techniques" in agricultural land. In particular, the following types of FMAs were defined in the SCSP: (1) urban areas, with two internal subtypes: compact dense towns, and low-density housing estates; (2) agricultural areas with two internal subtypes: irrigated fields for intensive agriculture and rain-fed fields; (3) industrial areas; and (4) natural areas.

As displayed in Figure 2, the SCSP was developed over a set of land-use layers, territorial systems, and sustainability dimensions. A sequential Public Participation Plan informed the development of the Strategic Plan during its three phases: analysis and diagnosis, strategies and objectives, and land-use/landscape and sectoral plans.

In particular, the metabolic studies developed during the analysis and diagnosis phase included the assessment of some of the main metabolic flows within the system (water, energy, and waste), and the calculation of the EFs of a set of representative user profiles (permanent and temporary residents).
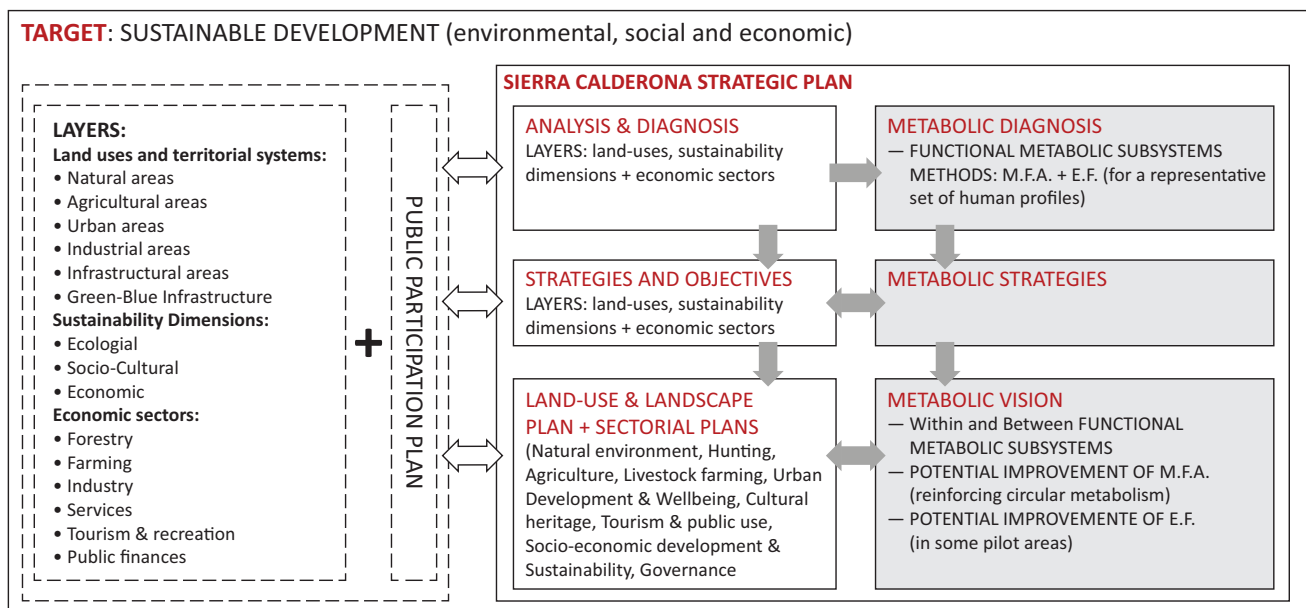
Figure 2. Contents of the SCSP and use of metabolic studies.

During the second phase, the strategies and objectives of the SCSP were formulated based on the outcomes of the first phase and the metabolic assessment of the Sierra Calderona.

Finally, the third phase included a land-use/landscape plan and a set of sectoral plans that responded both to the strategies and objectives and to the metabolic adjustments proposed in a regional metabolic model, which was developed as a part of the "Socioeconomic Development and Sustainability" sectoral plan.

Therefore, in the SCSP, sustainability and regional metabolism were used as transversal themes, guiding spatial, functional, and economic planning. This approach is aligned with previous works' recommendations to expand UM methods into a more comprehensive framework encompassing the "human, social, policy, economic, and related systems that both structure and govern specific urban metabolic processes" (Pincetl, Bunje, & Holmes, 2012, p. 200).

Thus, building on the model proposed by Baccini and Brunner (2012) for "resources correlations within a regional urban system", the SCSP resulted from the analysis of the interaction between a social metasystem and a physical metasystem. The social metasystem integrates the socio-cultural, economic, political, and governance drivers that operate in the anthroposphere as the "strings that are moved by the values of a society and its individuals" (Baccini & Brunner, 2012, p. 285). The physical metasystem consists of the nature system (geosphere and biosphere), and the anthropogenic environment, including the built environment and the colonised ecosystems (e.g., agricultural and semi-natural areas as well the human-managed natural areas). As displayed in Figure 3, the interactions between these metasystems and systems can be described in terms of metabolic flows, economic processes,

and socio-political frameworks that regulate human-environment relations. Moreover, the analyses, strategies, and sectoral plans included in the SCSP cover each of these dimensions although, due to their transversal character, the landscape and land use plan, the socio-economic and sustainability plan, and the metabolic studies can be perceived as overarching umbrellas affecting and affected by all the systems.

3.3. Metabolic Assessment of the Sierra Calderona

3.3.1. Methods and Data Sources

Based on the availability of datasets at the regional or national level, the metabolic study developed in the analytical phase of the SCSP concentrated on the following material flows: water (clean water and sewage) and waste (urban and industrial solid waste and green waste from agriculture, gardening, and forestry). On the other hand, flows of energy (in the form of electricity) were considered essential, due to their contribution to nearly all human activities and material processes. Finally, the use of EF methods complemented the information provided by material and energy flow accounting.

Table 1 summarises the methods used for the calculation of each metabolic flow or EF as well as the data sources and data accuracy. Most calculations were performed at the level of the spatial subsystems or FMAs defined for the Sierra Calderona. Due to the limited availability of high-resolution datasets, the metabolic analyses were based on approximations and extrapolations of regional/national data, and average per-capita ratios were used to estimate overall consumptions in the different Sierra Calderona subsystems (e.g., data or ratios extracted from: Ayuntamiento de Sevilla, 2008; City of Valencia, 2010).

Table 1. Metabolic methods, application scopes, data sources and data processing used in the SCSP.

METHOD	SCOPE IN SCSP	DATA SOURCES ANDA DATA PROCESSING IN SCSP	ACCURACY IN SCSP
Material Flow Accounting **WATER**	Assessed in different FMAs (associated with different land uses and urban or agricultural types)	**CLEAN WATER**: — **Domestic uses**: total consumption and generic ratios for compact and low-density housing (90 liters/inhabitant/day and 200 liters /inhabitant/day respectively) (Lloret, 2013; Indicadores de Sostenibilidad Ambiental de la Actividad Urbanística de Sevilla, 2008; Observatorio de la ciudad: Sistema de ratios e indicadores_Valencia (2010)) — **Agricultural uses**: average water supply for irrigated crops (areas devoted to each crop were extracted from the municipal report prepared by Caja España 2012 and average consumption of water in irrigated crops from the Boletín Informativo de cifras-INE 2008) — **Industrial use**: % of total water demand (estimated as 4% of the overall consumption of water, following the chapter "Pressions antròpiques. Aigua Urbano industrial (Anthropic presures: urban and industrial water)" in the report La situació del País Valencià 2007. — **Services use**: not accounted **SEWAGE** — **Treated sewage**: Data provided by sewage treatment plants. — **Untreated sewage**: A significant portion of sewage goes to cesspits in low density housing estates, especially in those constructed some decades ago — **Sewage directly poured in water courses**: not calculated **LIQUID MANURE**: produced by livestock farming	MEDIUM ACCURACY ROUGH MATERIAL (water) BALANCING
Material Flow Accounting **WASTE**	Assessed in different FMAs (associated with different land uses, activities and urban typologies)	**MUNICIPAL SOLID WASTE**: Calculated using the average production of domestic solid waste in the Valencian Region (1.28 kg/inhabit/day) **CONSTRUCTION, INDUSTRIAL AND ATMOSPHERIC WASTE**: Calculated using the following ratios (from "Flujos de energía, agua, materiales e información en la Comunidad de Madrid (*Flows of energy, water matter and information in the Madrid region*)"): — **Atmospheric waste**: 10.5 kg CO_2 per inhabitant/day — **Construction debris**: 7.2 kilos per inhabitant/day — **Industrial waste**: 1.28 kg per inhabitant/day (80% non-toxic and 20% toxic). This ratio could be decreased due to the low industrial activity in the studied region — **Agricultural waste (plastic and similar)**: 0.05 Ton/ha/year of intensive agricultural land (10% in the Calderona area) **GREEN RESIDUES**: — **From forestry**: An average production of 0.25 Ton/ha/year of forest residues is estimated (based on Forestry chapter in SCSP; see Galan, 2014, 2018). — **Agricultural residues**: 1 Ton/ha/year of agricultural residues (ratio from the study Biomass in Andalusia, September 2011 by the Andalusian Energy Agency, and assuming that 60% of agricultural land in the Sierra Calderona area produces this kind of residues) — **Gardening**: It assumed that the production of garden residues/ha is similar to the one from forest areas) **LIQUID MANURE**: produced by livestock farming based on the census of livestock heads in the five municipalities included in the SCSP (source: National Institute of Statistics [INE]) and the average production of liquid manure per type of livestock unit: bovine, ovine, caprine, porcine, equine	LOW ACCURACY NO MATERIAL BALANCING

Table 1. (Cont.) Metabolic methods, application scopes, data sources and data processing used in the SCSP.

| METHOD	SCOPE IN SCSP	DATA SOURCES ANDA DATA PROCESSING IN SCSP	ACCURACY IN SCSP
ENERGY Flow Accounting	Assessed in different FMAs (associated with different land uses, economic sectors and urban typologies)	**POWER CONSUMPTION**: Calculated with the data provided by the power supply companies and extrapolations. The disaggregation of the consumption between different Metabolic Functional Areas and Economic sectors was developed using standard ratios that were adjusted following the importance of each sector in each municipality. **ENERGY CONSUMPTION IN TRANSPORTATION**: not assessed **RENEWABLE ENERGY PRODUCTION**: In Náquera and Olocau there are solar farms and Náquera also has a Hydrothermal Carbonization Plant of biomass. Gátova rabbit farm is self-sufficient in electricity supply. There is no evidence that public facilities make use of renewable energy	LOW ACCURACY NO ENERGY BALANCING
ECOLOGICAL FOOTPRINT ANALYSIS	For different user/inhabitant profiles (before and after metabolic adjustments)	Profile simulation (different user/inhabitant profiles were selected and their ecological footprints were calculated after analysing their ways of living and patterns of production/consumption). The selection of profiles was based on a socio-demographic study of the Sierra Calderona and due to the need of including profiles of individuals living in different types of urban fabrics (compact towns and low-density housing estates). The ecological footprints were calculated with the application http://myfootprint.org.es through a simulation process in which the team working in the preparation of the SCSP assumed the roles of the selected profiles.	LOW due to the simulation method used to calculate the Ecological Footprints
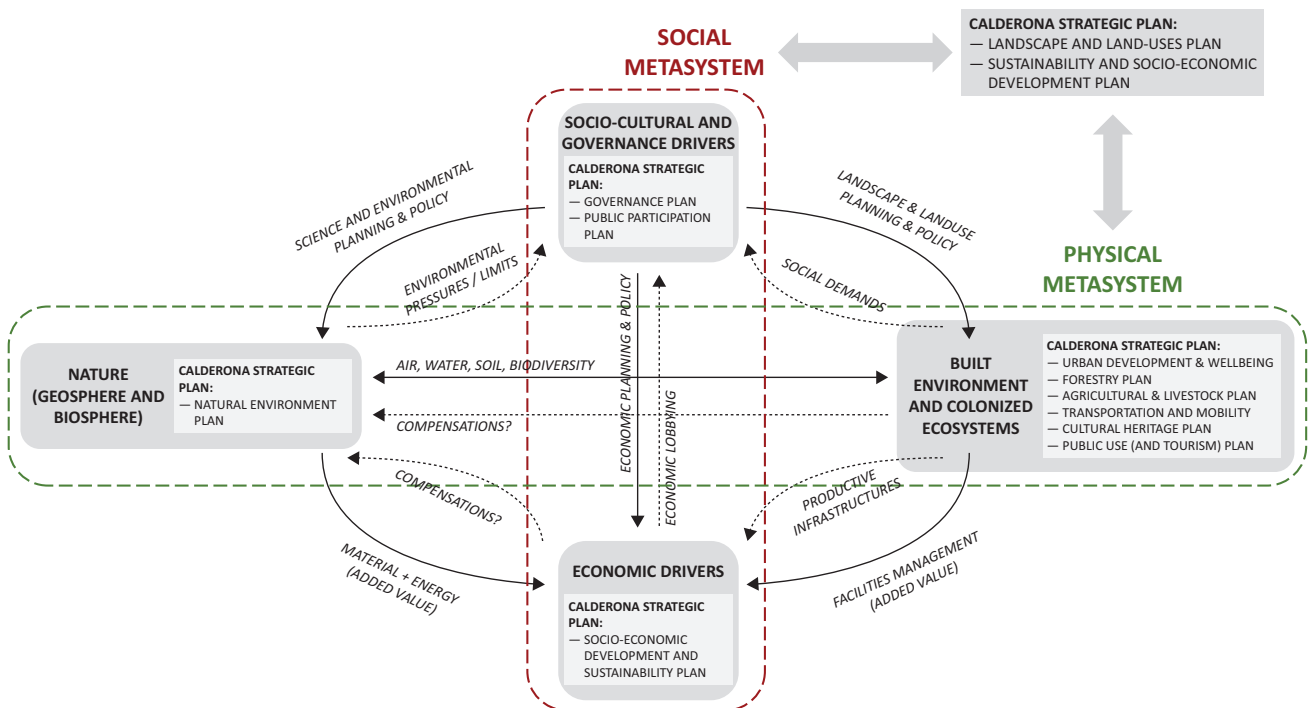
Figure 3. Integration of the social and physical metasystems in the SCSP and links with the proposed sectoral plans, landscape and land use plan, and overarching metabolic studies. Source: based on the model for resources correlations within a regional urban system in Baccini and Brunner (2012).

3.3.2. Water

Figure 4 summarises the flows of water that were analysed in the SCSP. Their magnitudes are in line with the

general pattern observed in other semirural areas of the Valencian Region and Eastern Spain. The higher rate of water consumption in low-density housing estates explains the big share of domestic water used in this urban

type (or FMA) even in low tourist seasons. It should be noticed that the water used in the service sector was not accounted in the water flow analysis.

The residential and industrial water treated in the local sewage plants (2,530m^3/day in low tourist season and 3,816m^3/day in high season) accounts for approximately 60% of the water entering the domestic and industrial water systems. Almost all the sewage produced in compact urban areas and industrial sites is treated. By contrast, in some housing estates, especially old ones, the use of cesspits is still common, with potential risks for vulnerable aquifers.

3.3.3. Waste

In the SCSP, waste was considered as a family of materials at the end of the metabolic loop of the system. Accordingly, a better knowledge of waste types and volumes was key to understand how the system works/metabolises/recycles and how it deals with the most problematic end-waste products. However, the waste study did not include a mass balancing revealing hidden or unused wastes.

Waste was divided into three categories. "Conventional waste" (MSW) includes domestic waste from compact neighbourhoods and low-density housing estates, industrial waste (either non-toxic or toxic), and non-organic agricultural waste and manure from livestock farming (accounted partially as sewage, conventional waste, and green residues). The "Green residues" category includes natural residues from forestry, agriculture, and gardening. "Debris waste" includes the inert waste

produced in the construction sector, both in residential and industrial areas.

Since domestic waste was calculated using the same ratio for compact towns and low-density housing estates (Table 1), the amount of this type of waste varies according to the population of these two urban subsystems (or FMAs) rather than to their specific ways of functioning. However, since waste collection in low-density settlements is less efficient, it has both an extra energy and economic cost.

As displayed in Figure 5, the "Green residues" type includes residues from gardening, agriculture, and forestry and totalled up to 3,823ton/year. However, this amount varies considerably depending on the management regime of the natural and agricultural areas, which cover 65% and 27% of the studied region respectively. This calculation allowed capturing the substantial production of residual biomass that can be reused for different purposes (e.g., waste-to-energy conversion).

3.3.4. Energy (Electricity)

Power consumption in each municipality was calculated using the method and databases presented in Table 1. This consumption was then disaggregated between different FMAs and Functional Economic sectors using standard ratios that were adjusted according to the size of each sector or land use in each municipality (see Figure 6).

Since the sourced energy data referred only to electricity, other essential energy flows (e.g., natural gas, fossil fuels) were not accounted, resulting in a substan-
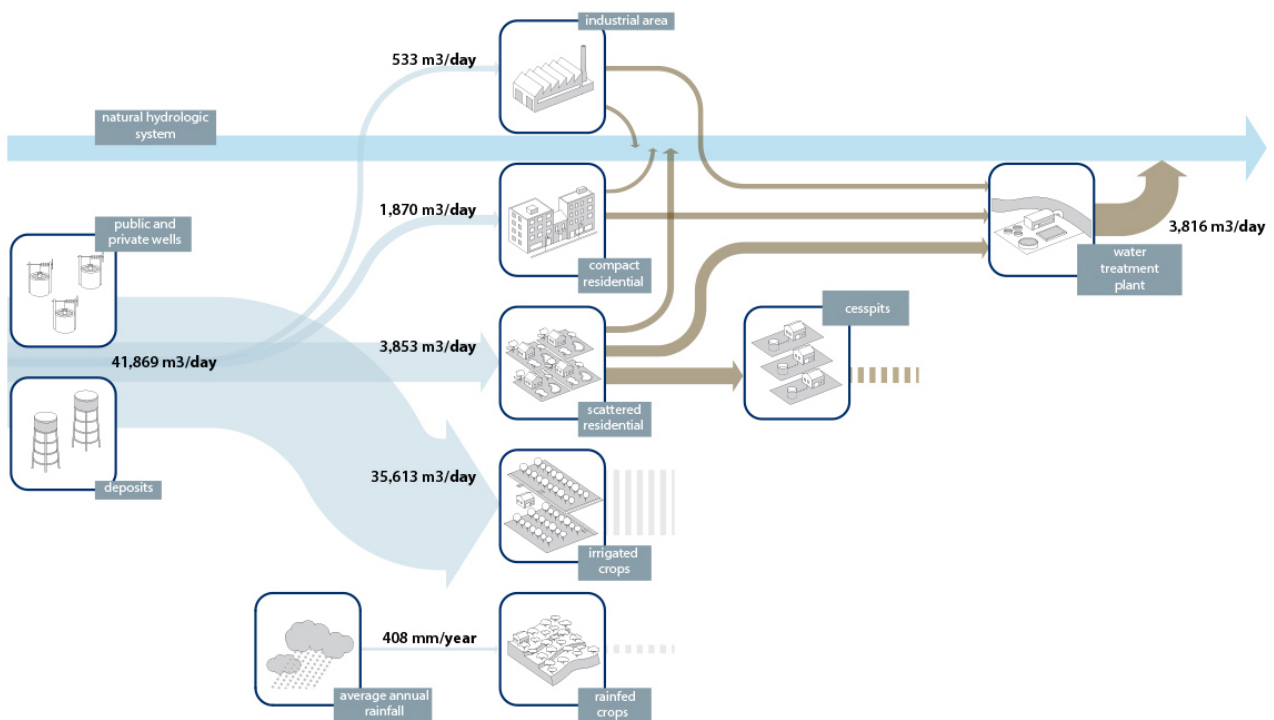

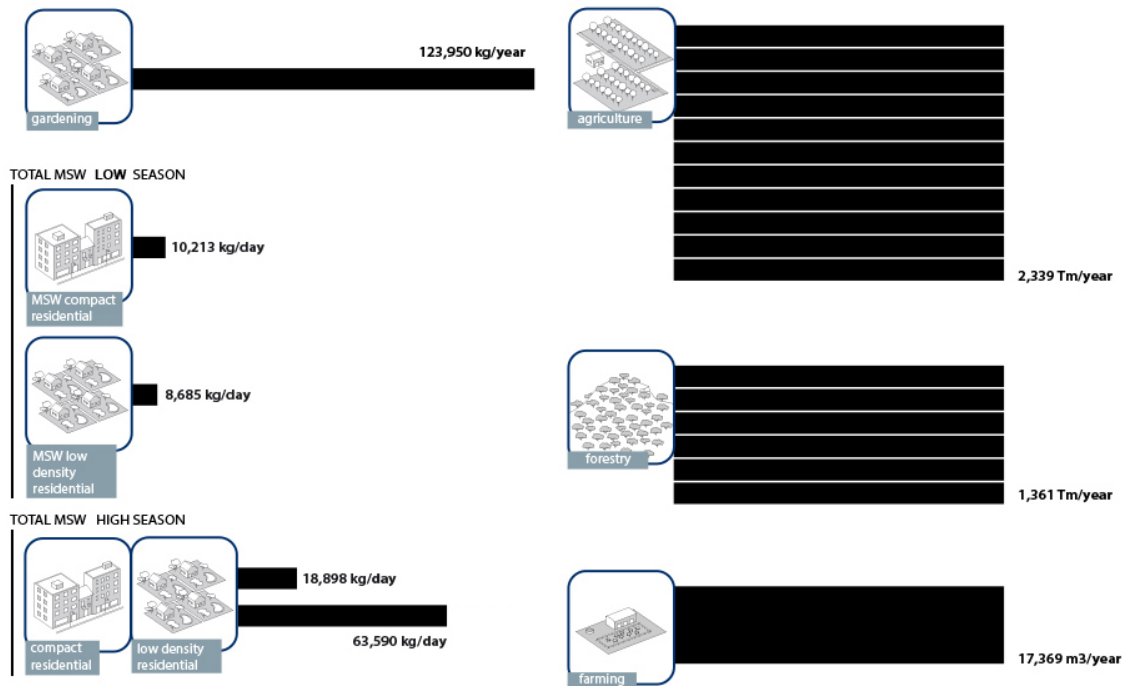**Figure 4.** Main water flows in the SCSP. Source: Galan (2014b).

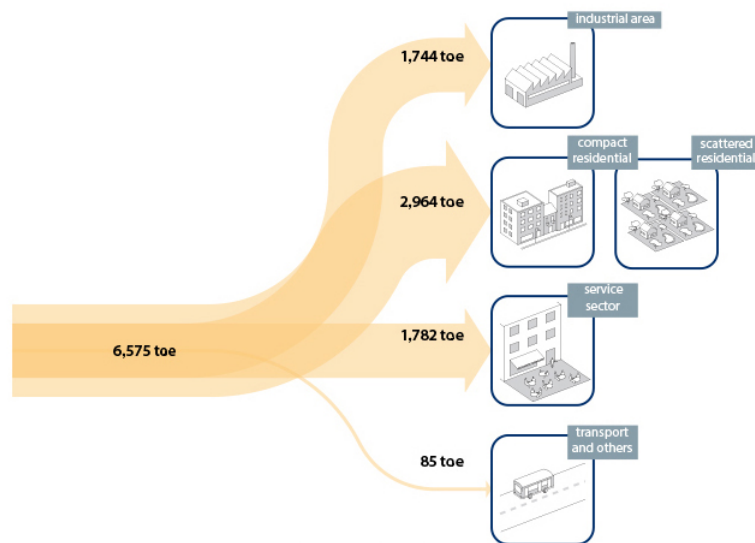Figure 5. Main waste or residues flows in the SCSP. Source: Galan (2014b).

Figure 6. Main electricity flows in the SCSP. Source: Galan (2014b).

tial lack of information regarding some crucial activities like transportation.

Nevertheless, the calculation of EFs for different user's profiles (see Section 3.3.5) allowed identifying and including levels of overall energy consumption in different types of urban fabrics (compact towns or more monofunctional low-density housing estates), as well as estimating the energy-intensity of different ways of living. In addition, EFs allowed accounting other energy usages than electricity consumptions, such as fossil fuels for transportation.

Concerning the production of renewable energy, this is still quite limited in the Sierra Calderona given the ad-

ministrative constraints for installing wind turbines in the elevated areas of the Natural Park. The main sources of renewable energy are biomass (converted in a CHP plant) and solar energy (photovoltaic systems).

3.3.5. EFs

The calculation of EFs was used in the SCSP to complement the study of material and energy flows. In particular, the use of EFs allowed integrating different material flows in the same analytical framework and including energy flows that were not accounted in the analysis of electricity consumptions.

The selection of a representative set of profiles for the EFs calculation was based on the sociodemographic study of the Sierra Calderona (Galan, 2014a), and resulted from the need of including profiles of inhabitants of different urban fabric types and people with different professional situations (see the first column of Table 2). As explained in Table 1, the EFs calculation was developed using a standard online quiz that divides the footprint of one individual into four consumption categories: carbon (home energy use and transportation), food, housing, and goods and service.[1] However, the use of EF-apps more adjusted to ways of living in the Sierra Calderona would have provided more reliable data.

As displayed in Table 2, significant differences between user/inhabitant profiles were observed, especially between people living in compact towns or villages and those living in low-density housing estates. Such profiles revealed two radically different mobility patterns (with longer and more frequent trips in private cars for people living in low-density housing estates), with highly contrasted mobility-related carbon footprints. As explained in section 3.4, these results were essential to inform the drafting of strategies, sectoral plans, and pilot projects aimed at reducing the transportation share of the studied EFs.

3.4. Metabolism of the Sierra Calderona: Strategies, Plans and Pilot Projects

3.4.1. Sustainable and Metabolic Strategies

The SCSP included 52 strategies/objectives for the natural environment, agriculture and livestock farming, urban environment and wellbeing, transport infrastructure and mobility, cultural heritage, tourism and use of public spaces, landscape, sustainability, socio-demography, economic development, and governance. Although the sustainability goal was embedded in all the strategies, the following five "mainstream" strategies were proposed as a means to improve the sustainability performance of the region and to optimise its metabolism. Firstly, to promote a multifunctional and efficient land use management of the region and its economy, favouring locally sourced flows of energy and materials (see Figure 7). Secondly, to monitor levels of sustainability through active engagement of the local population (e.g., use of more effective EF accounting methodologies). Thirdly, to optimise water consumption and wastewater management. Fourthly, to decrease waste production and to promote recycling and reuse of materials; and fifthly, to reduce energy consumption, increase en-

Table 2. Current EFs (global hectares) for different user/inhabitant profiles in the Sierra Calderona. Source: Galan (2014b).

|	Carbon Footprint	Food Footprint	Lodging Footprint	Services Footprint	Total Footprint	Number of Earths
Average Area in Strategic Plan	11.68	17.19	4.79	9.75	43.4	2.76
Person living in a compact town and working in a nearby industrial estate	4.9	16.5	3.6	7.5	32.62	2.08
Housewife living in a compact town	5.7	14.9	3.6	7.5	31.75	2.02
Person living in housing estate and working in the city of Valencia	17.1	19.5	4.5	10.6	51.73	3.29
Part-time farmer living in a compact town and working in the local service sector	5.7	16.5	6.1	12.7	40.92	2.6
Retired person living in a compact town	4.9	12.4	3.2	6.6	27.03	1.72
Retired person living in a low-density housing estate	15.2	17	6.5	9.1	47.73	3.04
Child living in a compact town	5.7	16.5	2.4	11.6	36.22	2.31
Child living in a low-density housing estate	17.4	19.5	7.4	12	56.24	3.58
Young person studying at a university in the city of Valencia and living in a compact town or low density housing estate	9	16.5	3.6	7.5	36.59	2.33
Seasonal resident (summer)	22.8	19.5	6.5	12	60.82	3.87
Person working in the military camp	20.1	20.3	5.3	10.1	55.78	3.55
National Average	12.9	14.9	4.8	9.4	42	2.5

---

[1] myfootprint.org
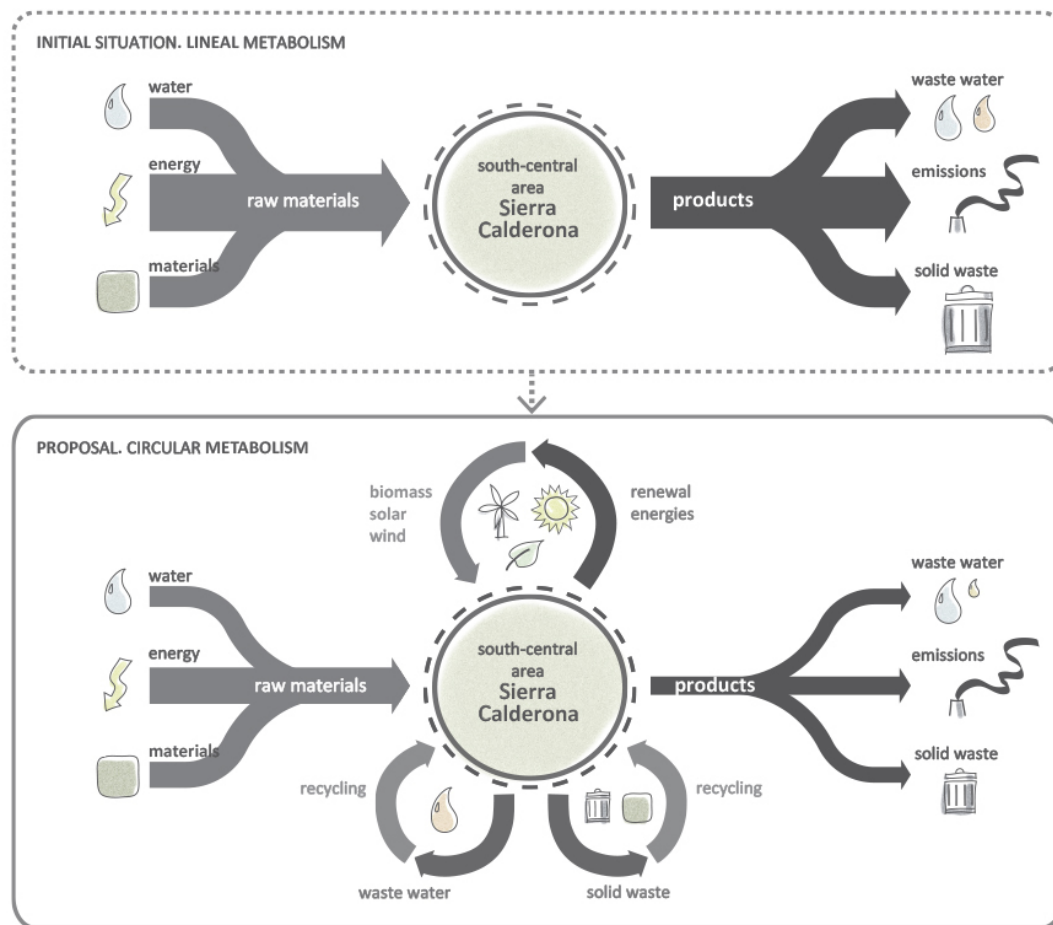
Figure 7. Overview of first-level regional "mainstream" strategies to favour transition towards a circular metabolism in the Sierra Calderona. Source: Galan (2014b) adapted from Rogers (1997).

ergy efficiency and promote the use of renewable energy (Galan, 2014b).

In the SCSP case, the use of material and energy flow accounting and EFs analysis was perceived as a tool to streamline the proposed "mainstream" sustainability strategies and adjust them to the specific conditions of each site.

3.4.2. FMAs and Metabolic Profiles

The difference between the main types of FMAs in the Sierra Calderona is illustrated in Figure 8, where "resource production" and "resource demand" are presented in a qualitative manner for different types of FMAs. Inspired by the diagrammatic representation of the "relation between urban density and productive capacity of land within a polyurban region" (Ferrão & Fernandez, 2013), the figure displays the difference between using per capita ratios or spatial ratios (m^2).

In particular, the conceptual diagram was elaborated based on the FMA's resource demand as well as on the internal production needed to maintain existing activities in each FMA. The following underlying assumptions were made:

1. Resource production: the existing level of production within each FMA needed to maintain the current functioning of the FMA. This can apply to a specific resource (water, oxygen, energy, waste recycling, etc.) or their combination;
2. Resource demand: the demand for a resource or a group of resources within each FMA needed to maintain the current functioning of the FMA;
3. The difference between resource production and demand can be described as the Resource Surplus (when positive) or Deficit (when negative).

Additionally, it was understood that the modification of flows exchanged between FMAs, according to FMAs' respective deficits and surpluses, could lead to internal adjustment of the overall Sierra Calderona metabolism.

The conceptual diagram suggests the value of applying metabolic approaches and accounting methods not only within urban areas but also across these and different types of agricultural or natural areas.

3.4.3. Regional Metabolic Model for the Sierra Calderona

This subsection presents the regional metabolic model defined for the Sierra Calderona. The model conceives
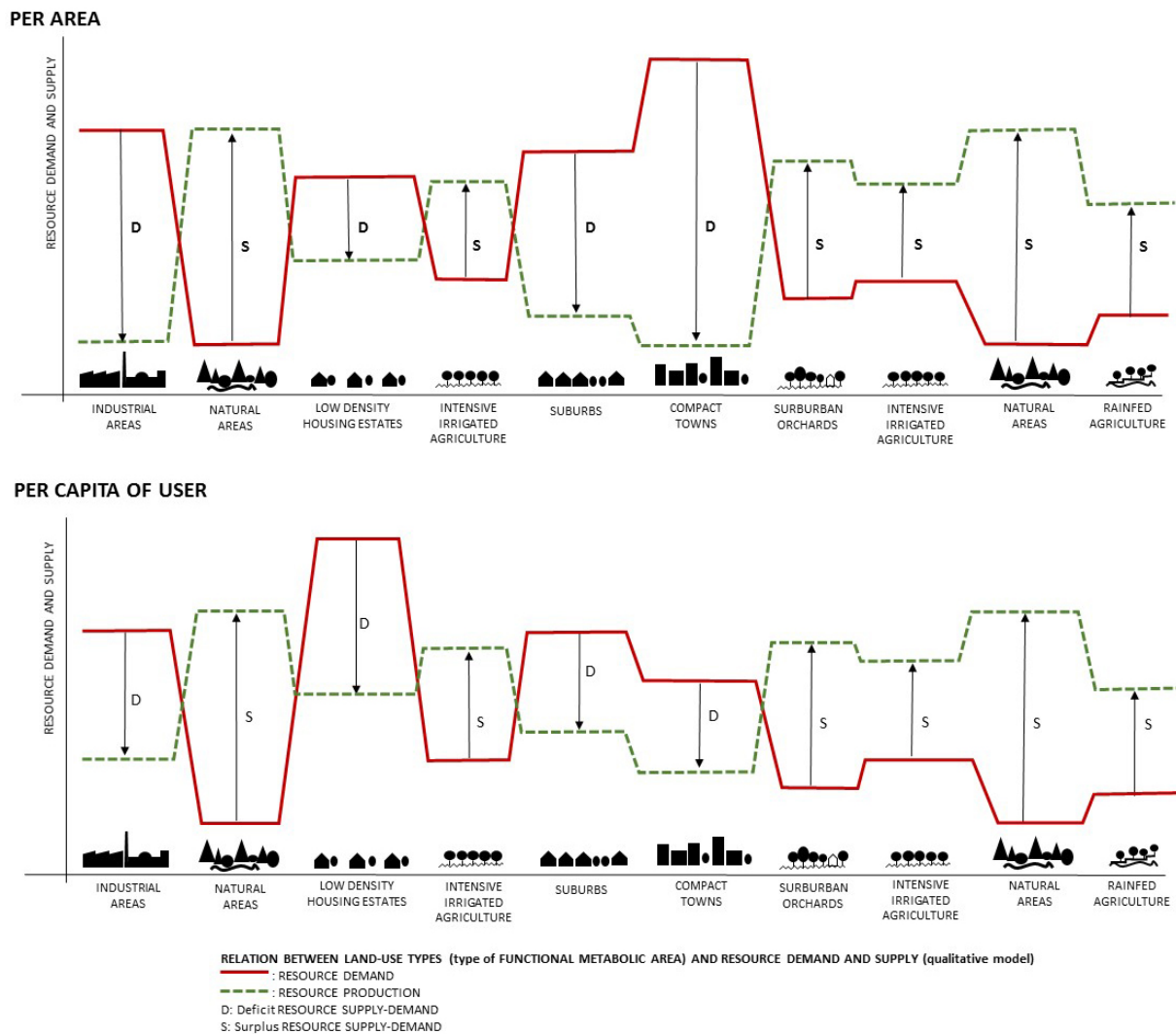
PER AREA

PER CAPITA OF USER

RELATION BETWEEN LAND-USE TYPES (type of FUNCTIONAL METABOLIC AREA) AND RESOURCE DEMAND AND SUPPLY (qualitative model)
──── : RESOURCE DEMAND
- - - - : RESOURCE PRODUCTION
D: Deficit RESOURCE SUPPLY-DEMAND
S: Surplus RESOURCE SUPPLY-DEMAND

Figure 8. Conceptual diagram expressing resource production and resource demand for different types of FMAs in urban and non-urban areas of the Sierra Calderona per area (on top) or per capita (bottom).

the Sierra Calderona as a collage of different types of FMAs and considers the flows between those types of FMAs based on the metabolic assessment presented in Section 3.3 and the resource surpluses and deficits presented in Figure 8.

The proposed evolution of the regional metabolic model is based on the Sustainable and Metabolic Strategies explained previously and is aimed at exemplifying the transition from linear to circular metabolism represented in Figure 7, both at the system (Sierra Calderona) and subsystem level (FMAs). The improvement at the system level would be based on the modification of flows between FMAs. The proposed adjustments are informed by the results of the metabolic assessment presented in Section 3.2 (water, waste, energy-electricity), and the EF analysis (Section 3.3.5).

In particular, the model is structured around the five main types of FMAs and Economic Sectors identified in the region: compact urban, low-density suburban, agricultural areas, natural areas, and industrial areas. Due to

their relevance to the regional economy and impact on the overall regional metabolism, the service sector and the "visitors/tourists" user's profile were also included.

Building on the results of the metabolic assessment/EF analysis, and on the suggestions provided by the sectoral plans, the following flows were considered:

1. Energy: renewable energy;
2. Waste: forest residues, agricultural and gardening residues, urban residues/waste;
3. Materials and services: forest resources, agricultural products, processed products and services, spaces for public use, public transport;
4. Workforce: use of local workforce.

As displayed in Figure 9, these flows were scored on a qualitative basis (low, medium, high) for both the current situation and future projections. In addition to flows analysed in the metabolic assessment (urban waste, forest residues, and agricultural residues, see Section 3.2),

other flows were derived from the analysis of activities and land use types in the SCSP (Galan, 2014a; e.g., renewable energies, forestry resources, agricultural products, use of local workforce, use of public spaces, and public transport).

As detailed in Section 3.4.4, the model for the metabolic transition presented in Figure 9 guided the drafting of the Landscape & Land Use plan and sectoral plans in the SCSP.
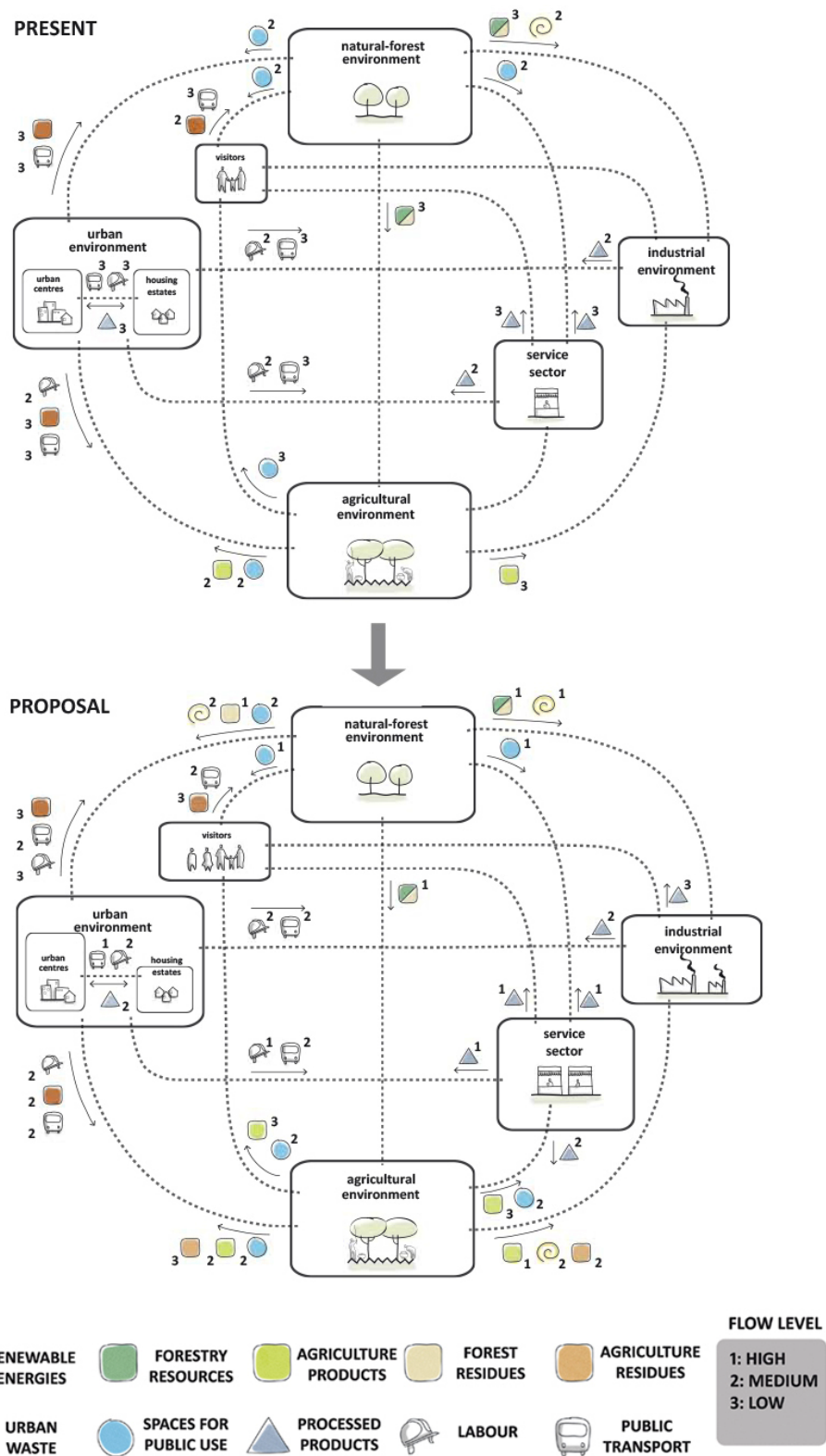

Figure 9. Regional model: Potential improvements of metabolic cycles in the Sierra Calderona region. Source: Galan (2014b).

3.4.4. Landscape and Land Use Plan and Sectoral Plans

The SCSP landscape and land use plan and the sectoral plans were informed by the metabolic assessment of the Sierra Calderona and were used to support the implementation of the strategies and model for the planned metabolic transition (Figures 7 and 9). In the national and Valencian planning system, sectoral plans (dealing with specific activities or land uses) are generally not compulsory at the municipal level. However, due to the supra-municipal character of the SCSP and the interest in exploring the interaction between activities and land uses, the SCSP included a set of sectoral plans (e.g., agriculture, management of the natural environment, urban planning and well-being, cultural heritage, tourism and use of public spaces, etc.), together with an overarching landscape and land/use plan (see Figure 2).

From a metabolic point of view, the Natural Environment Plan proposed the basic conditions for the sustainable use of the natural areas of Sierra Calderona. The Plan quantified sustainable levels for the extraction of natural resources in order to adjust resource flows exchanged between the natural environment and other FMAs (see variation of flows of forestry resources and residues, workforce, renewable energy, and people in Figure 9).

In line with this approach, the Agriculture Plan and Livestock Farming Plan defined the key lines for the sustainable transition of agriculture and farming in the Sierra Calderona. As displayed at the bottom of Figure 9, this evolution involved, in some cases, a significant change in the type and magnitude of metabolic flows towards/from other FMAs (agricultural produces and residues, organic urban waste, and renewable energy), as well as change in metabolic flows within the agricultural FMAs.

As shown in Figure 9, in the Urban and Well-Being Plan, the urban and industrial areas were at the core of the proposed metabolic transition for the Sierra Calderona. In particular, it was proposed to intensify the magnitude of some of the metabolic flows exchanged between natural/agricultural areas and urban/industrial areas (e.g., use of natural resources and agricultural products in local markets, waste processing in agricultural areas, use of local workforce in local industries or functional connections between housing estates and compact towns).

In addition, the Socioeconomic Development and Sustainability Plan, together with the Governance and Implementation Plan, defined a set of programmes and management tools to support the metabolic transition of the Sierra Calderona.

3.4.5. Pilot Project for the Metabolic Transition of the Pedralbilla-Torre de Portaceli Housing Estate

The SCSP sectoral plans included a set of pilot projects, in which the most innovative or critical aspects of the plans were applied and developed on a more detailed level. The biggest housing estate in the Sierra Calderona was selected as one of the pilot projects' areas due to the strong impact of low-density housing typologies on the metabolic performance of the Sierra Calderona and in light of the significant morphological and metabolic differences between this type of FMA/urban tissue and compact towns (see Tables 1 and 2).

The pilot project was developed on the Pedralbilla-Torre Portaceli housing estate (232 hectares) and was part of the SCSP Urban and Well-being Plan. As shown in Figure 10, the main objective of the pilot project was to facilitate the transition from a mono-functional residential area to a multifunctional and sustainable neighbourhood. It was assumed that this transition could be facilitated by: (1) promoting a strategic and controlled densification; (2) adding new functions (e.g., working

Figure 10. Conceptual proposal for the sustainable transformation of the Pedralbilla-Torre de Portaceli housing estate. Source: Galan (2014b).

places and service hubs); (3) improving the quality of the public spaces and green infrastructure at all scales; and (4) strengthening social and community cohesion.

In particular, in the pilot, it was proposed to modify the metabolic performance of the urban fabric by minimising per-capita water and energy consumption (see Tables 1 and 2), optimising waste collection/recycling, and decreasing the EFs of some of the inhabitants' profiles (see Table 3).

The proposal focused on increasing the number of dwellings by 33% (up to 2,060 units) and the permanent population by 70% (4,950 new inhabitants) while decreasing the fluctuating population by 50% (1,240 people). The expected result was a 37% increase in the urban density (up to 26.6 inhabitants/ha), as well as the creation of new public and private services and public transport hubs. The currently underused Portaceli brook was proposed as the spine of a reinforced green infrastructure, contributing to the regulation of water cycles and the provision of other ecosystem services.

Table 3 illustrates the expected change in the EFs of different inhabitants' profiles following the implementation of the Pedralbilla-Torre de Portaceli proposal. The EFs were calculated following the same method as for the user/inhabitant profiles in the whole Sierra Calderona region (Table 2). Moreover, ways of living in compact towns were taken as a baseline for the transformed housing estate (it is worth noting the convergence between EFs in compact towns in table 2 and EFs in the housing estate after the implementation of the proposal in Table 3).

4. Discussion and Conclusion

4.1. Challenges of Incorporating UM Thinking into Regional Planning

There were three main challenges in the development of the Sierra Calderona metabolic study. Firstly, its location

at the edge of a metropolitan area made it particularly difficult to differentiate the metabolic flows exchanged between the system (the five municipalities included in the SCSP) and their hinterland. Secondly, the amount and diversity of urban areas in the Sierra Calderona, together with their heterogeneous levels of interaction with the natural and semi-natural environment, resulted in a complex spatial distribution of flows and a wide range of user's profiles, from self-sufficient farmers to semirural/urban inhabitants. Thirdly, the demographic seasonality due to the local touristic activities generated large fluctuations in the metabolic flows.

In response to these challenges, the SCSP concentrated on the optimisation of the internal metabolic flows within the areas/FMAs, assuming that this would result in a positive effect on the inputs and outputs of the whole system.

Secondly, the complex spatial and functional system of the Sierra Calderona was simplified through the definition of metabolic area types that were associated with FMAs or spatial metabolic subsystems. The material and energy flows of these subsystems were studied using data from national and regional sources. However, this spatial approach was complemented with the calculation of EFs for a set of representative users' profiles. This combination of methods (MFA and EF) can potentially inform sustainable urban and regional planning (Galan, 2013, 2014a).

Thirdly, the seasonality challenge was addressed by examining the temporal variation of the metabolic flows that were more likely to be affected by demographic fluctuations (e.g., water, energy, waste).

Another aspect that limited a deeper incorporation of the UM approach into the SCSP was that the regional model (Figure 9) considered only the main types of FMAs. This was due to pragmatic reasons and to the need for simplifying a complex system and reducing the quantity of data processed to a reasonable amount. A broader

Table 3. Current and expected EF (global hectares) for different inhabitants profiles in the Pedralbilla-Torre de Portaceli housing estate. Source: Galan (2014b).

	Carbon Footprint	Food Footprint	Lodging Footprint	Services Footprint	Total Footprint	Number of Earths
Permanent Resident Working in the Area (Current)	17.1	19.5	4.5	10.6	51.7	3.29
Permanent Resident Working in the Area (After Proposal)	4.9	16.5	4	7.5	32.9	2.09
Retired Resident (Current)	15.2	17	3.2	6.6	42	2.67
Retired Resident (After Proposal)	4.9	12.4	4.5	9.1	30.9	1.97
Child Resident (Current)	17.4	19.5	7.4	12	56.3	3.58
Child Resident (After Proposal)	5.7	16.5	3.4	11.6	27.2	2.37
Seasonal Resident (Current)	22.8	19.5	6.5	12	60.8	3.87
Seasonal Resident (After Proposal)	7.5	16.5	3.2	11.6	38.8	2.47

diversification of the number of FMAs and the development of a specific metabolic model for each FMA would have resulted in the elaboration of a more sensitive regional model. Given the internal diversity of both geographic and metabolic features of the region, this would have also allowed for a more accurate translation of UM knowledge into local planning. Moreover, although one of the objectives of the model was to illustrate the impact of the FMAs spatial configuration on the users' and inhabitants' lifestyles, the model fell short in capturing the cause-consequence nexus within each FMA. However, it is worth noting that the simplicity of the model facilitated the incorporation of UM inputs into the SCSP, and the study of flows between FMAs opened a pathway for future investigations.

4.2. Incorporation of the UM Results into the SCSP: Limitations of Used Methodologies

First considerations when evaluating the UM assessment approach adopted in the SCSP relate to the interplay between quantitative and qualitative methods. Although in an initial stage the SCSP included a quantitative assessment of metabolic flows, the final accounting method was influenced by the availability of datasets as well as the need to present results in a comprehensible manner for decision-makers. Thus, the material and energy flow accounting (Table 1) was not performed following the Eurostat's MFA methodology. For example, not all flows were quantified using mass metrics (e.g., tons) and the total mass balance was not calculated. It should also be noted that, due to the informative nature of the SCSP, the effectiveness of the proposed planning strategies in the real world was neither estimated nor monitored (and consequently excluded from the scope of this article).

The calculation of the EF based on alternative user/inhabitant profiles in both the overall plan (Table 2) and the pilot project (Table 3) was performed using the online tool Myfootprint (see Section 3.3.5), instead of applying more rigorous scientific methods as the one described in Wackernagel et al. (2006). It is also worth noting that the majority of tools available online to calculate EFs are based on North American lifestyles, which may significantly differ from lifestyles in other regions of the world. Finally, although the comparison between the EFs analysis before and after the high-density housing proposal in the pilot project suggests a positive impact on the UM (see Section 3.4.5), a more accurate estimation of the EFs (exiting and forecasted) would have helped to move the implementation of the project to the next stage. Overall, rather than as a scientific analytical tool, the EF concept was used as a means to communicate the effects of the urbanisation process and related externalities in a language that could be easily understood by decision-makers and planners.

In conclusion, more user-friendly and intuitive methodologies, such as the material and energy flow accounting and the online-tool based EF calculation used

in the SCSP, can provide results that are more intuitive and easier to comprehend by decision-makers. Moreover, one very distinctive characteristic of the SCSP was that the author endeavoured to combine two different UM assessment methods, which allowed broadening the analysis through the specific scope and strengths of each method. For example, it could be argued that the use of the EF calculation can facilitate the integration of resource flows that are normally accounted separately in traditional UM assessment frameworks (e.g., energy, food, etc.). As such, EF analysis can represent a valuable intermediate step between more rigorous UM assessment models and planning practice. In addition, EF analysis can provide a level of information on the metabolic functioning of a system that is more informed by the "micro-scale" of the user's lifestyles (bottom-up) than by the "macro-scale" of the aggregated assessment of the whole system (top-down). In this sense, EFs can help translate UM scientific knowledge into operational tools that may be closer to those used by planning practitioners.

However, the use of qualitative UM assessment tools and their combination into user-friendly analytical frameworks should not preclude the integration of rigorous UM knowledge into planning practice. For example, scientific models (e.g., the Eurostat's MFA) can be used to validate the results of the analysis internally, before their incorporation into planning documents. This would involve more diversified working teams, in which researchers and practitioners would be able to test emerging methodologies through a multiple feedback loop. Similar experiences have been conducted within the two EU-FP7 interdisciplinary projects mentioned in the Introduction (Chrysoulakis et al., 2015; Davoudi & Sturzaker, 2017).

4.3. Questions for Future Research

Following our evaluation of the way in which metabolic data were used in the SCSP, the following question for future research emerges: Can regional and urban planning act as a catalyst for adjustments and advances in metabolic analytical frameworks? As a suggestion for future investigations, it could be argued that a two-way interrelation exists between planning disciplines and UM studies. On the one hand, UM assessments are of utmost importance when modelling different kinds of resource flows across urban scales and for compiling comprehensive sets of urban sustainability indicators. On the other hand, planning practice can provide a "proving ground" for testing the operational potential of UM assessment methods and tools in real-world settings, thereby advancing UM research in a systemic way. As seen in the Sierra Calderona case, this involves addressing weaknesses and methodological shortcomings emerging from the testing of new conceptual frameworks and modelling approaches (availability of high-resolution datasets, combination of qualitative and quantitative methodologies,

as well as methods using different kinds of datasets such as material and energy flow analysis and EF calculation). In addition, planning practice can advance current black-box models, for example by facilitating a better understanding of the spatial dynamics associated with the distribution of resource flows, through concepts such as FMAs.

Explorative planning research based on the integration of qualitative/quantitative methods and spatially resolved analyses of cities and regions (as in the case of the SCSP), can help formulate new research questions for the UM scientific community and, thus, stimulate future science-practice collaborative research. Moreover, a "designerly way of knowing" (Cross, 2007) can represent a valuable complement to purely analytical or theoretical approaches in UM research. It is our conviction that collaborations between planning practitioners and UM scientists have a great potential to drive societies towards a shared understanding and achievement of more sustainable metabolisms of cities and regions.

Conflict of Interests

The authors declare no conflict of interests.

References

Alberti, M. (2005). The effects of urban patterns on ecosystem function. *International Regional Science Review*, *28*(2), 168–192.

Ayres, R., & Kneese, A. (1969). Production, consumption and externalities. *American Economic Review*, *59*(3), 282–297.

Baccini, P., & Brunner, P. H. (2012). *Metabolism of the anthroposphere* (2nd ed.). Cambridge, MA: MIT Press.

Bahers, J. B., Barles, S., & Durand, M. (2018). Urban metabolism of intermediate cities: The material flow analysis, hinterlands and the logistics-hub function of Rennes and Le Mans (France). *Journal of Industrial Ecology*. Advance online publication. https://doi.org/10.1111/jiec.12778

Barles, S. (2009). Urban metabolism of Paris and its region. *Journal of Industrial Ecology*, *13*(6), 898–913. http://dx.doi.org/10.1111/j.1530-9290.2009.00169.x

Beloin-Saint-Pierre, D., Rugani, B., Lasvaux, S., Mailhac, A., Popovici, E., Sibiude, G., . . . Schiopu, N. (2017). A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. *Journal of Cleaner Production*, *163*(S), S223–S240.

Bringezu, S. (1997). From quality to quantity: Material flow analysis. In S. Bringezu, M. Fischer-Kowalski, R. Kleijn, & V. Palm (Eds.), *Proceedings of the ConAccount workshop* (pp. 43–57). Wuppertal: Wuppertal Institute. Retrieved from www.researchgate.net/profile/Marina_Fischer-Kowalski/publication/239550950_Regional_and_National_Material_Flow_Accounting/links/00b7d529dc4cca2bcf000000.pdf#page=43

Castán Broto, V., Allen, A., & Rapoport, E. (2012). Interdisciplinary perspectives on urban metabolism. *Journal of Industrial Ecology*, *16*(6), 851–861.

Chrysoulakis, N., de Castro, E., & Moors, E. (Eds.). (2015). *Understanding urban metabolism. A tool for urban planning*. New York, NY: Routledge.

Codoban, N., & Kennedy, C. (2008). Metabolism of neighborhoods. *Journal of Urban Planning and Development*, *134*(1), 21–31. http://dx.doi.org/10.1061/(ASCE)0733-9488(2008)134:1(21)

Cross, N. (2007). From a design science to a design discipline: Understanding designerly ways of knowing and thinking. In R. Michel (Ed.), *Design research now, essays and selected projects* (pp. 41–54). Basel: Birkhauser Verlag AG.

Cui, X. (2018). How can cities support sustainability: A bibliometric analysis of urban metabolism. *Ecological Indicators*, *93*, 704–717.

Davoudi, S., & Sturzaker, R. (2017). Urban form, policy packaging and sustainable urban metabolism. *Resources, Conservation and Recycling*, *120*, 55–64.

Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., . . . Zeyringer, M. (2018). Exploring urban metabolism: Towards an interdisciplinary perspective. *Resources, Conservation & Recycling*, *132*, 190–203.

Engel-Yan, J., Kennedy, C. A., Saiz, S., & Pressnail, K. (2005). Towards sustainable neighbourhoods: The need to consider infrastructure interactions. *Canadian Journal for Civil Engineering*, *32*(1), 45–57.

Eurostat (2001). Economy-wide material flow accounts and derived indicators. A methodological guide. European Communities. *Ec.Europa*. Retrieved from ec.europa.eu/eurostat/documents/1798247/6191533/3-Economy-wide-material-flow-accounts...-A-methodological-guide-2001-edition.pdf

Ferrão, P., & Fernandez, J. E. (2013). *Sustainable urban metabolism*. Cambridge, MA: MIT Press.

Galan, J. (2013). *Cullera: Urbanismo y Paisaje 2011* [Cullera: Urbanism and Environment 2011]. Valencia: UPV Press.

Galan, J. (2014a). *Nazaret: Urbanismo y paisaje 2012* [Nazaret: Urbanism and environment 2012]. Valencia: UPV Press.

Galan, J. (2014b). *Plan estratégico de le Sierra Calderona* [Sierra Calderona strategic plan]. Valencia: UPV Press.

Galan, J. (2018). *Analysis and Strategies for sustainable regional planning: The Sierra Calderona strategic plan*. Berlin: Springer.

Girardet, H. (1992). *The Gaia atlas of cities*. London: Gaia Books Limited.

Glasson, J., & Marshall, T. (2007). *Regional planning*. Oxfordshire: Routledge.

Hammer, M., Giljum, S., Bargigli, S., & Hinterberger, F. (2003). *Material flow analysis on the regional level: Questions, problems, solutions* (NEDS Working Papers 2 04/2003). Vienna: Sustainable Europe

Research Institute (SERI). Retrieved from alt.seri.at/en/publications/other-working-papers/2009/09/20/material-flow-analysis-on-the-regional-level-questions-problems-solutions

Ibañez, D., & Katsikis, N. (Eds.). (2014). *Grounding metabolism*. Cambridge, MA: Harvard University Press.

Ayuntamiento de Sevilla. (2008). *Indicadores de sostenibilidad ambiental de la actividad urbanística de Sevilla: metabolismo urbano* [Indicators of environmental sustainability for the urbanistic activity of Seville]. Sevilla: Ayuntamiento de Sevilla, Observatorio de Sostenibilidad Urbanística and Agencia de Ecologia Urbana de Barcelona. Retrieved from www.ecourbano.es/imag/00%20DOCUMENTO%20ENTERO.pdf

Kennedy, C., Cuddihy, J., & Engel-Yan, J. (2007). The changing metabolism of cities. *Journal of Industrial Ecology*, *11*(2), 43–59. http://dx.doi.org/10.1162/jie.2007.1107

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*, *159*(8/9), 1965–1973. http://dx.doi.org/10.1016/j.envpol.2010.10.022

Li, H., & Kwan, M.-P. (2018). Advancing analytical methods for urban metabolism studies. *Resources, Conservation & Recycling*, *132*, 239–245.

Lloret, J. (2013). *Anàlisis del grau de sostenibilitat urbana dels diferents tipus dássentament urbans* [Analysis of the sustainability levels of different urban fabrics] (Unpublished Master's dissertation). Universitat Politecnica de Valencia, Valencia, Spain.

Monfreda, C., Wackernagel, M., & Deumling, D. (2004). Establishing national natural capital accounts based on detailed Ecological footprint and biological capacity assessments. *Land Use Policy*, *21*, 231–246.

Newell, J. P., & Cousins, J. J. (2014). The boundaries of urban metabolism: Towards a political–industrial ecology. *Progress in Human Geography*, *39*(6), 702–728.

Niza, S., Rosado, L., & Ferrão, P. (2009). Urban metabolism: Methodological advances in urban material flow accounting based on the Lisbon case study. *Journal of Industrial Ecology*, *13*(3), 384–405. http://dx.doi.org/10.1111/j.1530-9290.2009.00130.x

City of Valencia. (2010). *Observatorio de la ciudad: Sistema de ratios e indicadores: Valencia* [City observatory: System of ratios and indicators for the City of Valencia]. Valencia: Centro de Estrategias y Desarrollo de Valencia.

Oswald, F., & Baccini, P. (2003). *Netzstad–Designing the urban*. Basel: Birkhäuser.

Perrotti, D., & Stremke, S. (2018). Can urban metabolism models advance green infrastructure planning? Insights from ecosystem services research. *Environment and Planning B: Urban Analytics and City Science*. Advance online publication. https://doi.org/10.1177/2399808318797131

Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and Urban Planning*, *107*, 193–202.

Quinn, D. J. (2007). *Urban metabolism: Ecologically sensitive construction for a sustainable New Orleans* (Unpublished Master's thesis dissertation). MIT, Cambridge, Massachusetts.

Quinn, D. J. (2012). *Estimating material and energy intensities of urban areas* (Unpublished Doctoral dissertation). MIT, Cambridge, Massachusetts.

Rees, W. E. (1992), Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environment and Urbanization*, *4*(2), 121–130.

Rogers, R. (1997). *Cities for a small planet*. London: Faber and Faber.

Voskamp, I. M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J. P., & Rijnaarts, H. H. M. (2017). Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism. A material flow analysis of Amsterdam. *Journal of Industrial Ecology*, *21*(4), 887–902.

Wachsmuth, D. (2012). Three ecologies: Urban metabolism and the society-nature opposition. *The Sociological Quarterly*, *53*(4), 506–523.

Wackernagel, M., Kitzes, J., Moran, D., Goldfinger, S., & Thomas, M. (2006). The ecological footprint of cities and regions: Comparing resource availability with resource demand. *Environment and Urbanization*, *18*, 103–112.

Yin, R. K. (2014). *Case study research. Design and methods* (5th ed.). Thousand Oaks, CA: Sage.

Zhang, Y., Yang, Z., & Yu, X. (2015). Urban metabolism: A review of current knowledge and directions for future study. *Environment Science and Technology*, *49*, 11247–11263.

Zhang, Y. (2013). Urban metabolism: A review of research methodologies. *Environmental Pollution*, *178*, 463–473.

About the Authors

Juanjo Galan is Associate Professor at the Department of Architecture, Aalto University, Finland. Galan's research focuses on landscape planning, regional and urban planning, landscape design and, in a general level, the intersections between ecological and social systems. His Doctoral Dissertation explored the methodological and planning dimensions of the European Landscape Convention. The use of metabolic inputs in sustainable regional and urban planning has been a key element in his academic and research activity since 2011.

Daniela Perrotti is Professor of Landscape Architecture at Catholic University of Louvain, Belgium. Her research interests cover applications of urban metabolism models in urban planning and design, with a focus on green infrastructure strategies to mitigate energy demand and the resource-intensity of cities. Daniela serves/has served as Principal Investigator and co-Investigator for several research projects on integrated urban metabolism modelling approaches, in collaboration with local authorities and academic/industry partners in Europe, China, and South America. Daniela has published over 30 peer-reviewed papers in international journals and books.