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A socioecological integrated analysis of the Barcelona metropolitan agricultural landscapes

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ABSTRACT

To implement the Milan Urban Food Policy Pact while enhancing ecosystem services, the Barcelona Metropolitan Authority has commissioned a socioecological assessment of the metropolitan agriculture. A Socioecological Integrated Analysis has been carried out to incorporate ecosystem services as fundamental elements of the new Master Land Use Plan. This analysis involves assessing the functioning of metropolitan agricultural landscapes focusing on different dimensions: socio-metabolic efficiency (energy return on investment), biodiversity conservation, landscape functionality, global change, ecosystem services (supporting, regulation, provisioning) and social cohesion. After accounting indicators separately, they have been grouped through a principal component analysis into three factors: socio-metabolic flows, landscape functionality and system efficiency. An exploratory factor analysis has revealed trade-offs and synergies between these factors, with relevant implications for land-use policy. Finally, a correlation analysis has evaluated how the indicators interrelate among them. The results show that the improvement of complex socioecological systems requires new multi-criterial management where the different interrelated dimensions are jointly addressed. A new sustainability-oriented land-use planning combined with agricultural and environmental policies aimed at integrating farming with forestry and livestock activities would help reduce the dependence on non-renewable external energy inputs and, indirectly, the greenhouse gas emissions stemming from agri-food chains.

1. Introduction

Mapping and Assessing Ecosystem Services (MAES), an activity included in the European Union's (EU) Biodiversity Strategy for 2030, aims to help inform policy decisions that affect the environment (e.g. within a framework of nature, biodiversity, climate change, agriculture, forestry and water policies). In this paper, we use Maes et al. (2020) to highlight Ecosystem Services (ES) as key parameters in urban planning and to identify priorities when restoring and fomenting the deployment of green infrastructures (European Commission, 2014; Harrison et al., 2014). We propose that 'metropolitan agricultural landscapes' should be identified as a specific reference case since they represent the largest surface area of non-urbanized open spaces in metropolitan areas. They usually consist of a mosaic of forests, farmland and pastures that exist as natural protected areas and productive or abandoned agricultural areas (Maruani and Amit-Cohen, 2007).

Metropolitan agricultural landscapes also represent the greenbelts needed for more efficient agri-food supply chains, as outlined in the Milan Urban Food Policy Pact and the EU Farm to Fork Strategy (Moragues-Faus and Morgan, 2014), and also deliver many regulatory and cultural ES provided by associated biodiversity (Haines-Young and Potschin, 2010). Therefore, MAES can act as a useful framework for assessing the urban agroecosystems that are relevant components of the overall set of Ecosystem Service Providers for city dwellers in metropolitan areas. With this in mind, the new Urban Master Plan of the Barcelona Metropolitan Area, to be approved in 2021, has commissioned from the Metropolitan Laboratory of Ecology and Territory of Barcelona an initial assessment of how urban agroecosystems function. These spaces are regarded as the most important element of the green infrastructures in the metropolis that this plan aims to foster as Ecosystem Service Providers (Benedict and McMahon, 2002; Lafortezza et al., 2013).

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This assessment covers all the 36 municipalities included in the Barcelona Metropolitan Area, in which 43% of the Catalan population live in just 2% of its land surface at a population density of 236 inhab./km^2. The study takes into account all the productive soils that remain, which still cover 56% of this metropolitan area and act as Ecosystem Service Providers in this metropolitan area's green infrastructures (Marull et al., 2010). A novel approach in the new Urban Master Plan was the inclusion of all abandoned areas that had been cultivated or used for forestry in 1956 – but as yet are not occupied by urban-industrial areas – as productive agroecosystems that could potentially be restored in the future. With this objective in mind, and under the auspices of the Milan Urban Food Policy Pact signed and co-directed by the Barcelona City Council, the MAES evaluation carried out by the Metropolitan Laboratory of Ecology and Territory of Barcelona focused on metropolitan agroecosystems. Consequently, the evaluation presented here is a first step towards a broader MAES for the whole Barcelona Metropolitan Area.

By focusing on urban agroecosystems as Ecosystem Service Providers, this study uses a novel way of exploring the role of ES in metropolitan areas. Although it is consistent with the cascade model of ES (Haines-Young and Potschin, 2018), the conceptual and spatial framework of this study remains focused on the biophysical structures of agroecosystems as providers of material and energy flows. Interacting with natural processes at landscape level, these flows give rise to different final ES that extend human well-being when they enter into the social and economic system from the environment (Potschin-Young et al., 2018; Costanza et al., 2017). The principal reason for proceeding in this way was the assessment commissioned by Barcelona Metropolitan Area aimed at providing useful criteria and indicators for planning these metropolitan agricultural landscapes in different ways (e.g. restoring, protecting and incentivizing) according to their current state (e.g. abandoned, degraded, intensively cultivated or included in the network of natural protected areas). The overall objective was to help transform these areas into green infrastructures and enhance and promote ES provision. It is clear that the Urban Master Plan cannot simply hope to preserve a series of green areas and assume that natural functioning will lead to an optimal provision of ES.

Agroecosystems are natural ecosystems transformed by the material and energy flows driven by human labour and information whose objective is to increase food, fodder and energy supply. The key issue, however, is to what extent do increases in provisioning ES take place at the expense of regulating cultural ES. On the other hand, a synergistic improvement of all ES could be possible (Hansen and Pauleit, 2014; TEEB, 2018). In 2005, the first Millennium Ecosystem Assessment report brought this question to the fore by including intermediate supporting ES within its framework (MEA, 2005). In this paper, we do not discuss the consensus reached subsequently to suppress intermediate supporting ES (Potschin-Young et al., 2018); however, this consensus also means replacing these ES with an evaluation of the socioecological state of the underlying biophysical structures, whose functioning leads to an adequate level of provisioning, regulating and cultural ES. A good socioecological state cannot be taken for granted, above all in agroecosystems that are hybrid biophysical structures where society and nature constantly interact to co-produce different ES (Haberl et al., 2004; Van der Ploeg, 2014; Gliessman and Engles, 2015). The question is how to assess the socioecological state of metropolitan agricultural landscapes in order to improve their capacity to provide ES.

Thus, our study adopts the Material and Energy Flow Accounting (MEFA) of the social metabolism that takes place within agroecosystems (González de Molina and Toledo, 2014; Guzmán and González de Molina, 2017). We use it as the basis for carrying out an Energy-Landscape Integrated Analysis (ELIA) on how these matter-energy flows interact with natural processes and create agroecological territories with different capacities for hosting biodiversity and associated ES (Altieri and Nicholls, 2012; Wezel et al., 2016; FAO, 2018). By combining quantitative values and geospatial layers with other socioecological indicators, we obtained an Integrated Socio-Ecological Analysis (SIA) of the metropolitan agricultural landscape. The conceptual approach underpinning this multidimensional evaluation (SIA) combines the views, methods and indicators of Ecological Economics (MEFA) and Landscape Agroecology (ELIA), together with Land-Use Planning aimed at enhancing ES (Hansen and Pauleit, 2014).

This multidisciplinary assessment of the biophysical structures of metropolitan agriculture seeks to contribute to research on the mechanisms of ES provision. This assessment highlights the key nexuses between the way farmers manage the land, the type of landscapes they create, the aboveground and belowground biodiversity they maintain, and the provisioning, regulating and cultural ES provided as an end product (Oteros-Rozas et al., 2019). This approach supports land-use planners in the identification of key drivers linking land-uses with agroecological processes to be able to improve their multifunctional nature and enhance their roles as Ecosystem Service Providers within metropolitan green infrastructures (Davies et al., 2006; de Groot et al., 2010; Bastian et al., 2012). This approach considers not only land-use patterns but also the ecological processes underpinning ES (Palmer and Febria, 2012; Maes et al., 2016) to explain how farming activities, despite the ecological disturbance they cause, can contribute to the functioning of complex bio-cultural landscapes capable of supplying provisioning as well as regulating and cultural ES (Boumans et al., 2015; Hamann et al., 2015; Santos-Martín et al., 2019).

2. Conceptual approach

2.1. *Socio-metabolic approach to metropolitan agriculture*

Green infrastructure planning implies the adoption of a complex socioecological perspective. The cascade model connects the functioning of the biophysical structures of ecosystems with human well-being as a means of highlighting the sequence of causes and effects that are transmitted from the ecological functioning of the land matrix to the satisfying of citizens' needs (Tzoulas et al., 2007; Haines-Young and Potschin, 2010; Haines-Young and Potschin, 2018; Baró et al., 2016; Potschin-Young et al., 2018). However, this cascade approach is also under debate since the marginalizing of 'supporting' (MEA, 2005) or 'habitat' (TEEB, 2008; TEEB, 2010) ES for being only indirectly related to human wellbeing can lead to the underestimation of the importance of ecosystem functions such as biodiversity, soil fertility and primary production that underlie provisioning, regulating and cultural ES (Costanza et al., 2017).

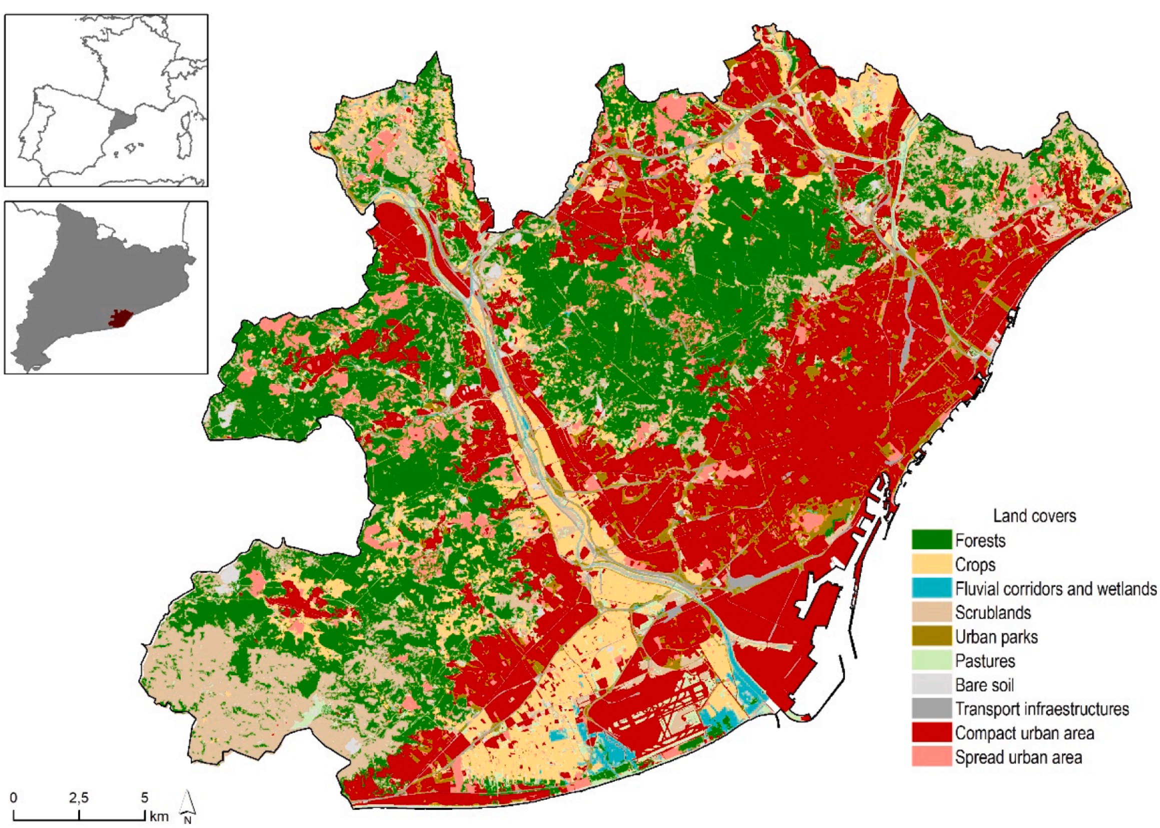
According to the fund-flow bio-economic approach, all biophysical flows that sustain societal metabolism are provided by live funds that, in order to continue providing, need to be nourished and reproduced (Georgescu-Roegen, 1971; Giampietro et al., 2011; Giampietro et al., 2013). This approach leads to a circular bioeconomic view that assesses the sustainability of socioecological systems in terms of the reproducibility of the fund components of the biophysical structures of our societies (Tello et al., 2016; Gingrich et al., 2018; Marco et al., 2020). In agroecosystems, this means taking into account both the reproduction of live funds such as soil fertility, which requires the replenishment of organic matter and nutrients (Maeder et al., 2002; Watson et al., 2006), and aboveground biodiversity, which requires differentiated habitats in heterogeneous landscapes with sufficient Net Primary Production free of human appropriation (Loreau et al., 2003; Hole et al., 2005; Gabriel et al., 2006; Tscharntke et al., 2012). Instead of an unidirectional, tiered relationship that goes from ecosystems to the ES received by society, the socioecological processes at stake should be understood and planned as a set of interrelated biophysical cycles in which the live fund components of the land matrix requires maintaining an investment of socio-metabolic flows in order to maintain their ecological functioning (Ho and Ulanowicz, 2005; Marull et al., 2016).

This becomes even more important when agroecosystems and agri-food chains are taken into account to compensate for the lack of attention paid to urban agriculture from an ES point of view (Sandhu et al., 2008; Tancoigne et al., 2014; TEEB, 2018). Adopting an eco-agri-food system approach, ES research and planning have to consider how agricultural multi-functionality give rise to synergies and trade-offs between different dimensions and components of the biophysical structures of the land matrix such as the live funds of agroecosystems, which in turn can lead to different patterns of Ecosystem Service Providers (Hansen and Pauleit, 2014). The multifunctional approach to the different ES provided by each landscape unit is an important step towards facilitating the integration of nature conservation from a land-sharing approach (Perfecto and Vandermeer, 2010; Phalan et al., 2011), an agri-food transition towards agroecological territories and culturally meaningful foodscapes (Altieri and Nicholls, 2012; FAO, 2018; Moragues-Faus and Morgan, 2014), and land-use planning of green infrastructures from an ES perspective (Tzoulas et al., 2007; Burkhard et al., 2012; Hansen and Pauleit, 2014).

2.2. Conceptual outline of the socioecological integrated analysis

The SIA assessment presented here focuses on the multiple dimensions of the contribution to social welfare made by agroecosystems in metropolitan agricultural landscapes. The set of integrated indicators generated enable strategic land-use planning to improve agroecosystem functioning, make agroecosystems part of the green infrastructure, and help them move towards more sustainable agro-futures. This conceptual approach is outlined in Fig. 2, adapted from Cardinale et al. (2012), in an attempt to highlight the society-nature interactions that take place in agro-ecosystems in metropolitan areas from a reproductive point of view (Padró et al., 2019). A SIA is a socio-metabolic-territorial assessment designed to be applied in land-use planning. It is fuelled above all by databases on agricultural, forestry and livestock socio-metabolic flows and land-uses. Its nodal point is the idea that via farming society invests in a set of biophysical flows in the agricultural system to obtain ES indirectly. These ES can only be guaranteed by conserving the socio-metabolic agricultural flows that replicate a set of vital live funds such as the agrarian community, livestock, soil fertility and the functional landscape structure (Fig. 3). The closer the functioning of these funds to natural processes, the more sustainable the agroecosystem will be Gliessmann (1998).

The preservation of the ecological integrity of the biophysical structures that are Ecosystem Service Providers is a necessary condition for the maintenance of regulating, provisioning and cultural ES over time (MEA 2005; de Groot et al., 2010; Burkhard et al., 2012; Haines-Young and Potschin, 2018; Maes et al., 2020). However, this condition is often stated from a traditional nature conservation standpoint, which ignores how society has to intervene through eco-efficient forms of natural resource management to maintain the ecological integrity and functioning of biophysical structures whenever cultural landscapes are taken in account instead of natural ecosystems (Agnoletti, 2014; Agnoletti and Rotherham, 2015; Agnoletti and Emanueli, 2016). Given that agroecosystems are maintained due to a continuous society-nature interaction, these cultural landscapes should be assessed from a socio-ecological point of view (Antrop, 2006). In agricultural landscapes this interaction takes place through the imprint of farm metabolism on the



Source: Centre for Ecological Research and Forestry Applications (CREAF, https://www.creaf.uab.es/mcsc/).

Fig. 1. Land-cover map of the Barcelona Metropolitan Area (2015). Source: Centre for Ecological Research and Forestry Applications (CREAF, https://www.creaf.uab.es/mcsc/).

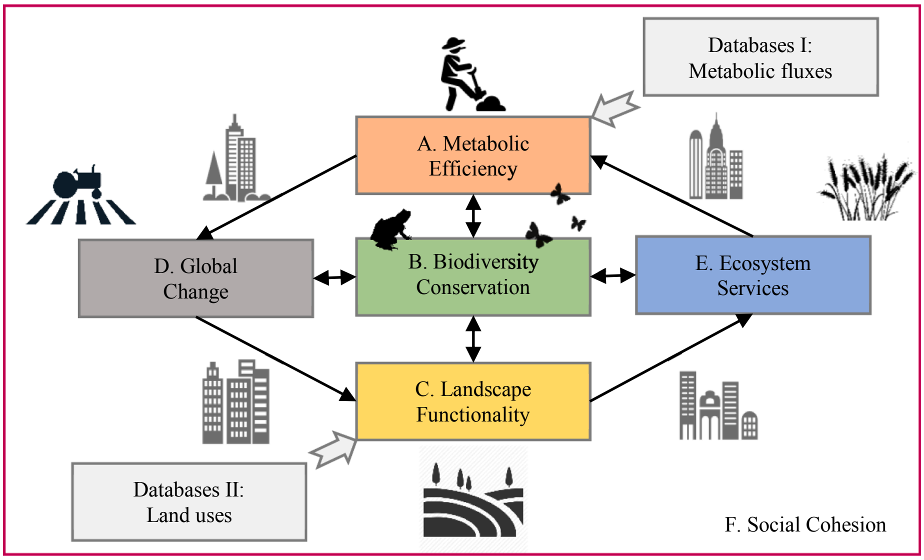


Fig. 2. Outline of the Socioecological Integrated Analysis (SIA) carried out as a metabolic-agroecology model applied to land-use planning feed by databases on agricultural socio-metabolic flows (I) and land-uses (II). Six dimensions are accounted: A. Agricultural Metabolic Efficiency; B. Biodiversity Conservation; C. Agroecology Landscape Functionality; D. Global Change; E. Ecosystem Services (regulation, provisioning, cultural); F. Social Cohesion. It highlights the importance of the green infrastructure in the functional structure of the network between cities and agriculture within metropolitan areas.

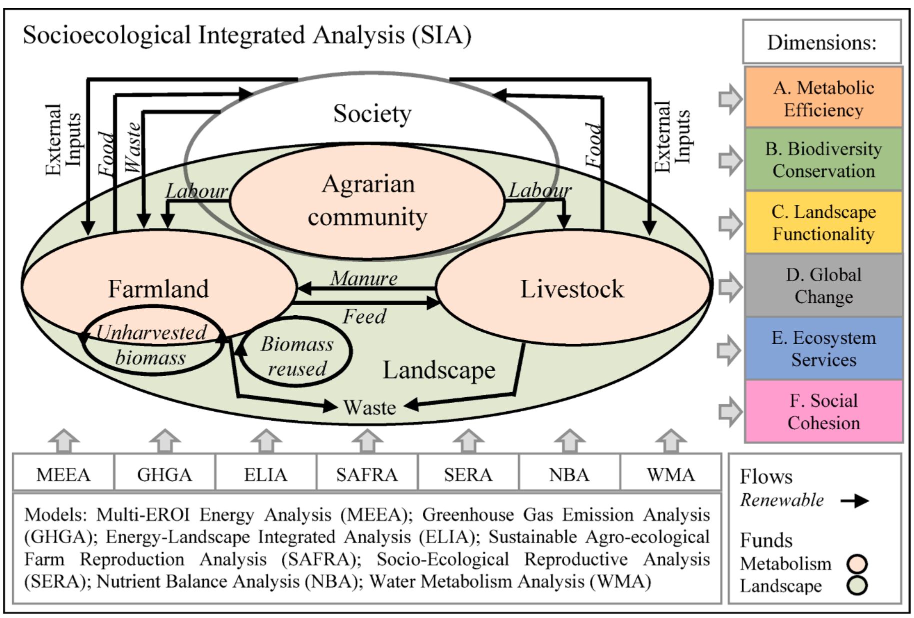


Fig. 3. Outline of the model run to carry out the Socioecological Integrated Analysis (SIA) according to the bioeconomy circular fund-flow approach adopted. Arrows show the main socio-metabolic flows of agroecosystems, and the ellipses the four live funds considered (society-agrarian community, livestock, soil fertility and landscape functional structure) that must be preserved to guarantee the sustainability of the socioecological system over time. Below are listed the primary models (MEEA, GHGA, ELIA, SAFRA, SERA, NBA, WMA) used to account for the different indicators (Table 1), according to the diverse dimensions to be finally assessed (Fig. 2).

functional structure of the territory, which ends up affecting the ecological patterns and processes that take place there (Marull et al., 2010). This embraces cultural ES, which includes many aesthetic and identity values that can be seen as a societal acknowledgement of the bio-cultural heritage present in cultural landscapes (Tenberg et al., 2012; Agnoletti and Emanueli, 2016), although there are also other factors that, for example, characterize leisure and recreational services (Plieninger et al., 2015). All these ES require the maintenance of the ecological functions of cultural landscapes. Whether measured directly or indirectly, biodiversity is key in the functioning of green infrastructures (Mell, 2009); precisely because society plays a relevant role in the reproduction of the live funds that support the ecological functioning of cultural landscapes, in addition to the ES obtained in return SIA includes job creation as a proxy for social cohesion.

Sustainability oriented land-use planning has to link all scales from local to global (Lafortezza et al., 2013). This includes the role agricultural landscapes play within metropolitan green infrastructures as a means of facing up to the current and future challenges of Global Change, which range from biodiversity loss (Benedict and McMahon, 2002; Mell, 2009) to climate change mitigation and adaptation (Gill et al., 2012)). SIA can address these issues within an agrarian metabolism framework by examining the characteristics of the biophysical structure of the land matrix that supports biodiversity (landscape heterogeneity, unharvested Net Primary Production), maintains soil fertility (organic matter replenishment and nutrient cycling through biomass reused), mitigates climate change (non-renewable energy consumed as external inputs and carbon sequestration) and improves the ecological status of water bodies (waste and pollution generated and water-use). It does so by using the set of models depicted in Fig. 3, although only some of these models and indicators are employed in this article.

3. Methodological approach

3.1. Case study and data sources

The Barcelona Metropolitan Area (63,611 ha) has 3.24 million inhabitants spread out over 36 municipalities (Fig. 1). This SIA assessment was performed on the full set of open spaces mapped in 2015 by the CREAF digital land-cover map (https://www.creaf.uab.es/mcsc/). Aside from the built-up area that occupies approximately 44% of the Barcelona Metropolitan Area, forest and scrub predominate and occupy, respectively, in 27% and 15% of the total surface area of the remaining open spaces. Croplands cover 8% of the total surface area and are mainly concentrated in the Llobregat river valley and delta, predominantly in the form of horticulture (mostly in fields with some greenhouses). A few patches of arable land, vineyards and arboriculture still form mosaics with forests in the Vallès plain and on the slopes of sparsely populated areas. There are also some meadows and pastures (3%) and, to a lesser extent, fluvial corridors and wetlands, mainly concentrated in the Llobregat delta and representing 2 and 1%, respectively.

The SIA was calculated with the same grid of 500 × 500-m cells as used in the Urban Master Plan of the Barcelona Metropolitan Area. Socio-metabolic flows were calculated using land-cover and farming databases for agriculture, livestock, forestry and trade. Land surfaces were taken from the DARPA (http://agricultura.gencat.cat/ca/inici), and the production and yields of the main crops in each municipality from the DUN (http://agricultura.gencat.cat/ca/ambits/desenvolupament-rural/declaracio-unica-agraria/) and SIGPAC (https://www.mapa.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/default.aspx) databases, which also provide farm and livestock census, and information on annual wildfires. We took provincial data from the MAPA livestock survey (https://www.mapa.gob.es/en/), as well as data for dairy, egg, honey and wool production, the yearbook of annual statistics on crops, fertilizers, the five-year statistics of phytosanitary products consumed, and the annual statistics for forestry and the management balances of cereals. We took from IDESCAT (https://www.idescat.cat/?lang=es) data on agricultural machinery in terms of ownership and, finally, used trade data from DATACOMEX (http://datacomex.comercio.es/) to obtain the origin of foreign imports to calculate the embodied energy.

3.2. Main indicators of the socioecological integrated analysis

A SIA assessment links the different dimensions of the socio-ecological system (Fig. 2) to the indicators that evaluate them (Table 1). To this end, a selection of these indicators is made in a hierarchical sequence: main indicators (transversal in all the applications of the assessment), secondary indicators (variables according to the case of study), and specific indicators (that assess more acutely the relationship between agricultural open spaces and built-up spaces). These indicators were obtained from the SIA modelling, which is fed by two fundamental sources of information: land-cover, and agricultural, forestry and livestock socio-metabolic flows (Fig. 2). The socio-metabolic flows were established between the four funds of the agroecosystem: i) land-uses; ii) livestock; iii) landscape functional structure; and iv) the agrarian community and society at large (Fig. 3). We defined an integrated system of indicators to evaluate the contribution of each different dimension to the functioning of the agricultural landscapes that are to be promoted as part of the overall green infrastructure in the metropolitan system. This integrated assessment also allowed us to identify synergies and trade-offs between indicators.

3.2.1. Energy socio-metabolic efficiency

Socio-metabolic efficiency (A) is represented by the main indicator A1 that accounts for the energy efficiency of metropolitan agriculture

Table 1
Multi-criteria set of indicators used to evaluate quantitatively the contribution of the metropolitan green infrastructure in the provision of ecosystem services.

	Dimension		Main Indicator	Specific Indicators	Rural-Urban Indicators
Socioecological Integrated Analysis (SIA)	A. Metabolic efficiency		A1. Energy efficiency	A2. Energy reused	Au1. Agricultural reuse of urban waste
				A3. Energy redistributed	
	B. Biodiversity conservation		B1. Energy-landscape integration	B2. Biodiversity	Bu1. Biodiversity in urban public spaces
	C. Landscape functionality		C1.Landscape complexity	C2. Landscape heterogeneity	Cu1. Connectivity of urban public spaces
				C3. Ecological connectivity	
	D. Global Change		D1. Non-renewable external inputs	D2. Global energy footprint	Du1. Footprint of the city imports of agricultural products
	E. Ecosystem services	Support	E1A. Soil nutrients recirculation	E2A. Water use efficiency	Eu1A. Reuse of treated water in open spaces
		Regulation	E1B. Carbon stock	E2B. Carbon sink	Eu1B. Contribution of urban parks to the quality of the air
		Provisioning	E1C. Agricultural production	E2C. Woody biomass production	Eu1C. Food sovereignty in the metropolis
		Cultural	E1D. Bio-cultural heritage	E2D. Potential use of open spaces	Eu1D. Urban frequentation of open spaces
	F. Social cohesion		F1. Agricultural jobs	F2. Farm income	Fu1. Social inequality in agri-food chains

Source: Metropolitan Laboratory of Ecology and Territory of Barcelona (LET).

(Table 1). Energy efficiency (A1) measures the energy return on the inputs spent (EROI), calculated on the basis of the final product obtained per unit of external inputs originating from outside the agroecosystem (EFEROI) (Tello et al., 2016). This agricultural socio-metabolic balance determines the input and output flows of each crop per land unit of analysis. This also allows us to observe the relationships between different agroecosystem fund components, above all between livestock and agricultural uses, and the dependence on external inputs for producing biomass (provisioning ES), while bearing in mind the needs of soil nutrient replenishment, animal nutrition and the reproduction of human labour. The energy efficiency value (A1) is determined in each cell by the following formula:

$$A1 = \frac{\sum_{i=1}^{i=k} FP_i}{\sum_{i=1}^{i=k} EI_i}$$

FP is the amount of final useful energy produced (MJ) from all agricultural uses in the sample cell, regardless of its destination (human consumption or animal feed). EI is the investment in external inputs (artificial fertilizers, herbicides and pesticides, agricultural machinery, greenhouse facilities where they exist, water pumping, seeds and human labour) of each agricultural use in the sample cell, based on the calculation of the socio-metabolic energy balance. For external inputs, all the energy incorporated into the production processes is considered (embodied energy), together with the useful internal energy (enthalpy).

3.2.2. Biodiversity conservation

Biodiversity conservation (B) is represented by the principal indicator B1 (energy-landscape integration in Table 1) that measures the energy-information-landscape relationship (Marull et al., 2016). Energy-landscape integration (B1) evaluates the socio-ecological conditions for hosting biodiversity (Marull et al., 2019), based on landscape patterns and processes (landscape complexity, C1) and the flows of agrarian metabolism that imprint the land-use patterns and intervene in the landscape ecological processes (energy reused, A2; and energy redistributed, A3). The fraction of biomass left that is available for non-domesticated ecological trophic chains (A2) is obtained from the socio-metabolic balance of the agroecosystem (the unharvested fraction of the photosynthetic Net Primary Production). Then, the distribution pattern for these biomass flows (A3, energy redistributed) can be calculated. Once these secondary indicators are obtained, we calculate the energy-landscape integration (B1) for each cell:

$$B1_i = \sqrt[3]{\frac{A2_i \cdot A3_i}{k} \cdot C1_i}$$

where k allows us to scale factor A2 · A3 to the maximum theoretical value. The values of B1 lie between 0 and 1.

3.2.3. Landscape functionality

Landscape functionality (C) is represented by the principal indicator (C1), which is the landscape complexity of agroecosystems (Marull et al., 2016). Landscape complexity (C1) evaluates the functional landscape structure (patterns and processes) based on the nexus between land-cover heterogeneity (C2) determining landscape patterns, and ecological connectivity (C3) determining landscape processes (Marull and Mallarach, 2005). Its value per cell can be calculated thus:

$$C1_i = \left(C2_i + \frac{C3_i}{10}\right)/2$$

The ecological connectivity (C3) is divided by 10 since it is the maximum value that ecological connectivity can take; on the other hand, landscape heterogeneity (C2) ranges between 0 and 1 to allow a value for landscape complexity (C1) between 0 and 1 to be obtained.

3.2.4. Global change

Global change (D) is represented by the principal indicator of non-renewable external energy inputs (D1), which measures in MJ per hectare the total amount of non-renewable external energy spent on maintaining forestry, livestock and agricultural production according to the socio-metabolic balance (Tello et al., 2015). Higher values of non-renewable external energy consumed (D1) are associated with more intensive industrial farming that depends on external fossil-fuel inputs and therefore is more likely to generate more greenhouse gas emissions. In the case of the energy flows from agriculture or forestry, their site-specific georeferencing requires calculating their value for each land-use (machinery, fertilizers, greenhouse facilities, herbicides and pesticides, and energy consumption in water pumping). Conversely, for livestock the georeferencing of flows is measured by the energy costs of the transport of feed, together with the energy consumed in stables or industrial feed-lots. Finally, costs of livestock maintenance are imputed to the land-covers where animal excreta are spread following the procedure described in Marull et al. (2016).

3.2.5. Ecosystem services

Biophysical integrity (support) of ecosystem services providers (EA) are assessed by a principal indicator, soil nutrient recirculation (E1A). Soil nutrient recirculation measures the relative amount of Phosphorus (P) that recirculates within the agricultural system in interaction with livestock uses. High values of E1A represent a higher capacity of the farm system to deal with the closure of nutrient cycles. The recirculation of nutrients is calculated for each farm land-use by taking into account the flows previously calculated in the socio-metabolic balance (A1) according to the nutrient flows considered in the framework defined by González de Molina et al. (2010). Thus, there are specific values for the recirculation of nutrients in the specific cases of horticulture vegetable production, greenhouses, arable land and irrigated herbaceous crops, irrigated and non-irrigated fruit trees, irrigated and non-irrigated olive trees, and vineyards, all obtained from their corresponding N-P-K balances. Since these balances account for the main macronutrients using homogeneous data, the most limiting nutrient (in our case P) was selected to account for soil nutrient recirculation (E1A). The units (%P) from agricultural, forest and pasture lands in the Barcelona Metropolitan Area divided by the total circulating in any land-use give the following formula:

$$E1A_i = \frac{\text{internal P cycling}_i}{\text{total P cycling}_i} \cdot 100$$

The origin of each source of fertilizers (biomass burial, animal manure or synthetic fertilizer) is evaluated using the socio-metabolic nutrient balance (Marco et al., 2018) in the Barcelona Metropolitan Area. The origins of biomass burial and synthetic fertilizers are internal and external to the metropolitan agroecosystems, respectively. For animal excreta, the percentage of livestock feed derived from biomass produced internally is estimated, from which the share of the amount P originating from the Barcelona Metropolitan Area agroecosystems can be obtained.

The indicator of the Carbon stock (E1B) is selected to represent part of the Regulating ecosystem services (EB). E1B measures the amount of total Carbon (C) stored in the vegetated open spaces of the agricultural metropolitan system; the different fractions of the C stock are calculated for two differentiated agricultural spaces, croplands and other farmland uses (forest, scrubland and pastures). Four fractions are considered: C in the mineral soil, C in the organic layer of the soil, and C in the roots of the plants and in their woody aerial structures. The accumulated C in herbaceous crops was not considered due to its low persistence. In cropland areas the average depth of soil samples taken was 30 cm but was 100 cm for forest soils. The value of C in mineral soils was taken in the case of croplands from the ICGC database (http://www.icgc.cat/). For forest soils, a regression model was developed to estimate the belowground C stock according to the characteristics of the forest cover (total aboveground C) and soils (mineral composition and texture) (Doblas-Miranda et al., 2013). The organic horizon in forest soils was estimated from coefficients of the total C stock in the mineral soil. For aboveground C, a map developed by CREAF was available for non-agricultural uses, while for plant roots the proportion between the aerial and the belowground C fractions was estimated after a literature review. In the case of cropland, an estimate was made of aboveground C and roots through factors used in other studies on climate change carried out in Catalonia, which vary according to the species, age and spatial pattern of tree planting (Funes et al., 2015).

Provisioning ecosystem services (EC) are assessed by the principal indicator of agricultural production (E1C) measured in weight units of

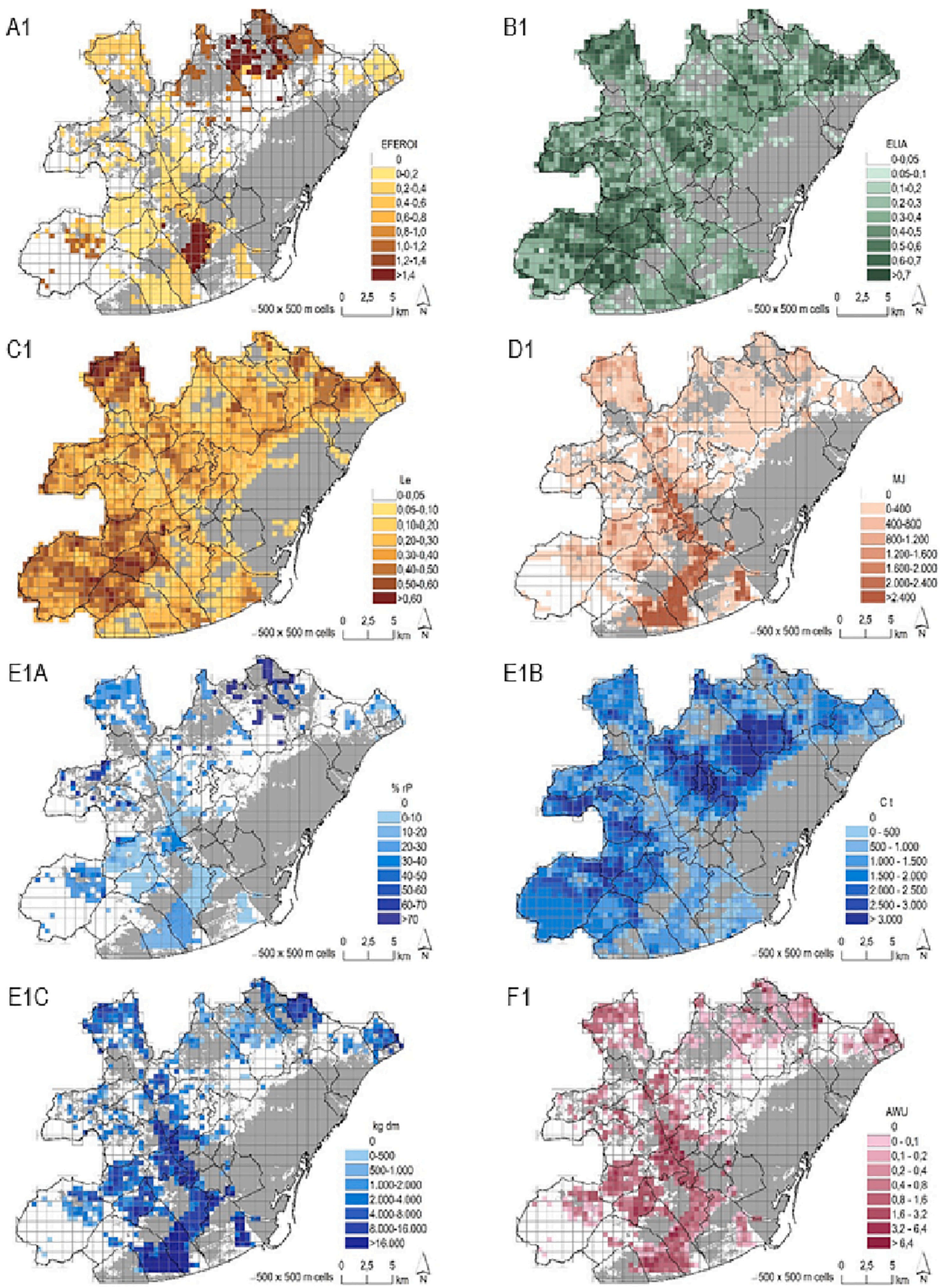


Fig. 4. Socio-ecological Indicators: A1 Energy Efficiency (Energy Return to External Inputs –EFEROI); B1 Energy-Landscape Integrated Analysis (ELIA); C1 Landscape Complexity (Le); D1 Non-Renewable External Inputs (MJ); E1A Soil Nutrients Recirculation (% rP); E1B Carbon Stock (t of C); E1C Agricultural Production (Kg d.m.); F1 Agricultural Jobs (AWU).

edible dry matter (Marco et al., 2018). We accounted for food production – leaving aside forestry and livestock production – and focused on the edible products of agricultural activity because livestock feed is mainly imported in the study area. Moreover, food crop production predominates compared to other types of agricultural production (forestry and livestock raising). High E1C values correspond to highly productive zones within the study area. The value of the indicator – corresponding to the absolute value in kg of dry matter per cell – was obtained from the statistical records of the average yield in each land-cover type and municipality. Given the great variability in moisture between products, water content was discounted from production data to obtain comparable values of dry matter.

3.2.6. Social cohesion

Social cohesion (F) is represented by the principal indicator F1 that measures the total number of agricultural jobs. F1 takes into account the potential for full-time equivalent agricultural jobs in Agricultural Working Units (AWU) that is required in the agricultural area of the metropolis (Padró et al., 2017). The most labour-intensive crops are awarded higher values, while more extensive agriculture or more mechanized activities have lower F1 values. Through the data obtained from the Xarxa Comptable Agrària de Catalunya (XCAC), the AWU working days required by the different crops, as well as by livestock and forestry, were estimated for each land unit. At cell level only the AWUs associated with agricultural activity were calculated.

3.3. Statistical analysis

Once the values of the socioecological indicators were obtained for the 500 × 500-m cells, a statistical Principal Component Analysis (PCA) was performed to identify the key SIA factors that characterize this case study. Then, an Exploratory Factor Analysis (EFA) was performed to visualize the distribution of indicators and land-cover categories in relation to the factors defined by the SIA modelling. Finally, Pearson and Spearman Correlation Analyses (PA and SA, respectively) enabled us to identify not only the presence of linear but also of non-linear relationships, and were performed to verify whether or not there are synergies and trade-offs between the indicators and the various dimensions considered. We used both coefficients because PA identifies linear relationships, while SA measures the concordance between indicators; comparing them allowed us to infer whether or not a linear relationship exists.

4. Results

4.1. Socioecological Integrated Analysis

The agricultural energy returns on the external energy inputs used (A1) show high values in the north-west plains and in some riverside municipalities due to the presence of energy-efficient herbaceous crops (Fig. 4). By contrast, along most of the Llobregat river axis, and in coastal municipalities, the A1 values are low due to the farming of crops requiring very intensive external inputs that include, for example, large-scale horticulture produced in the open or very small-scale flower production in greenhouses with energy efficiencies ranging between 0.12 and 0.25. Two thirds of the cells with agricultural crops have values below 0.4, with the most common category being 0–0.2. This clearly demonstrates how industrial agricultural management predominates over low-input farming.

The indicator of energy-landscape integration (B1) shows that the best conditions for hosting farm-associated biodiversity in the biophysical structures of the matrix of agriculture, forestry and pastures are found near the western hills in the Garraf massif (Fig. 4). The eastern mountains of Serralada de Marina also have high values of B1. In the whole Barcelona Metropolitan Area only 3% of cells have values over 0.7. These results also allow us to identify the areas with the best conditions for energy-landscape integration where the traditional mosaic pattern created by mixed farming of crops, forestry and extensive livestock grazing still remains. They are located at the eastern and western margins of Barcelona Metropolitan Area, as well as within the forested area in its centre where the Collserola Natural Park acts as a green belt embracing the northern part of the city of Barcelona.

The landscape complexity indicator (C1) shows a normal pattern of distribution, with fewer than 10% of the cells in the Barcelona Metropolitan Area with values over 0.5 (Fig. 4). These areas are clustered in three areas: in the north, on the edges of the natural protected areas in the Garraf massif, and, to a lesser extent, in the eastern mountains of Serralada de Marina. These results highlight the currently low values of C1 in the municipalities in the centre of Barcelona Metropolitan Area, where the Collserola Natural Park has lower values of C1 than those of the rest of the natural protected areas, with very few cells exceeding 0.5.

The indicator of non-renewable external inputs (D1) shows a strong polarization between open spaces with very low external energy inputs (56% of cells with values below 400 MJ/ha) and spaces specializing in horticultural production along the Llobregat river and in its delta (Fig. 4). In all, 51% of these external, fossil-fuelled energy inputs derive from four municipalities with the highest agricultural use of external energy flows (16% of the surface area of the Barcelona Metropolitan Area). For example, the municipality of Castellbisbal (at the northern tip of the metropolis) is notable for its agriculture that has a great dependence on external industrial inputs (D1) but also for its more spatially homogeneous cultural landscapes.

The indicator of soil nutrient recirculation (E1A) shows how only some municipalities in the north-east Vallès plain and the north-west mountains have high levels of self-sufficiency, and how in 13 municipalities P recirculation does not exceed 10% (Fig. 4). The degree of integration between livestock and crops plays a significant role in the P replenishment in the soil, and reveals that the industrial horticulture that specializes in the large-scale vegetable production in the Llobregat Agrarian Park currently has a strong dependence on imports of nutrients from outside the metropolitan system. Approximately 80% of the cells have soil P recirculation values below 30% (that is, 70% of P comes from outside the study area).

The Carbon stock indicator (E1B) shows that the wooded area within the Collserola Natural Park in the centre of the Barcelona Metropolitan Area possesses the greatest number of cells with high values, along with certain municipalities in the Ordal mountains, as well as Begues, Torrelles and Sant Climent de Llobregat, where arboriculture (cherry and other fruit trees) reinforce the role of forests. However, much of the Barcelona Metropolitan Area has low C stock values and the categories ranging from 0 to 2000 t C cover 51% of the total area.

The indicator of agricultural production (E1C) demonstrates that 51% of this provisioning service is concentrated in the Llobregat delta (17% of surface of the Barcelona Metropolitan Area), and in the flat land along the two banks of the Llobregat river in the protected Baix Llobregat Agricultural Park, where intensive horticulture is mainly carried out as conventional industrial farming (Fig. 4). Of the 6630 tonnes of dry matter a year produced in the Barcelona Metropolitan Area, two thirds are produced in the municipalities in the Llobregat valley and delta. The farmland located on the slopes of this valley and other smaller tributary valleys also plays a role, together with land in the south-western Ordal massif and on the western slopes of Collserola. The distribution of crop intensities by cells has an annual mean value within the category of 2000–4000 kg of dry matter.

Finally, the indicator of agricultural jobs (F1) shows that the intensive production of vegetables in the Baix Llobregat Agricultural Park (13% of the Barcelona Metropolitan Area) concentrates 28% of the area's whole AWUs (Fig. 4). Arboriculture located in the Ordal mountain range along the western axis also has a significant agricultural work potential. Overall, the distribution of agricultural jobs shows a strong concentration in the intensive horticulture in the Llobregat valley and delta, in contrast to other areas where extensive herbaceous croplands are highly mechanized and have a lower labour intensity.

4.2. Principal component analysis

The PCA shows that only three main components (which we call factors) account for 82% of the total variability (Table 2). These statistical associations between indicators are relevant to sustainable strategic land-use planning in agroecosystems orientated towards improving ES as green infrastructures in the Barcelona Metropolitan Area. A first factor groups together the indicators corresponding to the most relevant energy flows that enter and exit from the metropolitan agroecosystems: non-renewable external inputs (D1), number of agricultural jobs (F1) and agricultural production per unit of land (E1C). Factor 1 (the pattern of agrarian 'socio-metabolic flows') accounts for 32% of the variability.

A second factor, however, points to the functioning and properties of the land-matrix: Carbon stock (E1B), landscape complexity (C1) and energy-landscape interaction (B1) in agroecosystems. It highlights a group of indicators linked to the ecological processes that take place in agricultural landscapes and reveals their role as providers of a set of ES that can be enhanced to improve their functioning as green infrastructures. From a circular bioeconomic point of view, the biophysical structures supporting ES provision are a set of live funds whose integration can be improved to generate more complex cultural landscapes in the Barcelona Metropolitan Area. Factor 2 ('landscape functionality') accounts for 31% of the variability (Table 2).

Finally, a third factor reveals the importance of how society interacts with the land-matrix and eco-efficiency in the management of the natural resources that represent the biophysical structures that underpin most ES. This factor consists of two closely related indicators: farming energy efficiency (A1) and soil nutrient recirculation (E1A). The current low capacity for recirculating soil nutrients creates a great dependence in agriculture on external imports possessing large amounts of embodied

Table 2
Principal Component Analysis in the relationship between socio-ecological indicators and land-covers in the Barcelona Metropolitan Area (cells of 500 × 500 m).

Factors	Initial eigenvalues			Sum of square saturations (with rotation)		
	Total	Variance (%)	% accumulated	Total	Variance (%)	% accumulated
1	3.28	41.04	41.04	2.55	31.88	31.88
2	2.14	26.71	67.75	2.51	31.35	63.23
3	1.17	14.66	82.41	1.53	19.18	82.41
4	0.52	6.55	88.96			
5	0.44	5.55	94.51			
6	0.35	4.39	98.90			
7	0.07	0.86	99.77			
8	0.02	0.23	100.00			

Socioecological indicators	Factors (with rotation)		
	1	2	3
D1. Non-renewable external inputs	0.959		
E1C. Agricultural production	0.957		
F1. Agricultural jobs	0.788		
B1. Energy-landscape integration		0.930	
C1. Landscape complexity		0.913	
EB1. Carbon stock		0.871	
A1. Energy efficiency			0.866
E1A. Soil nutrients recirculation			0.822

Land covers	Factors (with rotation)		
	1	2	3
Compact Urban Area	-0.20	-0.83	-0.11
Low Density Urban Area	-0.05	-0.04	0.00
Woodland	-0.21	0.80	-0.11
Irrigated Woody Crop	0.50	0.00	0.05
Dry Woody Crop	0.31	0.28	0.09
Irrigated Herbaceous Crop	0.80	-0.08	0.18
Dry Herbaceous Crop	0.02	0.13	0.51
River Corridors % Wetlands	0.07	0.02	0.00
Scrubland	-0.08	0.43	-0.02
Grassland	0.18	0.06	0.15
Bare Soil	0.01	0.03	0.02
Transport Facilities	0.02	-0.31	0.05

Note: The Principal Component Analysis has been calculated using the socio-ecological indicators (coloured). Land-covers are supplementary variables.

energy and significant Carbon footprints. In turn, this high dependence on external inputs in industrial farming decreases energy and material eco-efficiency in the current management of metropolitan agro-ecosystems, a trait that underlines the considerable room for improvement that exists if farmers – and society at large – are able to enhance the green infrastructure for Ecosystem Services Providers by increasing the sustainability of the eco-agri-food system. Factor 3 ('system efficiency' for the provision of ES) accounts for 19% of the variability (Table 2), which confirms the relevance of considering the circularity and closure of the matter-energy flows required for the reproducibility of the live funds of metropolitan agroecosystems. It also attests to how the capacity of Ecosystem Services Providers will improve as they advance towards agroecology territories.

4.3. Exploratory factor analysis

The EFA shows that the different indicators are distributed orthogonally in relation to the three factors defined by the SIA. This confirms our starting conceptual assumptions, as well as the differentiated and complementary contribution of these factors to the provision of ES by metropolitan agroecosystems (Fig. 5). D1 ('dependence on non-renewable external inputs'), F1 ('agricultural job creation') and E1C ('agricultural production') are associated with Factor 1 ('socio-metabolic flows'). E1B ('Carbon stock'), C1 ('landscape complexity') and B1 ('energy-landscape integration') are associated with Factor 2 ('landscape functionality'), while A1 ('farming energy efficiency') and E1A ('soil nutrient recirculation') are associated with Factor 3 ('system efficiency').

Next, we examined how these factors are related to different land uses in the metropolitan area. Compact urban areas have an obvious negative role in Factor 2 ('landscape functionality') but not so much in Factor 1 ('socio-metabolic flows') and very little in Factor 3 ('system efficiency') (Fig. 5). By contrast, forests play a key role in Factor 2 ('landscape functionality') but their role is anecdotal in relation to the other factors, as is to be expected. To a lesser extent, the same happens with scrubland. This is mainly due to the state of abandonment of many

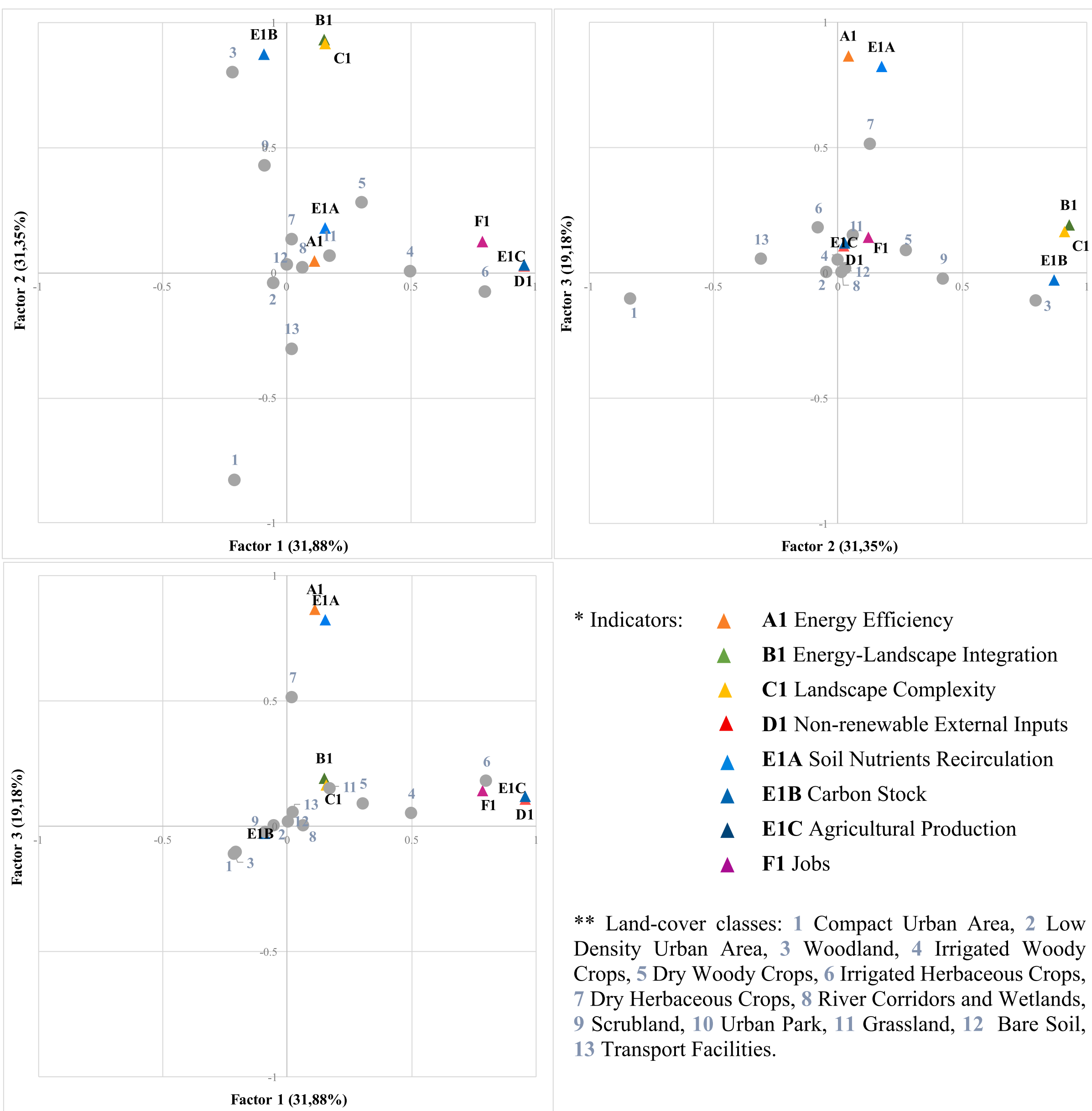


Fig. 5. Exploratory Factor Analysis. The socio-ecological indicators* and land-cover classes** are expressed according to their association to Factor 1 (*metabolic flows*), Factor 2 (*landscape functionality*) and Factor 3 (*system efficiency*).

forests and pastures in the area and their lack of integration with croplands as part of a complex mixed farming agroecosystem, a characteristic that indicates once again that there is room for improvement in their role as a green infrastructure.

It is interesting to note that each type of crop has a different profile (Fig. 5). While irrigated herbaceous crops and fruit trees play a major role mainly in Factor 1 ('socio-metabolic flows'), dry grain-farming is key in Factor 3 ('system efficiency') and dry arboriculture is relatively important in Factor 1 ('socio-metabolic flows') and also in Factor 2 ('landscape functionality'). These results have important implications for sustainable land-use planning, since these type of land-covers have been hither to regarded as belonging to the same 'agricultural' class, even though they actually provide very different contributions to the supply of ES. These differences allow us to identify the priorities in each case depending on the social values assigned to the different combinations of ES that ought to be obtained from the metropolitan agroecosystems acting as green infrastructures in the territory.

Finally, some land covers seem to possess certain counterintuitive characteristics (Fig. 5), especially in relation to Factor 2 ('landscape functionality'). This is the case of river corridors and wetlands or, conversely, low-density urban areas. It is important to note that these statistical analyses were calculated for 500 × 500-m cells. As metropolitan wetlands are often adjacent to urban areas, the relationship between Factor 2 ('landscape functionality') and wetlands is virtually null if all cells are considered. However, if only cells with 10% or more of the surface area actually covered by wetlands are accounted for, a clear upwards linear relationship with respect to B1 ('energy-landscape integration') or C1 ('landscape complexity') appears. The same relationship, albeit negative, is observed between low density urban areas and the B1 or C1 indicators, as was to be expected.

4.4. Pearson and spearman correlation analysis

The PA and SA allowed us to assess how certain socioecological indicators affect others (Table 3). If we consider the indicators that are part of Factor 1 ('socio-metabolic flows') to be configurators of farming socio-metabolic patterns such as the dependence on external energy inputs (D1), agricultural production (E1C) and social cohesion (F1), we found a clear positive relationship between these indicators with a Pearson coefficient that exceeds 0.6 in all cases. In the case of D1 (external inputs) and E1C (agricultural production) there was a unambiguous relationship, which indicates that any increase in agricultural production is currently highly associated with external energy inputs. This dependence on external energy inputs is also statistically related to more labour-intensive crops per unit of land. The maximum values of F1 (>5 AWU per cell) appear to be associated with intermediate levels of imports of external non-renewable flows.

Of the indicators associated with the configuration of landscape functionality in Factor 2 ('landscape functionality') – i.e. C stock (E1B), landscape complexity (C1) and energy-landscape integration (B1) – the most correlated ones are B1 and C1, with a Pearson coefficient above 0.92 (Table 3). At the same time, these indicators also maintain a clear relationship with C stock, although with a progressive increase in dispersion, both with Pearson coefficients above 0.64.

The main indicators determining the efficiency of the agricultural system as a provider of ES in Factor 3 ('system efficiency'), farming energy efficiency (A1) and soil P recirculation (E1A) also have a certain statistical relationship, although the Pearson correlation is lower (Table 3). The recirculation of nutrients is much more affected than energy efficiency by the lack of integration between livestock and agriculture. This is the case, for example, of the town of Sant Boi de Llobregat where, despite very high values of A1 (1.51 of EFEROI on

Table 3
Pearson and Spearman Correlation Analysis between the socio-ecological indicators considered in Barcelona Metropolitan Area (cells of 500 × 500 m).

		A1 Energy efficiency	B1 Energy-landscape integration	C1 Landscape complexity	D1 Non-renewable external inputs	E1A Soil nutrients recirculation	E1B Carbon stock	E1C Agricultural production
B1 Energy-landscape integration	Pearson	0.234						
	Spearman	0.422						
C1 Landscape complexity	Pearson	0.186	0.923					
	Spearman	0.404	0.938					
D1 Non-renewable external inputs	Pearson	0.231	0.195	0.176				
	Spearman	0.769	0.689	0.644				
E1A Soil nutrients recirculation	Pearson	0.491	0.315	0.307	0.223			
	Spearman	0.811	0.438	0.427	0.675			
E1B Carbon stock	Pearson	0.047	0.702	0.642	-0.036	0.118		
	Spearman	0.186	0.826	0.811	0.494	0.224		
E1C Agricultural production	Pearson	0.220	0.198	0.186	0.980	0.256	-0.033	
	Spearman	0.942	0.427	0.422	0.817	0.828	0.178	
F1 Agricultural jobs	Pearson	0.196	0.231	0.263	0.637	0.268	0.025	0.634
	Spearman	0.933	0.432	0.426	0.805	0.830	0.191	0.978

average), its capacity for soil replenishment of nutrients is very low (around 6% of total P) because its agricultural specialization in livestock feeding does not match the local number of heads of livestock, which are proportionally low (only 15% of the animal feed produced is consumed locally, which implies that there is an exchange of animal feed with neighbouring areas). This example demonstrates the need for a balanced integration of all the different fund components of the agroecosystem (soil-crop-livestock) to guarantee high values of socio-metabolic efficiency in the management of agricultural landscapes.

The three main factors ('socio-metabolic flows', 'landscape functionality' and 'system efficiency') are not independent of each other and, as can be seen from the relationships between the indicators that make up Factor 1 and Factor 2, there are some trade-offs (Table 3). Thus, if we look at the relationship between non-renewable external energy inputs and landscape functionality, we can see that high values of landscape complexity, energy-landscape integration and C stock are related to low levels of non-renewable external inputs. This highlights the importance of low-input mixed farming and organic management of agro-ecosystems. However, the higher values of these external inputs are also related to intermediate levels in landscape complexity and integration, and with C stock. This means that a point can be found at which intermediate levels of landscape transformation and high levels of socio-metabolic flows could lead to interesting combinations in terms of agricultural jobs and production. This result indicates that there are possibilities for agroecological intensification of farming but always within limits.

Factor 1 ('socio-metabolic flows') is also related to Factor 3 ('system efficiency'). This is a trade-off relationship and, although the Pearson coefficients do not exceed 0.27, Spearman coefficients were between 0.77 and 0.94 (Table 3). Accordingly, high values of energetic socio-metabolic efficiency or P recirculation reach an upper limit in regard to the reduction of non-renewable external inputs, job creation and agricultural production. This means that improving agroecosystem efficiency in the use of resources through the closure of socio-metabolic cycles at local level will lead – if above a maximum threshold – to detrimental impacts both on production and agricultural jobs, at least as long as the current model of conventional industrial farming is maintained and other possible agroecology synergies remain unexplored.

Lastly, it should be noted that there is no clear relationship between Factor 2 ('landscape functionality') and Factor 3 ('system efficiency'), since all the Spearman coefficients were less than 0.44 (Table 3). This means that, although efficiency in resource use influences socio-metabolic flows in farming, and that these are affected in turn by the ecological landscape functioning of the land-matrix, there is only a rather indirect and weak relationship. Therefore, there could be high quality levels of land-matrix functioning under a low level of efficiency in resource use. This finding helps explain why farming socio-metabolic flows have so often been neglected in analyses of ES provision, as well as in analyses of the role agroecosystems play as green infrastructures where traditional nature conservation approaches are usually adopted. In the same vein, Factor 1 ('socio-metabolic flows') has often been addressed by paying attention only to agricultural production as a provisioning ES without taking note of its dependence on non-renewable external inputs or job creation.

5. Discussion

The C stock is equivalent to the amount of organic C stored in metropolitan agricultural areas, forests and pastures, which is a fundamental ES in climate change mitigation and adaptation (Doblas-Miranda et al., 2013; Aguilera et al., 2013). It is worth noting that forest areas play a significant role in the total C stock in the Barcelona Metropolitan Area and that more than 55% of C is estimated to be found in soils. Average differences between forest and agricultural soils are not that large (40 t of C/ha in soils of certain crops vs. 68 t of C/ha in oak forests). This key ES has to be balanced out by the recovery of metropolitan agroecosystems that need to be enhanced as green infrastructures.

The results also show the poor capacity for dealing with the closure of soil nutrient cycles due to the prevalence of industrial farming and, in particular, the high proportion of P coming from outside the territory. This is a fundamental issue since P is currently the most limiting of all macronutrients (Garcia-Ruiz et al., 2012). Once more, the key is the lack of integration between livestock and crop production in their industrial management. Although the closure of metabolic cycles at landscape scale implies a long-term vision, greater rationality in the use of soil nutrients, as well as the change to organic sources, are fundamental improvements not only for the sustainable development of agri-food chains but also for avoiding air and water pollution by nitrates and soil degradation. This is a clear example of synergistic agroecological improvement in line with the EU Farm to Fork Strategy.

The recovery of metropolitan agriculture can also foster more landscape heterogeneity via the land-use mosaics established by organic mixed farming. Recent studies explain biodiversity conservation in cultural landscapes through the interaction between the energy flows available for trophic chains and the landscape complexity of agro-ecosystems (Tscharntke et al., 2005; Pierce, 2014; Marull et al., 2018; Marull et al., 2019). The SIA results support a proposal for land-use planning in metropolitan green spaces that encompasses all landscape units, including agricultural and forest areas, in order to achieve joint improvements in the metabolic efficiency and ecological functioning of the whole land matrix. This implies the need to recover old abandoned agricultural areas and promote a more circular pattern of biophysical flows within agroecological territories, combined with the positive effect of restoring cultural landscapes on biodiversity maintenance.

The landscape complexity assessment shows that Mediterranean land-cover mosaics (i.e. a heterogeneous and well-connected land-cover pattern) still exist and must be preserved and extended to take advantage of their contribution to the ecological processes that enhance the landscape's ability to host biodiversity in metropolitan areas (Santos et al., 2008; Marull et al., 2014). They must be identified and cared for in the metropolitan policies. According to the SIA results, there is a trade-off between the increase in agricultural land-uses and the heterogeneity of the resulting landscapes, which must be cared for when taking decisions on land-use planning in these open vegetated spaces.

Within the metropolitan system, food provisioning remains an important ES, despite the shrinking of urban agricultural activity due to urban expansion into flat land and the abandonment of steep terrains. In total, about 6630 t of dry matter a year are produced that represent nearly 10% of the fresh vegetables consumed in the metropolitan area and a smaller part of its animal protein intake. It is clear that the food needs of the 3.24 million people who live in the Barcelona Metropolitan Area cannot be satisfied internally. However, prioritizing those crops and agricultural activities that, beyond food provisioning, maximize other functions and ES for city dwellers could be a crucial way of highlighting the importance of metropolitan agroecosystems as highlighted by the Milan Food Policy Pact.

The agrarian sector generates at present over 900 full-time agricultural jobs (AWU), all of which are linked to the management of the vegetated areas of this territory and, especially, to farming (70% of these jobs). The ES derived from restoring forestry in certain areas to reduce the accumulation of dead biomass and the risk of wildfires could provide a supply of fuel for the biomass energy sector and create agricultural jobs in the metropolitan agroecosystems (Cervera et al., 2019). A more substantial change would come if there was a systemic change in the agricultural model, i.e. the recovery of extensive livestock grazing integrated with farming and forest activities, both under new types of agroecological management that are more labour-intensive and much less dependent on external inputs from fossil fuels. Further SIA research should incorporate the offer-demand vision of ES (Baró et al., 2016) and look deeper into rural–urban interactions.

Finally, perhaps the most important result obtained from this first SIA assessment of agroecosystems' capacity for multiple ES provision in the Barcelona Metropolitan Area is the joint statistical analysis that revealed which are the most important drivers, as well as their trade-offs and possible synergies. PCA grouped the SIA indicators into three main factors: the pattern of farming 'metabolic flows', the resulting 'landscape functionality', and the 'system efficiency' of multiple ES that increase citizens' welfare. In relation to the strategic planning of new green infrastructures aimed at increasing the supply of all ES in metropolitan areas, the main conclusion to be drawn is that the statistical correlations found between the different dimensions confirm that a new systemic vision of metropolitan land-use planning is required, based on a multi-criteria analysis and integrated indicators that imply setting to one side the outmoded sectoral public policies of the past.

Consequently, new multidimensional approaches are needed to understand and plan agroecosystems as part of metropolitan green infrastructures orientated towards enhancing the provision of a full array of ES (Padró et al., 2020). Furthermore, facing up to the emerging global socioecological crisis involves relocating the current globalized socio-metabolic flows (Levidow et al., 2014). To minimize the negative socio-ecological impacts of industrial agriculture, any new strategic planning of metropolitan areas aimed at improving green infrastructures as ES providers must take into account the fresh synergies and trade-offs that more sustainable forms of agriculture would imply. It is also important to consider what this implies for urban–rural relationships on a broader scale, a subject that will require additional research that could be carried out with the SIA model (Table 1). An integrated enlarged SIA would end up linking the sustainable planning of larger territories in a multi-scalar way as a means of exploring possible pathways towards feasible agroecological territories and culturally meaningful foodscapes.

6. Conclusions

A Socioecological Integrated Analysis of the Barcelona Metropolitan Area was carried out to identify strategic factors in sustainable land-use planning aimed at strengthening the ecosystem services provided by agricultural systems and landscape mosaics. The results show that the current industrial agriculture model that characterizes the Barcelona Metropolitan Area has very low energy efficiency. The prevailing agricultural model depends on huge external inputs with large carbon footprints (Tello et al., 2016; Cattaneo et al., 2018). To start an agri-food transition towards agroecological territories (FAO, 2018), energy and material efficiency must be significantly increased through farming management strategies based on increased biomass recirculation within the metropolitan system that will replace the external inputs. The high dependence on non-renewable external energy inputs can be linked to the greenhouse gases emitted by industrial agriculture (Sanz-Covena et al., 2017; González de Molina et al., 2020). Novel sustainable land-use planning combined with agricultural and environmental policies aimed at integrating farming with forestry and livestock activities would help reduce this dependence on external inputs and, indirectly, the greenhouse gas emissions stemming from agri-food chains.

The new Master Urban Plan of the Barcelona Metropolitan Area is being designed using these indicators and assessment in order to comply with the C40 commitment for climate action (https://www.c40.org/) and the Milan Urban Food Policy Pact (http://www.milanurbanfoodpolicypact.org/), both of which have been signed and co-led by the Barcelona City Council. This Plan aims to recover many former agricultural areas that are currently abandoned. Even if this implies strengthening the local biophysical flows that require some energy expenditure, we must consider the net balance with the external energy consumption and the greenhouse gas emissions that are avoided. Concurrently, the EU Biodiversity Strategy for 2030 (https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm), the Farm to Fork Strategy (https://ec.europa.eu/food/farm2fork_en) and the Green Deal (https://ec.europa.eu/info/strategy/priorities-2019–2024/european-green-deal_en) have all been adopted by the EU. All constitute a strong policy framework, requiring a holistic and systemic approach to the restoration of agroecosystems and to increasing food system sustainability, which can be developed via a Socioecological Integrated Analysis of agricultural landscapes.

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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