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Assessing the sustainability of contrasting land use scenarios through the Socioecological Integrated Analysis (SIA) of the metropolitan green infrastructure in Barcelona

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ABSTRACT

Urban development and the sprawl of transport infrastructures have disregarded the crucial function of metropolitan landscape in provisioning human well-being and biodiversity. This research aims to contribute to the challenges of Planning for Sustainability by proposing a Socioecological Integrated Analysis (SIA) to support the Land Use Master Plan in the Barcelona Metropolitan Area, to conciliate urban development with the performance of surrounding open spaces. The paper evaluates four different land cover scenarios (current, trending, alternative and potential), and two kinds of agricultural management (conventional and a socioecological transition towards organic agriculture). The results suggest that although there are significant improvements on job provisioning and nutrient-cycling closures (circular economy), certified organic agriculture is not enough to overcome some trends of industrialized agrarian systems such as low energy efficiency or poor improvements in greenhouse gas emissions. The results also show a crossed effect between social metabolism and landscape ecology where changes in the management could affect the landscape functioning while changes in the land covers are particularly affecting the resource use. Then, deeper changes that consider together land use and metabolic flows are required to promote more sustainable agroecological transitions. The SIA model is an important conceptual and methodological step forward that facilitates the transition towards sustainable land use policies.

1. Introduction

Creating metropolitan areas capable of conciliating population rise and the landscape ecological functioning should be a priority for planning cities and communities, in accordance to the 2030 UN Sustainable Development Goals (SDG). Building sustainable cities requires achieving the targeted objectives of participatory, integrated and sustainable human settlement planning and management (UUNN, 2015). However, up to now urban development has mainly gone by hand with the disconnection of cities from the surrounding territories due to globalized markets, the loss of natural areas, landscape fragmentation, natural resources and ecosystem services degradation, and a reduction on nature's capacity to respond to anthropogenic global changes (Antrop, 2004, Calvo-Iglesias et al., 2006, Tratalos et al., 2007). Simultaneously, this metropolitan growth has often increased administration costs in order to maintain basic functions of the open spaces for the provisioning of ecosystem services required by society (Benedict and McMahon, 2002, Tzoulas et al., 2007, Sandifer et al., 2015).

In order to overcome these trends towards a more sustainable economy, one of the main challenges of future cities and their metropolitan communities is how to provide close, sustainable and safe food for their population while contribute to a more circular economy (FAO, 2011). Along the decades of the green revolution, western agrarian activities simplified their complex socioecological functioning resulting in a loss in territorial and resource use efficiency (Gingrich et al., 2018, Marull et al., 2019). This affected both landscape functioning and metabolism in open spaces. Hence, although there is a

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growing trend advocating for the need of an agro-ecological transition (Aguilera et al., 2020, Gliessman, 1998), it is necessary to develop methodologies aiming to understand its feasibility and impacts from a multi-criterial perspective to better understand its potentials and shortcomings beyond its economic viability (Marull et al., 2020). In this sense, planning towards this socio-ecological transition of agriculture towards more sustainable management should aim, at least, at four objectives. The first one would imply to reduce the external inputs needed for agriculture (i.e. fertilizers, animal feed, seeds) (Tello et al., 2016). The second, to optimize material and energy flows between food production and animal husbandry (i.e. closing energy and material cycles at landscape scale (Tello and González de Molina, 2017). The third, to improve the autonomy of farms by promoting functional diversification and biodiversity by implementing more integrated and complex types of farming (Marull et al., 2016). And the last but not least, to strengthen climate change adaptations and contributing to net-zero emissions policies (Aguilera et al., 2015). Accordingly, a quantification of energy and matter flows inside agricultural systems is essential to understand how socio-metabolic exchange configures land uses, and landscapes that must provide vital food security and ecosystem services for cities.

Nowadays, multidimensional and multiscale governance approaches have become important decision-making tools for land planning, particularly in metropolitan areas. However, many of these models remain superimposing an environmental economics approach over an ecological economics, through cost-benefit methodologies, leading to a prioritization of economic growth as a key criterion for decision-makers (Thomas and Littlewood, 2010, Martínez-Alier et al., 1998). Then, only when the biophysical benefits to the metropolis are valued with a multi-criterial perspective, the socioeconomic pressures to the green infrastructure can be reduced (Thomas and Littlewood, 2010). Also, this process would allow understanding some issues that often remain out of focus with the classical cost-benefit analysis: the environmental externalities, the asymmetry of information, and the of open spaces as public goods in a wider perspective (Weimer and Vining, 1992).

As a response to these challenges, over the last years four conceptual developments have enriched territorial development and land planning debates by interaction with other disciplines such as ecological economics or landscape ecology. The first one is *social metabolism* as a methodological and theoretical framework from ecological economics to understand and quantify nature-society interactions (Fischer-Kowalski, 1997). This approach allows the adoption of a reproductive point of view, fundamental to identify what are the system's biophysical requirements to maintain the ecological functioning of renewable resource sources (Padró et al., 2019). Second, *ecosystem services* provide a crucial approach that recognizes the non-economic values of the nature and the human activities as key elements for the sustainability of the urban areas (Martínez-Alier et al., 1998; MEA, 2005). This concept has proved to be particularly useful at highlighting all the non-commodified values of nature and the impact that human activity generates on these values (Bastian et al., 2012). Third, acknowledging *green infrastructures* as socioecological systems allows land planners to overcome the historical limitation of focusing urban planning to built-up spaces (Benedict and McMahon, 2002). The role of green infrastructure is gaining importance as the definitions of a landscape are becoming more complex (Fischer and Lindenmayer, 2007), drifting away from a classical landscape ecology view of discrete elements such as patches, corridors and matrix (Forman, 1995). Finally, the notion of *cultural landscape* where its different elements (both social and natural) interact, through innumerable processes that characterize the functioning of the territory as a system as a result of a relation between nature and society in a given site-specific context (Marull et al., 2010, Agnoletti, 2006).

Together, the above-mentioned frameworks provide the conceptual bases for a paradigm shift towards an updated approach for land planning, redirecting the focus onto processes rather than just land uses towards a Planning for Sustainability. However, despite the developments of a new socioecological approach, currently there is a lack of models to assess the land planning on the multifunctionality of the green infrastructure (Maruani and Amit-Cohen, 2007). In order to guarantee a meaningful land Planning for Sustainability and advance in the knowledge of the metropolitan systems and the complexity of the decisions making processes, multi-criteria and multi-scale analysis are needed to facilitate the necessary deliberative processes (European Commission, 2013). This strategy is also an imperative by current policy roadmaps in order to identify the role of the green infrastructure in providing ecosystem services, nature-based solutions, climate change mitigation and adaptation, and maintaining natural capital (European Commission, 2013; Hansen and Pauleit, 2014).

In this paper, we use an improved version of the Socioecological Integrated Analysis (SIA) (Marull et al., 2020), a particularly comprehensive model of the landscape-scale social metabolism that includes its main structural, functional and managerial dimensions, to integrate social metabolism variables into land planning, through the quantification of the metabolic flows of the green infrastructure land uses. The work has two specific objectives. First, it aims to explore alternative but feasible horizons of the Barcelona Metropolitan Area (BMA) by applying the SIA to different theoretical land use scenarios defined by the Land Use Master Plan (PDU for its acronym in Catalan) of the BMA. Second, it aims to particularly assess the socioecological implications of a transition in the agrarian system from the current conventional management to an organic one.

2. Methodology

2.1. Case study

The Barcelona Metropolitan Area (BMA) is comprised of 36 municipalities in a total area of 63,611 ha (Fig. 1) and has a population of 3.3 million people (Idescat, 2020). According to the newest Land Cover Map of the BMA (CREAF, 2015), open spaces are still the predominant land covers (55%) distributed among forests and scrublands (42%), croplands (8%), pastures (3%) and other open spaces (2% water corridors and bare soil). The remaining 45% of the surface are built-up areas including compact and spread urban areas, urban parks, roads and other infrastructures. Agriculture is concentrated along the lower valley and the Delta of the Llobregat River, although some patches of arable land, vineyards and arboriculture still form mosaic patterns with forests in the Vallès plain and the slopes between sparsely populated areas.

The BMA has a metropolitan institution that seeks to integrate and create flexible, efficient and democratic governing tools to decide strategic policies for the correct management and development of the metropolis (Martí-Costa, 2018). This is fundamental for planning policies to harmonize and frame a consensus to achieve sustainable cities (11th goal of the SDG; UUNN, 2015). The General Metropolitan Plan from 1976 set the foundations of land use planning basis for the urban expansion up to 2014. After 38 years a new process was launched to achieve a new consensus under the Urban Master Plan (PDU). The Action Plan for the PDU considers 3 structural elements that constitute the socioecological system: i) urban and social structure; ii) mobility and utilities infrastructures; and iii) the green infrastructure (BMA, 2019). The current study focuses on the green infrastructure in order to provide tools and evidence on the priority and strategic areas of interest, the potentials and challenges of different types of management and planning and on the most relevant synergies and trade-offs among dimensions of the role of green infrastructure in the socioecological system. To this aim, the SIA model can be an effective tool.

2.2. Socioecological Integrated assessment

The Socioecological Integrated Assessment (SIA) (Marull et al.,

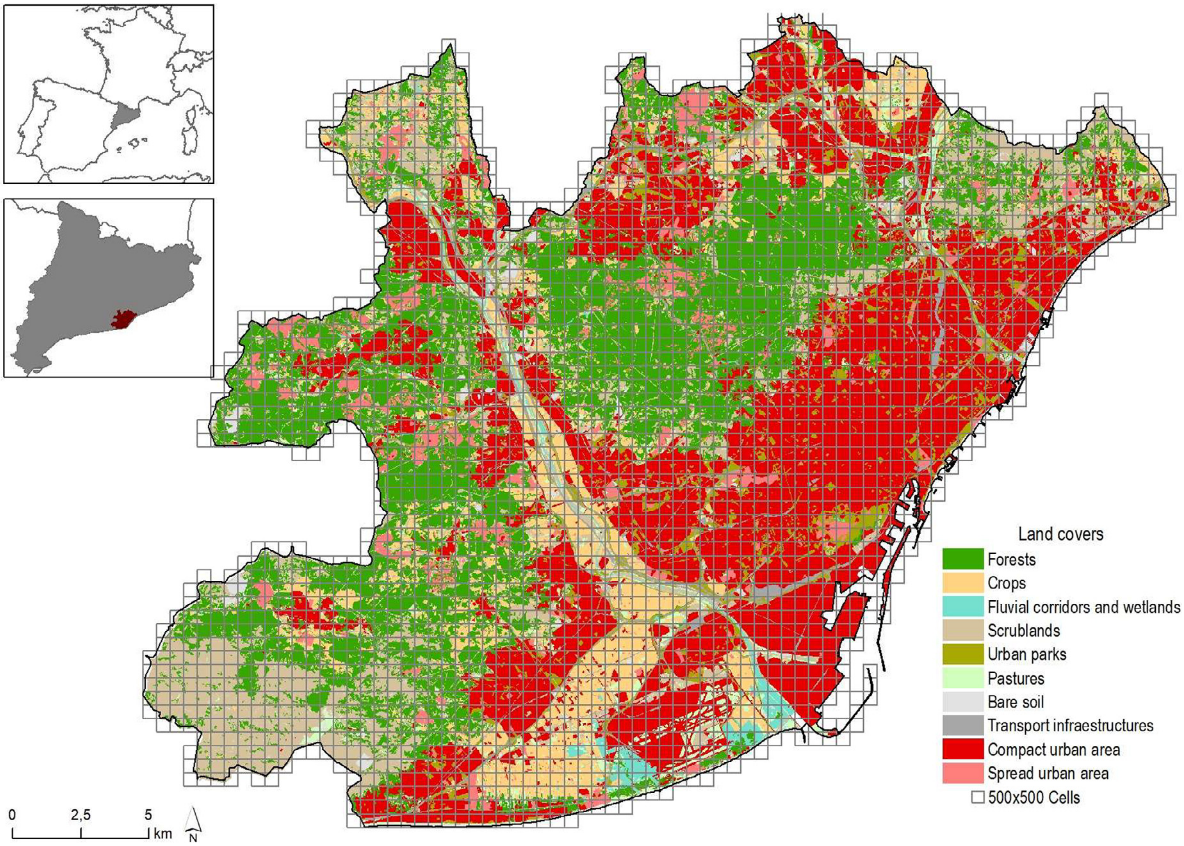

Fig. 1. Land cover map (2015) of the Barcelona Metropolitan Area (BMA). *Source*: CREAF, 2015.

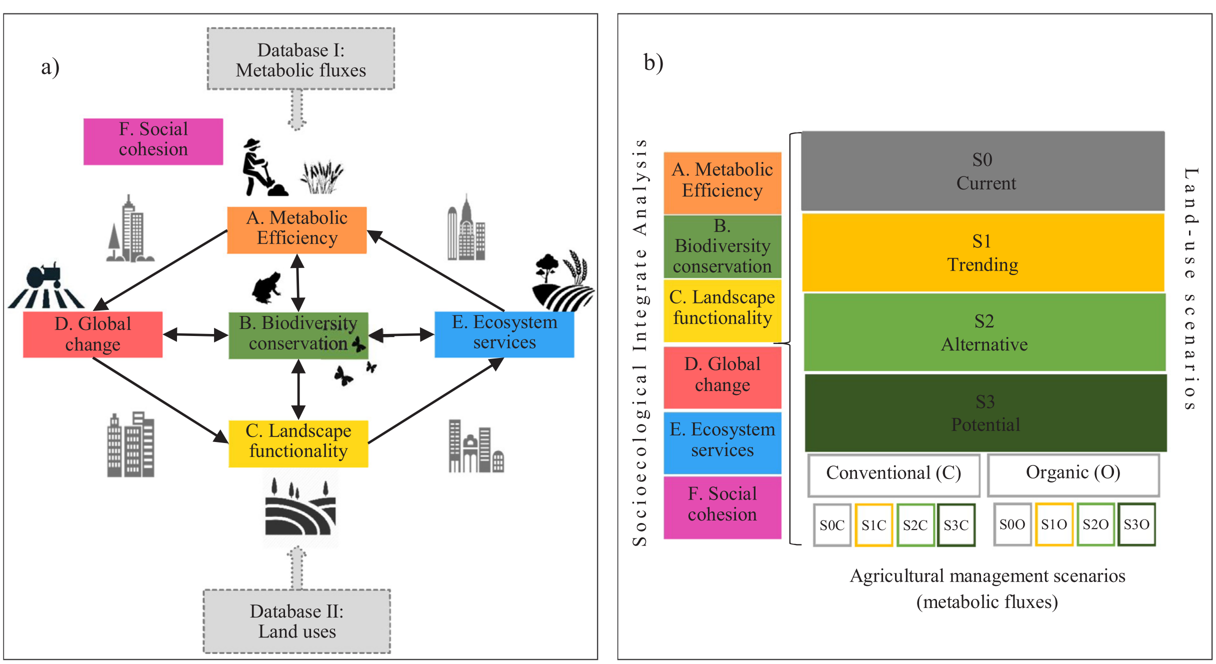

Fig. 2. Conceptual framework (a) and experimental design (b) for the evaluation of land cover scenarios and agricultural practices (conventional *vs* organic) with the Socioecological Integrated Analysis (SIA). *Source*: Our own modified from Marull et al. 2020.

2020) is a metabolic-territorial model that evaluates the contribution of the green infrastructure to the whole socioecological system of the BMA considering six interrelated dimensions (Fig. 2**a**): A. Metabolic efficiency, B. Biodiversity conservation, C. Landscape functioning, D. Global change, E. Ecosystem services and D. Social cohesion. Each of these six dimensions is assessed through one or more principal indicators (Table 1): energy efficiency (A1), energy-landscape integration (B1), landscape complexity (C1), non-renewable energy input (D1), nutrient recirculation (E1A), carbon stock (E1B), agricultural production (E1C), and, finally, agricultural jobs (F1). Indicators C1 and E1B depend directly and only on the land cover arrangement of each scenario, hence they will only present differences among land cover

Table 1
Socioecological Integrated Analysis (SIA) of the Metropolitan Green Infrastructure. Dimensions, indicators, methodological description and references.

Dimension		Indicator	Description
A. Metabolic efficiency		A1. Energy efficiency	Evaluates in energy terms the relation between the returned biomass obtained by the agricultural activities and the external inputs used by measuring the External Final Energy Return On Investment (EFEROI; Tello et al. 2016)
B. Biodiversity conservation		B1. Energy – landscape integration	Simultaneously evaluates the landscape complexity (C1) and the agricultural metabolic flows (A1) as a proxy for the conditions to host biodiversity (ELIA; Marull et al. 2016)
C. Landscape functionality		C1. Landscape complexity	Simultaneously evaluates the landscape heterogeneity and the ecological connectivity (Marull and Mallarach, 2005)
D. Global change		D1. Non-renewable energy	Evaluates the input of external non-renewable energy (Tello et al. 2015) as a proxy of greenhouse gas emissions.
E. Ecosystem services	Support	E1A. Nutrient recirculation	Estimates the amount of phosphorus that return to the agricultural system taking into account the rest of land use and the livestock system (Marco et al. 2018). This work used phosphorus as the reference nutrient after checking that it is the limiting one in nutrient cycling of nitrogen, phosphorus and potassium.
	Regulation	E1B. Carbon stock	Measures the stock of carbon that is present in soil, roots and woody aerial structures of the open spaces (Doblas-Miranda et al. 2013) by integrating several different territorial sources.
	Supply	E1C. Agricultural production	Evaluates the agricultural production of each land use available that exits the agroecosystem (orchards, greenhouses, dry grassland and irrigated land, fruit trees of dry land and irrigation, olive trees of dry land and irrigation and vineyard)
F. Social cohesion		F1. Agricultural jobs	Characterizes the potential of Agrarian Workers Units required to maintain agrarian activities in open spaces (Padró et al. 2017)

scenarios and not between agricultural management scenarios.

The selection of socioecological indicators has been done according to the main objectives for the green infrastructures' planning in the PDU Action Plan. The conceptual definition of these indicators was done through a semantic categorisation together the technicians in charge of the redaction of the PDU so as to ensure its usefulness of the multi-criteria assessment in the deliberative processes (Giampietro et al., 2009). The model is fed with land use digital maps and regional statistical data on inputs and products of agricultural systems. It considers the whole relevant biophysical fluxes that circulate within the agroecosystems and assesses its functioning based on four balances: phytomass, energy, animal feeding and biogeochemical cycles (Marco et al., 2018). This means the model accounts whether nutrients or the feed flows circulating through the case study are enough to ensure reproduction of soil fertility and livestock. If not, it is estimated the amount of feed or soil amendments that has to be imported from outside and all the corresponding implications on the indicators. This biophysical framework is also related to a set of landscape ecology models that account for patterns and processes considering the green infrastructure as a system (Marull et al., 2008). All together make up a set of interrelated models which allow to calculate the set of socio-ecological indicators. Thus, changes on management or on land use composition, would result in different values for the eight principal SIA indicators.

2.3. Land planning scenarios

The present analysis of land planning strategies is based on four theoretical land cover scenarios (current, trending, alternative and potential) provided by the PDU, and two management practices (conventional and organic) that consider changes in the metabolic fluxes that take place in agricultural systems. The study was carried out at two different scales: a landscape scale, with 500x500m cells (n = 2,764) proposed by the PDU methodology (Fig. 2**b**) and a regional scale that will provide an overview of the land planning scenarios for the entire BMA.

The current distribution of land covers for the BMA was considered as the reference or *current scenario* (S0) and was obtained from the latest available Land Cover Map (Fig. 1). Land cover composition for each scenario is detailed in Table 2 and changes from the *current* to the *trending* (S1), *alternative* (S2) and *potential* (S3) scenarios are shown in Fig. 3. The *trending scenario* (S1) corresponds to business-as-usual situation, with the full implementation of the current municipal urbanistic land plans, characterized by a general increase in the built-up areas and urban parks and leading to a decrease in forests, scrublands and agricultural areas. In the *alternative scenario* (S2), change from planned urban parks to productive agricultural areas is proposed. Finally in the *potential scenario* (S3) an important recovery of the pre-existing agricultural areas in the BMA is set (identified through an historical land cover map of 1956). Land uses, specifically crop surface and structure, were adjusted accordingly to the land cover distribution changes between scenarios (i.e. when herbaceous crop surface increased in S3, specific crop surface increased depending on the original distribution).

The *trending scenario* (S1) , supposes an increase in the built-up areas of 5500 ha (considering as well the urban parks) (Fig. 3). The most affected categories are the forest and the scrublands (1500 ha and 1330 ha respectively), but it is also relevant the loss of around 25% of current agricultural surface (1150 ha). The effect of the urban development in S1 is partially reverted in the *alternative scenario* (S2) where a large part of the urban park area considered in S1 is transformed into agroforestry activities (more than 80%). Also, around 520 ha and 600 ha, respectively, of compact and lax urban areas are reconsidered, increasing agricultural areas in the BMA from 4200 ha in S1 to 6950 ha in S2. In the *potential scenario* (S3), the increase in the agricultural surface is very important: up to 12,600 ha as all the agricultural areas from 1956 are recovered except for those already built-up areas (Giocoli, 2017). New transport infrastructures, which heavily impact on the fragmentation processes, increase in more than 720 ha in S1, 430 ha in S2 and few more than 320 ha in S3.

Each land cover scenario was analysed under two different agricultural management practices: conventional and organic (Fig. 2**b**). The first corresponds to the current agrarian management activities, and is mainly based on the 2009 agricultural census and updated with the statistical sources using the year 2015 as reference. This allows estimating the metabolic fluxes of the current agrarian activities and, by extension, of the complete green infrastructure (for more details see Marull et al., 2020).

To simulate organic agricultural management scenarios, we followed the guidelines for certified organic animal and food production stablished by the European Commission legislation (834/2007, 889/2008, and 1235/2008) and the Catalan Council of Ecological Agricultural Production (CCPAE, 2017). Given the many possible crop management practices under the official certification of CCPAE (i.e. fertilizing techniques, pest control management, crop rotations), for the specific purpose of this study, we defined organic agriculture management as: i) the complete removal of chemical non-mineral fertilizer use; ii) the complete removal of chemical pesticides and herbicides use; and

Table 2
Land planning scenarios of the Land Use Master Plan of the Barcelona Metropolitan Area (BMA) considered in the Socioecological Integrated Analysis (SIA) of the Green Infrastructure.

Land-planning scenario	Description	Land-cover				
		Urban*	Forest**	Agriculture	Pastures	Other***
S0. Current	2015 Land-cover map (CREAF)	45%	42%	8%	3%	2%
S1. Trending	Current urbanistic land plan of each municipality, considering the metropolitan land reserves and sectors defined in the General Metropolitan plan from 1976.	52%	38%	6%	2%	2%
S2. Alternative	S1 with recovery of open spaces in some areas expected to be urban parks, as well as in other reserves for metropolitan services	46%	38%	12%	2%	2%
S3. Potential	Based on S2, but with a recovery of agricultural uses outside built-up areas. The existing agricultural area in 1956 was joined to the new agricultural areas considered in S2	45%	32%	20%	2%	2%

Notes: * Includes low and high-density urban areas, urban parks and roads. ** Includes forests and scrubland. *** Includes fluvial corridors, wetlands and bare soils.

iii) the limited and regulated use of external inputs (i.e. animal feed and seeds). Under those definitions, organic agricultural practices were assumed to comply with the minimum CCPAE certifying criteria (Table A1 in Supplementary Material).

Additionally, a shift towards organic management would alter other agricultural fluxes such as yields (of both crops and animals), labour requirements and unharvested biomass and manure management. Consequently, based on the conventional scenarios' values set by the empirical statistical sources, these fluxes were modified using adjustment factors from a literature review (Table A1). In summary, three main assumptions were made: i) crop and animal yields decrease (De Ponti et al., 2012, Seufert et al., 2012); ii) labour requirements per product unit increase, as well as the intensity of machinery use (DAAR, 2007); iii) all biomass and manure are properly reused (nutrient cycles are closed) and there is no waste flow (biomass discard); and iv) crop species composition and crop structure remained the same between organic and conventional managements.

2.4. Cartographic and statistical analyses

To assess the implications of a potential territorial (land cover scenarios) or/and metabolic (management scenarios) transition in the BMA, each SIA indicator was calculated for each scenario at 500x500m sample cell and metropolitan (aggregated) scope. First, the SIA assessment at cell level allow a pairwise comparison of the indicators for each scenario and their statistically significant differences based on a bilateral test-t for each cell ($n = 2467$). This allows to find how strategies on land use changes or shifting management can suppose different green infrastructure's performances for each SIA dimension (Section 3.1). Then, in order to compare the overall impact of scenarios, a multicriterial assessment is performed through aggregate values (this is, the absolute value for the whole BMA), which allow to have the big picture on the overall functioning (Section 3.2). Finally, a Principal Component Analysis (PCA) was performed to assess the synergies and trade-offs among SIA dimensions through a statistical Exploratory Factorial Analysis (EFA). Finally, we used results at cell level to identify how the relation among dimensions and scenarios shifts and how changes in the landscape structure are associated with changes in the metabolism (Section 3.3).

3. Results and discussion

3.1. Contrasting land planning scenarios and management practices

Our study analysed how contrasting land planning strategies might result in different structural patterns of the green infrastructure in the BMA and how these patterns might contribute to the functioning of the metropolitan socioecological system, through pair-wise comparisons of SIA values per 500 × 500 m cell between alternative land planning scenarios, This is the first time that SIA is applied to assess different land cover scenarios and management practices so that associations among dimensions of the socioecological system can be assessed in terms of their contribution for a sustainable development.

Results show that, in general, the energy efficiency indicator (A1) is higher for all conventional scenarios compared with the same scenarios with organic agricultural practices, with the lowest A1 value found in the organic trending scenario (S1), although it is not statistically significant (Table 3). Scenarios of conventional management with larger agricultural land cover (S2 and S3), have significantly higher A1 values than S0 and S1 scenarios of the same management type.

The energy-landscape integration indicator (B1), has an overall higher and significant values when the agroforestry mosaic is recovered (S2 and S3) and when there is a transition towards organic management in each land cover planning scenario, despite those effects remain around 5% (Table 3). Thus, despite a greater energy efficiency of conventional scenarios, the lesser reliance on external inputs favours

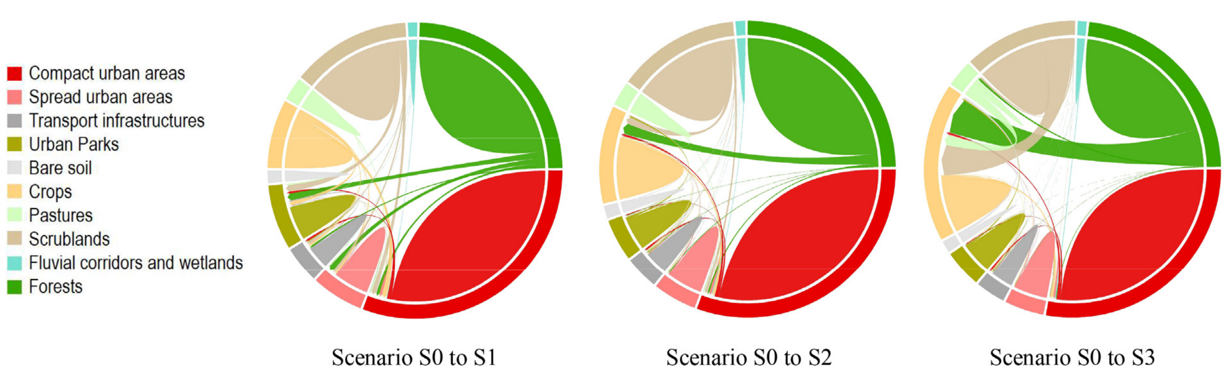

Fig. 3. Land cover changes among land planning scenarios (S0 = current scenario, S1 = trending scenario, S2 = alternative scenario, S3 = potential scenario) in the Barcelona Metropolitan Area (BMA). Changes from one land cover category to another are shown, from the current to the planning scenarios. *Source*: Our own from CREAF, 2015.

Table 3
Socioecological Integrated Analysis (SIA) of the Barcelona Metropolitan Area (BMA) Green Infrastructure. Indicators comparison between land-planning scenarios (S0 – S3), and conventional (C) and organic (O) management scenarios. Data based on result indicators for each 500x500m cells.

SIA Indicator	Scenarios															
	Current (S0)				Trending (S1)				Alternative (S2)				Potential (S3)			
	C (a)		O (b)		C (c)		O (d)		C (e)		O (f)		C (g)		O (h)	
A1	3.53	b,d	3.24		3.31		3.15		3.59	b,d	3.53	b,d	3.73	b,c,d	3.58	b,c,d
B1	0.41	c,d	0.43	a,c,d,e	0.35		0.37		0.40		0.42	c,d,e	0.41		0.44	a,c,d,e,g
C1	0.31	c,d	0.31	c,d	0.26		0.26		0.30		0.30		0.31		0.31	
D1	97.99	d	86.45		91.09		77.82		116.01	b,c,d	101.54	d	186.92	a,b,c,d,e,f	174.41	a,b,c,d,e,f
E1A	27.42	g	47.82	a,c,e,g,h	29.60	e,g	49.99	a,c,e,g,h	26.13	g	45.83	a,c,e,g,h	21.95		34.06	
E1B	1,642	c,d,g,h	1,642	c,d,g,h	1,502		1,502		1,597	c,d	1,597	c,d,	1,537		1,537	
E1C	1,421	b,d,f	926		1,315	b,d	803		1,487	b,d,f	1,067	d	2,210	a,b,c,d,e,f,h	1,743	a,b,c,d
F1	0.89		1.16	a,c,e	0.82		1.07	a,c	0.93		1.22	a,c,e	1.39	a,b,c,d,e	1.80	a,b,c,d,e,f

Note: Indicators: energy efficiency (A1), energy-landscape integration (B1), landscape complexity (C1), non-renewable energy input (D1), nutrient recirculation (E1A), carbon stock (E1B), agricultural production (E1C), and agricultural jobs (F1). Letters (a, b, c, d, e, f, g, h) indicate statistically significant differences among scenarios for each indicator based on that bilateral test-t (n = 2,467) and with alpha value of 0.05.

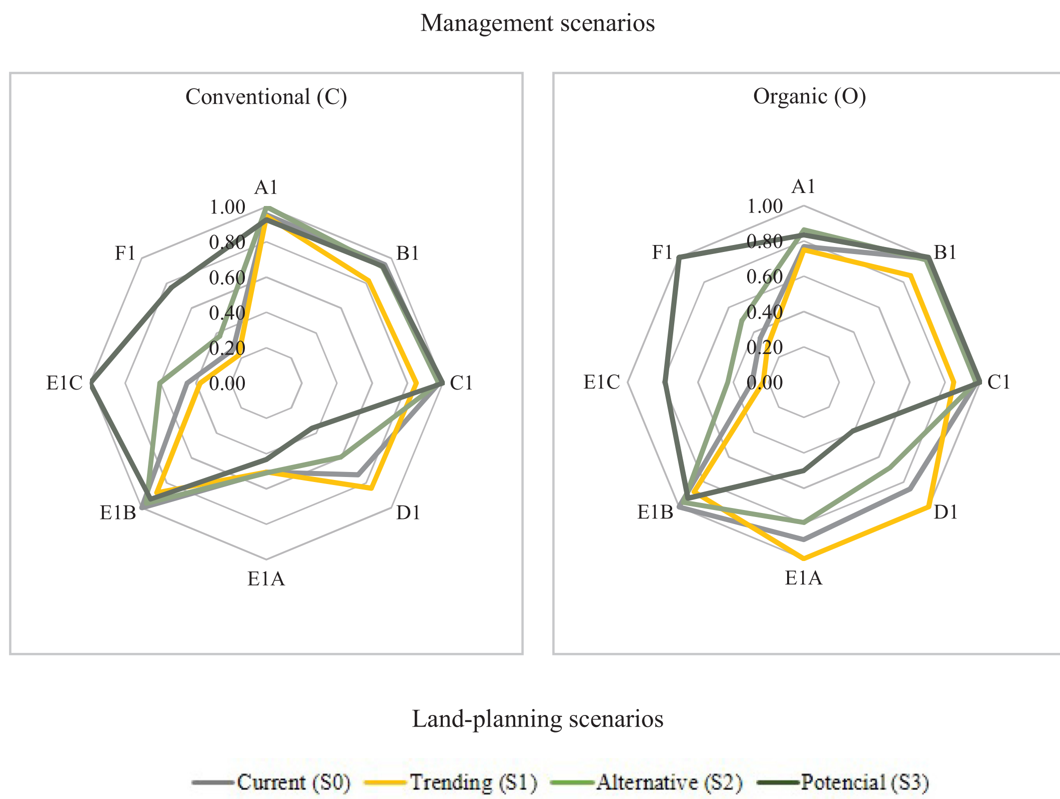

Fig. 4. Results of the Multi-criteria Analysis of the evaluated land planning scenarios (S0 = current scenario, S1 = trending scenario, S2 = alternative scenario, S3 = potential scenario), under conventional (C) and organic (O) managements, in the Barcelona Metropolitan Area (BMA). *Note*: Socioecological Integrated Analysis (SIA) indicators: energy efficiency (A1), energy-landscape integration (B1), landscape complexity (C1), non-renewable energy input (D1), nutrient recirculation (E1A), carbon stock (E1B), agricultural production (E1C), and agricultural jobs (F1).

better conditions to host biodiversity in organic scenarios.

The indicator of landscape complexity (C1), a proxy for the landscape functioning, shows small differences among land cover scenarios, only a significant decrease between the current (S0C and S0O) and the trending (S1C and S1O) scenarios (Table 3). There are no significant changes between the alternative and potential scenarios, but they both present relatively low differences compared to changes in other dimensions.

Regarding the non-renewable energy inputs (D1), the transitions from conventional into organic management generally resulted in lower non-renewable energy inputs, although these differences were not significant (Table 3). As organic farming maintains machinery or greenhouses, which are an important part of external energy inputs, the exclusion of pesticides, herbicides and chemical fertilizers is not enough to significantly affect total external inputs. However, like A1, the indicator was especially sensitive to the substantial agricultural area increase of the potential scenario (S3).

In terms of nutrient recirculation (E1A), regardless of the land planning scenario, mean indicator values under conventional management were always lower than under organic management (Table 3). These differences are significant for the current (S0), trending (S1) and alternative (S2) scenarios. However, the greater the agricultural surface the lower the system's ability to provide enough nutrients to close the nutrient cycles at local level. The carbon stock indicator (E1B) reveals higher values in the current scenario (S0). With respect to agricultural production (E1C), values are always significantly higher for conventional management mainly due to the lower yields considered for organic management. These sustained differences (an overall drop in production of 17%), are also affected by the increase in agricultural area that makes the average value of production per cell increase significantly in the potential scenario (S3) in relation to the current scenario (S0).

Finally, the agricultural jobs indicator (F1) showed for all land cover scenarios higher labour intensities in organic production (Table 3). This difference was significant for the current, trending and alternative scenarios (S0, S1 and S2 respectively). Additionally, the shift from the current scenario into the potential scenario (S3), where agricultural land cover considerably increased, would imply an increase in the average amount of work in relation to any of the other scenarios.

3.2. Multi-criteria assessment of the scenarios and practices

3.2.1. Land cover planning scenarios, metropolitan landscapes on change

Changing from current to the trending scenario result in a loss of landscape complexity (C1) given the increase of urban sprawl, and the subsequent loss of forest, scrublands and agricultural areas (Fig. 4). This loss of complexity, together with the increase of urban sprawl, would also worsen the conditions for biodiversity conservation (B1). In general, all fluxes are reduced in the trending scenario, resulting in less production (E1C), lower job provision (F1) but less external entries as well (D1), as a counter-effect.

The high values of the carbon stock (E1B) indicator found in the current scenario, might be explained because in the short to medium term, changes in land covers mean the loss of an important part of the accumulated biomass (both aerial and belowground) (Fig. 4). This means that S0 has more stock than the trending scenario (S1) but also compared to the potential scenario (S3).

In terms of the alternative (S2) and potential (S3) scenarios, regarding the soil nutrients recycling (E1A), an increase in the agricultural surface causes a drop in the ability to close the nutrient cycles, because nutrients are lost through sewage sludge and are not recycled to agricultural areas (Padró et al., 2017) (Fig. 4). This makes difficult to close the nutrient cycles, increasing the heavy reliance on imports as seen in the D1 results, regardless of the type of fertilizer imported (manure or chemical).

The transition between S1 to S2, where the agroforestry land recovered, shows the potential to mitigate the impacts of the trending scenario (S1), although its effects would not be even equal to the situation in 2015 (S0) (Fig. 4). This agroforestry recovering in the alternative and potential scenarios, has also potential benefits for biodiversity conservation (B1), which can go hand in hand with the increase of total agricultural production (E1C), the later with a 2.2-fold increase from the current (S0) to the potential scenario (S3). This synergy found in the SIA indicators supposes an interesting trend that should be corroborated in further studies, supported under the hypothesis of the so-called *land sharing* strategy (Fischer et al., 2014, Marull et al., 2019), so that increasing agricultural production by increasing cropland cover while maintaining intermediate levels of human disturbance can hold greater levels of biodiversity than intensifying the already existing cropped surface.

3.2.2. Management practices, a socioecological transition towards organic production

A transition to organic farming (Fig. 4) meeting the CCPAE criteria (Table A1) is particularly favourable facilitating a greater degree of autonomy closing the nutrient cycles (E1A) and providing agricultural jobs (F1). But this process is associated with a decrease of agricultural production (E1C) and energy efficiency (A1). A reduction on agricultural yields was expected considering the yield factors estimated in the model (De Ponti et al., 2012, Seufert et al., 2012). Despite the decrease of external fertilizers use and the complete elimination of herbicides and pesticides, a significant decrease on energy efficiency under organic practices could be explained by the elevated use of external inputs: in this particular case the feed, imported from regional organic sources when the local production did not satisfy the requirements, as well as machinery use also slightly increased.

The effect of an organic transition would significantly reduce aggregate agricultural production (E1C), with an average drop of 17% (Fig. 4). Indeed, this decline in productivity per hectare is not as much as the decline in productivity, even though the total amount of inputs per hectare decrease. Thus, energy efficiency of agriculture falls between 9% and 20% at the aggregate level. On the contrary, the average difference among agricultural practices in terms of nutrient recirculation (E1A) is a relevant 30% increase between the conventional and the organic management, as following the legal criteria livestock is mainly feed with local sources trying to maximize the circular functioning and limiting external imports of grains and hay.

A similar effect is observed with the slight reduction in the dependence on external inputs (D1) or the energy-landscape interaction (B1), but in this case the increase is much more restrained as they only improve on average between 10 and 5% respectively when compared to the conventional production (Fig. 4). Those two aspects are probably showing the biophysical limits of an organic management versus an agroecological one (Tello and González de Molina, 2017), challenging the transition and the goals of a sustainable management.

Finally, the average agricultural job provisioning (F1) increased 24% Agrarian Working Units (AWU) (Fig. 4). An ecological transition would increase the current estimated 640 to almost 2,400 AWU in the potential land cover scenario (S3). This increase of 3.7 times in the volume of workers is explained mainly by the increase of surface, but by the shift to organic farming as well as by the agricultural expansion towards cropping areas with productivities below the average.

3.3. Trade-offs and synergies on the socioecological functioning

The Principal Component Analysis (PCA) results in the identification of 2 components with eigen values over 1 that represent around 66.9% of the total variance in the case study and have very different composition (Table 4). The first component mostly includes energy-landscape integration (B1), landscape complexity (C1) and carbon stock (E1B). Then, it is more related to the landscape structure and functioning, reflecting a classical perspective on the land covers from a landscape ecology viewpoint. On the contrary, the second component is a good proxy of the biophysical flows circulating through the landscape. The variables of agricultural production (E1C), use of non-renewable inputs (D1), and energy efficiency (A1) or agricultural labour (F1) to a lesser extent, represent the material flows that occur in the green infrastructure. This gives prominence to the agricultural metabolic dimensions when considering the approach that must be considered for a land Planning for Sustainability. It is worth noting that while component 1 explain 42% of the total variance, component 2 accounts for the 25%. This means that while land use planning for sustainability cannot set aside the metabolic flows, the landscape patterns and processes play a fundamental role to understand variability along the territory.

It is also relevant to bring to light the shared contribution of the E1A indicator (soil nutrient recycling) to both components, suggesting that this is an important aspect to be considered in land planning given its ability to integrate metabolic and territorial aspects of the socio-ecological system (Table 4). From a conceptual perspective means that this indicator is affected by both the landscape funds and the metabolic flows and gives relevance to the reproductive processes needed by the green infrastructure to keep its socioecological functioning. In this sense, the recirculation of nutrients, as a fundamental regulating

Table 4
Principal Component Analysis (PCA).

Component	Eigenvalues			Sums of square saturations of the extraction			Sums of square saturations after rotation		
	Total	Variance (%)	Accumulated Variance (%)	Total	Variance (%)	Accumulated Variance (%)	Total	Variance (%)	Accumulated Variance (%)
1	3.36	41.95	41.95	3.36	41.9	41.9	2.77	34.6	34.6
2	1.99	24.92	66.86	1.99	24.9	66.9	2.58	32.3	66.9
3	0.98	12.19	79.05						
4	0.71	8.92	87.97						
5	0.47	5.93	93.90						
6	0.29	3.63	97.53						
7	0.14	1.77	99.30						
8	0.06	0.70	100.00						

Composition of the Principal Components after rotation

Indicator	Component 1	Component 2
A1	0.2469	0.7248
B1	0.9407	0.2132
C1	0.9327	0.1414
D1	0.0138	0.8356
E1A	0.4191	0.4023
E1B	0.8673	−0.0717
E1C	−0.0511	0.8657
F1	0.1463	0.6129

Note: Indicators: energy efficiency (A1), energy-landscape integration (B1), landscape complexity (C1), non-renewable energy input (D1), nutrient recirculation (E1A), carbon stock (E1B), agricultural production (E1C), and agricultural jobs (F1).

ecosystem service, represents the paradigm of the reproductive management of the landscape funds (soil fertility, livestock, farming community and associated biodiversity). However, this hypothesis could be extended to other reproductive processes such as the integration of livestock breeding and land uses or other practices that maintain the cultural landscape capital (such as terraces or the selective management of forests).

The Exploratory Factor Analysis (EFA) allows assessing the contribution of landscape structure (component 1) and socio-metabolic processes (component 2) in each land planning scenario and agricultural practices (Fig. 5). As can be seen, scenarios are much more affected by changes in component 2 (‘metabolic flows’) than component 1 (‘landscape ecology’). For this case study, the trending scenario is the only land use scenario that supposes a relevant change on the landscape component, with an average loss of 0.31 points in component 1, while for the rest of land use scenarios are practically null with an average change around 0.02 points. On the other hand, the performance of component 2 is much more sensible to land use scenarios, with an average loss of 0.14 points in the trending scenario, a gain of 0.25 for the alternative and a much more greater 0.87 increase in the potential compared with the current one.

The observed low and high sensitivity of land cover scenarios to landscape pattern and metabolic flows variables, respectively, lead us to a draw a relevant statement for policy making in this study: land use planning is much more affecting the agricultural metabolic flows than traditionally expected. Finally, organic farming scenarios compete with conventional ones in terms of the metabolic flows (component 2) but also result in a better performance in relation to sustainability objectives of the landscape in an average increase of 0.11 points (Fig. 5). Something that, again, reinforces this crossed effect of land use planning on metabolic performance and *viceversa* (the effect of metabolic changes on landscape performance).

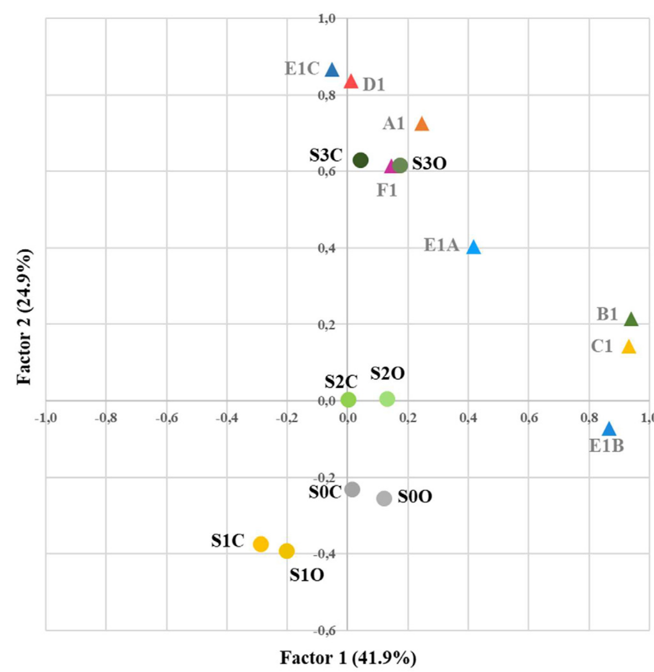

Fig. 5. Exploratory Factor Analysis (EFA). Land planning scenarios* (dots, dark text) and Socioecological Integrated Analysis (SIA) indicators** (triangles, grey text) in the Barcelona Metropolitan Area (BMA). *Notes*: * Land-planning scenarios: (S0 = current scenario, S1 = trending scenario, S2 = alternative scenario, S3 = potential scenario), under conventional (C) and organic (O) managements, in the Barcelona Metropolitan Area (BMA). ** Indicators: energy efficiency (A1), energy-landscape integration (B1), landscape complexity (C1), non-renewable energy input (D1), nutrient recirculation (E1A), carbon stock (E1B), agricultural production (E1C), and agricultural jobs (F1).

3.4. Strengths and limitations of the model

The SIA assessment is focused on the multiple dimensions of the contribution provided to social welfare by the joint operation of the metropolitan agricultural landscapes through its functioning as agroecosystems. The set of integrated indicators generated will inform the strategic land-use planning to improve its operation as a green infrastructure to help move them towards more sustainable agro-futures. The SIA approach highlights the society-nature interactions that take place through agroecosystems within metropolitan areas from a reproductive point of view. SIA is a socio-metabolic-territorial assessment designed to be applied to land-use planning. Its nodal point is considering that society invest through farming a set of biophysical flows in the agricultural system in order to obtain ecosystem services. These ecosystem services can only be ensured by keeping those metabolic flows that reproduce a set of vital live funds, such as agrarian community, livestock, soil fertility and functional landscape structure. The closer the functioning of these funds to natural processes, the more sustainable the agroecosystem will be.

The SIA model is innovative because brings a set of indicators and maps on the ecosystem services they currently provide to city dwellers, and how to improve them by changing the interaction between the biophysical flows of agricultural, livestock and forestry activities with the land use and cover patterns of those landscapes planned as green infrastructures. It is important, because it becomes a useful tool for a sustainability-oriented land-use planning that seeks to integrate urban-industrial and green infrastructures as complementary components of metropolitan areas, acknowledging that the continuous expansion of the former at the expense of the latter means degrading or even supressing the provision of the ecosystem services these horticultural and agroforest landscapes provide to the citizens living on the metropolis. And it is relevant, because the indicators and maps here presented are currently being applied in the approach of land-use planning adopted by the new Master Urban Plan of the Metropolitan Area of Barcelona, in line with the SDG of the United Nations 2030 Agenda and the Milan Urban Food Policy Pact.

Metropolitan agricultural landscapes can become the greenbelts needed for a closer agri-food supply in line with the Milan Urban Food Policy Pact (Moragues-Faus and Morgan, 2014), as well as for the delivery of many ecosystem services (Haines-Young and Potschin, 2010). The proposed SIA model has proven to be a useful assessing tool for this new sustainability-driven approaches to urban planning, remarking the need to redirect and take care of the biophysical flows that shape these horticultural and agroforest landscapes within metropolitan areas. It confirms the relevance of the FAO's 2018 Scaling Up Agroecology Initiative that claim to leap forward from current organic farming to more integrated agroecology territories able to ensure the provision of all kinds of ecosystem services to society. Land-use planning can enhance all the ecosystem services delivered to citizens from the metropolitan green infrastructures by driving towards socially desired scenarios these farming matter-energy flow that shape the agroforest landscape mosaics. Thus, land-use policy can do it through incentives and regulations which set in motion positive synergies with farmers.

However, in this current version, the SIA model has certain limitations that should be addressed in future research. Some indicators could be improved (for example, nitrogen flows in nutrient recycling, carbon balance of all agricultural activity, or agroecological EROIs), and additional indicators could be added in order to highlight certain dimensions that have not been prioritised in the first SIA assessment (for example, in relation to water cycle, greenhouse gas emissions, or the impact of green infrastructure on health -a relevant aspect in the current context of COVID-19 crisis). The model is not considering the dynamic synergies and trade-offs involved in changing the pattern of energy and material flows interlinking the agroecosystem funds involved (i.e. livestock and feed coming from local crops). It does not allow to connect land and livestock uses with dietary changes in the consumers' food baskets. We are then considering the average most unfavourable scenario for organic production yields, based on the estimations of a literature review (De Ponti et al., 2012, Seufert et al., 2012). The proposed organic production model only takes into account the food supply service, but it does not explain dependency from the outside. The SIA should be put in relation to the territorial scale that makes the functioning of the BMA sustainable, beyond its administrative limits. All these limitations mean that, while being a useful tool to help land-use planers to make better decisions aimed at improving the landscape capacity to provide ecosystem services to metropolitan areas, SIA cannot deliver yet scenarios of dynamic systemic changes such as scaling up organic farming into agroecological territories.

4. Conclusions

The proposed Socioecological Integrated Analysis (SIA) model has proven its ability to inform about the territorial effects of changing the land covers and the agrarian metabolism through modifying the management practices in metropolitan landscapes in order to facilitate the policymaking decision processes, in this case applied to the Barcelona Urban Master Plan. Using this multi-criterial perspective, integrating ecological economics and landscape ecology could enable and enrich informed debates on circular economy and land planning. The SIA model is an important conceptual and methodological step forward that facilitates the transition towards Planning for Sustainability. This planning strategy aims to reconcile urban development with the biophysical limits of territories, as well as to improve the socioecological functioning of green infrastructures.

Regarding the land cover scenarios considered, the increase in urban areas of the business as usual scenario would severely affect dimensions directly related to landscape patterns and processes. It would also affect the ability of the green infrastructure to close nutrient cycles, improve food provisioning, maintain agricultural jobs and increase its metabolic efficiency as well, calling for imminent revision on the projected land planning scenario. Planning land covers to restore agricultural areas lost during these past decades would allow to mitigate some of the negative socioecological impacts of past urban growth, increasing the diversity of the ecosystem services provisioned by the metropolitan green infrastructure, specially food security, and diminishing its reliance on massive external imports. Despite that, some indicators such as the total carbon stock or the expected emissions from agrarian activities would be negatively affected in total, as measured at the local level. However, this requires an additional assessment considering the net global effect considering the food provisioning replaced.

With respect to an organic transition in agricultural management, considering the minimum criteria to be certified following the CCPAE, the results show how this would suppose improving significantly nutrients recirculation and job provisioning at the cost of decreasing the overall production. However, the contribution of the green infrastructure to the socioecological functioning on metropolitan areas during a possible organic transition should be carefully accounted. Strict compliance with ecological regulations might not necessarily translate into overall improvements, and might not be enough to face challenges such as the decrease on the use of external inputs or on the increase on the energy efficiency improvement.

The results reinforce that, when considering transitions towards more sustainable functioning of agrarian systems, models must take into account a proper optimization of metabolic flows and land uses to satisfy specific social goals (i.e. food provisioning, biodiversity conservation). This means that those organic practices must also consider, for example, the type of crops needed to promote synergies among food demand, livestock functioning, food provisioning and the other ecosystem services and socioecological functions. From our results arises a new hypothesis relevant for this new paradigm of Planning for Sustainability: it seems to be a crossed effect on the changes in land covers and agricultural management and the impact on dimensions of landscape ecology and social metabolism. This means that land cover changes would be more related to changes on metabolic flows, while management changes could affect also dimensions of landscape functioning.

In summary, the challenge of sustainable land planning and circular economy in metropolitan areas could be addressed by adopting an integrated view that allows for the identification of both land uses and metabolic flows changes. A socioecological transition towards organic agriculture should be evaluated on a case by case level, considering the specific socioecological limits and demands. We are still entering on a new paradigm where landscape ecology and ecological economics can play hand by hand a relevant role for understanding the interaction among ecological processes and human intervention on the territory.

CRediT authorship contribution statement

Roc Padró: Conceptualization, Formal analysis, Writing - original draft. **María José La Rota-Aguilera:** Writing - original draft. **Annalisa Giocoli:** Writing - original draft. **Jacob Cirera:** Writing - original draft. **Francesc Coll:** Formal analysis. **Manel Pons:** Formal analysis. **Joan Pino:** Writing - original draft. **Silvia Pili:** Writing - original draft. **Tarik Serrano:** Writing - original draft. **Gara Villalba:** Writing - original draft. **Joan Marull:** Conceptualization, Writing - original draft.

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Appendix A. Supplementary data

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