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Modelling Land Use Planning: Socioecological Integrated Analysis of Metropolitan Green Infrastructures

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Abstract

Land use planning of global metropolis is essential to meet the socioecological challenges of the next decades. This paper aims to contribute to sustainable land use policies by proposing a socioecological integrated analysis of metropolitan green infrastructures, applying this landscape-metabolism model to the Urban Master Plan of the Barcelona Metropolitan Area. The paper assesses the multiple functions and services of the green infrastructure in four land use scenarios and two types of agricultural management. The results show that the trending scenario of applying the current land use planning would have a negative impact in the ecological functioning of the landscape, affecting biodiversity and the provision of ecosystem services to society. The results also show that certified organic farming is not enough to overcome some trends of industrial agriculture as low energy efficiency or greenhouse gas emissions. Finally, the results show different interactions between social metabolism and landscape ecology, as changes in the form of metabolism affect the functioning of the landscape, while changes in land cover specially affect resource use. Therefore, deeper changes are needed in land use policies that consider not only land covers, as has traditionally been done, but also metabolic flows to promote agroecological transitions towards more sustainable metropolitan green infrastructures under climate change scenarios.

Keywords

rural land use; landscape planning; agroecological transition; green infrastructure; multicriterial analysis; ecosystem services

1 Introduction

The United Nations' population estimate of 9.8 billion people inhabiting the planet by 2050 is accompanied by a growth factor of 2 to 3 on the global energy and materials demand (Krausmann et al. 2008). We are reaching planetary limits, facing challenging global climate change scenarios (IPCC 2022) and biodiversity loss, among others (Steffen et al. 2015). As never before, a global consensus calls for the urgent need to change nature-society relationships and promote socioecological transitions towards more sustainable land uses and related metabolisms in human-transformed landscapes (Tilman et al. 2002). One essential dimension of social metabolism, both historically and at present, relies on agricultural systems. Inside these systems, energy, materials, and information constantly enter, exit, and recirculate, not only altering but ultimately shaping the territories (Font et al. 2020). Although agriculture has been the basis of subsistence for our societies, current agricultural systems have reached a critical transition point in their performance, environmental impacts, and energy patterns (Gingrich and Krausmann 2018). Specifically, agricultural and food systems are directly related to five of the nine planetary boundaries (Steffen et al. 2015): global climate change, land-system changes, biosphere integrity, freshwater use, and biogeochemical flows. The predominantly resource-intensive agricultural systems have impacted biogeochemical cycles and degraded soils (Tilman et al. 2011). Agro-industrial systems have also been closely related to biodiversity losses worldwide (Tscharntke et al. 2005). Since the Green Revolution, agriculture went from being a provider to a net energy consumer (Pelletier et al. 2011). Today agri-food systems are responsible for nearly one-third of the world's greenhouse gas emissions (Crippa et al. 2021), mainly originated by the production procedures (i.e., land use change, fertilizer applications, irrigation, and machinery use).

Metropolitan areas are key cases to study these sustainability challenges. Today, near to 55.3% of the world's population (4,220 million people) live in urban areas, and it is estimated that by 2030, 5,167 million people (60.4% of the world's population) will live in a city of at least 500,000 inhabitants (UN 2019). Urban growth poses great challenges that involve the peri-urban and rural matrix in which they are usually integrated. These issues are especially concerning food security (Satterthwaite et al. 2010), climate change mitigation and adaptation (Demuzere et al. 2014), water quality and availability (Madrid et al. 2013), waste management (Chen 2007), and habitat degradation and fragmentation (Fischer and Lindenmayer 2007), compromising their ecological functionality and its ability to provide multiple ecosystem services (Riley et al. 2003; McDonald et al. 2013; Liu et al. 2016). Under this scenario, metropolitan agriculture can play various roles both as a driver or mitigator of unsustainability (Cattaneo et al. 2018). Therefore, comprehensive, scientifically supported and socially viable land use management and planning of metropolitan areas, is essential to meet the socio-ecological challenges of the next decades (Darvishi et al 2020; Marull et al. 2021; Mendoza-Beltran et al. 2022; La Rota-Aguilera et al. 2023). This implies the consideration of a myriad of interactions between ecological, economic, social, cultural, and technological perspectives along the urban-rural gradient (Padró et al. 2020). Specially, incorporating the agrarian systems to metropolitan landscape planning through the notion of the 'green infrastructure' (Benedict and Mcmahon 2002), as one specific example of nature-based solutions to biological conservation, ecosystem service supply and territorial resilience, while warranting social and economic benefits for its population, improving climate change adaptation and mitigation (Maes and Jacobs 2017).

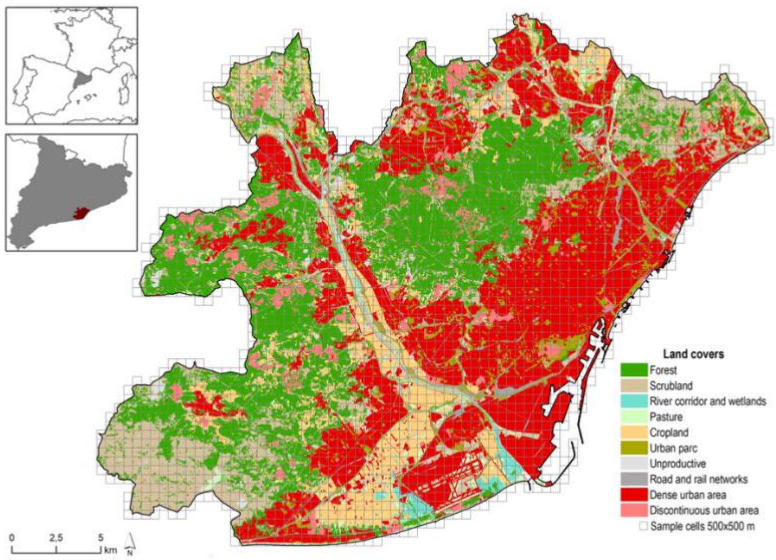
The scientific consensus states that a systemic change in the global food system is crucial to achieving the Paris Climate Agreement and the Sustainable Development Goals: only replacing non-renewable energy sources is not enough (Clark et al. 2020). As well, European strategies such as Farm to Fork or the Biodiversity Strategy call for a new agenda transforming these green infrastructures (European Commission 2020). Although the concept of green infrastructure is widely recognized in urban development plans, the existing methodologies for assessing the effect of each of its elements on its structure, functioning, and impact on the metropolitan system are still under development (Xu et al. 2018; Darvishi et al 2022; La Rota-Aguilera and Marull 2023). In this article we will assess the contribution of agriculture to metropolitan sustainability, and the possibilities that it offers to transform food systems to mitigate climate change and biodiversity loss (FAO 2019). The objective of this article is to evaluate the contribution of agriculture to the sustainability of metropolitan areas, through the development of a Socioecological Integrated Analysis (SIA) that enrich our capacity to propose green infrastructure scenarios for sustainable land planning purposes.

2 Methodology

2.1 Case study

The case study includes the whole Barcelona Metropolitan Area (BMA), formed by 36 municipalities, a total area of 63,611 hectares, and a population of 3.3 million inhabitants (IDESCAT 2019). According to the latest land cover map (CREAF 2016), open spaces are still the majority (55%), divided between forests and woodlands (42%), agricultural areas (8%), pastures (3%), and other open spaces (2% river corridors, wetlands). The remaining 45% of the BMA includes compact and disperse urban areas, and transport infrastructures (**figure 1**). The study includes all the current open spaces, defined by the planning proposal as non-developable urban land, as well as the urban park network, due to their contribution in both structural and functional aspects of the green infrastructure, as is also included in the Urban Master Plan (PDU) (AMB 2019). The unit of analysis are cells of 500 x 500 meters, obtaining a total of 2,326 cells covering the entire BMA.

Figure 1 Major land covers in the Barcelona Metropolitan Area (BMA)



2.2 Planning scenarios

The analyses were carried out on four theoretical land use planning scenarios defined by the PDU (**figure 2**). *Current* scenario (S0): represents the current land cover situation of the BMA (CREAF 2016), it offers the baseline diagnosis to draw comparisons with the land planning scenarios. *Trending* scenario (S1): it exemplifies the strict application of the current urban planning of all the metropolitan municipalities, implying an increase in urbanized areas and urban parks. *Alternative* scenario (S2): it considers that there is a transformation of the planned urban parks into agricultural areas as well as the cultivation of certain sectors of doubtful urban consolidation, thus increasing the agricultural surface area by 65%. *Potential* scenario (S3): it implies the possible recovery of agricultural areas in the BMA and is based on the 1956 land cover map (it is considered to correspond to the most suitable areas for agriculture, where it is still possible), which represents an increase of more than 150% compared to the current agricultural area (Giocoli 2017).

Figure 2 Theoretical scenarios defined by the Urban Master Plan (PDU) of the Barcelona Metropolitan Area (BMA) used in the Socioecological Integrated Analysis (SIA) model

		Description	Scenarios		
Land Use Planning	S0. *Current*	Obtained from the latest available land cover map	**S0 C**	C. *Conventional*	*Agroecological Transition*
			S0 O	O. *Organic*	
	S1. *Trending*	Business-as-usual situation, with the full implementation of the current land plans	**S1 C**	C. *Conventional*	
			S1 O	O. *Organic*	
	S2. *Alternative*	Change from planned urban parks to productive agricultural areas	**S2 C**	C. *Conventional*	
			S2 O	O. *Organic*	
	S3. *Potential*	Recovery of all pre-existing agricultural areas, when possible	**S3 C**	C. *Conventional*	
			S3 O	O. *Organic*	
Green Infrastructure Characterization		**Socioecological Integrated Analysis**		*Agricultural Management Practices*	

The four planning scenarios (**figure 2**) correspond to a greater or lesser degree of urban development and in the application of the land uses defined in the current urban plan, as well as the application of measures for the permeabilization to ecological connectivity of current and planned transport infrastructures. Additionally, each of these land planning scenarios (S0-S3) was evaluated using the SIA model under two types of agricultural management (conventional *vs* organic), considering changes in the way natural resources and external inputs are used inside agricultural and livestock systems (Padró et al. 2019). Conventional agriculture scenarios reproduced the current main management conditions reflected in the 2009 agricultural census. This census was updated taking 2015 as a reference year. To simulate the scenarios of organic management, the study followed the guidelines to produce certified organic food and animals established by the legislation of the European Commission (834/2007, 889/2008, 1235/2008) and the Catalan Council of Organic Agricultural Production (CCPAE 2017). The parameters required for organic agricultural management are defined according to the following criteria: total removal of the use of non-mineral chemical fertilizers; removal of the consumption of chemical pesticides and herbicides; and limited and regulated use of external inputs. A shift to organic agricultural management also has other biophysical implications: reduction in agricultural yields per unit area or animal output per unit time (de Ponti et al. 2012; Seufert et al. 2012), labor requirements and machinery use (DAAR 2007), the amount of unharvested biomass generated, or the management of animal manure (Villamor et al. 2020).

2.3 Delimitation of the categories of open spaces

To define the categories of open spaces, the structural components of the green infrastructure were considered. These components work together to maintain a network that supports ecological processes and provide ecosystem services (Benedict and McMahon 2002). The definition started from the proposal of categories of the PDU preliminary reports (AMB 2019). The proposal presented here is based on a delimitation of the current structural characteristics of the open spaces, considering both the dynamics of the metropolis (i.e., the spaces in transition) and a landscape ecology approach. The structural delimitation (such as the minimum surface area of a category) was adapted to the specific conditions of the BMA. **Table 1** summarizes the 6 categories and 17 subcategories established for the metropolitan green infrastructure.

Table 1 Criteria for the definition of categories and subcategories of open spaces proposed for the green infrastructure of the Barcelona Metropolitan Area (BMA)

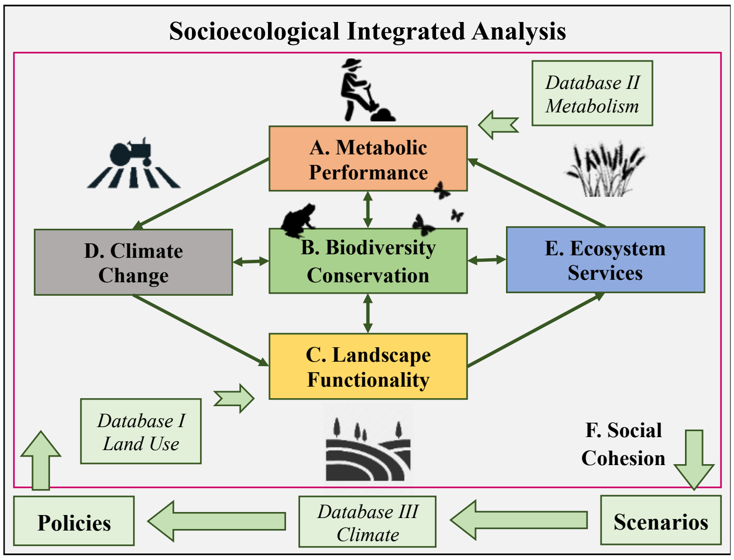
Category	Subcategory	Defining criteria
Conservation core areas	Forest	Forest polygons > 100 ha
	Scrub	Shrub polygons > 100 ha
	Wetland	Wetland's polygons > 25 ha
Specialized agricultural areas	Irrigated crops	Irrigated fields with polygons > 10 ha
	Dryland crops	Dryland fields with polygons of > 25 ha
Mosaic or transition areas	Mosaic landscape	Mixed areas formed by forest, scrub, pastures, crops, corridors, or wetlands, larger than 40 ha, and with more than 10% of the crop (irrigated or rainfed) area
	Agricultural space in transition	Polygons that are not part of the landscape mosaic and limit with a conservation core area or specialized agricultural area, and with urban space at the same time. It has more than 5% of agricultural uses.
	Forest space in transition	Polygons that are not part of the landscape mosaic and limit with a conservation core area or specialized agricultural area, and with urban space at the same time. It has less than 5% of agricultural uses.
Riparian areas	Shores and riparian vegetation	It includes river surfaces, riverbeds, and riparian vegetation that have an area of more than 1 ha.
	Space adjacent to the river course	Open space polygons that do not form conservation core areas, mosaics, or specialized agricultural areas, and are adjacent to riverbeds or riparian vegetation
Interstitial areas	Interstitial in conservation areas	Open space polygons inside conservation core areas without sufficient entity to be specialized agricultural areas or areas with agrarian dynamization.
	Interstitial in agricultural areas	Open space polygons inside specialized agricultural areas without sufficient entity to be specialized agricultural areas or areas with agrarian dynamization.
	Interstitial associated with urban parks	Open space polygons inside an urban plot that intersects with an urban park with a minimum surface area of 2 ha.

	Interstitial in an urban matrix	Open space polygons inside an urbanized plot that do not intersect with any urban park larger than 2 ha.
	Interstitial in infrastructure	Open space polygons surrounded by infrastructure
Landscaped or restored areas	Urban parks	Urban parks estates
	Beach	Polygons of the recreational bathing area and maritime dune system

2.4 Modeling application to the open spaces' proposal

To evaluate the socioecological contribution of the green infrastructure to the BMA, the SIA model was applied. A detailed description of the SIA model can be found in Marull et al. (2021). This model integrates social metabolism and landscape ecology analyses to assess how different land use or agricultural management scenarios can alter the contribution made by the green infrastructure to the overall system. The research presented in this article considerably improves previous versions of the model, including water consumption (as a limiting factor in agriculture), biomass appropriation (due to its importance for biodiversity) and greenhouse gas emissions (due to its impact on climate change). This landscape-metabolism model has six interrelated dimensions (**figure 3**): A *Metabolic efficiency*; B *Biodiversity conservation*; C *Landscape functionality*; D *Climate change*; E *Ecosystem services*; and F *Social cohesion*.

Figure 3 Socioecological Integrated Analysis (SIA) of the metropolitan green infrastructure of Barcelona, considering six interrelated dimensions



The SIA assessment requires linking the different dimensions of the socioecological system accounted (**figure 3**) with the indicators that evaluate them (**table 2**). The SIA modelling is fed by two fundamental sources of information: land covers and socio-metabolic flows. The socio-metabolic flows are established among the four funds of the agroecosystem: land uses, livestock, landscape, and society. The six dimensions of the metropolitan green infrastructure are characterized by 10 interrelated indicators:

A1A *Energy efficiency*, which measures the amount of energy obtained in the agricultural areas according to the amount of external energy invested (Tello et al. 2016). This agricultural metabolic balance determines the input and output energy flows of each crop per land unit of analysis. This allows observing the relationships between the different fund components, especially between livestock and agricultural uses, and the degree of dependence on external inputs to produce useful biomass, while meeting the needs of soil nutrients replenishment, animal nutrition and reproduction of human labor.

A1B *Water consumption*, which estimates the theoretical amount of water used by the metropolitan green infrastructure (Madrid et al. 2013). It is based on meteorological data on observed precipitation, average temperature, and reference evapotranspiration. To calculate the potential evapotranspiration, maps of plant species coefficients are made. The calculation of all the estimated flows for each point in the territory is done: interception, effective precipitation, irrigation, real evapotranspiration and drainage.

A1C *Biomass appropriation*, which estimates the percentage of current net primary productivity that has been appropriated by human activities (Haberl et al. 2007). It involves the appropriation of plant biomass, through modification of land covers and use of natural resources (agriculture, forestry, etc.). This appropriation affects the amount of energy, in the form of biomass, available to other species. In this way, the biomass appropriation has great impacts on the landscape structure (land covers) and its functioning (biogeochemical cycles) to a degree that can exceed its carrying capacity.

B1 *Habitat suitability*, which assesses the conditions for biodiversity based on the landscape complexity and energy efficiency of agricultural practices (Marull et al. 2019). It is based on the landscape patterns and processes and the energy flows of agrarian metabolism that imprint those land patterns and intervenes in those processes. The fraction of biomass left available for non-domesticated ecological trophic chains is obtained from the socio-metabolic balance of the agroecosystem (the unharvested fraction of the photosynthetic net primary production).

C1 *Landscape complexity*, which values the patterns and processes of the landscape from the heterogeneity of the land covers and its ecological connectivity (Marull and Mallarach 2005). It assesses the functional landscape structure from the conjunction between the habitat diversity, that determines the landscape patterns, and the ecological connectivity, that determines landscape processes.

D1 *Greenhouse gas emissions*, which assesses the contribution of agriculture to global warming through greenhouse gas emissions (Aguilera et al. 2015a, b). It is based on the machinery, biomass burning, fertilizers, pesticides, water, greenhouses, carbon fixed in the soil and nitrogen balances. The calculations are limited to detailing emissions from agriculture. They therefore do not consider the rest of open spaces of the green infrastructure, nor the role played by livestock (beyond the provision of excreta which is considered part of the emissions of fertilizers and N_2O).

E1A *Nutrients recirculation*, which estimates the amount of phosphorus that re-circulates within the agricultural system in interaction with other uses and grazing (Marco et al. 2018). It is calculated considering the flows previously measured in the socio-metabolic assessment. There are specific values of recirculation of nutrients for each crop, all of them obtained from their corresponding N-P-K balances. Since these balances have been accounted for the main macronutrients using homogeneous data, the most limiting nutrient (in our case P) has been selected to account for soil nutrients recirculation.

E1B *Carbon stock*, which measures the total amount of carbon stored to open spaces as soils, roots and air-filled structures (Doblas-Miranda et al. 2013). The following fractions are considered: C in mineral soil, C in organic layer of the soil, and C in roots of plants and their woody aerial structures. C in mineral soil is obtained from cropland databases (http://www.icgc.cat/). For forest soils, a regression model has been developed to estimate the belowground C stock according to forest cover (total aboveground C) and soil (mineral composition, texture and thick elements). The organic horizon in forests is estimated from coefficients of C stock into mineral soil, and in croplands is estimated from aboveground C and roots, which depends on species, ages and spatial patterns.

E1C *Agricultural production*, which reports the production of each cover (horticultural, winter crops, dry and irrigated grassland, dry and irrigated fruit trees, olive trees and vineyards). It accounts for food production leaving aside forestry and livestock production to focus on the edible products of agricultural activity, and because livestock feed is mainly imported from external territories. It is obtained from the statistical records of the average productions of each municipality and agricultural land cover.

F1 *Agricultural Jobs*, which characterizes the number of Agricultural Work Units (AWU) required to keep running the open spaces (Padró et al. 2017). It measures the potential of full-time equivalent agricultural jobs that would be required in the agrarian spaces of the metropolitan area, which are used as a proxy to the jobs required by the metropolitan agroecosystems. The AWU working days required by each land unit of the different existing crops, as well as for livestock and forestry, have been estimated.

Table 2 Socioecological Integrated Analysis (SIA) main indicators for the land planning and agricultural management (conventional *vs* organic) evaluation of scenarios

	Dimension		Main indicator	Description
Integrated Socioecological Analysis (SIA)	A *Metabolic performance*	*Energy*	A1A *Energy efficiency*	Measures the energy obtained in agricultural areas according to the external energy invested
		Water	A1B *Water consumption*	Estimates the theoretical amount of water used by the metropolitan green infrastructure
		Matter	A1C *Biomass appropriation*	Estimates the percentage of actual net primary production appropriated by human activities
	B *Biodiversity conservation*		B1 *Habitat suitability*	Evaluates conditions for biodiversity based on landscape complexity and agricultural metabolism
	C *Landscape functioning*		C1 *Landscape complexity*	Values patterns and processes of landscape based on heterogeneity and ecological connectivity
	D *Climate change*		D1 *Greenhouse gas emissions*	Assesses the potential contribution of metropolitan agriculture to global warming
	E *Ecosystem services*	*Regulation*	E1A *Nutrient recirculation*	Estimates the amount of phosphorus that recirculates within the agricultural system
		Support	E1B *Carbon stock*	Measures the total amount of carbon (soils, roots, aerial woody structures) stored in open spaces
		Provisioning	E1C *Agricultural production*	Derives from the productions of each land cover (horticultural, grassland, fruit trees, etc.)
	F *Social cohesion*		F1 *Agricultural jobs*	Characterizes the agricultural work units that requires the maintenance of open spaces

2.5 Statistical analysis of the SIA application

The 10 SIA indicators (**table 2**) and the distribution and extension of open spaces categories (**table 1)** were calculated for each one of the 500x500m cells of the BMA. The SIA assessment at cell level allows 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. Principal Components Analysis (PCA) with the SIA results for each scenario was performed to identify the key factors characterizing the green infrastructure. Subsequently, an Exploratory Factor Analysis (EFA) was performed to visualize the distribution of the indicators and the categories of the open spaces concerning the main factors defined by the SIA. Finally, a Multiple Linear Regression Analysis (MLRA) was applied to evaluate the contribution of each open space category to the SIA indicators. In this way, it was possible to verify whether the open space categories are useful to identify differentiated functions and services of the metropolitan green infrastructure and thus facilitate the land use planning and management of the territory.

2 Results and discussion

3.1 Characterization of open spaces for the different planning scenarios

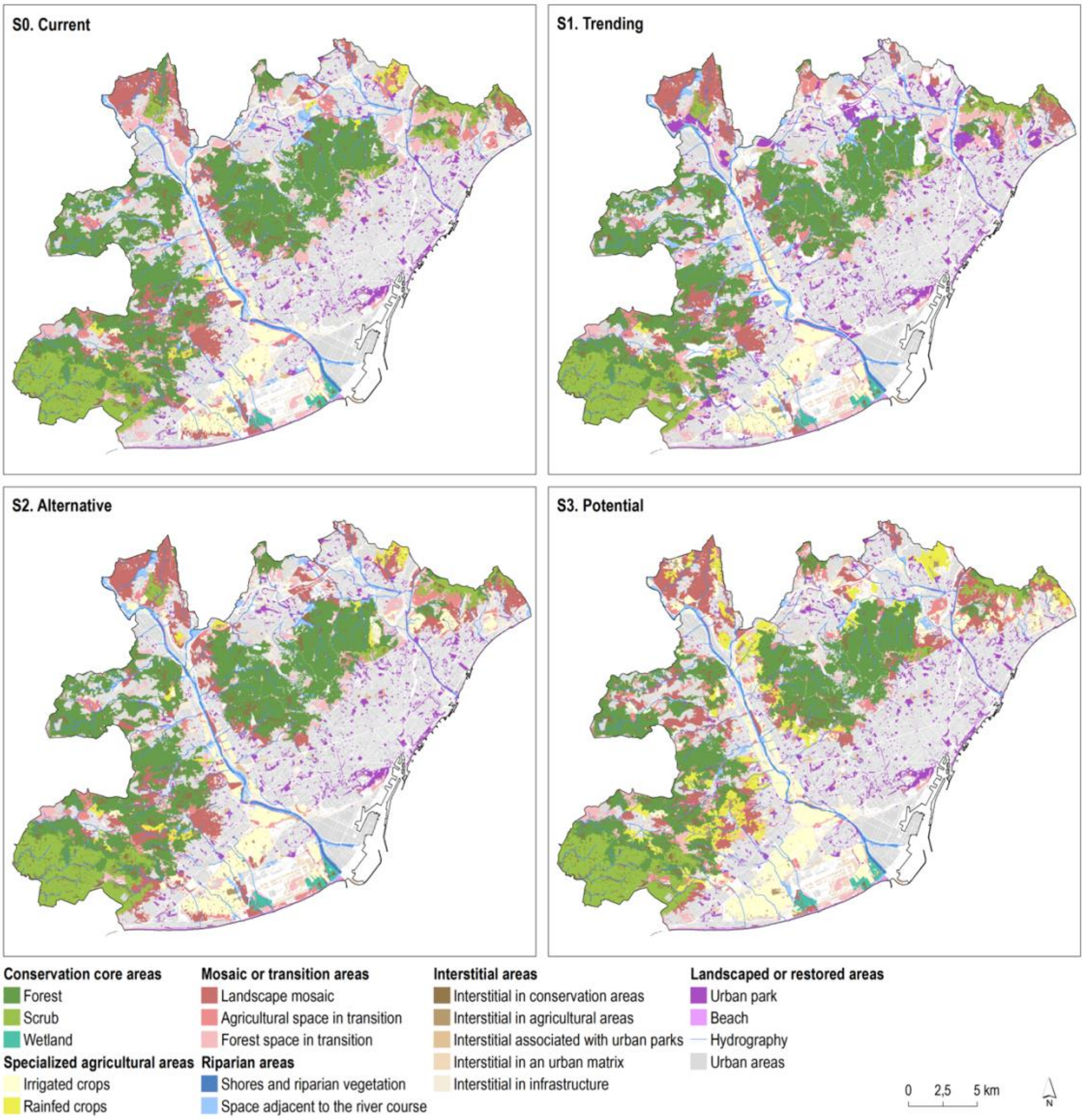
The open spaces constituting the BMA's green infrastructure currently cover 55% of its surface area (35,032 ha). The predominant open space category for the current scenario (S0) are *Conservation core areas* (51.0% of the AMB's surface), followed by *Mosaic or transition areas* (24.0%), and *Specialized agricultural area*s (7.9%). Finally, with less surface area are *Urban interstitial areas* (6.2%), *Agricultural interstitial areas* (5.6%), and finally *Riparian Areas* (5.3%) (**table 3**).

Table 3 Transformation matrix from land covers to open space categories of the green infrastructure of the Barcelona Metropolitan Area (BMA) in the current scenario (S0)

Land covers	Open space categories of the metropolitan green infrastructure						
	Conservation core areas	Specialized agricultural areas	Riparian Areas	Mosaic or transition areas	Urban interstitial areas	Agrarian Interstitial areas	Total
Forest	13,651	0	103	2,739	467	441	17.402
Crops	0	2,753	342	1.665	207	371	5.338
Fluvial corridors and wetlands	267	0	716	239	76	86	1.383
Scrubland	3,842	0	366	2.866	504	848	8.426
Meadows and grasslands	0	0	267	889	398	209	1.762
Green roads	0	0	53	159	510	0	722
Total (ha)	17,760	2,753	1,846	8,556	2,161	1,955	35.032
%	51.0	7.9	5.3	24.0	6.2	5.6	100

The **figure 4** shows the maps of the structural delimitation of the green infrastructure for the S0, S1, S2 and S3 scenarios. The most relevant differences between the S0 *Current* and the S1 *Trending* scenarios are the substitution of many transition areas by urban parks and the loss of rainfed crops from specialized agricultural areas. In the case of the S2 *Alternative* scenario, some specialized agricultural areas appeared and there was an expansion of mosaic landscapes. Finally, the effect of the increasing agricultural land if the S3 *Potential* scenario is materialized in a massive expansion of specialized agricultural areas but also of landscape mosaics.

Figure 4 Structural delimitation of the green infrastructure of the Barcelona Metropolitan Area (BMA) for the S0 *Current*, S1 *Trending*, S2 *Alternative*, and S3 *Potential* scenarios



3.2 Application of the model in different planning and management scenarios

We analyze the impact of land planning (S0, S1, S2, S3) and agricultural management scenarios (conventional *vs* organic) in the BMA through the 10 indicators of the SIA model (**table 4**). Since A1B *Water consumption* and C1 *Landscape complexity* were calculated based on land covers, there are no differences between conventional and organic values within the same land planning scenarios. In this sense, A1B tends to increase in scenarios S2 *Alternative* and S3 *Potential*, as the extension of agricultural areas and urban parks increases. C1 also increases in scenarios with more landscape mosaics, but this difference is only significantly lower concerning the scenario S1 *Trend*, indicating the potential loss of landscape functionality, as built-up areas and infrastructure increase, causing fragmentation and habitat loss. This can as well be seen through B1 *Habitat suitability* which accounts for the biodiversity conservation dimension, and slightly improving in organic management scenarios.

While a transition to organic agriculture following only CCPAE criteria allows for a higher degree of autonomy by improving E1A *Nutrient recirculation* and F1 *Agricultural labor*, the process is associated with a decrease in E1C *Agricultural production* and A1A *Energy efficiency* (**table 4**). Previous studies have reported agricultural yield decreases under organic management, but this yield gap could be reduced over time precisely because of improving nutrient recirculation (Schrama et al. 2018). Regarding the contribution to climate change, there is an overall reduction of D1 *Greenhouse gas emissions* when shifting to organic management, although this improvement is only significant for land planning scenarios where agricultural land covers increase (S2, S3). The significant decrease in A1A *Energy efficiency* in organic management can be explained by the decrease in productivity, which implies higher external inputs per unit of product. These external inputs dependence also leads to a rise in D1 *Greenhouse gas emissions* when the agricultural area increases.

Table 4 Socioecological Integrated Analysis (SIA) of the Barcelona Metropolitan Area (BMB) green infrastructure. Mean comparison of the SIA indicators* values between land planning scenarios (S0 - S3) and agricultural management (conventional *vs* organic)

SIA		Scenarios							
		Current (S0)		Trending (S1)		Alternative (S2)		Potential (S3)	
Dimension	**Indicator**	**Con. (a)**	**Org. (b)**	**Con. (c)**	**Org. (d)**	**Con. (e)**	**Org. (f)**	**Con. (g)**	**Org. (h)**
Metabolic performance	A1	1,14 c,d	0,99 d	0,84	0,80	1,48 a,b,c,d	1,38 a,b,c,d	2,29 a,b,c,d,e,f,h	2,04 a,b,c,d,e,f
	A1B	186,92 c,d	186,92 c,d	150,46	150,46	190,50 c,d	190,50 c,d	213,95 a,b,c,d,e,f	213,95 a,b,c,d,e,f
	A1C	17,59	15,94	18,44	16,65	24,83 a,b,c,d,f	21,33 a,b,c,d	36,72 a,b,c,d,e,f,h	31,59 a,b,c,d,e,f
Biodiversity conservation	B1	0,33 c,d	0,34 c,d	0,28	0,29	0,32 c,d	0,34 c,d	0,33 c,d	0,35 a,c,d,e
Landscape functioning	C1	0,25 c,d	0,25 c,d	0,22	0,22	0,25 c,d	0,25 c,d	0,26 c,d	0,26 c,d
Climate change	D1	3,40 d	2,78	2,80	2,33	4,66 a,b,c,d,f	3,81 b,c,d	7,74 a,b,c,d,e,f,h	6,12 a,b,c,d,e,f
Ecosystem services	E1A	8,88	15,74 a,c	7,43	12,68 a,c	10,74 c	19,30 a,b,c,d,e,g	13,22 a,c,e	20,37 a,b,c,d,e,g
	E1B	1159,68 c,d	1159,68 c,d	1017,09	1017,09	1116,87 c,d	1116,87 c,d	1078,75	1078,75
	E1C	10,00 b,d	6,49	8,32 d	5,08	13,46 a,b,c,d,f	9,57 b,d	22,31 a,b,c,d,e,f,h	17,49 a,b,c,d,e,f
Social cohesion	F1	0,25	0,33 c	0,21	0,27	0,36 a,c	0,47 a,b,c,d,e	0,73 a,b,c,d,e,f	0,95 a,b,c,d,e,f,g

* SIA indicators: A1A *Energy efficiency*; A1B *Water consumption*; A1C *Biomass appropriation*; B1 *Habitat suitability*; C1 *Landscape complexity*; D1 *Greenhouse gas emissions*; E1A *Nutrient recirculation*; E1B *Carbon stock*; E1C *Agricultural production*; F1 *Agricultural jobs*. The results are based on the two-tailed t-test assuming equal variances with a significance level of 0.05. For each significant pair, the key under the category (a, b, c, d, e, f, g, h) shows up beneath the category with a major average value. Using the Bonferroni correction, tests have been adjusted for all pair-wise comparisons.

3.3 Insights for an agroecological transition

The effect of an organic transition would significantly reduce E1C *Agricultural production*, with a drop of 17% (**table 4**). As already mentioned, however, this drop is greater than the fall in external inputs, which under the assumptions established for the organic scenario require in some cases the import of organic fertilizers to support agricultural production, thus causing a drop in A1 *Energy efficiency* of between 9% and 20% at the aggregate level. In terms of the capacity to E1A *Nutrient recirculation*, it is interesting that the S1 *Trending scenario* results in a higher capacity to close the nutrient cycles (where more than 35% of the phosphorus comes from the same BMA). In this case, the reduction of agricultural area implies a more balanced relationship between livestock and agriculture, which facilitates to close more nutrient cycles and explains this difference, due to the ability of agriculture to reuse agricultural resources and vice versa.

On the other hand, the difference between scenarios implies an increase of more than 30% of E1A between conventional and organic management (**table 4**). Despite this increase, it should be noted that strict compliance with organic production regulations does not ensure a significant overall improvement in the contribution of the green infrastructure to the socioecological functioning of the metropolitan area. This is the case with the moderate reduction of D1 *Greenhouse gas emissions*, which only improve by an average of 18% when compared to conventional production. This reduction only come from agricultural production, without involving the entire agri-food system including the food industries, packaging, transport, storage, wholesale and retail. It also does not include changes in diet. It is important to highlight here that the shift to organic farming is not enough, and the necessary changes to get higher climate change mitigation and biodiversity improvements must go towards a systemic agroecological transition.

Finally, in terms of F1 *Agricultural jobs*, the average increase is 24% AWU (**table 4**). A socioecological transition would imply an increase from the 640 AWU currently estimated to 2,400 AWU in the S3 *Potential* scenario. This increase in the volume of workers is mainly explained by the increase in surface area, but also by the change to organic agriculture and, to a lesser extent, by the expansion of agriculture to areas with above-average productivity in the area.

3.4 Exploratory analysis of the factors involved in the model

Based on the results obtained for the SIA indicators in each of the spatial planning and agricultural management scenarios, a PCA was performed separately for conventional and organic management to identify the differences (**table 5**). Under conventional management, two main factors explain 68.8% of the total variance of the model. Factor 1 (37.8% of explained variance) groups the indicators associated with 'metabolic flows and system efficiency': A1A *Energy efficiency*, A1C *Biomass appropriation*, D1 *Greenhouse gas emissions*, and E1C *Agricultural production*. Factor 2 (31.0% of explained variance), groups the indicators corresponding to 'structure and functioning of the territorial matrix': E1B *Carbon stock*, C1 *Landscape complexity*, and B1 *Habitat suitability*. The PCA for scenarios under organic management was also defined by the same two factors but with explained variances of 37.0% and 32.3%, respectively.

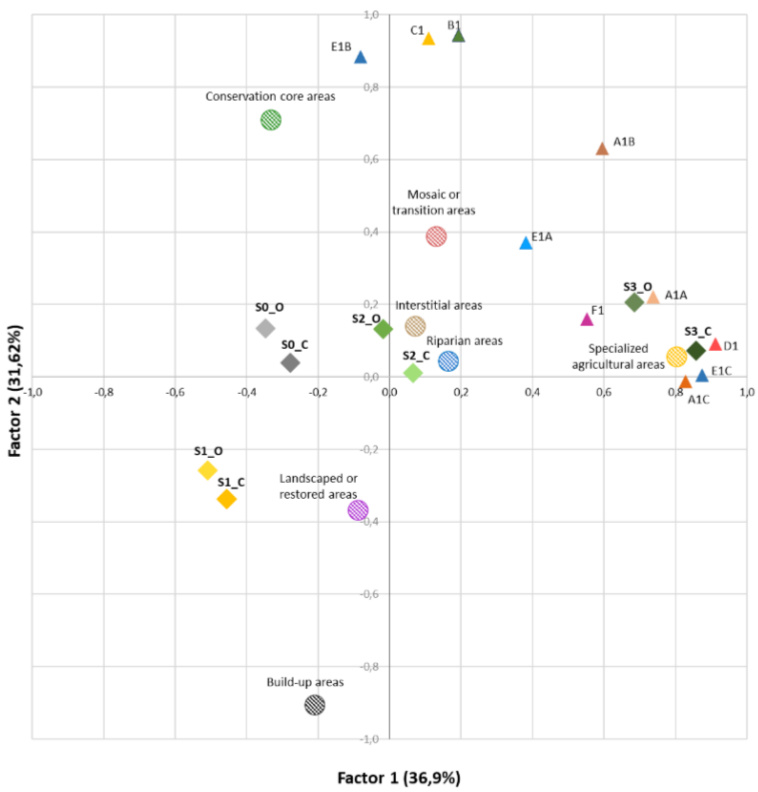
Table 5 Principal Component Analysis (PCA) of the Socioecological Integrated Analysis (SIA) under the different land planning and agricultural management scenarios

Conventional	Eigenvalues			Sum of the square saturations after rotation		
Component	Total	Variance (%)	Ac. variance (%)	Total	Variance (%)	Ac. variance (%)
1	4.505	45.049	45.049	3.780	37.798	37.798
2	2.371	23.713	68.762	3.096	30.965	68.762
3	1.017	10.167	78.929			
4	0.753	7.530	86.459			
5	0.428	4.282	90.741			
6	0.337	3.366	94.108			
7	0.292	2.921	97.028			
8	0.172	1.723	98.751			
9	0.064	0.643	99.393			
10	0.061	0.607	100.000			
Organic	**Eigenvalues**			**Sum of the square saturations after rotation**		
Component	**Total**	**Variance (%)**	**Ac. variance (%)**	**Total**	**Variance (%)**	**Ac. variance (%)**
1	4.626	46.259	46.259	3.698	36.985	36.985
2	2.301	23.007	69.266	3.228	32.281	69.266
3	1.099	10.992	80.258			
4	0.704	7.039	87.297			
5	0.376	3.764	91.061			
6	0.350	3.503	94.564			
7	0.282	2.822	97.386			
8	0.166	1.656	99.043			
9	0.055	0.547	99.590			
10	0.041	0.410	100.000			

Rotated component matrix	Conventional Component		Organic Component	
	1	2	1	2
A1A Energy efficiency	0.750	0.155	0.716	0.301
A1B Water consumption	0.605	0.627	0.594	0.628
A1C Biomass appropriation	0.842	-0.021	0.814	-0.010
B1 Energy-Landscape integration	0.180	0.942	0.217	0.942
C1 Landscape complexity	0.126	0.932	0.100	0.938
D1 Greenhouse gas emissions	0.911	0.088	0.917	0.091
E1A Nutrient recirculation	0.437	0.315	0.388	0.411
E1B Carbon stock	-0.066	0.890	-0.092	0.881
E1C Agricultural production	0.868	0.001	0.881	0.012
F1 Agricultural jobs	0.562	0.153	0.580	0.151

To graphically represent the EFA, in relation to the categories of open spaces proposed for the green infrastructure of the BMA (**table 1**), the PCA was considered based on the eight agricultural planning and management scenarios (**figure 2**). In the EFA (**figure 6**), *Specialized agricultural areas* have a positive association with 'metabolic flows and system efficiency' (Factor 1). *Mosaic or transition areas*, *Interstitial areas*, and *Riparian areas* also have a positive relationship with Factor 1, but less than in the case of *Specialized agricultural areas*. Finally, *Conservation core areas* have a negative relationship with Factor 1, as do the build-up and non-open space areas and *Landscaped or restored areas*. Regarding *Conservation core areas* and *Mosaic or transition areas*, they are positively associated with Factor 2. In contrast, *Interstitial areas* and *Riparian areas* are related to Factor 2 to a much lesser extent, and *Specialized agricultural areas* have almost no effect. Finally, *Landscaped or restored areas* and *Conservation core areas* are negatively related to Factor 2.

Figure 6 Exploratory Factor Analysis (EFA) of the Barcelona Metropolitan Area (BMA) green infrastructure. Open space categories (circles), SIA indicators* (triangles), and land planning and agricultural management scenarios (rhombi)** are displayed



* SIA indicators: A1A *Energy efficiency*; A1B *Water consumption*; A1C *Biomass appropriation*; B1 *Habitat suitability*; C1 *Landscape complexity*; D1 *Greenhouse gas emissions*; E1A *Nutrient recirculation*; E1B *Carbon stock*; E1C *Agricultural production*; F1 *Agricultural jobs*. ** Land Planning scenarios: S0 *Current*, S1 *Trend*, S2 *Alternative*, and S3 *Potential*, under conventional (_C) or organic (_O) management.

There is a clear triad in the positive effect of the factors obtained by the PCA, which defines a boundary of possibilities for improvement. *Conservation core areas* are key for the ecological functioning of the territorial matrix, *Specialized agricultural areas* for the metabolic flows, and *Mosaic or transition areas* for both factors at the same time (**figure 6**). These latter categories have a mixed role that, in relative terms, is more positive for the functioning of the landscape than for the achievement of metabolic flows. This fact highlights that the mosaics have multiple and complex functions and services. These results corroborate the need to understand in-depth the contribution of the different open spaces to the functionality and services that the green infrastructure provides, or should provide, to society.

Finally, in general, the EFA shows a better performance of organic scenarios on Factor 2 while a slight decrease on the performance on Factor 1 (**figure 6**). The S1 *Trending* scenario would imply a decrease in the structure and functioning of the territorial matrix (Factor 2), and the S3 *Potential* scenario would imply an increase in the metabolic energy and biomass flows, system efficiency, and greenhouse gas emissions (Factor 1), compared to the S0 *Current* scenario.

3.5 Contribution of the open space categories to the values of the indicators

To analyze the contribution of the different categories of open spaces to the functioning and services provided by the green infrastructure in the BMA and its role in a possible socioecological transition, a MLRA is performed. In this analysis, the SIA indicators (**table 2**) are related separately to the categories of the open spaces (**table 1**). In this way, a first validation of the correspondence between the structural criteria of the delimitation of the open spaces proposed (**figure 4**) and their functionality (**figure 6**) is obtained. These functionalities are analyzed for each of the contributing dimensions of the green infrastructure to the metropolitan system (**figure 3**). To facilitate the interpretation of the results (**table 6**), it is shown: (i) the percentage of explained variance by the regression model undertaken (R^2) in each case; (ii) the non-standardized coefficients (ß); and (iii) the predicted values for homogeneous cells of a single open space category (value of the constant of the multiple regression model). The results obtained for each indicator are explained below.

Table 6 Multivariant Linear Regression Analysis (MLRA) for each of the Socioecological Integrated Analysis (SIA) indicators*, according to the land planning and agricultural management (conventional *vs* organic) scenarios, and for each of the open space categories** of the Barcelona Metropolitan Area (BMA) green infrastructure

Categories	Indicators																			
	A1A		A1B		A1C		B1		C1		D1		E1A		E1B		E1C		F1	
	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.
Constant	*0.323*	*0.197*	*236.257*	*236.257*	*0.483*	*0.968*	*0.545*	*0.558*	*0.543*	*0.543*	*-0.180*	*-0.114*	*0.923*	*1.140*	*1051.76*	*1051.76*	*-0.154*	*0.198*	*0.038*	*0.052*
CCA	0.144	0.356	26.784	26.784	-	-	-	-	-0.137	-0.137	-	-	2.404	6.977	1711.342	1711.342	-	-0.843	-	-
SAA	5.645	4.593	346.676	346.676	103.261	87.125	-0.071	-	-0.238	-0.238	45.133	37.799	21.369	34.390	236.163	236.163	163.370	114.045	2.179	2.179
MTA	2.528	2.904	50.139	50.139	36.750	29.984	0.187	0.222	-	-	9.149	6.656	32.212	53.327	758.380	758.380	12.707	9.320	0.955	1.211
RIA	5.084	4.227	83.316	83.316	84.391	72.714	0.129	0.179	-	-	9.999	7.935	47.204	70.979	-	-	20.362	14.052	0.915	1.188
INA	4.065	3.785	-	-	81.141	72.214	0.148	0.158	-0.070	-0.070	6.692	5.322	29.657	52.848	-	-	12.045	9.568	0.955	1.253
LRA	-	-	233.079	233.079	-	-	-0.564	-0.572	-0.497	-0.497	-	-	-	-	-1049.14	-1049.14	-	-	-	-
CNA	-	-	-232.00	-232.00	12.042	10.507	-0.555	-0.572	-0.517	-0.517	-	-	-	-	-1051.92	-1051.92	-	-	-	-
R^2	*0.294*	*0.323*	*0.846*	*0.846*	*0.471*	*0.437*	*0.873*	*0.873*	*0.819*	*0.819*	*0.809*	*0.829*	*0.233*	*0.231*	*0.816*	*0.816*	*0.716*	*0.716*	*0.243*	*0.231*

* SIA indicators: A1A *Energy efficiency*; A1B *Water consumption*; A1C *Biomass appropriation*; B1 *Habitat suitability*; C1 *Landscape complexity*; D1 *Greenhouse gas emissions*; E1A *Nutrient recirculation*; E1B *Carbon stock*; E1C *Agricultural production*; F1 *Agricultural jobs*. ** Open space categories of the metropolitan green infrastructure: CCA *Conservation core areas*; SAA *Specialized agricultural areas*; MTA *Mosaic or transition areas*; RIA *Riparian areas*; INA *Interstitial areas*; LRA *Landscaped or restored areas*; CNA Constructed or non-open space areas.

A1A *Energy efficiency*. In conventional scenarios, the model explains 29% of the variance (**table 6**), according to which *Specialized agricultural areas* contribute the most, followed by *Riparian areas* and *Interstitial areas*. On the other hand, the predicted value for a *Mosaic or transition areas* cell would be 2.528 (ß), thus being below all the other categories in which agriculture is present. If the comparison is made with the scenarios with organic management, the estimated values for *Specialized agricultural areas* are lower than in the conventional scenarios. However, it is interesting to note that in *Mosaic or transition areas* the predicted indicator is higher in organic than in conventional management while is lower for the other ones. This result highlights how an ecological transition is particularly favorable in those mosaic areas, which historically have maintained a more complex and efficient functioning of natural resources.

A1B *Water consumption*. The explanatory capacity of the model is very high (85%) (**table 6**). The model shows that *Specialized agricultural areas* are the open spaces that consume more water in the BMA, followed by *Landscaped or restored areas*. The open spaces that use less water are *Mosaic or transition* areas and *Conservation core areas*. The explanatory capacity of *Interstitial areas* for this model is not significant.

A1C *Biomass appropriation*. With an explanatory capacity of 47% (**table 6**), the model indicates that the open areas with the highest biomass appropriation are *Specialized agricultural areas* and, to a lesser extent, *Riparian areas*. Interestingly, a low but positive relationship is found for *Mosaic or transition areas*, where the biomass uptake is not very high. When contrasting the management scenarios, the biomass uptake is lower in organic scenarios for all agricultural areas. This could be explained due to productive yields decrease (see E1C), which the greatest effects of this reduction are for *Specialized agricultural areas*.

B1 *Habitat suitability*. The model can explain 87% of the total variance (**table 6**). The values obtained in organic would be higher than those obtained in conventional. Particularly interesting are *Specialized agricultural areas* that have a significant, although small, relationship in conventional scenarios, but not in organic scenarios. On the other hand, *Mosaic or transition areas* would present higher values than the rest of the agricultural areas, while *Riparian areas* and *Interstitial areas* also contribute moderately. This indicator reinforces the land-sharing conservation strategy according to which the intervened spaces with intermediated disturbance levels (such as agroforestry mosaics), can provide favorable conditions for biodiversity. *Landscaped or restored areas* and constructed or non-open space areas have a sustained negative effect.

C1 *Landscape complexity*. In this case, the explanatory capacity of the model is 82% (**table 6**). It can be observed that the effect of *Landscaped or restored areas* and constructed or non-open space areas reduce the complexity of the landscapes. Although with negative effect, *Core conservation areas*, being large homogeneous masses, imply a small decrease in complexity. *Mosaic or transition areas* and *Riparian areas* have no specific estimator, thus resulting statistically insignificant in this model.

D1 *Greenhouse gas emissions*. This indicator presents higher absolute values in the conventional scenarios and has an explanatory capacity of around 81% of the total variance (**table 6**). The predicted value is similar in the different categories, with the highest values being obtained in *Specialized agricultural areas*, followed to a much lesser extent by *Riparian areas*, where crops are usually irrigated. *Mosaic or transition areas* and *Interstitial areas* follow with a slightly lower contribution to emissions. The scenarios in organic production have predicted values below those of conventional production, with the minimum difference being in *Specialized agricultural areas* (with a 16% reduction in emissions contribution) and the maximum in *Mosaic or transition areas* (with a 27% reduction in emissions contribution). Again, agroforestry mosaics present particularly favorable contributions to reduce pressures over the environment.

E1A *Nutrient recirculation*. In general, the percentages of nutrient recirculation are higher in organic scenarios, especially in *Interstitial areas*, *Riparian areas*, and *Mosaic or transition areas* (**table 6**). The latter is again the most beneficial in terms of nutrient recirculation in the face of ecological transition. The behavior of the models is similar in conventional and organic production, with an explained variance of only 23%. *Riparian areas* obtained the higher estimated value regardless of management, followed by *Mosaic or transition areas*. In contrast, *Specialized agricultural areas*, due to the strong pressure on the use of natural resources, has the lowest values, although much lower than areas without agricultural uses, on which this indicator was not calculated directly.

E1B *Carbon stock*. The multiple regression model explains 81% of the total variance (**table 6**). The high values of this indicator might be explained because changes in land covers mean the loss of an important part of the accumulated biomass (both aerial and belowground) and, as in the case of C1, does not present differences between organic and conventional scenarios. In this case, the highest values are obtained in *Conservation core areas*, followed by *Mosaic or transition Areas* and, far behind, by *Specialized agricultural areas*.

E1C *Agricultural production*. This model, with an explained variance of 72% (**table 6**), reveals statistically significant associations for the categories containing agricultural uses. It is interesting to see how, obviously, the most productive areas are *Specialized agricultural areas*, but then there are *Riparian areas* that also present high productivity. However, the expected value of these areas not differ much from the predicted value in *Mosaic or transition areas* and *Interstitial areas*. Likewise, the only significant difference between conventional and organic scenarios is found in *Specialized agricultural areas*, thus showing that these would be the most affected by an ecological transition.

F1 *Agricultural jobs*. For this indicator, a model has been obtained with an explanatory capacity of around 24% of the total variance for the conventional and organic scenarios (**table 6**). As in the case of E1C and D1, the jobs generated are much higher in the case of *Specialized agricultural areas*. It is followed by *Interstitial areas, Mosaic or transition areas*, and *Riparian areas*. The relationship between agricultural jobs and the different agricultural areas is stronger and more positive in both organic and conventional *Specialized agricultural areas*. In other agricultural areas, the number of jobs increases considerably (up to 30%) in organic settings.

4 Conclusions

The results of applying a Socioecological Integrated Analysis (SIA) model in the Barcelona Metropolitan Area (BMA) reinforce the hypothesis that an operational green infrastructure is an essential structural element of the metropolitan system, as it can provide multiple functions and services. The establishment of categories of open spaces allows deepening the understanding of the socioecological interrelation between the different components of the green infrastructure. These interrelations are crucial to maintaining an adequate cohesion and integration between the different types of open spaces and with the rest of the metropolitan system, a fundamental issue for landscape and urban planning. Thus, each of these categories of open spaces has a differential role that can be developed from a multi-criteria, multi-scale, and systemic perspective, necessary to understand the sustainability of the metropolis.

The creation of four theoretical planning scenarios for the Urban Master Plan (PDU) allows us to analyze the territorial and metabolic consequences of adopting differential forms of planning and management of the green infrastructure. The *Trending* scenario of applying the current land-use planning would have a very important negative impact, especially in the dimensions more related to the ecological functioning of the landscape, affecting biodiversity and the provision of ecosystem services to society. On the other hand, the *Alternative* and *Potential* scenarios, where agricultural land would be recovered, are particularly favorable in terms of the circularity of metabolic flows, agricultural production, and job creation, but also increasing greenhouse gas emissions.

All these land-use planning scenarios have been evaluated concerning agricultural management (conventional *vs* organic) to evaluate the synergies and tradeoffs associated with a possible ecological transition. Organic agriculture would be very effective to enhance nutrient recirculation and generating new jobs but would be less effective in other dimensions such as biodiversity conservation or reduction of greenhouse gas emissions.

On the other hand, organic management would be particularly negative in terms of energy efficiency and agricultural production. All in all, limiting oneself to complying with the regulations for organic agricultural production (CCPAE) is not enough for an ecological transition to promote dimensions such as climate change mitigation or energy efficiency. To achieve a significant improvement on these dimensions, it would be necessary to consider agroecological and not only organic management. Further research should evaluate the impact of possible agroecological transitions, considering landscape-metabolism models, under climate change scenarios.

To identify the contribution of the different open space categories to the green infrastructure, a Multivariate Linear Regression Analysis was used to determine the extent to which the categories themselves explain the SIA indicator values. We can highlight the particularly multifunctional contribution of the agroforestry mosaics with a rich and heterogeneous mix of land uses, which have a positive impact both concerning the dimensions related to the landscape ecological functioning, as well as those that refer to metabolic flows. These agroforestry mosaics have an important potential for surface area increase in the *Alternative* and *Potential* scenarios. Based on the statistical models' results, the agroforestry mosaics counteract the observed losses in agricultural production and energy efficiency. On the other hand, the interstitial areas play a more important role than is often considered by introducing land cover diversity that favors certain patterns and processes in the landscape. In summary, the integration among livestock-agriculture and forests is needed to reduce external reluctance and to improve agroecosystems functionality that would entail better energy efficiency performance as well as further greenhouse gas emission reduction or nutrient recirculation.

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