Working Paper

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

Metropolitan Laboratory of Ecology and Territory of Barcelona

Project CP_2019_6.1.2_a

December 2019

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Acknowledgements

This work has been funded by the Barcelona Metropolitan Area (project 2019_6.1.2a) in order to obtain criteria and methods for the Metropolitan Land Use Master Plan of Barcelona (PDU), and has also received funding by the Barcelona Metropolitan Strategic Plan (PEMB) through the 2019 Francesc Santacana Grant, the European Union (ERC Consolidator Grant 818002-URBAG), and The Spanish Ministry of Science, Innovation and Universities (project RTI2018-093970-B-C32).

Abstract

Urban developments and the sprawl of transport infrastructures have been done at the cost for the landscape functioning and the provisioning of human wellbeing. Disregarding the open spaces in land use policy has been the mainstream for years. The notion of green infrastructure allows to conciliate the urban development with the correct performance of its surrounding open spaces as a key infrastructure for the functioning of metropolis by providing goods and services for society. 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. 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.

Key words

Land Use Policy, Socioecological Transition, Social Metabolism, Ecosystem Services, Multi-criteria Analysis, Organic Agriculture

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. Building sustainable cities requires achieving the targeted objectives of participatory, integrated and sustainable human settlement planning and management (UUNN 2016). 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 and walk 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 of territorial efficiency and on the resource use as well (Gingrich et al. 2018, Marull et al. 2019). This affected both, the landscape functioning and the metabolism in open spaces. Hence, although there is a 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 the economic viability of this transition (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). Second, to optimize material and energy flows between food production and husbandry (i.e. closing energy and material cycles at landscape scale (Tello and González de Molina 2017). Third, to improve the autonomy of farms by promoting functional diversification and biodiversity by implementing practices (Marull et al. 2016). Fourth, 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 pressures for economic self-sufficiency of the green infrastructure can be reduced (Thomas and Littlewood 2010). As well, this process would allow to understand aspects that often remain out of focus with the classical cost-benefit analysis: the environmental externalities, the asymmetry of information, and the role and contribution of open spaces as public goods in a wide 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 et al 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 dialectical 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). This would allow the dialogue between agents with an in-depth debate about who and how to face the maintenance of this green infrastructure according to the benefits obtained (Benedict and McMahon 2002). In sum, this complex set of requirements inevitably lead to an integrated analysis.

In this paper, we improve and apply a Socioecological Integrated Analysis (SIA) (Marull et al 2020) to integrate social metabolism variables into territorial planning, through the quantification of the metabolic flows of the green infrastructure land uses. This work has two specific objectives. First, it aims to explore feasible, viable and desirable horizons of the Barcelona Metropolitan Area (BMA) land planning by applying the SIA to different theoretical land use scenarios defined by the Land Use Master Plan (PDU for its acronym in Catalan). Second, it aims to explore 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 hectares (Figure 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%), agricultural lands (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, as well as is present in a more scattered pattern along the Vallès plain and the littoral mountainous range.

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 2016). 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 SIA (Marull et al 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 (Figure 2a): 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 scenarios and not between agricultural management scenarios.

The model relies on one side on the land use cartography and on the other on municipal and regional production and inputs consumption statistics in the 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 nutrients (Marco et al. 2018). 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 itself (Marull et al. 2008). All together compose a set of interrelated models which allow to calculate the set of socioecological 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 (Figure 1) 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 of the BMA (CREAF, 2015). Land cover distributions for each scenario and its description are detailed in Table 2 and changes from the *current scenario* to the *trending* (S1), *alternative* (S2) and *potential* (S3) scenarios are shown in Figure 3.

The *trending scenario* (S1) exemplifies the business-as-usual situation, characterized by an increase of the built-up areas and urban parks, leading to a detriment of the forests, scrublands and agricultural areas. In the *alternative scenario* (S2), there is a change from planned urban parks to productive agricultural areas. Finally, in the *potential scenario* (S3) an important recovery of the pre-existent agricultural areas in the BMA is set (based on an historical land cover map of 1956).

The *trending scenario* (S1), which would be the full implementation of the current municipal urbanistic land planning, suppose an increase in the built-up areas of 5,500 ha (considering as well the urban parks) (Figure 3). The most affected categories are the forest and the scrublands (1,500 and 1,330 has respectively), but it is also relevant the loss of around 25% of current agricultural surface (1,150 has).

The effect of the urban development in S1 is partially reverted in the *alternative scenario* (S2) where much of the urban parks considered in S1 are transformed into agroforestry activities (more than 80%). Also around 520 has of compact urban areas and 600 has of lax urban areas are reconsidered, increasing the total surface of agricultural areas in the BMA from the 4,200 in S1 to 6,950 in S2.

In the last *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 with the exception of those already built-up areas (Giocoli 2017). Regarding new transport infrastructures, that heavily impact on the fragmentation processes, the trend is to increase in more than 720 has its surface in S1, 430 has in S2 and few more than 320 has in S3 (figure 3).

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

To simulate organic agricultural management scenarios, this study 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). Based on the previous sources and for the purpose of this study, we define organic agriculture management is as: i) the complete removal of chemical non-mineral fertilizer use; ii) the complete removal of chemical pesticides and herbicides use; and iii) the limited and regulated use of external inputs (i.e. animal feed and seeds). Under those definitions, organic agricultural practices were assumed (Table A1 in Supplementary Material) to comply with the minimum CCPAE certifying criteria.

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 (DAAAR, 2007);

and iii) all biomass and manure are properly reused (nutrient cycles are closed) and there is no waste flow (biomass discard).

2.4 Cartographic and Statistical Analysis

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). 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=2,467). 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 multi-criterial 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) puts light on the synergies and trade-offs among dimensions through a statistical Exploratory Factorial Analysis (EFA). In this last part of the study (section 3.3), we use results at cell level to identify how the relation among dimensions and scenarios shifts and how changes in the landscape structure affect the metabolism and *vice versa*.

3 Results and Discussion

3.1 Contrasting land planning scenarios and management practices

This is the first time SIA is applied to assess different land cover scenarios and management practices so that relations among dimensions of the socioecological system can be assessed in terms of its contribution for a sustainable development. In this section we analyse how and why contrasting strategies result in a different performances of the green infrastructure's contribution to the metropolitan socioecological system by comparing results at 500 x 500 m cell level and performing bilateral test by scenarios, as shown in Table 3.

In general, the energy efficiency indicator (A1) is higher for all conventional scenarios in contrast to the same scenario with organic agricultural practices, with the lowest A1 value found in the organic trending scenario (S1), although it is not statistically significant. Conventionally managed scenarios with larger agricultural land surfaces (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%. Thus, despite a greater energy efficiency of conventional scenarios, the lesser reliance on external inputs favours 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. 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. 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 cover scenario, mean indicator values under conventional management were always lower than under organic management. These differences are significant for the current (S0), trending (S1) and alternative (S2) scenarios. However, the greater agricultural surface the lower 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), the indicator values are always significantly higher for conventionally managed scenarios, mainly due to the lower yields considered for organic management. These sustained differences (an overall drop on the 17% of the production), 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. 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 surface 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 (Figure 4). This loss of complexity, together with the increase of urban sprawl, would endanger as well 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). 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 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). This makes difficult to close the nutrient cycles, increasing the heavy reliance to 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). This agroforestry recovering in the alternative and potential scenarios, has also potential benefits for biodiversity conservation (B1), which can go in hand with the increase of total agricultural production (E1C), the later with an increase of 2.2-fold 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. 2019b), so that increasing agricultural production by expanding cropping surface 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 (Figure 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 be associated with a decrease of agricultural production (E1C) and energy efficiency (A1). A reduction on the agricultural yields was expected considering the yield factors estimated in the model (De Ponti et al. 2012, Seufert et al. 2012). But the significant energy efficiency decrease on organic practices in the land cover scenarios is also explained because of the elevated use of external inputs, mostly feed and machinery use, despite a decrease of external fertilizers or the complete elimination of herbicides and pesticides.

The effect of an organic transition would significantly reduce aggregate agricultural production (E1C), with an average drop of 17%. 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.

Similarly happens with the slight reduction in the dependence to the 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. 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). 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 above the average.

3.3 Trade-offs and synergies on the socioecological functioning

This last section focuses on the relation found among dimensions in order to better understand the complexity of the green infrastructure as a part of the metropolitan socio-ecological system. 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. 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 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 share contribution of the E1A indicator (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. 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 regulation 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 (Figure 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 two trends observed (land cover scenarios show low sensitivity to landscape variables and high sensitivity to metabolic flows variables) lead us to a draw a relevant statement for policy making in this study: land use planning is affecting much more the metabolic flows than it is normally considered. This tentative hypothesis calls for further research. Finally, organic 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. Something that, again, reinforces this crossed effect of land use planning on metabolic performance and *viceversa* (the effect of metabolic changes on landscape performance).

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 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, food provisioning and agricultural jobs and on 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 impacts of the 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.

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 an 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 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 a PCA 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 overcome 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.

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Tables

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)

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.

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.

Table 4 Principal Component Analysis (PCA).

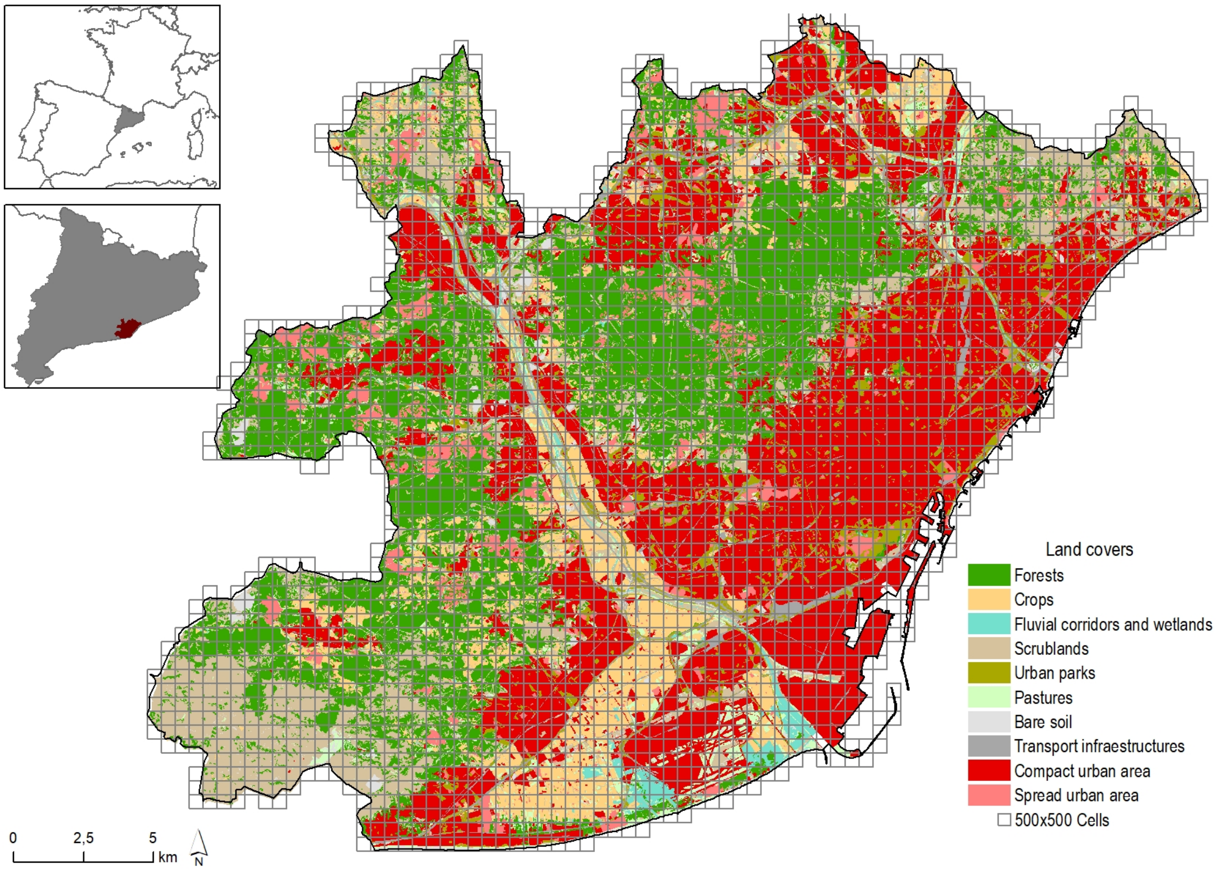
Component	Eigenvalues			Sums of square saturations of the extraction			Sums of square saturations after rotation		
	Total	Variance (%)	Accumulated Variance (%)	Total	Variance (%)	Accumulated Variance (%)	Total	Variance (%)	Accumulated Variance (%)
1	3.36	41.95	41.95	3.36	41.9	41.9	2.77	34.6	34.6
2	1.99	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).

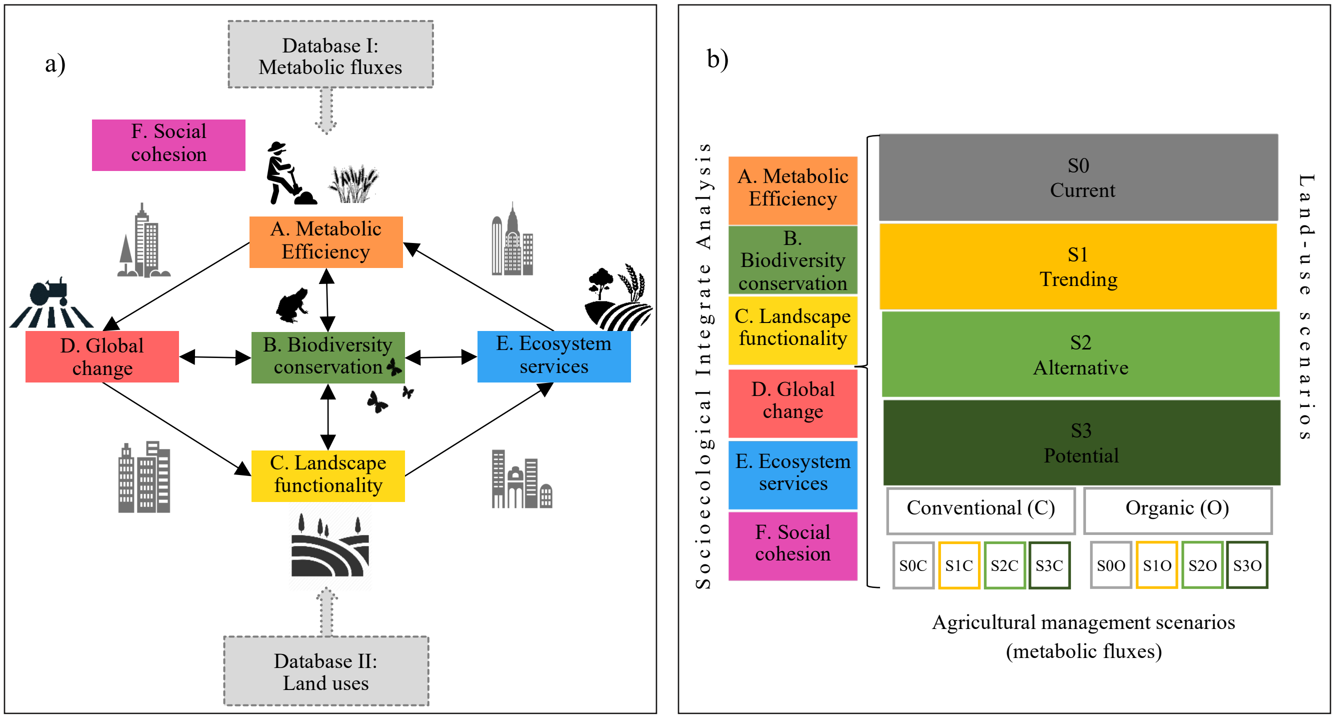
Figures

Figure 1 Land cover map (2015) of the Barcelona Metropolitan Area (BMA).



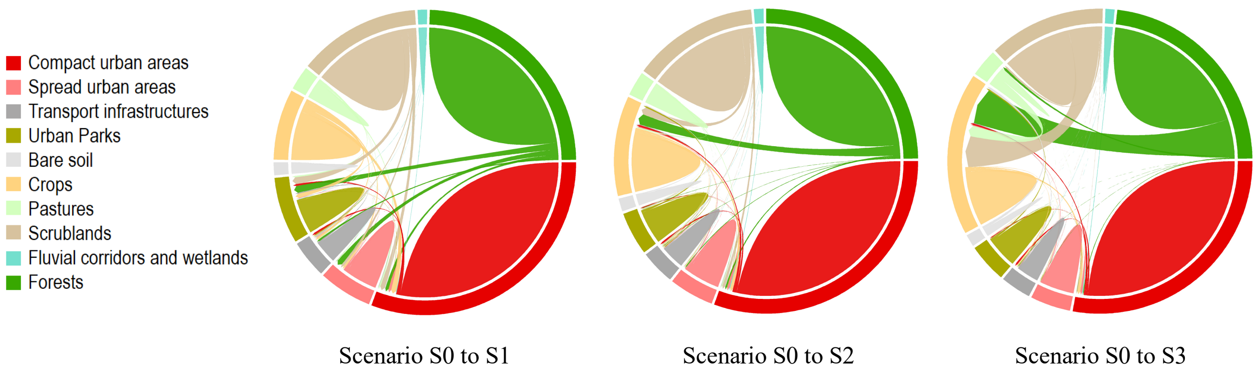
Source: CREAF, 2015.

Figure 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).



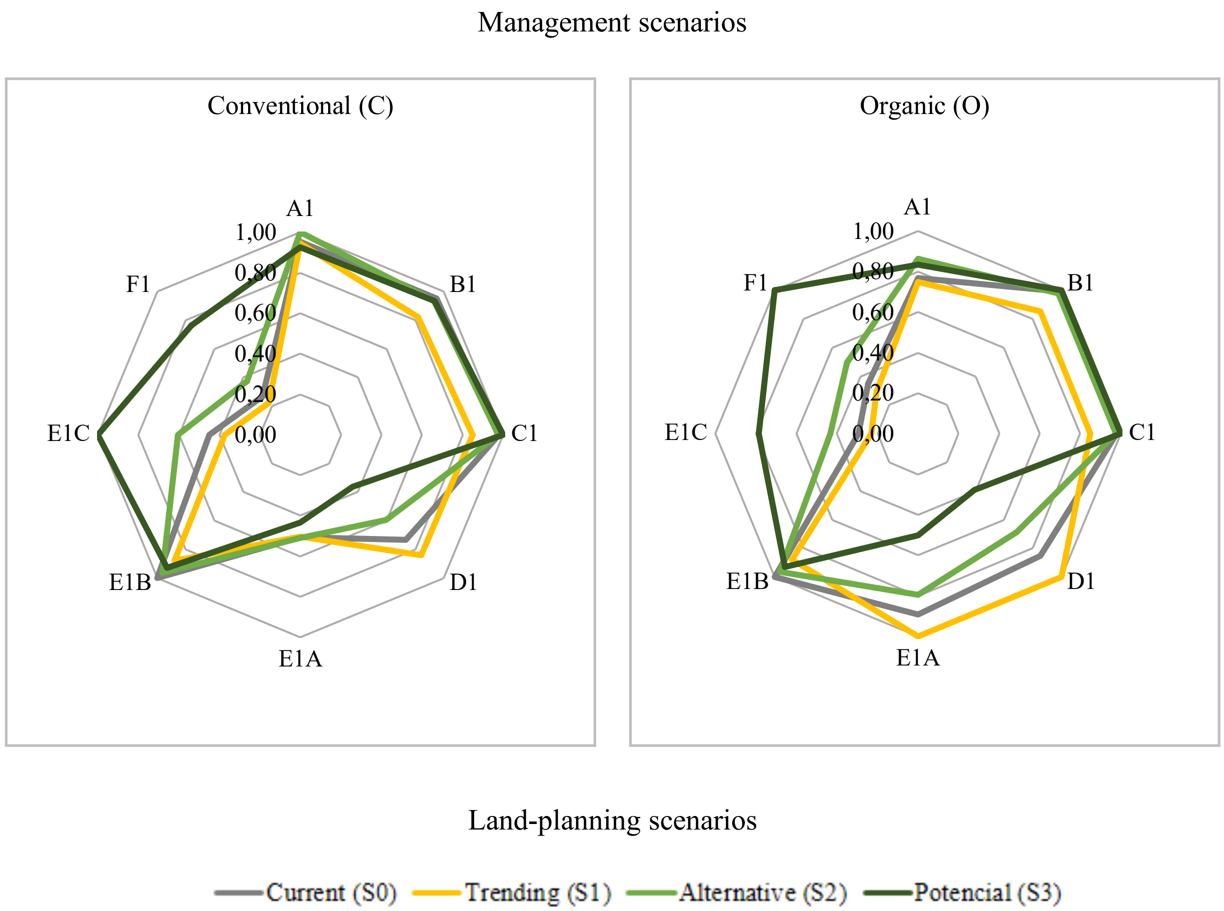
Source: Our own modified from Marull et al. 2020.

Figure 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.



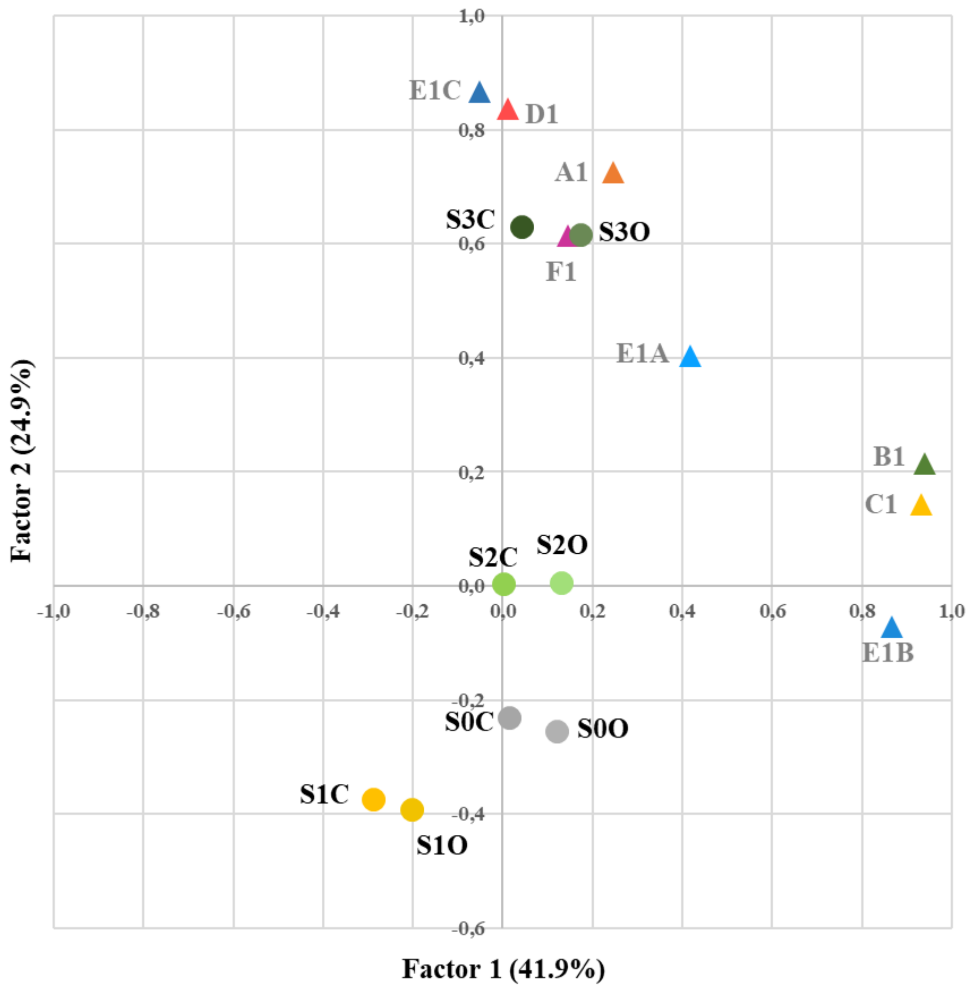
Source: Our own from CREAF 2015.

Figure 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).

Figure 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).

Appendices. Supplementary material

Table A1 Conditions and assumptions for the modelling of conventional and organic scenarios

Dimension	Theme	Conventional	Organic
General definition		Current agricultural management in the MAB defined from land uses, comarcal agricultural production. It relies on chemical intervention to fight pests and weeds and provide plant nutrition and animal feed imports.	Hypothetical scenarios that restrict the use of external agrochemical inputs and animal feeds. Aims to close nutrient cycles whenever it is possible by adjusting the livestock load to the area's resources.
Land use distribution		Land covers based on CREAF 2015 4 Scenarios of land use given by PDU 2019	Same as in conventional. See table 2.
Agriculture	Yields	Current crop yields (DARPA 2015).	Yields per hectare decrease up to 30% (Seufert et al. 2011, De Ponti et al. 2012, CCPAE, 2017).
	By-product management	Olive and vine pomace are considered waste.	Used for animal feeding (olive and vine leaves and pomace)
	Net primary production and waste management	Fruit woodcuts and branches are burn.	Fruit woodcuts and branches are not burned but considered Final Product. Woodcuts are buried and used as compost. Associated biodiversity increases (Guzmán et al., 2014).
	Crop losses due to herbivory	Conventional management factors (Oerke et al. 1994)	Higher than in conventional Factors adjusted to Organic management records (Oerke et al. 1994).
	Fertilization	Chemical fertilization is allowed and unrestricted. (Data sources: MAGRAMA 2015, MAPMA 2015).	The use of synthetic and industrial fertilizers is prohibited The use of synthetic nitrogen fertilizers is prohibited External mineral inputs are only applied when necessary (i.e. In extreme cases of mineral deficiencies) and must proceed from natural sources and authorized products by the CCCPAE. Organic in-bound fertilization: use of unharvested biomass as compost (i.e. woodcuts) and local manure.
	Pesticides and herbicides	Chemical management is allowed and unrestricted (data sources: MAGRAMA 2015, MAPMA 2015).	Chemical management is restricted. The model assumes zero input of chemical inputs.
	Seed source	Local and imported seeds.	Reused from local production. No imports.
Husbandry	Size (number of animals)	Actual livestock units as given by the DARPA (2015) at municipal, comarcal and provincial scale. In addition, the agrarian census 2009.	Adjustment of the livestock cabin with regard local food availability (see diet conditions below).
	Diets	Used of type- diet for each species (Flores and Roriguez-Ventur 2014) adjusted for ovine and caprine grazing.	Minimum 60% of the animal diet should come from local production. Minimum daily ration of common forages (Animal feed consumption limit): Herbivores: 60% (40%) Poultry and pigs: 20% (60%) Grazing adjusted by minimum advised outdoor (grazing) time (CCCPAE 2017).
	Manure management		Surplus use optimized according to agricultural nutrient requirements of local and organic production.
	Animal life cycles and productivity		Longer life cycles Meet, milk and eggs production was adjusted to life cycles of each species under Organic management.
Labour	Human labour	Base data from the 2009 Agrarian census.	Overall increase of human labor (up to 20%) (Departamento de Agricultura, Alimentación y Acción Rural – Generalitat de Catalunya, 2007).

Figures A1-A11 Socioecological Integrated Analysis (SIA) – Barcelona Metropolitan Area (BMA)

The SIA results through their territorial expression along the BMA (500x500 m sample cells) is presented in the supplementary material, which includes all the maps generated by the different indicators applied to each of the considered scenarios and a detailed analysis.

The first transition, from current scenario (S0C) to trending scenario (S1C), shows a marked change that would occur along the all the six dimensions of the green infrastructure in the socioecological system with a general trend on weakening its contribution. However, this impact is not homogeneous along the territory nor for all the dimensions. Even indicators such as the soil nutrient recirculation (E1A) experience an increase at aggregated level mainly due the slight increase in the values all along the agricultural areas in the *Llobregat* region, despite the big losses in other municipalities such as *Montcada i Reixac* and *Cerdanyola*. On the contrary, the effect for energy efficiency (A1), biodiversity conservation (B1), landscape functioning (C1), social cohesion (F1) and provisioning and regulatory ecosystem services (E1C and E1B), is negative. The loss in B1 is greater than C1 as the impacts are deepen in *Cerdanyola*, *Gavà* or along the agro-forestry mosaics that connect from *Castellbisbal* to *Sant Feliu de Llobregat* municipalities. As well, losses on carbon stock (E1B) have a similar pattern as B1 but also include another spot that scores low in the bottom of *Montcada* as well as on the southern part of *Serralada de Marina*.

The alternative scenario (S2C) keeping the conventional management shows a more balanced situation compared to the trending scenario (S1C) and some aggregated improvements too. The greatest ones are those for the agricultural production (E1C) especially in the mountainous range located between *Badalona* and *Tiana* but in *Sant Feliu* and *Gavà* too, despite the losses along the *Delta of the Llobregat*. This goes in hand with a significant increase in the energy efficiency (A1) in the same regions as well as all along the municipalities located in the eastern part of the area. On the contrary, the general impacts on A1, B1 and E1B are still relevant in *Cerdanyola*, northern part of *Montcada i Reixac* and on the surroundings of *Begues*.

If there is a shift from the alternative conventionally managed scenario to an organic one (S2C to S2O), there are many differences associated to the loss of productivity but also an improvement on functionality. These trade-offs result in polarizing the tendencies along the BMA. For example, in S2O, a check on how for energy efficiency (A1), despite a decrease in the municipalities from the *Vallès County* and those in the *Delta of the Llobregat*, the increase in efficiency in other municipalities result in an overall improvement of the whole efficiency. In terms of the soil's nutrient recirculation (E1A) it is apparent also that compared to S2C there is a massive increase on the nutrients recirculation. Something similar happens with the agricultural jobs (F1). Finally, the non-renewable external inputs (D1) comparatively decline in the organic scenario (S2O), consistent with the trends observed in table 3.

As expected, a transition towards a potential conventionally managed scenario (S3C) results in an increase of agricultural production (E1C) (due to the agricultural land expansion), especially in the coastal zones. However, an increase in E1C is additionally associated with a surge on the non-renewable external inputs (D1) and a general loss on carbon stock (E1B). This is a general trend with an exception in some areas of the *Delta of the Llobregat*. An expansion of agricultural areas also translates into an overall rise of agricultural jobs (F1). However, the magnitude of this increase depends on the type of crop. As a result, areas with orchards and fruit trees as the predominant crops will present higher labor demands. In terms of nutrient recirculation (E1A), the general trend is a decline while some municipalities such as *Montcada i Reixac* and Castellbisbal experience an increase. Finally, the restoration of agricultural areas affecting the mountain range from *Papiol* to *Sant Just Desvern* translates into an improvement of the landscape complexity (C1), an interesting result that reinforces the importance of these land covers as key socioecological elements of the metropolitan landscapes.

The last transition, towards the potential scenario organically manage (S3O) presents a similar trend as the explained towards the other organic scenario (S2O). Here, the effect of changing the metabolic functioning is particularly positive for the metabolic efficiency (A1), the energy-landscape integration (B1), the soil's nutrient recirculation (E1A) and the agricultural jobs (F1). Even so, despite the agricultural production (E1C) decreases in yield per hectare, the increase in surface supposes an increase in the overall production of the area.

Figure A1 Territorialized Socioecological Integrated Analysis (SIA) indicators for the current land planning scenario under conventional agricultural practices (S0C)

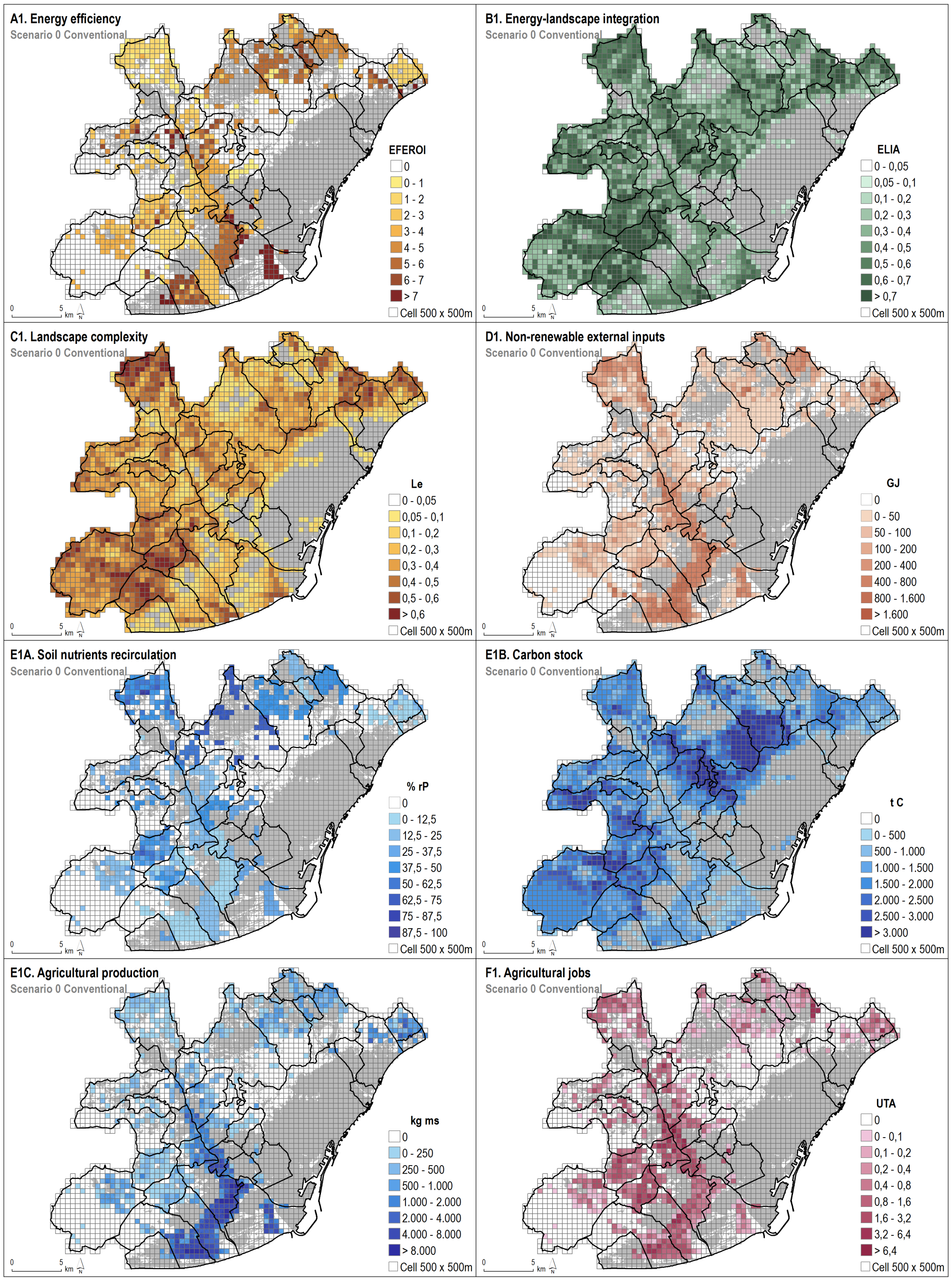


Figure A2 Territorialized Socioecological Integrated Analysis (SIA) indicators for the trending land planning scenario under conventional agricultural practices (S1C)

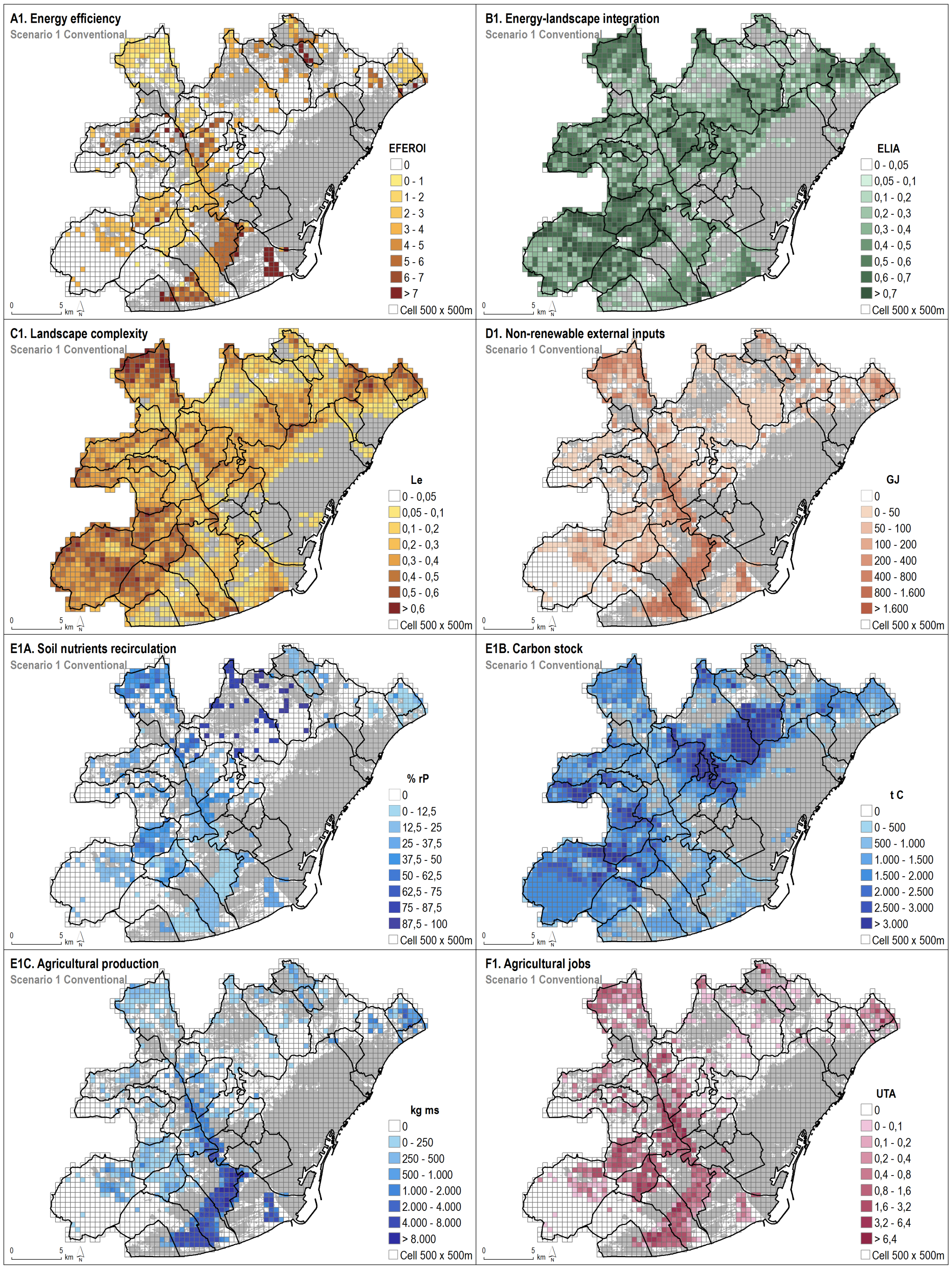


Figure A3 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario between current conventional (SC0) and trending conventional scenario (SC1).

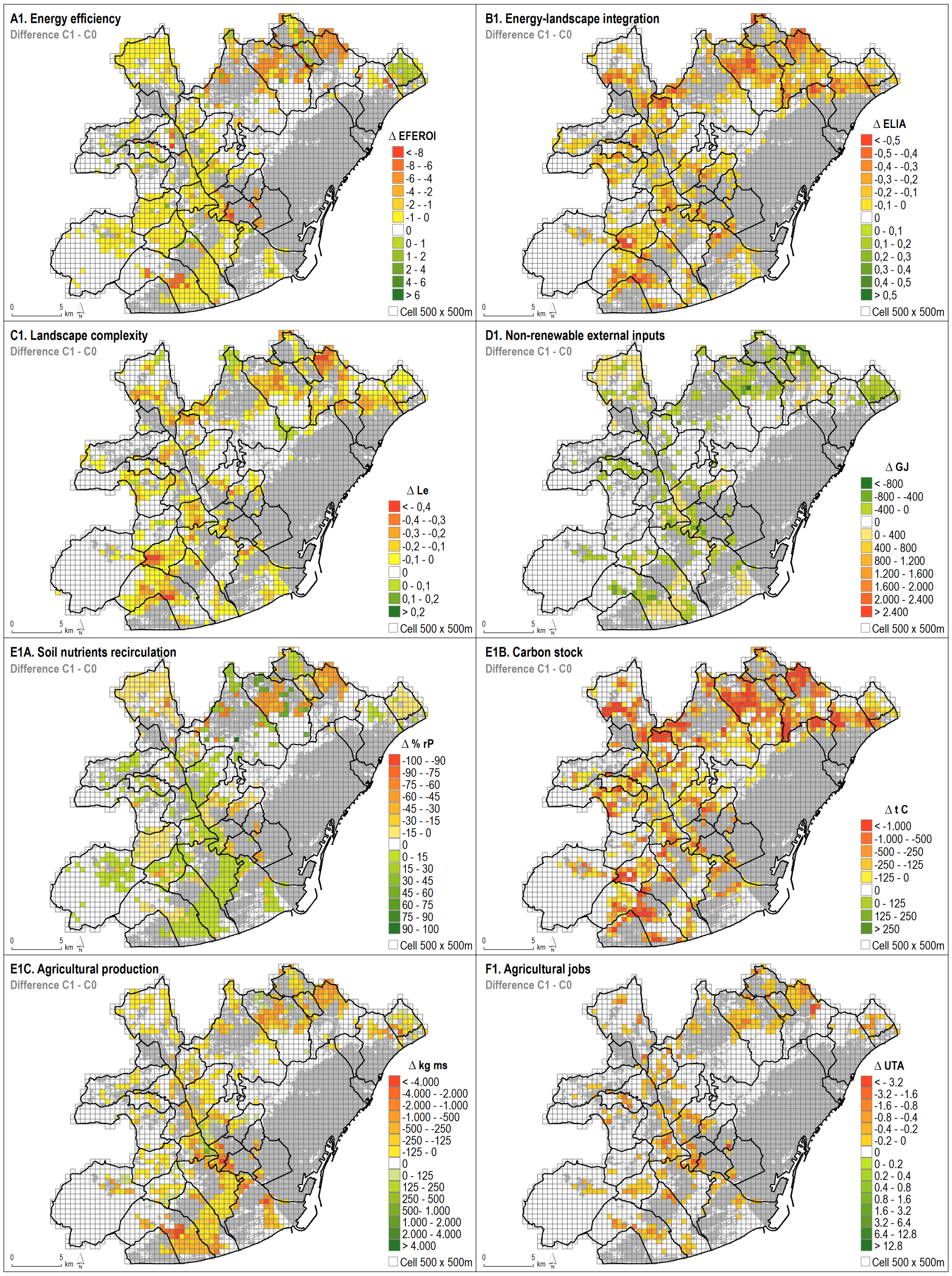


Figure A4 Territorialized Socioecological Integrated Analysis (SIA) indicators for the alternative land planning scenario under conventional agricultural practices (S2C)

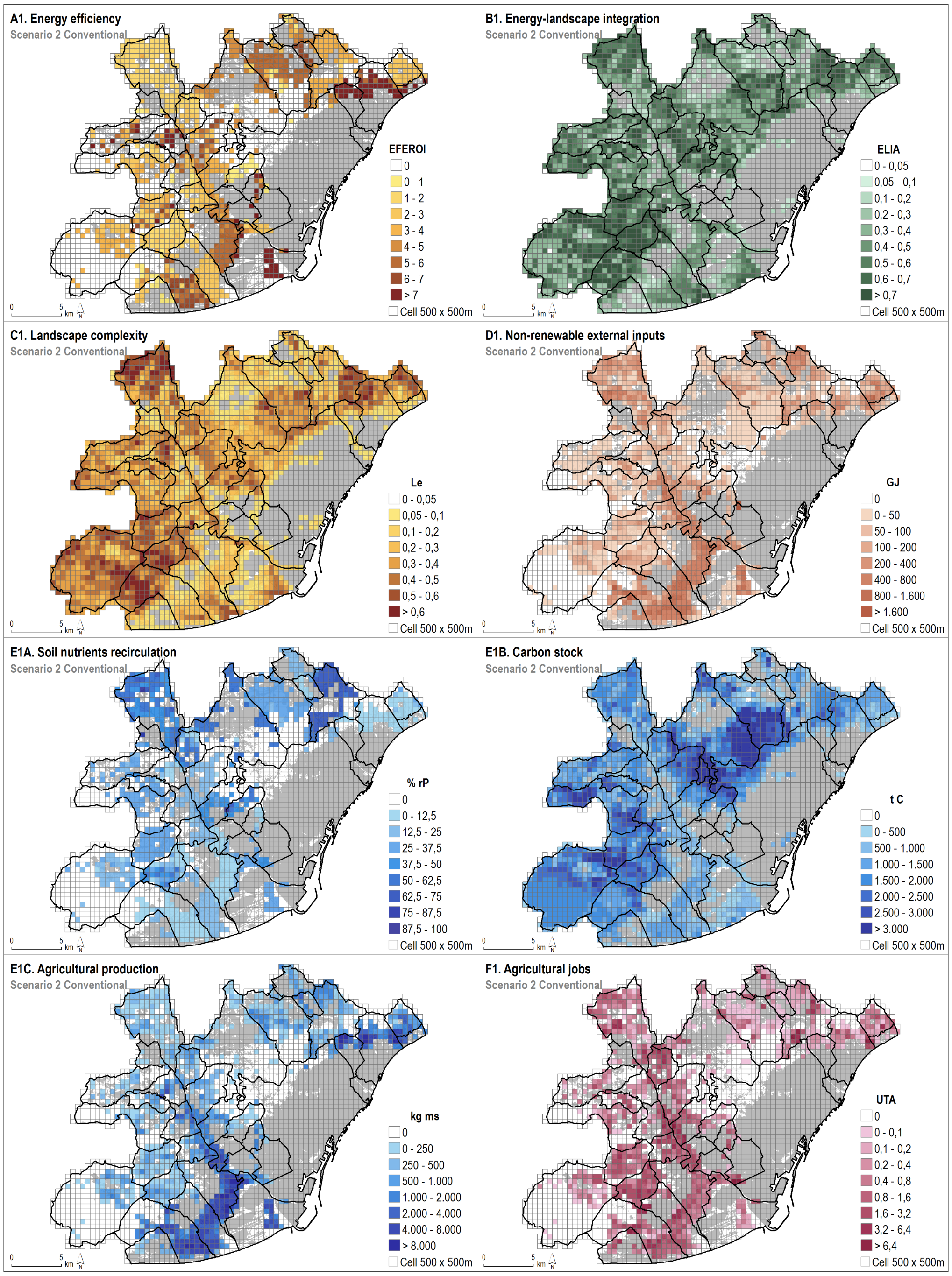


Figure A5 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario between current conventional (SC0) and alternative conventional scenario (SC2)

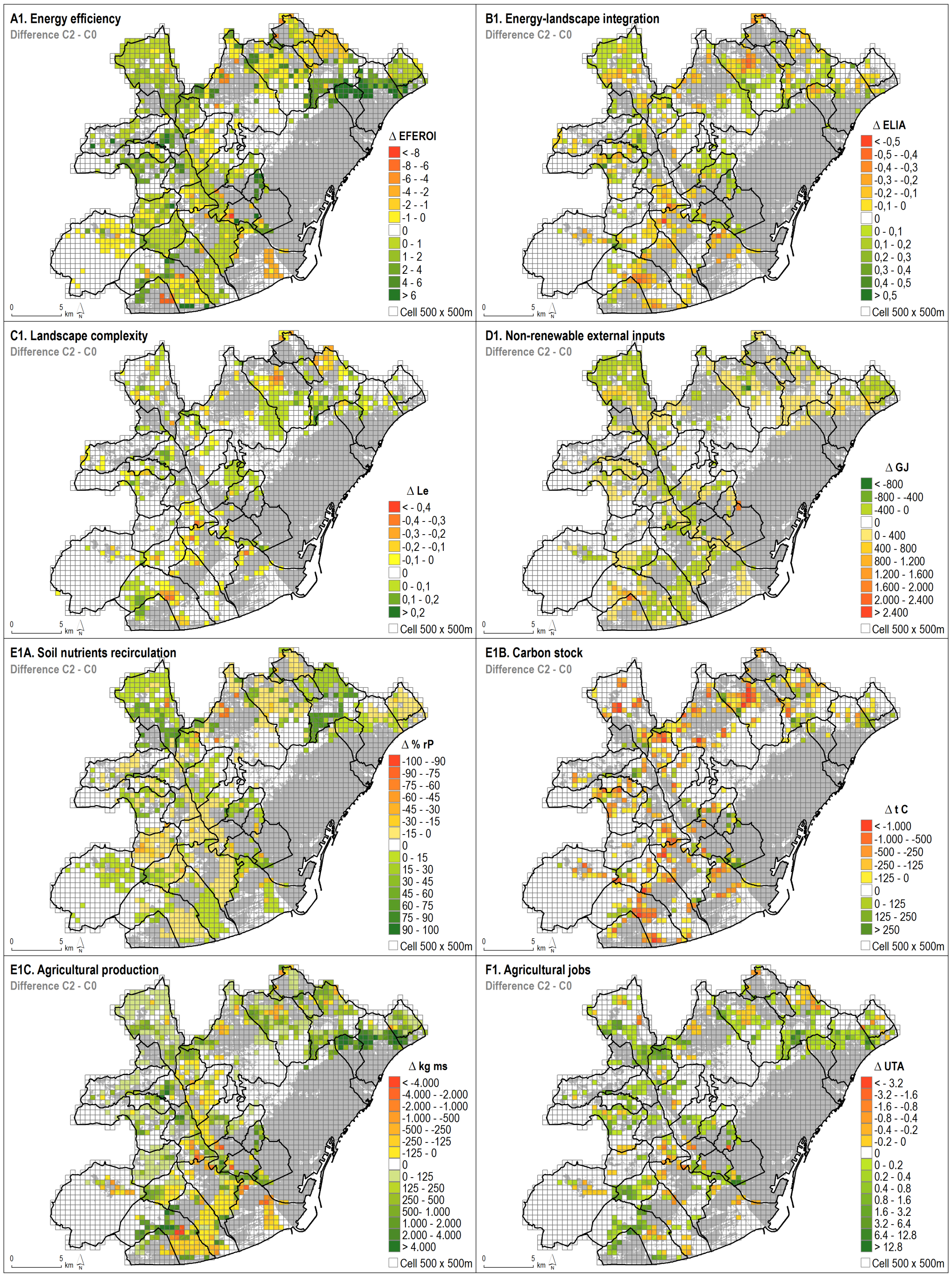


Figure A6 Territorialized Socioecological Integrated Analysis (SIA) indicators for the alternative land planning scenario under organic agricultural practices (S2O)

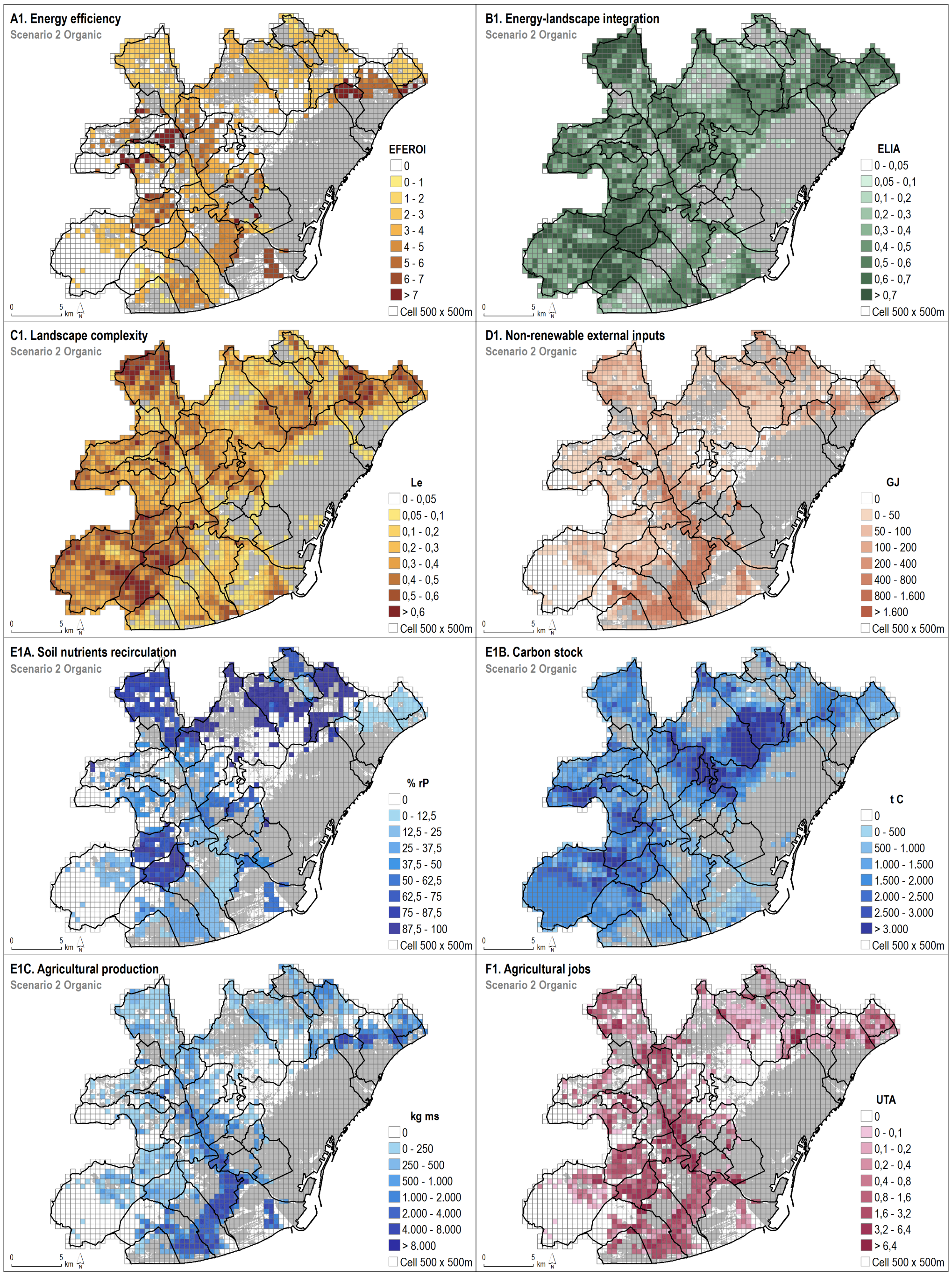


Figure A7 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario from the current conventional (SC0) to an alternative organic scenario (SO2)

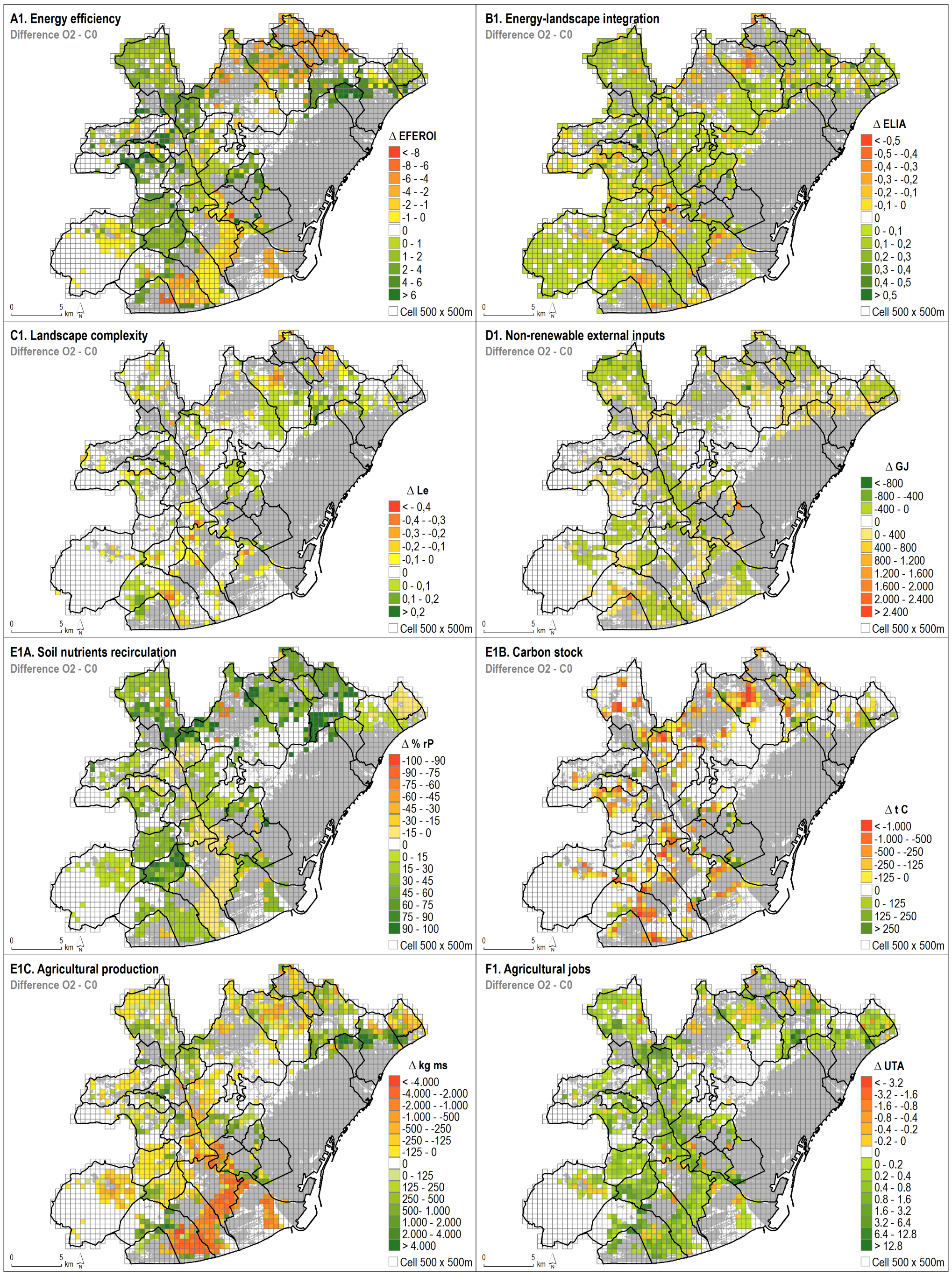


Figure A8 Territorialized Socioecological Integrated Analysis (SIA9 indicators for the potential land planning scenario under conventional agricultural practices (S3C)

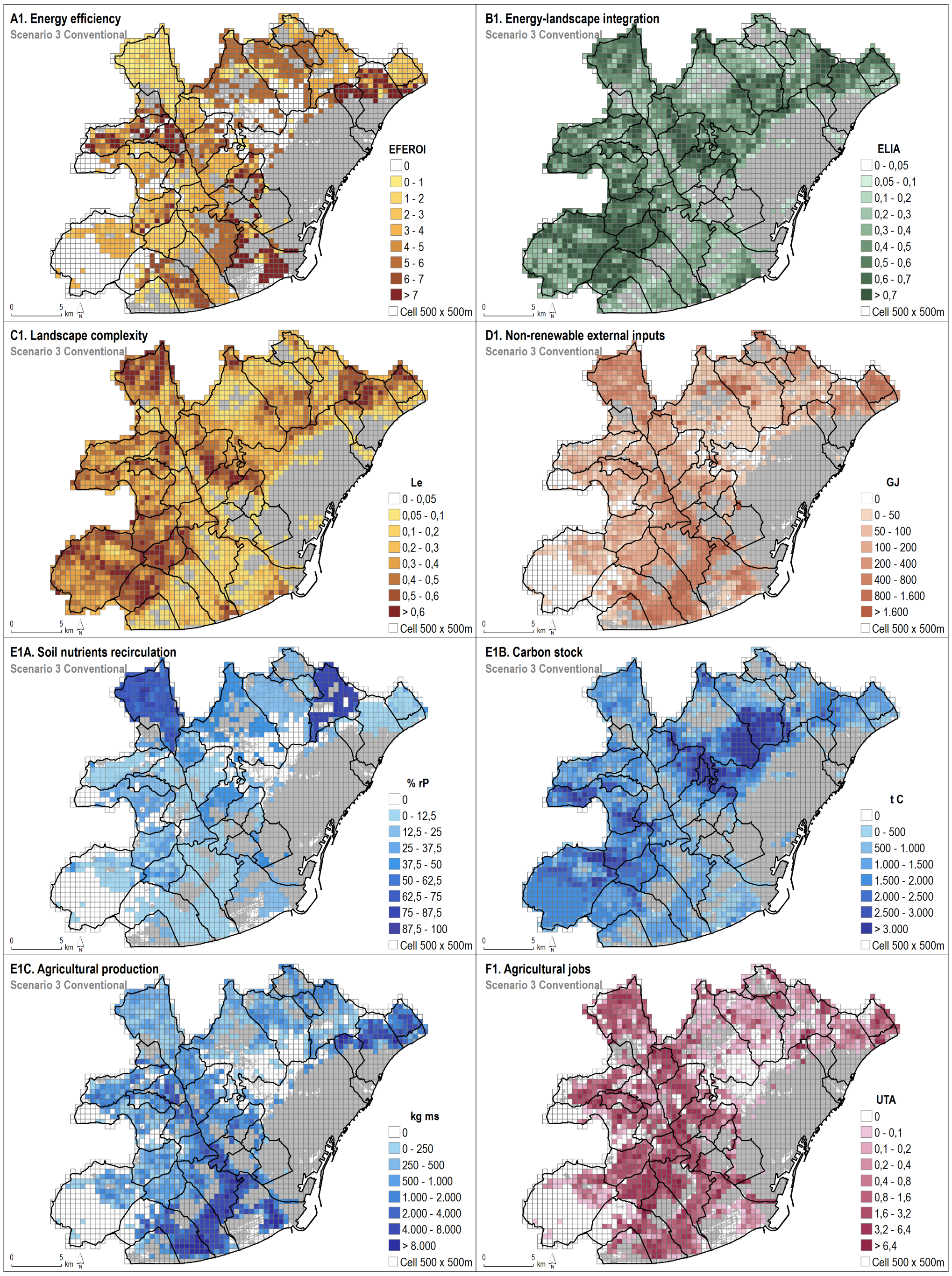


Figure A9 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario from the current conventional (SC0) to a potential conventional scenario (SC3)

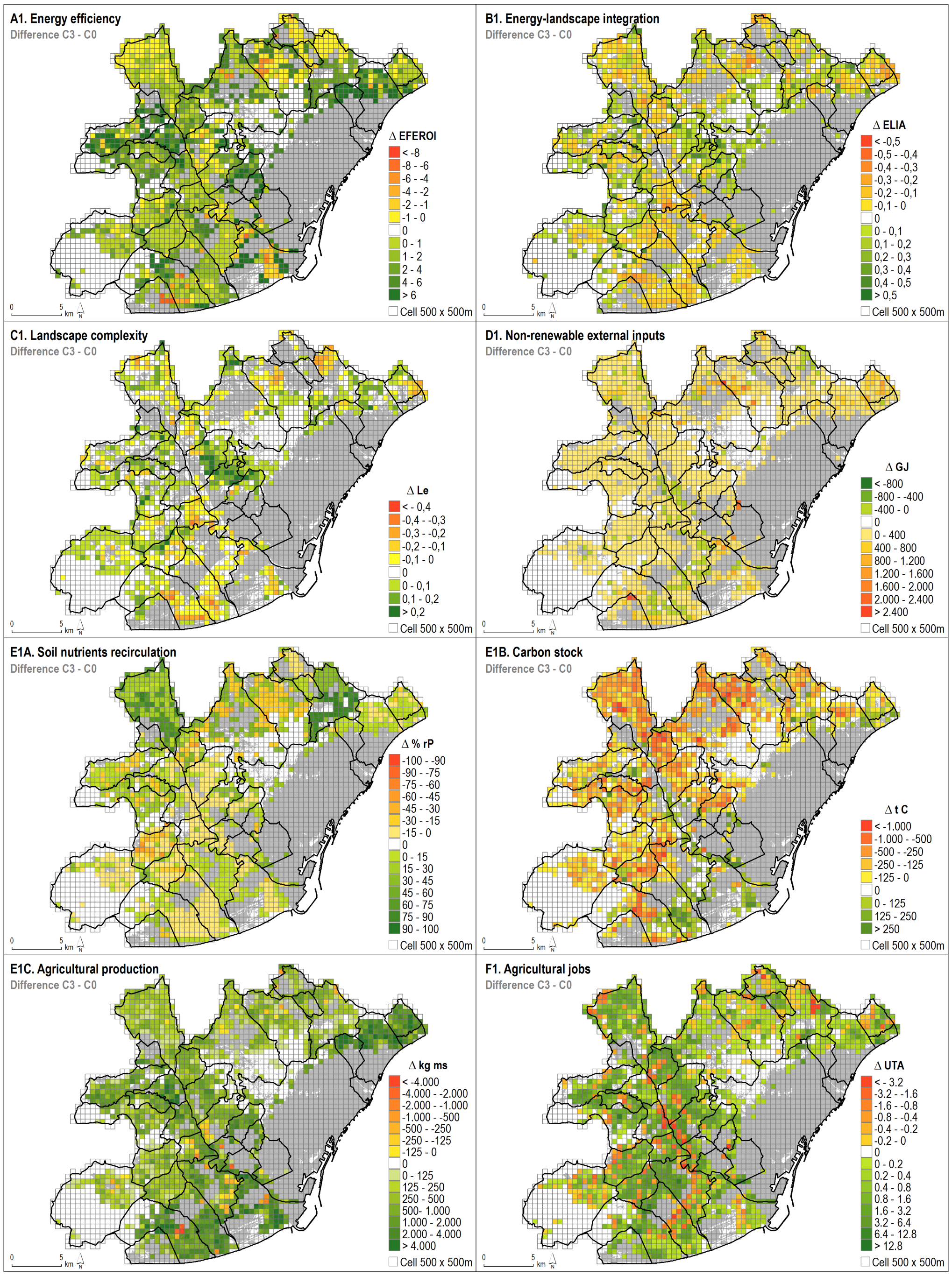


Figure A10 Territorialized Socioecological Integrated Analysis (SIA) indicators for the potential land planning scenario under organic agricultural practices (S3O)

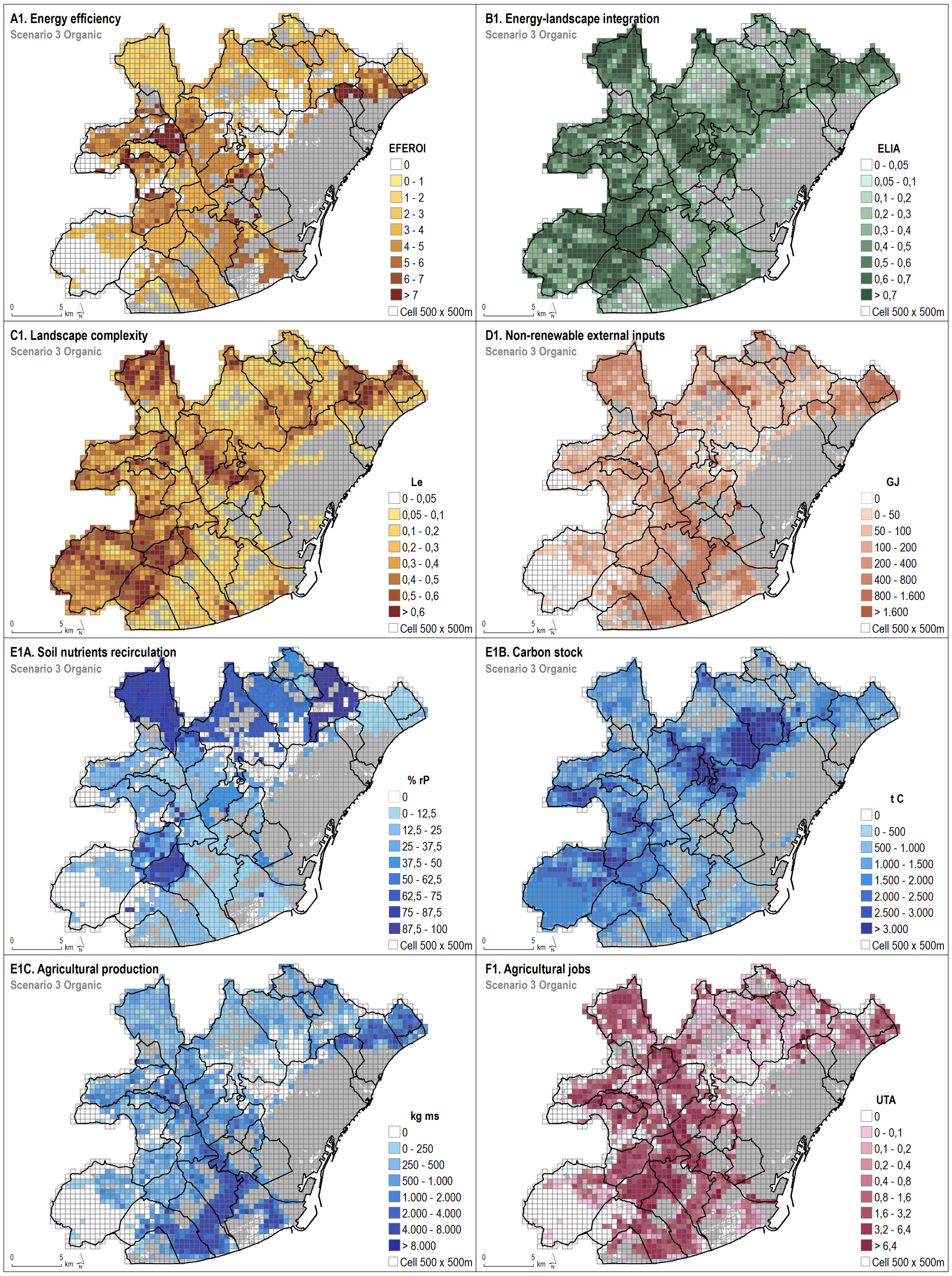


Figure A11 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario from the current conventional (SC0) to a potential organic scenario (SO3)