Universitat Autònoma de Barcelona

A new Socio-ecological Integrated Analysis for Agricultural Land Use Planning in Metropolitan Areas: Applications for Tropical (Cali, Colombia) and Mediterranean (Barcelona, Spain) Biocultural Landscapes

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Doctoral Thesis

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de Barcelona

CREAF EXCEL·LÈNCIA SEVERO OCHOA

LET
Laboratori Metropolità d'Ecologia i Territori de Barcelona

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By

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A dissertation submitted in fulfilment of the requirements of the
Doctoral degree in Terrestrial Ecology

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SUSTAINABLE FARM SYSTEMS
LONG-TERM SOCIO-ECOLOGICAL METABOLISM IN WESTERN AGRICULTURE

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Un Nou Anàlisi Socioecològic Integrat per l'Ordenament Territorial d'Àrees Agricoles Metropolitanes: Aplicacions per als Paisatges Bioculturals Tropicals (Cali, Colòmbia) i Mediterranis (Barcelona)

Un Nuevo Análisis Socioecológico Integrado para el Ordenamiento Territorial de Áreas Agrícolas Metropolitanas: Aplicaciones para los Paisajes Bioculturales Tropicales (Cali, Colombia) y Mediterráneos (Barcelona)

A mi familia,
Por su apoyo y amor infinitos.

A mis amigas,
Por su compañía y escucha.

Durante el desarrollo de este trabajo (2016 – 2021) más de 1200 líderes y lideresas sociales en Colombia han sido asesinados por defender sus derechos, territorios, el medio ambiente y a sus pueblos.
Mujeres, hombres, jóvenes defensores de la vida…

A esas las personas que resisten y persisten en ese bello pero doloroso pedazo del planeta llamado Colombia,
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Bellaterra, December 2021

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ABSTRACT

The exponential growth of the world's human population over the past 100 years has accentuated the world's social metabolism at an unprecedented rate. According to the United Nations, in the next 30 years, the human population will reach 9.8 billion people. At that same point, 68% of the world population will live in metropolitan regions. This trend will inevitably increase the demand for food, raw materials, and energy to support the world's demand, anticipating the unsustainability of our current and predominant social metabolism.

Interesting scenarios that exemplify the situation mentioned above are metropolitan regions. These territories face a double challenge: sustainably satisfy their population's biophysical (i.e., food and material) and energy needs while maintaining the ecological structure and functionality of their territories, and lessening their vulnerability to climate change, food insecurity and disease outbreaks. Many of the metropolitan areas of the world are surrounded by rural and peri-urban agricultural land. Although agriculture has been the basis of subsistence for our societies, providing us with food, raw materials, and energy for millennia, current agricultural systems have reached a critical transition point in their performance, environmental impacts, and energy patterns, affecting local, regional, and global sustainability.

As socio-ecological systems, metropolitan areas hold complex urban-rural and nature-society interactions, occurring at different scales (i.e., local, landscape, regional) and dimensions (i.e., social, economic, ecological, cultural). Despite the pivotal role of agricultural expansion and intensification, and unplanned urban growth on global sustainability, tackling these issues stills represents a great methodological and conceptual challenge for scientists, land planners, and policymakers.

Focused on the experience of two contrasting metropolis: Barcelona (Spain) and Cali (Colombia), this thesis presents integrative landscape-metabolism tools to assess the role of agriculture on the sustainability of the metropolitan socioecological system. The thesis discusses the potential role, implications, and contributions of different agroecosystems for land planning in regions where economic growth and demographic dynamics are in a complex interplay with sociocultural and ecological process fundamental for their long-term sustainability.

The thesis encompasses four original research chapters, two developed in Cali and two in Barcelona. The first two chapters discuss the importance of approaching Cali's metropolitan development from a regional perspective, both geographically and culturally. It describes the importance of traditional smallholder agriculture in the configuration of agricultural mosaics, key for ecosystem services provision, but also the protection of rural livelihoods and culture. They conclude with a series of specific land planning recommendations for local authorities. The second part of the thesis focused on Barcelona Metropolitan Area. It takes a step forward on the multidimensional assessment of the AMB's green infrastructure, with a particular focus on the agricultural spaces. The work is part of a collaboration with the Urban Master Plan of Barcelona in the elaboration of the strategic environmental evaluation. It aims to assess different land planning and agricultural management scenarios with a Socio-ecological Integrated Analysis. The last chapter presents the application of the land planning and agricultural management modelled scenarios to a land-use optimization tool that aims to contribute to the understanding and development a new paradigm for metropolitan agriculture.

KEY WORDS

Agroecosystems, Sustainability, Metropolitan regions, Integrated analysis, Socioecological system, Agroecology, Traditional agriculture, Social metabolism.

RESUMEN

El crecimiento exponencial de la población humana mundial durante los últimos 100 años ha acentuado el metabolismo social mundial a un ritmo sin precedentes. Según Naciones Unidas, en los próximos 30 años, la población humana alcanzará los 9,8 mil millones de personas. En ese mismo momento, el 68% de la población mundial vivirá en regiones metropolitanas. Esta tendencia aumentará inevitablemente la demanda de alimentos, materias primas y energía para sustentar la demanda mundial, anticipándose a la insostenibilidad de nuestro metabolismo social actual y predominante.

Las regiones metropolitanas son interesantes escenarios que ejemplifican la situación antes mencionada. Estos territorios enfrentan un doble desafío: satisfacer de manera sostenible las necesidades biofísicas (es decir, de alimentos y materiales) y energéticas de su población, manteniendo la estructura ecológica y la funcionalidad de sus territorios y disminuyendo su vulnerabilidad al cambio climático, la inseguridad alimentaria y los brotes de enfermedades.

Muchas de las áreas metropolitanas del mundo están rodeadas de tierras agrícolas rurales y periurbanas. Si bien la agricultura ha sido la base de la subsistencia de nuestras sociedades, proporcionándonos alimentos, materias primas y energía durante milenios, los sistemas agrícolas actuales han alcanzado un punto crítico de transición en su desempeño, impactos ambientales y patrones energéticos, afectando la sostenibilidad local, regional, y global.

Como sistemas socioecológicos, las áreas metropolitanas mantienen complejas interacciones urbano-rural y naturaleza-sociedad, que ocurren en diferentes escalas (local, paisajístico, regional) y dimensiones (social, económica, ecológica, cultural). A pesar del papel fundamental de la expansión e intensificación agrícola y el crecimiento urbano no planificado en la sostenibilidad, abordar estos problemas aun representa un gran desafío metodológico y conceptual para los científicos, los planeadores territoriales y para los responsables de la formulación de políticas.

Centrada en la experiencia de dos áreas metropolitanas contrastantes: Barcelona (España) y Cali (Colombia), esta tesis presenta herramientas integradoras del metabolismo del paisaje para evaluar el papel de la agricultura en su sostenibilidad de sistema socioecológico metropolitano. La tesis discute el papel potencial, las implicaciones y las contribuciones de diferentes agroecosistemas para la planificación territorial en regiones donde el crecimiento económico y la dinámica demográfica están en una interacción compleja con procesos socioculturales y ecológicos fundamentales para su sostenibilidad a largo plazo.

La tesis engloba cuatro capítulos originales de investigación, dos desarrollados en Cali y dos en Barcelona. Los dos primeros capítulos discuten la importancia de abordar el desarrollo metropolitano de Cali desde una perspectiva regional, tanto geográfica como culturalmente. Describe la importancia de la agricultura tradicional en pequeña escala en la configuración de mosaicos agrícolas, clave para la provisión de servicios ecosistémicos, pero también para la protección de los medios de vida y la cultura rurales. Concluyen con una serie de recomendaciones específicas de ordenamiento territorial para las autoridades locales. La segunda parte de la tesis se centró en el Área Metropolitana de Barcelona. Da un paso adelante en la evaluación multidimensional de la infraestructura verde del Área Metropolitana de Barcelona, con especial énfasis en los espacios agrícolas. El trabajo se enmarca en una colaboración para la elaboración de la evaluación ambiental estratégica del Plan Director Urbanístico de Barcelona. Tiene como objetivo evaluar diferentes escenarios de ordenación territorial y gestión agrícola con un Análisis Socioecológico Integrado. El último capítulo presenta la aplicación de los escenarios modelados de ordenamiento territorial y gestión agraria a una herramienta de optimización del uso del suelo que tiene como objetivo contribuir a la comprensión y desarrollo de un nuevo paradigma de la agricultura metropolitana.

PALABRAS CLAVES

Agroecosistemas, Sostenibilidad, Regiones metropolitanas, Análisis integrado, Sistemas socioecológicos, Agroecología, Agricultura tradicional, Metabolismo social

RESUM

El creixement exponencial de la població humana mundial durant els últims 100 anys ha accentuat el metabolisme social mundial a un ritme sense precedents. Segons Nacions Unides, en els propers 30 anys, la població humana arribarà als 9,8 mil milions de persones. En aquest mateix moment, el 68% de la població mundial viurà a les regions metropolitanes. Esta tendència augmentarà inevitablement la demanda d'aliments, matèries primeres i energia per a sostenir la demanda mundial, anticipant-se a la insostenibilitat del nostre metabolisme social actual i predominant.

Les regions metropolitanes són interessants escenaris que exemplifiquen la situació abans mencionada. Aquests territoris s'enfronten a un doble desafiament: satisfer de manera sostenible les necessitats biofísics (és a dir, d'aliments i materials) y energètics de la seva població, mantenint l'estructura ecològica i la funcionalitat dels seus territoris i disminuint la seva vulnerabilitat al canvi climàtic, la inseguretat alimentària. y los brotes de malalties.

Moltes de les àrees metropolitanes del món estan envoltades de terres agrícoles rurals i periurbanes. Si bé l'agricultura ha estat la base de la subsistència de les nostres societats, proporcionen aliments, matèries primeres i energia durant mil·lennis, els sistemes agrícoles actuals han aconseguit un punt crític de transició en el seu rendiment, impactes ambientals i patrons energètics, afectant la sostenibilitat local, regional i global.

Com sistemes socioecològics, les àrees metropolitanes mantenen complexes interaccions urbà-rural i natura-societat, que ocorren en diferents escales (local, paisatgístic, regional) i dimensions (social, econòmica, ecològica, cultural). A pesar del paper fonamental de l'expansió i la intensificació agrícola i el creixement urbà no planificat en la sostenibilitat, abordar aquests problemes a un representar un gran desafiament metodològic i conceptual per als científics, els planificadors territorials i els responsables de la formulació de polítiques.

Centrada en l'experiència de dos metròpolis contrastants: Barcelona (España) i Cali (Colòmbia), aquesta tesis presenta eines integradores del metabolisme del paisatge per avaluar el paper de l'agricultura en la seva sostenibilitat del sistema socioecològic metropolità. La tesis discuteix el paper potencial, les implicacions i les contribucions de diferents agroecosistemes per a la planificació territorial en regions on el creixement econòmic i la dinàmica demogràfica estan en una interacció completa amb processos socioculturals i ecològics fonamentals per a la seva sostenibilitat a llarg termini.

La tesis engloba quatre capítols originals d'investigació, dos desenvolupats a Cali i dos a Barcelona. Els dos primers capítols discuteixen la importància d'abordar el desenvolupament metropolità de Cali des d'una perspectiva regional, tant geogràficament com culturalment. Descriu la importància de l'agricultura tradicional en petita escala en la configuració de mosaics agrícoles, clau per a la provisió de serveis ecosistèmics, però també per a la protecció dels mitjans de vida i la cultura rural. Conclouen amb una sèrie de recomanacions específiques d'ordenament territorial per a les autoritats locals. La segona part de la tesi es va centrar a l'Àrea Metropolitana de Barcelona. Da un pas endavant en l'avaluació multidimensional de la infraestructura verda de l'Àrea Metropolitana de Barcelona, amb especial enfocament en els espais agrícoles. El treball s’emmarca en una col·laboració per a l'elaboració de l'avaluació ambiental estratègica del Pla Director Urbanístic de Barcelona. Teniu com a objectiu avaluador diferents escenaris d'ordenació territorial i gestió agrícola amb una anàlisi socioecològica integrada. L'últim capítol presenta l'aplicació dels escenaris modelats d'ordenament territorial i gestió agrària amb una eina d'optimització de l'ús del sòl que té com a objectiu contribuir a la comprensió i desenvolupament d'un nou paradigma de l'agricultura metropolitana.

KEY WORDS

Agroecosistemes, Sostenibilitat, Regions metropolitanes, Anàlisi integrada, Sistemes socioecològics, Agroecologia, Agricultura tradicional, Metabolisme social

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List of abbreviations

AMB: Area Metropolitana de Barcelona
APU: Agricultural Production Unit
DANE: Departamento Administrativos de Nacional Estadístico
ECI: Ecological Connectivity Index
EEA: European Environmental Agency
ELIA: Energy-Landscape Integrated Analysis
EROI: Energy Return on Investment
FAO: Food and Agriculture Organization of the United Nations
HANPP: Human Appropriation of Net Primary Production
IAASTD: International Assessment of Agricultural Knowledge, Science and Technology for Development
IEI: Instituto de Estudios Interculturales. Universidad Javeriana de Cali
IERMB: Instituto de Estudios Regionales y Metropolitanos de Barcelona
IFOAM: International Federation of Organic Agriculture Movements
IFOAM: The International Federation of Organic Agriculture Movements
IPCC: International Panel for Climate Change
LET: Laboratory of Ecology and Territory
MA4SURE: Awarded Prima research project on the “Mediterranean Agroecosystems for Sustainability and Resilience under Climate Change”
NPP: Net Primary Productivity
PDU: Plan Director Urbanístico (Barcelona Urban Master Plan)
PRIMA: European Union Programme for Research and Innovation solutions in the Mediterranean region.
SAFRA: Sustainable Farm Reproductive Analysis
SFS: International research team on “Sustainable Farm Systems: long-term socio-ecological metabolism in western agriculture”
UCRV: Upper Cauca River Valley

PREFACIO

Esta tesis fue desarrollada entre Octubre de 2016 y Octubre de 2021 en cumplimiento con el programa de doctoral de Ecología Terrestre del CREAF en la Universidad Autónoma de Barcelona (UAB). El primer año y medio de la tesis lo realicé desde la ciudad de Cali, Colombia, en donde me desempeñé como investigadora del Instituto de Estudios Interculturales de la Universidad Javeriana de Cali, en el área de Ordenamiento territorial y Desarrollo rural, y en dónde tuve la oportunidad de trabajar y conocer de primera mano junto con las comunidades indígenas, afrodescendientes y campesinas, los diversos retos que impone la agricultura y la ruralidad en la región. Este trabajo contó con la financiación del proyecto Sustainable Farm Systems Project (del Social Sciences and Humanities Research Council de Canada -SSHRC 895-2011-1020), el Plan Estratégico Metropolitano (PEMB) a través de la beca Francesc Santacana 2019, y la universidad Javeriana de Cali. El desarrollo de los métodos y criterios empleados para apoyar el planeamiento del Área Metropolitana de Barcelona financiados a través del Laboratorio de Ecología y Territorio (LET) del Instituto de Estudios Regionales y Metropolitanos de Barcelona (IERMB) como parte del proyecto para el asesoramiento del Plan Director Urbanístico (PDU) Metropolitano de Barcelona (Project 2019_6.1.2a).

Esta tesis analiza las contribuciones de los sistemas agrícolas a la sostenibilidad territorial de las áreas metropolitanas. Su novedad radica en el desarrollo nuevos criterios para la evaluación socioecológica integral en miras a apoyar ejercicios de planeamiento territorial y una transición agroecológica. Adicionalmente, presenta los resultados de un análisis metabólico territorial a escala regional para el Valle del Cauca, sin precedentes, en donde se prueba el modelo IDC en diferentes paisajes bioculturales de ecosistemas tropicales y su relación con la capacidad de los paisajes de proveer múltiples servicios ecosistémicos.

La tesis se encuentra redactada en su totalidad en ingles, al ser una compilación de los artículos científicos presentados y/o publicados en revistas académicas internacionales y en cumplimiento con los requisitos para obtener el título doctoral con mención internacional de la UAB. Así mismo, para facilitar su diseminación en el entorno académico ampliamente angloparlante. Sin embargo, versiones divulgativas de los capítulos 2, 3 y 4, pueden encontrarse en español (para el caso de Colombia) y catalán (para el caso de Barcelona), tal y como se referencia en el apartado *1.6 Related Publications* de esta tesis. Consiente de la amplia brecha y las limitaciones en el acceso a la información para realizar investigación y apoyar la toma de decisiones en países como Colombia, se pone así mismo a disposición los resultados del presente estudio con fines no comerciales, estrictamente académicos e institucionales. Los interesados pueden contactar conmigo al correo mariajose.larota@uab.cat.

PREFACE

This thesis was developed between October 2016 and October 2021 in compliance with the doctoral program in Terrestrial Ecology of CREAF at the Autonomous University of Barcelona (UAB). I did the first and a half year of the thesis from Cali, Colombia. There I worked as a researcher at the Institute of Intercultural Studies (IEI) of the Javeriana University of Cali, as part of the Territorial Planning and Rural Development. At the IEI, I had the opportunity to work and learn first-hand, together with indigenous, Afro-descendant and peasant communities, the various challenges posed by agriculture and rurality in the region. The Sustainable Farm Systems Project funded this work (from the Social Sciences and Humanities Research Council of Canada -SSHRC 895-2011-1020), the Metropolitan Strategic Plan (PEMB) through the Francesc Santacana 2019 grant, and the university Javeriana from Cali. The development of the methods and criteria used to support the planning of the Barcelona Metropolitan Area financed through the Laboratory of Ecology and Territory (LET) of the Institute of Regional and Metropolitan Studies of Barcelona (IERMB) as part of the project for the assessment of the Plan Urban Director (PDU) Metropolitano de Barcelona (Project 2019_6.1.2a).

This thesis analyzes the contributions of agricultural systems to the territorial sustainability of metropolitan areas. Its novelty lies in developing new criteria for a comprehensive socio-ecological evaluation to support territorial planning exercises and an agroecological transition. Additionally, it presents the results of an unprecedented territorial metabolic analysis at a regional scale for Valle del Cauca, where the IDC model is tested in different biocultural landscapes of tropical ecosystems and its relationship with the capacity of landscapes to provide multiple ecosystem services.

I wrote the thesis entirely in English, as it is a compilation of scientific articles presented or published in international academic journals and in compliance with the requirements to obtain the doctoral degree with international mention from the UAB. Likewise, to facilitate its dissemination in the wider English-speaking academic environment. However, general public versions of chapters 2, 3 and 4 can be found in Spanish (for the case of Colombia) and Catalan (for the case of Barcelona), as referenced in section 1.6 Related Publications of this thesis. Aware of the wide gap and limitations in access to information to carry out research and support decision-making in countries like Colombia, the results are also available for non-commercial, strictly academic, and institutional purposes. Those interested can contact me at the email mariajose.larota@uab.cat.

1 Introduction

Today, nearly 40% of the Earth's surface is covered by agricultural land. This area is predicted to double in the next 30 years to satisfy the population's demands (Tilman et al., 2002a, 2001). The United Nations estimates that the world population will reach 9.8 billion people by 2050, which will be accompanied by a growth factor of two to three times, on the demand for global energy and materials (Krausmann et al., 2008a). We are reaching planetary limits, facing challenging global climate change scenarios (IPCC, 2018) and biodiversity loss (Steffen et al., 2015). As never before, an international consensus calls for the urgent need to transform nature-society relationships and promote socio-ecological transitions towards more sustainable land uses and related social metabolisms (González de Molina and Toledo, 2014, chap. 14).

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; González de Molina and Toledo, 2011; Guzmán et al., 2018). 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 (Tilman et al., 2002a), and energy patterns (Gingrich and Krausmann, 2018). Specifically, agricultural and global food systems which directly contribute to five of the nine *planetary boundaries* (Steffen et al., 2015): global climate change, land-system changes, biosphere integrity, freshwater use, and biogeochemical flows. Crossing these boundaries will increase the risk of generating abrupt and irreversible environmental changes and threatened humanity’s development (Rockström et al., 2009). This challenge is primarily projected for Global South regions which, offer a surplus of agricultural land, suitable climatic and soil conditions, and a large labour force (Smeets et al., 2007).

Agro-industrial systems are high-input, resource-intensive agricultural systems that have impacted nitrogen and phosphorus biogeochemical cycles and degraded soils (Tilman et al., 2011, 2001). Agro-industrial systems have also been closely related to biodiversity losses worldwide (Tscharntke et al., 2005). Since the Green Revolution, where agricultural systems around the world abruptly changed into high-input and resource-intensive systems, agriculture went from being a provider to a net energy consumer (Pelletier et al., 2011). Today the agri-food systems are responsible for nearly one-third of the world's greenhouse gas emissions (Thornton, 2012; Vermeulen et al., 2012a) mainly originated at the production phase (i.e., fertilizer applications, irrigation, and machinery use), the transportation phase (global transport and the cold chain of food trading) and by associated land use changes (Aleksandrowicz et al., 2016; Garnett, 2011; Houghton et al., 2012). Furthermore, from a social perspective, industrial agriculture has driven the loss of local and peasants' economy and autonomy promoting unfair labour relations in rural areas (Holt-Giménez and Altieri, 2013; Kay, 2015; Schneider and Niederle, 2010). The world is facing one of the biggest socio-ecological challenges of human history.

Metropolitan areas are important case studies in terms of sustainability challenges. Today, nearly 55.3% of the world's population (4,220 million people) live in urban areas. It is estimated that by 2030, there will be 5,167 million people (60.4% of the world's population) living in a city of at least 500,000 inhabitants (United Nations, 2019a), mainly in economically under-developed regions. Urban growth poses great challenges that involve the peri-urban and rural environments in which they are often integrated (Steel, 2008). For instance, urban population growth challenges food security and sovereignty (Satterthwaite et al., 2010; Steel, 2020, 2008); as well as water quality and availability, and waste management (Chen, 2007). Unplanned urban sprawl might increase vulnerability to climate change related environmental disasters, challenging mitigation and adaptation strategies (Demuzere et al., 2014). And habitat degradation and fragmentation are compromising the ecological functionality of the metropolitan territories and their ability to provide the ecosystem services needed for the maintenance of the Earth’s life system (Burak Güneralp et al., 2013; Liu et al., 2016; McDonald et al., 2013; Riley et al., 2003).

In this sense, metropolitan agriculture can play both as a driver or mitigator of unsustainability (Cattaneo et al., 2018; Marull et al., 2016; Yacamán-Ochoa et al., 2020). 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 30 years (European Commission, 2013). his requires the consideration of a myriad of complex interactions between ecological, economic, social, cultural and technological perspectives along the urban-rural gradient (Vallecillo et al., 2018). One way to tackle this challenge is by incorporating agricultural systems into metropolitan landscape planning through the concept of "green infrastructure" as a strategic framework to plan, implement and assess metropolitan open spaces (Benedict and McMahon, 2002; Monteiro et al., 2020; Yacamán-Ochoa et al., 2020). The purpose of green infrastructures is to reproduce a complex system in which its components (e.g., farmland, parks, nature reserves, greenways) become an interdependent element that allows the reproduction of critical socio-ecological processes. For instance, green infrastructure aims at contributing to maintaining biodiversity, providing ecosystem services, mitigating climate change, increasing territorial resilience and warranting social and economic benefits for its population (Cohen-Shacham et al., 2016; Maes and Jacobs, 2017).

Scientific consensus states that replacing non-renewable energy sources will not be enough to achieve the goals of global temperature and net-zero carbon emissions in the Paris Climate Agreement and the 2030 Sustainable Development Goals. A systemic change in the global food system is crucial (Clark et al., 2020; European Commission, 2021). Therefore, in this Doctoral Thesis, we will assess the contribution of agriculture to metropolitan sustainability through landscape-metabolism models. We will explore the possibilities and challenges that agricultural landscapes offer to consolidate functional green infrastructures. We aim this work at supporting land planners, policymakers, and local communities to advance towards the common goal of transforming food systems to mitigate climate change and biodiversity loss (Clark et al., 2020; Francis et al., 2003; Godfray et al., 2010; HLPE, 2019; Holt-Giménez and Altieri, 2013; Vermeulen et al., 2012). We propose new criteria and analysis methods, and apply them in two metropolitan areas of the world, located in the Global South and North, respectively: Cali (Colombia) and Barcelona (Spain). While these two study cases are embedded in different socio-ecological contexts, they exemplify many of the sustainability challenges of the 21st-century metropolis around agri-food systems and metropolitan development.

1.1 Understanding sustainable agricultural systems in human-transformed landscapes

Humans have transformed the Earth for millennia, to the point that today close to 83% of the Earth's ice-free land area is directly influenced by human beings and between 20% to 40% of Earth's potential net primary production is appropriated by domestic species (Haberl et al., 2007a; Imhoff et al., 2004; Sanderson et al., 2002). The historical relationship between humans and nature has been characterized by the exchange of energy, material and information through appropriation, transformation, circulation, consumption and excretion (González de Molina and Toledo, 2014). The way in which human societies organize these exchanges with their biophysical environment to reverse the entropic process of decay is conceptualized as the social metabolism (Fischer-Kowalski, 1998; González de Molina and Toledo, 2014). Accounting for these interactions provides valuable information to assess a society's environmental sustainability (González de

Molina and Toledo, 2014, 2011; Haberl et al., 2019). Moreover, these complex human interactions with nature have changed original ecosystems through the movement of energy, material and information, into biocultural landscapes (Tello et al., 2006). Hence, landscapes can be considered the territorial expression of a society's metabolism (Antrop, 2005; González de Molina and Toledo, 2014, p. 110; Terkenli, 2001).

From a sociometabolic perspective, agricultural systems are complex, coupled cultural and natural systems (Liu et al., 2007a) in which through human inputs of energy (e.g., labour) and information (e.g., culture and knowledge) into the land, produces matter with an energy content (i.e., food). Agricultural systems or agroecosystems are considered dissipative structures designed and managed by farmers through colonizing natural ecosystems and appropriating a fraction of their net primary productivity (Mae Wan Ho and Ulanowicz, 2005). Although every agricultural activity follows this rationality, since the industrial and subsequently green revolution, agricultural systems have become monocultures heavily dependent on external, energy-intensive inputs (Pingali, 2012) that operate under a linear paradigm of economic profit, with severe implications for their sustainability (Odum, 1969).

According to the 'fund-flow' approach (Georgescu-Roegen, 1971), agroecosystem's sustainability relies on its capacity to reproduce its 'fund' elements, namely the fertile soil, livestock, crops, pastures, forests, associated biodiversity, and the community (Tello et al., 2016). This self-reproduction condition is achieved by reinvesting part of the 'flows' in the agroecosystem (e.g., biomass reused and unharvested (Figure 1.1). Furthermore, Margalef (1973) proposes that the more diverse living funds are, and the more integrated they are through the flows of matter and energy that interconnect them, the more complex these agroecosystems and the emerging landscapes will be. In this line, the differentiated land-use pattern resulting from low-intensity, organic farming gives rise to landscape mosaics likely linked to more associated biodiversity and a wide variety of ecosystem services (Figure 1.2) (Barral et al., 2015; Marull et al., 2018, 2021).

The opposite scenario would be a lineal, simplified agricultural landscape, made up of fewer and disconnected living funds, in which disturbance is very intense and homogenously exerted across the territory, reducing the diversity of suitable and heterogenous potential habitats for farm-associated biodiversity. This hypothesis has been supported by modelled and empirical research on what is known as the 'spatial insurance' offered for biodiversity in temporally fluctuating and spatially heterogeneous natural and human-dominated environments (José-María et al., 2010;

Loreau et al., 2003; Marull et al., 2018, 2019; Montero et al., 2021; Shanafelt et al., 2015; Tscharntke et al., 2012b).

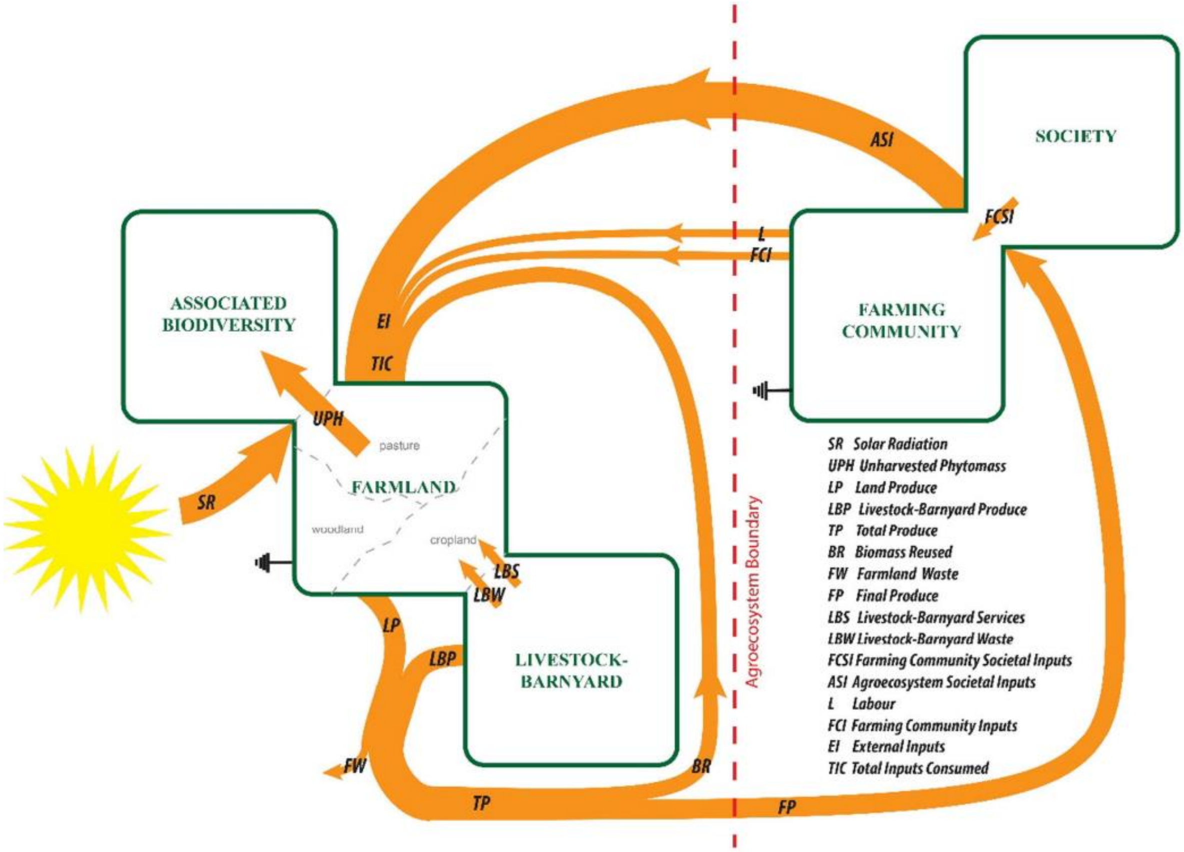

Figure 1.1 Agroecosystem fund-flow model (Tello et al. 2016)

An agroecosystem in good ecological condition will have various multidirectional relationships (matter-energy flows, orange arrows) occur between the fund elements (green boxes) increasing the complexity of the system. The expression of these relationships in the territory are represented by different land uses and give rise to different landscape configurations more or less capable of hosting biodiversity and providing ecosystem services.

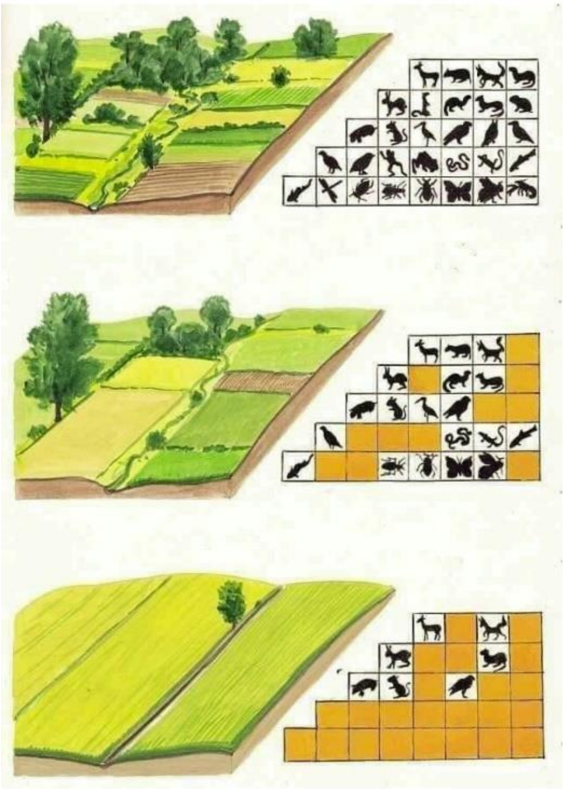

Figure 1.2. Agroecological landscapes

Differentiated land-use pattern give rise to landscape mosaic with heterogeneous land covers and hedgerows offering 'spatial insurance' to biodiversity (Loreau et al. 2003). Different landscape configurations will have differential impact on the provisioning of ecosystem functions and services. Source: Fischesser and Dupuis-Tate (1997).

These principles are found within the agroecological paradigm that millions of farmers around the world have been practising historically in their territories, maintaining the fund elements that allow farm systems to endure over time while protecting natural resources and preserving biocultural landscapes (Gliessman, 1990; Holt-Giménez and Altieri, 2013). Additionally, recent studies have determined that in agroecosystems, most of the essential biophysical cycles are closed at larger scales than plot and farm scales (i.e., by replenishing nutrients to agricultural soils Marull et al., 2016; Tello et al., 2012). Furthermore, at this landscape scale, the interplay of diverse land covers gives rise to emergent properties that support vital ecological processes for adequate ecosystem functioning (e.g., pollination, pest regulation, water cycles) (Jeanneret et al., 2021).

Overcoming the unsustainability trap of the current agricultural model, farm systems must entail two conditions: first, to reduce external input dependence (i.e., synthetic fertilizers and pesticides) through increasing system circularity, and ii) configure intermediately disturbed and well-connected heterogeneous landscapes. If these two conditions are satisfied at a farm-scale, complex agroecosystems can be developed and scaled up into agroecological landscapes (González de Molina, 2013) and advance towards integrated agroecology territories (Wezel et al., 2016).

Over the two last two decades, the food-biodiversity dilemma has been the centre of a conservation agenda aiming to halt human-driven biodiversity loss (Fischer et al., 2008a; Godfray, 2011; Tscharntke et al., 2012a). This dilemma has given rise to the related land-sparing *vs* land-sharing debate (Fischer et al., 2008b). These two land planning strategies were confronted with finding an ideal plan for feed the growing world population while maximizing biodiversity conservation. The first strategy proposes setting aside an area for conservation while another land is used intensively to produce agricultural commodities (land-sparing), and the second one suggests combining smaller conservation areas with less intensive, wildlife-friendly agricultural production techniques (land-sharing). Many studies approaching this debate have deepened our understanding of agroecosystems and evidenced the crucial role both can play as habitats for biodiversity and the maintenance of ecological functions and ecosystem services in different gradients of anthropogenized landscapes (Perfecto and Vandermeer, 2008; Tscharntke et al., 2012a). The oversimplification of this dichotomy has been widely argued (Fischer et al., 2014a; Grau et al., 2013a; Kremen, 2015). The debate has made apparent the need to develop more complex conceptual and interdisciplinary methodological frameworks to approach food-biodiversity and land scarcity issues (Castiblanco and Etter, 2013; Lambin and Meyfroidt, 2011a) by taking into account different geographical scales of analysis, environmental heterogeneity, food sovereignty, and the role of globalization on this food and biodiversity crisis (Fischer et al., 2014a; Grau et al., 2013a; Kremen, 2015; Scariot, 2013).

Understanding the relationship and trade-offs between agricultural activity, biodiversity conservation, ecological functioning, climate change mitigation and adaptation and human population growth is a top priority for sustainability scientists (Kates et al., 2001). The food-biodiversity nexus must be analysed from a systemic approach, which takes into account the multidimensionality (i.e., social, ecological, economic, cultural), multiscalar (i.e., local, landscape, national, regional) and the emergent properties of these complex socio-ecological systems, on which global food security and the Earth's support system depend (Grau et al., 2013a). Therefore, there is a need to adopt a social-ecological framework. The approach adopted in this Doctoral Thesis will allow us to reconsider these systems as dissipative structures (González de Molina and Toledo, 2014; Jørgensen and Fath, 2004; Prigogine, 1984). We will account account for the different landscape-metabolic processes in the agricultural land specifically by assessing the energy efficiency of metropolitan agricultural systems, their capacity to close nutrient cycles, supply ecosystem services and assess their contributions to landscape ecological functionality.

1.2 The role of metropolitan agriculture in addressing the current socioecological crisis

It is estimated that urbanization trends worldwide will cause an expansion of the built space of approximately 1.2 million km^2 in the upcoming decades (Seto et al., 2012a). In many cases, these land use changes could involve the degradation or fragmentation of peri-urban areas, leading to habitat and species loss, compromising the functionality of ecosystems and their ability to provide ecosystem services to society (Liu et al., 2016; McDonald et al., 2013; Riley et al., 2003). For example, in the Global South, rural to urban migrations can lead to rural population decline, accentuating the loss of traditional small-scale, wildlife-friendly agricultural practices (Seto et al., 2012b) and triggering agro-industrial land grabbing (Borras et al., 2012; Torres Vélez, 2012). While in some regions of the Global North, such as Europe, where urbanization is an older phenomenon, abandoned agricultural land has led to the loss of agroforest mosaics and a forest transition with significant implications for ecosystems' resilience. For instance, abandoned agricultural land has led to the loss of traditional farming practices, such as grazing, that use to contributed to the biocultural maintenance of landscapes and control wildfire occurrence (Cervera et al., 2019; Marull et al., 2015; Mather et al., 1999; Otero et al., 2015).

There is an inextricable relationship between rural and urban areas on which the sustainability and well-being of the population depend and where agriculture is a key element. In the past, the sustainability of the cities relied entirely on their hinterlands' (or oceans') capacity to provide enough food for their population (Steel, 2008). Although these limits changed as humans evolved technologically and became capable of transporting food from across the world by vessels, trains, and planes to feed the growing cities, this is no longer a sustainable nor a wise option for humanity. It is imperative to transform our food systems, and metropolitan agriculture plays a fundamental role in this transformation for two main reasons. First, because land use changes around metropolitan are already having an impact on food security (Olsson et al., 2016; Urrego-Mesa, 2021a), food sovereignty (Altieri, 2009) and population diets (Seto et al., 2012b) around the world. And because agriculture in metropolitan areas can play an important role by providing ecosystem services or maintaining a functional ecological structure around highly anthopogenized territories (Cattaneo et al., 2018; Marull et al., 2016; Yacamán-Ochoa et al., 2020).

In this sense, the agroecological transition claimed by all the agroecology movements (IFOAM, Agroecology Europe[1], Via Campesina[2], Slow Food[3] and others) and already proposed by FAO (FAO, 2019a, 2019b) and the European Commission[4] is a critical task in this endeavour to address food sovereignty simultaneously with climate change mitigation and adaptation, biodiversity improvement, soil fertility regeneration by closing the return of organic matter and N and P nutrients, and water pollution prevention (Agroecology Europe, 2021; IFOAM, 2019; Sinclair et al., 2019; Tittonell, 2014; Wezel et al., 2009). This transition aims at integrating agroecological territories by scaling up current organic and other sustainability-oriented ways of farming (Wezel et al., 2016) as a step towards a more comprehensive change of the current agri-food system by reconnecting producers and consumers in these relocated foodscapes with healthier diets (Gliessman, 2016). However, despite having some analytical tools to foresee and plan the scaling-up processes of agroecology transition, nobody knows in advance the scope, extent, and exact configuration of these agroecological territories that will connect natural protected areas with green infrastructures of metropolitan areas (EEA, 2011, 2015, 2019; Padró et al., 2020; Vallecillo et al., 2018).

Therefore, to harness the agricultural potential for sustainability, scientists, land planners, and policymakers must undergo another paradigm shift, switching from urban ecology to metropolitan socio-ecological systems that consider the multiple urban, peri-urban and rural connections, including the water-energy-food-land uses and society nexus. To achieve this goal, it is necessary to consider open spaces as a green infrastructure that re-signifies the metropolitan territory as a socio-ecological system (Dupras et al., 2016; Marull et al., 2016). The concept of green

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[1] https://www.agroecology-europe.org/our-approach/principles/

[2] https://viacampesina.org/en/what-are-we-fighting-for/biodiversity-and-genetic-resources/

[3] https://www.slowfood.com/

[4] https://knowledge4policy.ec.europa.eu/global-food-nutrition-security/topic/agroecology/navigation-page/online-resources-agroecology/tools-applications-agroecology_en

infrastructure was proposed by Benedict and McMahon, (2002) and assigns a functional role to the network and all its elements of non-built-up spaces (i.e., open spaces) within metropolitan areas and cities. It can be established that the core function of metropolitan green infrastructure relies on its multifunctionality and connectivity (Hansen and Pauleit, 2014). These two characteristics are directly related to the network's capacity to provide society with important ecosystem services and maintain the life's support systems (Salomaa et al., 2017; Tzoulas et al., 2007), as well as with the possibility of developing a more circular and sustainable economy than the current one (Billen et al., 2021; Cattaneo et al., 2018). However, to that aim, metropolitan green infrastructures need to be well planned to become ecologically connected to the larger land matrix (Marull et al., 2008, 2021; Rey Benayas et al., 2009).

Finally, the role that metropolitan agriculture can have in helping to overcome the current socio-ecological crisis must consider land-use policies that have been collectively built with different actors and backed up with rigorous scientific data. It is fundamental to find the appropriate tools to connect the various social and ecological processes across the metropolitan territorial matrix and study the impacts of future landscape planning and agricultural management practices on the territory. Therefore, there is a need to advance in developing systemic, comprehensive, and transferable methodologies to analyse these landscape-metabolism interactions in different world regions that support and guide decision-making processes to configure sustainable metropolitan areas and integrated food systems. This thesis aims to contribute to these methodologies Here is where this Thesis aims to contribute.

1.3 Tools to advance towards more sustainable metropolitan agricultural systems

To transit towards more sustainable metropolitan systems, and ultimately, food systems, by scaling up current organic farming into integrated agroecology territories, it is advised to incorporate the agroecological approach and strengthen community-led nature-based solutions, such as the green infrastructure restoration and improvement, into land use planning and policy (Chatzimentor et al., 2020; Cohen-Shacham et al., 2016; Fan et al., 2017; Francis et al., 2003; Godfray et al., 2010). However, accomplishing that aim poses some difficulties due to the lack of a systemic approach that allows accounting for the complexity of metropolitan socio-ecological systems in different global contexts (Fischer et al., 2014a; Grau et al., 2013a; Hansen and Pauleit, 2014; Kremen and Miles, 2012a).

On one side, the dominance of the technocratic discourses and the industrial agriculture paradigm after the green revolution have led to biases in our understanding of the diversity of agricultural systems (González de Molina, 2013; Sanderson Bellamy and Ioris, 2017; Vanloqueren and Baret, 2009). There is still a predominance of scientific studies, and land use policies focused on the prevailing industrial agriculture, compared to other sustainability-oriented forms of agriculture, such as organic farming and agroecology. In fact, agroecology, as a practice and a science, has been predominantly approached and developed at the farm, agroecosystem, or local scales (González de Molina, 2013; Wezel et al., 2009). The above conditions have contributed to leaving agroecology out of planning instruments for so long that it is now challenging to integrate it into state and regional planning (González de Molina, 2013; Vanloqueren and Baret, 2009). Therefore, the scalability of agroecological proposals becomes the central knowledge gap to address the forthcoming agroecology transition.

On the other side, in theory and practice, the concept of green infrastructure is relatively new and still carries some ambiguities related to its definition (Chatzimentor et al., 2020; Wang and Banzhaf, 2018). Furthermore, there is a significant gap in the knowledge about its possibilities and implementation between the global North and South (Chatzimentor et al., 2020; European Commission, 2016; Pauleit et al., 2021; Slätmo et al., 2019; Vásquez et al., 2016, 2019). Nonetheless, perhaps the main limitation of its incorporation into land use policies also relies on the lack of a systemic approach to assess one of its core traits: the multifunctionality. These knowledge gaps point out the need of accounting for the differential role of green infrastructure elements (i.e., natural forest, urban parks, agricultural mosaic) and the multiple social and environmental dimensions that shape them, as well as the relationship among these driving forces and ruling actors, to ultimately understand their overall contribution to sustainability both at metropolitan and regional levels (Sundseth, 2008).

In summary, there are still knowledge gaps in our understanding of how different types of agricultural proposals can effectively contribute to the overall sustainability of metropolitan systems (e.g., the multiple ecosystem services and disservices of metropolitan agriculture) and the multiscalar possibilities of more sustainable proposals (i.e., agroecological transition), hindering its necessary implementation at the landscape, regional and country scales (Altieri and Nicholls, 2012; Jeanneret et al., 2021; Padró et al., 2020). To fill these gaps is crucial to approach the territory as a socio-ecological system and develop new interdisciplinary criteria and methods to assess its functionality and capacity to provide multiple ecosystem services to society (Marull et al., 2010, 2021).

To support decision-making on territorial planning, it is essential that these methodologies acknowledge the multiscalar and multidimensional processes within the territories and can be easily incorporated in different land planning tools. In this sense, two conceptual and methodological frameworks are crucial. First, Landscape Ecology provides a quantitative and visual set of tools to analyse land use patterns and their ecological processes that help maintain biodiversity and ecosystem services (Fahrig et al., 2011; Fischer and Lindenmayer, 2006; Mastrangelo et al., 2014). Second, Ecological Economics, through its sociometabolic approach (González de Molina and Toledo, 2014), allows to account in different ways the circularity of flows of matter and energy to assess through a functional vision the relationship of societies and their biophysical environment (Galán et al., 2016; Gerber and Scheidel, 2018; Giampietro et al., 2013, 2014; Tello et al., 2015, 2016). This Thesis draws on both approaches and combines them to tackle the research questions addressed.

1.4 Objective and research questions

The main objective of this Doctoral Thesis is to evaluate the contribution of agricultural landscapes to the sustainability of metropolitan areas through the development of landscape-metabolism models that enrich our capacity to propose green infrastructure scenarios for sustainable land planning.

With this objective in mind, this Thesis seeks to address the following research questions:

What is the contribution of different agricultural systems to the socio-ecological sustainability of metropolitan areas? Additionally, how could this knowledge contribute to metropolitan land use planning to meet the current socio-ecological challenges?

Those questions will be approached through the analysis of metropolitan agriculture in two different regions of the world (the tropical Andes and the Mediterranean), and specifically answer the following questions:

- What is the contribution of biocultural landscapes to the ecological functionality of metropolitan areas? **(Chapter 2)**
- What is the relationship between the different metabolic configurations of the metropolitan biocultural landscapes with their capacity to provide ecosystem services? **(Chapter 3)**

- What would be the implications of an agricultural transition to organic management on the socio-ecological sustainability of metropolitan areas? And how can it guide future land policies on green infrastructure? **(Chapter 4)**
- What could be some optimal land use and management scenarios that maximize key reproductive characteristics of metropolitan landscapes? **(Chapter 5)**

1.5 Structure of the Thesis

The Thesis is structured in two parts:

Part I: **"Towards an Intermediate-Disturbance Complexity (IDC) model to assess landscape functionality and ecosystem services. Application in the metropolis of Cali (Colombia)."** This part presents a regional approach to metropolitan sustainability of the Cauca River valley and, by adopting an IDC model, investigates the effect of agricultural intensification processes associated with the development of the sugarcane industry, as well as the role played by indigenous, black, and peasant communities in structuring biocultural landscapes through different agricultural practices, possibly representative of traditional agroecology. Chapter 2 assesses the contribution of different agricultural production systems to the ecological functioning of the region. Based on georeferenced census data, it builds a farm system typology of the region's agricultural systems. Subsequently, it adopts a multiscalar (farm to landscape to region) and space-for-time approach to analyse the potential effects of historical agricultural and territorial transformations. This approach seems promising to elucidate the environmental costs of neo-extractive policies, often hidden in contemporary political debates. In the same line, this research makes apparent that ecosystem services are a valuable tool to support sustainable landscape management, as shown with a further analysis links the configuration and composition of biocultural landscapes with their capacity to provide ecosystem services for the metropolitan area of Cali. Therefore, Chapter 3 tests the metabolic-territorial IDC model and its ability to predict the capacity of anthropogenized landscapes to provide ecosystem services and maintain their ecological functionality based on the biocultural landscape configurations. Additionally, it evaluates the opportunities and challenges for land planning at a metropolitan scale. It discusses a proposal to adopt a metropolitan green infrastructure to face the numerous sustainability problems that affect the region of the geographic valley of the Cauca River. This integrated approach sheds light on some preliminary yet inspiring possible horizons of agroecological landscapes in the tropical Andes that could be supported by land use public policy and land planning strategies in a context where production landscapes are at the centre of sustainability and socioeconomic challenges.

Part II: "**Towards a Socio-ecological Integrated Analysis (SIA) of the green infrastructure to assess land use planning. Application to the Metropolitan Area of Barcelona (Spain).** This part presents new developments of a SIA model and its application to land policy in the Barcelona Metropolitan Area. With these advancements, we aim to explore possible future scenarios, not only of land use planning but agricultural management as well, in a theoretical ecological transition of metropolitan agriculture. Chapter 4 presents the results of the SIA model applications to the AMB green infrastructure at a supramunicipal scale. It analyses the contributions of green infrastructure, particularly agriculture, to the configuration and ecological functioning of the metropolitan area regarding climate change, ecosystem service provisioning, biodiversity conservation, and social cohesion. In this chapter, a new criterion to evaluate a theoretical organic transition scenario of metropolitan agriculture is developed, together with the integrated analysis of three land planning scenarios (i.e., business as usual, alternative, and potential) proposed by the PDU. Chapter 5 elaborates from Chapter 4's theoretical organic transition scenario's results to explore optimal scenarios for land use management at the municipal scale that maximize different specific land planning criteria (i.e., agricultural yields, the energy efficiency of agroecosystems, biodiversity conservation, etc.). We did that through an Energy-Landscape Optimization analysis.

Finally, in Chapter 6, we present the conclusions on the different approaches used to study agriculture in metropolitan areas, their implications and contributions for land planning, and the possible scenarios of agroecological transition.

1.6 Related publications

This thesis is based on a set of submitted or published peer-reviewed articles

- **LaRota-Aguilera, M. J.,** & Marull, J. (Submitted). Towards a Landscape-Metabolism Model for the Tropical Andes. Application in the Metropolitan Region of Cali (Colombia). Submitted to: *Environmental Science and Policy* (Q1: Geography, Planning, and development).
- **LaRota-Aguilera, M. J.,** Zapata-Caldas, E., Buitrago-Bermúdez, O., and Marull, J. (Submitted) New criteria and methods for sustainable land use planning of metropolitan green infrastructures in the tropical Andes. Submitted to: *Land Use Policy*. (Q1: Forestry).
- Padró, R., **La Rota-Aguilera, M. J**., Giocoli, A., Cirera, J., Coll, F., Pons, M., Pino, J., Pili, S., Serrano, T., Villalba, G., & Marull, J. (2020). Assessing the sustainability of contrasting land use scenarios through the Socio-ecological Integrated Analysis (SIA) of the metropolitan green infrastructure in Barcelona. *Landscape and Urban Planning*, *203*(April), 103905. https://doi.org/10.1016/j.landurbplan.2020.103905 (Q1: Ecology).
- Marull, J., Torabi, P., Padró, R., Alabert, A., **LaRota-Aguilera, M. J**., & Serrano, T. (2020). Energy-Landscape optimization for land use planning. Application in the Barcelona Metropolitan Area. *Ecological Modelling*, *431*(June), 109182. https://doi.org/10.1016/j.ecolmodel.2020.109182 (Q2: Ecological Modelling)

Articles related to this research work, but not included as part of the dissertation.

- **La Rota-Aguilera, M. J**. Delgadillo, O.L., Tello, E., (In press). Sociometabolic Research in Latin America: A Review on Advances and Knowledge Gaps in Agroecological Trends and Rural Perspectives. *Ecological Economics.* https://doi.org/10.1016/j.ecolecon.2021.107310 (Q1: Economics and Econometrics)

Presentation of results or preliminary results

- “Sustainability of tropical Andes agricultural frontiers: a socio-ecological integrated assessment of the Cauca River valley (Colombia)”. Simposio Latinoamericano de Historia Ambiental – SOLCHA (Julio 2021). Mesa: Los aportes del enfoque metabólico a la historia ambiental latinoamericana. Ecuador (Online) July 7th, 2021.

- “Espacios abiertos y transición socioecológica del área metropolitana de Barcelona: Un análisis socioecológico integrado para la evaluación de escenarios para la planificación territorial sostenible”. Jury presentation: Francesc Santacana Scholarship. Plan Estratégico Metropolitano de Barcelona. Barcelona, November 7th, 2020.
- “Assessing the sustainability of contrasting land use scenarios through the Socio-ecological Integrated Analysis (SIA) of the metropolitan green infrastructure in Barcelona”. LIFE UrbanGreeningPlans Workshop. Brussels. November 24th , 2021.

Dissemination science publications and projects

- “Revista Papers 64: Reptes i oportunitats de la infraestructura verda metropolitana”. Publisher: IERMB, Barcelona. Editorial coordination: **La Rota-Aguilera, M.J**., Editors: Dr. Joan Marull (IERMB) **La Rota-Aguilera, M.J**. and Dr. Joan Pino (CREAF). October 2021.
- **La Rota-Aguilera, M.J**., Padró, R., Pino, J., Giocoli, A., Cirera, J., …& Marull, J. (2020). Espais oberts i trancisió socioecológica de l’Àrea Metropolitana de Barcelona: noves eines d’anàlisi per a una planificació territorial sostenible. *Anuari metropolità de Barcelona*. La metròpoli en transició. Reptes i estratègies. Barcelona, Spain.
- Marull, J., **LaRota-Aguilera, M.J.,** Pino, J. (2021) Introducciò: Reptes i oportunitats de la infraestructura verda metropolitana en el context de crisi socioecològica actual. Revista Papers 64. IERMB. Barcelona, Spain.
- **LaRota-Aguilera, M.J.**, Marull, J. Rojas, E. (2021) Un modelo integrado de paisaje-metabolismo para los Andes tropicales. Aplicación en la región metropolitana de Cali (Colombia). Revista Papers 64. IERMB. Barcelona, Spain
- Marull, J., **LaRota-Aguilera, M.J.**, Ruiz-Forés, N., Coll. F., Padró, R., Serrano-Tovar, T., Giocoli, A., Cirera, J. (2021) Espais oberts i transició socioecològica: noves eines d’anàlisi per a una planificació territorial sostenible. Revista Papers 64. IERMB. Barcelona, Spain
- Marull, J., Padró., Gordillo, J., Serrano, T., Guzmána, P., **LaRota-Aguilera, M.J.**, and Joan Pino. El funcionament socioecològic del territori metropolità de Barcelona en 10 indicadors. Revista Barcelona Societat. Adjuntament de Barcelona. 2019

Other activities related to the doctoral degree

- Academic stay at the Instituto de Estudios Interculturales – IEI (Javeriana University Cali, Colombia) from January 2017 – January 2018 under the supervision of Dr. Carlos Arturo Duarte and Dr. Manuel Ramiro Muñoz.
- 3-year Research position (2021 – 2024) at the Laboratory of Ecology and Territory (IERMB). Specifically related to the development and optimization of models for the agroecological transition.

Active participation in ongoing research projects where the SIA model is being applied:

- The SIA is currently being used to support for strategic environmental assessment and drafting of the PDU. The SIA is being applied in the Project LIFE UrbanGreeningPlans 2021-2022 of the Metropolitan Area of Barcelona. Current role: part of the research team and coordinator of the strategic action.
- The SIA model is the methodological core of the PRIMA MA4SURE Mediterranean Agroecosystems for Sustainability and Resilience under Climate Change Project 2021-2024. Current role: Project manager and leader of work-package No. 4

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PART I. A regional socio-ecological approach to territorial metabolism through metabolic and landscape metrics models

2 Towards a Landscape-Metabolism Model for the Tropical Andes. Application in the Metropolitan Region of Cali (Colombia)

This chapter is based on the following submitted journal paper: **LaRota-Aguilera, M. J.,** & Marull, J. Towards a Landscape-Metabolism Model for the Tropical Andes. Application in the Metropolitan Region of Cali (Colombia). Submitted to: *Environmental Science and Policy*. (Q1: Geography, Planning, and development)

2.1 Introduction

The exponential growth of the world's human population over the past 100 years has accentuated at an unprecedented rate two of the most critical drivers of global socio-ecological change: urbanization and cropland expansion (Grimm et al., 2008; Zabel et al., 2019). According to the United Nations, in the next 30 years, the human population will reach 9.8 billion people, and 68% of the world population will live in metropolitan regions (United Nations, 2019a). This scenario has already set an extraordinary pressure on the environment by transforming landscapes and ecosystems, impacting biodiversity, and threatening fundamental socio-ecological processes needed for human maintenance (Cardinale et al., 2012; Tscharntke et al., 2012). On the one side, urban sprawl has caused landscape fragmentation, natural habitat, and ecosystem services losses, and has reduced socio-ecological systems' capacity to respond to global changes (Antrop, 2004; Dupras et al., 2016; Tratalos et al., 2007). On the other side, the predicted demographic changes will entail a record increase in the food, raw material, and energy demand per capita, doubling the current extension of land designated for agriculture (Lambin and Meyfroidt, 2011b; Tilman et al., 2001).

Often established within rural environments, metropolitan regions exemplify these issues. They hold complex urban-rural and nature-society interactions, facing a double challenge: sustainably satisfy their population's biophysical and energy demands while maintaining their territories' ecological structure and functionality (Padró et al., 2020b). The global consensus recommends building metropolises articulated to a territorial matrix that protect nature and essential ecosystem services, foment positive economic, social, and environmental links between urban, peri-urban, and rural areas, and strengthen national and regional development planning (Elmqvist et al., 2013; United Nations, 2019b). However, building sustainable metropolitan regions require integrative assessment tools to encompass the different dimensions of these socio-ecological systems (Pickett et al., 2001, 2011). There is, therefore, a demand for new integrative approaches to conceptualize and understand the complexity of these regions (Giampietro et al., 2014, 2013; Marull et al., 2016a).

Despite its global relevance, the debates about metropolitan regions' sustainability and agricultural development are crucial for Latin America, and specifically the Tropical Andes, given various conditions. First, one-quarter of Latin America's largest cities and 22% of its metropolitan population are in the Tropical Andes (United Nations, 2019a). Second, their culture and economies are historically based on agricultural activities related to maintaining rural livelihoods, food production, or agro-industrial activities (Marull et al., 2017). Third, Latin America has a long-known predominant role as a food and commodity world supplier (Infante-Amate et al., 2020); resulting in an increase in the monetary value of land, water, and other natural resources and placing agriculture as one of the main drivers of land use and land cover transformations (Lambin et al., 2003). Fourth, currently, the Tropical Andes show alarming rates of ecosystem loss, threatening several of the most culturally and biologically diverse places on the planet (Cincotta et al., 2000; Lambin et al., 2003; Laurance et al., 2014). Fifth, a long history of institutional weakness, social turmoil, and inequality has resulted in disorganized land planning, leading to thousands of social-environmental conflicts (Martínez-Alier et al., 2016). Moreover, the predominant current agricultural models, implemented throughout a set of neoliberal policies (Brannstrom, 2009), has shown disastrous social and environmental consequences through a growing, but still insufficient, empirical research (Altieri, 1998; Grau and Aide, 2008; Holt-Giménez and Altieri, 2013). Therefore, there is a need to understand Latin America's 'metropolitanization' and develop tools to support land planning policies that integrate ecological (i.e., resources availability, ecosystem services) and social (i.e., land and ethnic tenure, food sovereignty) parameters.

Although agriculture in the Tropical Andes has been undergoing a slow transition towards more intense management systems (Grau and Aide, 2008), small-farming and low-intensity agriculture are still the most common production systems and hold great agroecological potential (Altieri and Toledo, 2011). However, the contribution of different farming practices to regional sustainability and the consequences of agricultural intensification on socio-ecological systems remain unclear (Jeanneret et al., 2021; Yacamán-Ochoa et al., 2020). This work focuses on Colombia, a megadiverse country where 31% of its ecosystems have already suffered transformation mainly driven by infrastructure development, agricultural intensification, and diffuse land-use policies (Higgins et al., 2017). A clear example is the metropolitan region of Cali, the third-largest city of Colombia. This multicultural region has been the epicentre of a less than a century-long territorial transformation driven by an agroindustry model and a disorganized urbanization process.

This article aims to assess the implications of these general Tropical Andes territorial transformations on the ecological functioning of Cali's metropolitan region. We hypothesize that biocultural landscapes (Hong et al., 2014), configured by diverse indigenous, peasant, and afro traditional agricultural systems, significantly contribute to the ecological functionality of this inter-Andean metropolitan region. We propose a multiscale integrated landscape-metabolism assessment based on georeferenced farm system typologies (local scale) and land cover data (landscape scale). We have set three specific objectives: i) identify the main agricultural systems of the region; ii) assess the territorial expression of the different agriculture-related anthropogenic disturbances and the landscape ecological functionality; and iii) characterize the current state of the green infrastructure sustainability through an integrated landscape-metabolism approach. Finally, we discuss the socio-ecological implications of different agricultural systems in the region to identify critical elements for more sustainable metropolitan planning in the Tropical Andes.

2.2 Materials and methods

2.2.1 Case study

Because the metropolitan region of Cali does not have any administrative limits, the study considers the Upper Cauca River Valley (henceforth UCRV) boundaries as so. It was defined using the topographic boundaries of the river basin for the West-East limits and socioeconomic criteria given by (Martínez-Toro and Patiño-Gómez, 2015) for the North-South limits (Figure 2.1). The entire study region is 10,040 km^2 and includes heterogeneous flat, hillside, and mountainous landscapes. The annual precipitation average oscillates between 800 and 1,500 mm (IDEAM, 2020).

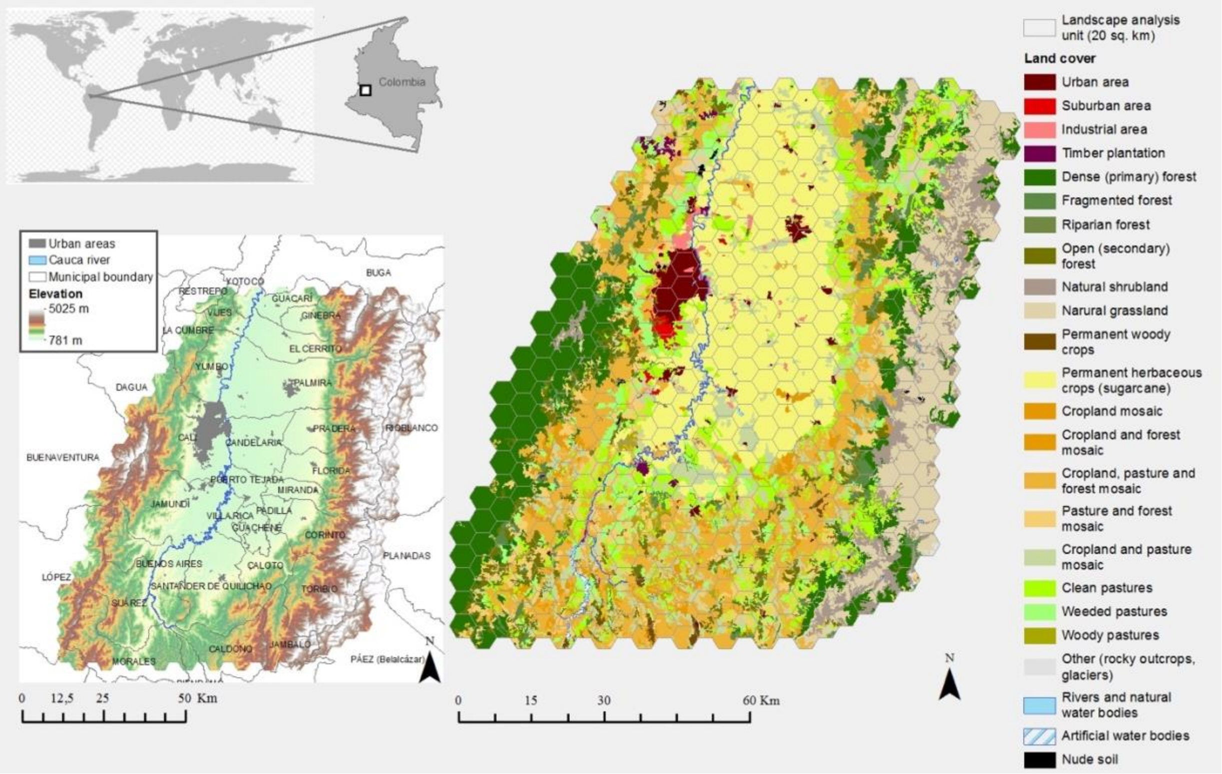


Figure 2.1 Location, administrative boundaries, and land covers of the Upper Cauca River Valley.

Source: Corine Land Cover Map for Colombia 2012. 1:100.000 (IDEAM, 2010. Level 3 Legend).

The UCRV comprises tropical humid, montane forests, and key paramo ecosystems. Also, one of the five enclaves of tropical dry forests in Colombia, one of the most threatened ecosystems in Colombia. The region concentrates several hotspots of persistent high human footprint in the last 50 years (Correa Ayram et al., 2020). Today, more than half of the surface is covered by agricultural land, including cropland mosaics (31.1 %), pastures (13 %), and sugarcane plantations (19.2 %), this last one covering close to 90 % of the valley's flat area (192,000 ha). The remaining surface is distributed among forest and other natural areas (32.5 %), mainly located on the top of the Central and West Andes Cordillera, and urban and industrial areas (2.4 %) (Figure 2.1, Table A1).

Administratively speaking, the UCRV comprises the south of the Valle del Cauca department and north of the Cauca department. The total population is 3,666,784 inhabitants, of which 59% live in the Cali urban centre (2,172,527 inhabitants), 23% in other urban centres of the region (840,559 inhabitants), and 18% lives in rural areas (653,698 inhabitants) (DANE, 2018).

The region began experiencing a socio-ecological transition (Fischer-Kowalski and Haberl, 2007) in the mid-19th century, from an organic to an industrial agriculture implementation of sugarcane plantations (Delgadillo-Vargas, 2014). This transition has generated traditional agricultural systems' displacement towards the slopes of the UCRV (Pérez-Rincón et al., 2011). Although currently, this metropolitan region is not considered a political-administrative entity, over the last 20 years, it has been configuring itself as a metropolis. The drivers of this ‘metropolitanization’ lie in the rural-urban relationships taking place in this case study: the consolidation of an agro-industrial sector, mainly related to the sugar and ethanol industry, has connected the flat area municipalities through its agricultural and business model; the demographic dynamics and rapid urban and peri-urban population growth, being the largest city in the south of the country, Cali host hundreds of thousands of internal refugees who come fleeing violence, illegal economies, and poverty in rural areas, searching for different economic opportunities (Martínez-Toro, 2005; Martínez-Toro and Patiño-Gómez, 2015). The political, economic, and social dynamics have led to disorganized and improvised urban growth, demonstrating that urban-rural issues transcend political-administrative boundaries. Therefore, the look for socio-ecological sustainability suggests considering this region as a metropolitan one.

2.2.2 Conceptual approach

We used a combined landscape ecology and societal metabolism approach to offer a holistic understanding of the human-modified landscapes and link ecology to the social implications of Land Use and Cover Change (LUCC) in the Tropical Andes. We understand the landscape as the biophysical expression of the social metabolism (González de Molina and Toledo, 2014). To assess the sustainability of human agricultural activity in this region, we adopted an ecological economics framework (Martínez-Alier et al., 1998), aspiring to overcome classical economic growth approaches that externalize social and environmental impacts. Specifically, we used the Human Appropriation of Net Primary Production (HANPP) that characterizes human impacts on biomass flows and could ultimately provide a picture of ecosystems degradation (Haberl et al., 2007).

We adopted a landscape continuum model (Fischer and Lindenmayer, 2006) focused on the 'land matrix,' defined as a heterogeneous, dynamic, and multiscale system, resulting from the interrelationship between the biophysical matrix and the anthropogenic activity. This approach has been previously applied to other metropolitan regions, characterized as complex socio-ecological systems, in which different processes occur at different scales (Dupras et al., 2016; Mallarach and Marull, 2006). Methodologically the work relies on a landscape ecology approach that allows visualizing, quantifying, and analysing the effects of LUCC using cartographic tools that represent transformations of both the spatial configuration of the elements of the land-matrix and its ecological functioning (Fischer and Lindenmayer, 2006; Perfecto et al., 2009). Finally, we related landscape complexity (heterogeneous and well-connected land covers) with anthropic disturbance (HANPP) to obtain an integrated landscape-metabolism model (Marull et al., 2018) to assess the socio-ecological performance of this tropical Andean region. The literature describing the relationship between anthropic disturbances and ecological processes has been mainly done at global and regional levels and usually focused has the Global North (Krausmann et al., 2013; Marull et al., 2019c). These approaches have been less used to elucidate this relationship at landscape scales and in tropical scenarios (Marull et al., 2017; Montero et al., 2021).

2.2.3 Experimental design and databases

The integrated landscape-metabolism model used georeferenced farm system typologies at the local scale and land cover data at the landscape scale. A farm system typology was constructed for the local scale analysis based on socioeconomic household-level census data of the Third National Agrarian Census of Colombia- NAC (DANE, 2014)). The analysis unit was defined as each Agricultural Production Unit (APU n = 700,615). Anonymously georeferenced census surveys at the APU level were analysed by constructing farm system typologies defined in terms of their geography, land uses, productive vocation, yield capacity, livestock barn characteristics, technological management, resource use strategy, demography, ethnic and socio-cultural profile, as well as the scale and intensity of the production. The authors built a set of 83 standardized variables derived from the 250 questions of the NAC's original questionnaire, assuring they provided vital information needed to describe the main farm system typologies in the UCRV (Table A2).

To perform the landscape scale analysis, the UCRV was divided into 502 hexagons of 20 km^2; each one was considered a unit of analysis (Figure 2.1). This experimental design was aimed to observe the variation of the combined landscape and social metabolism processes across an altitudinal and land-use intensification gradient. Land cover data were obtained from the Corine

Land Cover (CLC) map for 2010-2012 (1:100,000) adapted for Colombia. The official CLC map presented a 10 % cloud coverage given the location at the intertropical convergence zone; this limitation was solved by manually reclassifying each cloud patch using aerial photography, satellite imagery, and expert knowledge of the area. The analyses were based on the Level 3 of the CLC legend (IDEAM, 2010), which initially included 27 land cover classes; these were revised in terms of their representativeness for the study area and reclassified in 20 final land cover classes to perform the landscape assessment (Table A1). From these, 18 land covers were considered habitats for biodiversity (i.e., forests and other natural areas, cropland, timber plantations, water bodies). In contrast, build-up areas (i.e., urban, suburban, industrial) and nude soils were classified as non-habitats. Land covers representing less than 0.1% of the UCRV were included in the analyses but not illustrated in the results for visual clarity.

2.2.4 Socio-ecological assessment

2.2.4.1 Landscape metrics

The proposed metrics describe the patterns and processes that define the landscape complexity (L) (Dupras et al., 2016). We calculated six metrics: Largest Patch Index (LPI), Patch Density (PD), Edge Density (ED), Effective Mesh Size (EMS), and Shannon-Weaver Index (H'), and Ecological Connectivity Index (ECI), for each one of the 502 units of analysis (hexagons) of the study area.

LPI refers to the proportion of the unit of analysis occupied by the largest habitat patch. Its calculation considered all land covers, except urban areas and bare soils. PD refers to the number of potential habitat patches divided by the total area of the unit of analysis (in hectares). ED refers to the sum of lengths (in meters) of all land cover edge segments divided by the total area of the unit of analysis (in hectares); its calculation is an approach to the landscape's ecotony. EMS is an inverse measure of landscape fragmentation (Jaeger, 2000; Moser et al., 2007).

Eq. 2.1. $$\text{EMS} = \sum_{i=1}^{p} Ai^2 \,/ \sum_{i=1}^{p} Ai$$

where Ai is the area (km^2) of each land cover polygon i, and p is the number of polygons within each unit of analysis.

H' is understood as a measure of information in the land cover distribution and analyses the landscape heterogeneity (equi-diversity of land covers) as a function of the number and proportion of each hexagon's different patches (Shannon and Weaver, 1948):

$$\textbf{Eq. 2.2.} \quad H' = \sum_{i=1}^{j=k} pj \cdot \text{Log } pi$$

where *k* is the total number of different land covers, and p_i is the proportion of the surface of each land-cover *i* in a specific hexagon.

For H’ calculation, 8 aggregated land cover classes (*j*) as potential habitats for biodiversity were considered (forests, shrublands, grasslands, heterogeneous crops, sugarcane, pastures, others, and water bodies), and one non-habitat category (that grouped urban and industrial areas, degraded lands and road infrastructures). H’ values range from 0 to 1, with 0 reflecting a homogeneous landscape and 1 the maximum landscape heterogeneity.

Finally, ECI analyses the role of different Ecological Functional Areas (EFA) to maintain the ecological connectivity (Fischer and Lindenmayer, 2007) in each region (Pino and Marull, 2012). It is a measurement of the land matrix's functionality, through which the relationships and the potential role of the EFAs, as core connectivity areas, can be evaluated. The index was calculated through a cost-distance model based on a matrix of affinities between land covers and a matrix of affectations made up of anthropogenic barriers (see (Marull and Mallarach, 2005) for a detailed description of this model). ECI_b emphasizes the role played separately by each EFA (e.g., forestland, grassland, or farmland) in the landscape ecological connectivity:

$$\textbf{Eq. 2.3.} \quad ECI_b = 10\text{-}9 \ln(1+Xi)/\ln(1+X_t)^3$$

where xi is the value of the cost distance per pixel sum, and Xi the maximum theoretical cost distance.

The ECI values obtained for all EFAs in each unit of analysis are the sum of all ECI_b in a normalized range between 0 and 10; 10 reflecting the highest ecological connectivity:

$$\textbf{Eq. 2.4.} \quad ECI = \sum ECIb\ /m$$

where m is the total number of EFAs considered in each landscape.

2.2.4.2 Social metabolism

HANPP is used to measure the disturbance exerted by society on a given ecosystem (Haberl et al., 2004). HANPP considers NPP as the net amount of biomass produced each year by plants and measures the degree to which humans modify its availability to other species, fundamentally through two processes: the land cover change (ΔNPP_{Lu}) and the removal of a portion of NPP as food, fibre, and material for society (NPP_h) (Haberl et al., 2007; Krausmann et al., 2013):

$$\textbf{Eq. 2.5.}\ HANPP_i = \underline{\underline{\Delta}}NPP_{Lu} + NPP_h$$

$$\textbf{Eq. 2.6.} \quad \Delta NPP_{Lu} = NPP_0 - NPP_{act}$$

where ΔNPP_{Lu} is the difference between the potential NPP (NPP_0) and the actual NPP (NPP_{act}). NPPo values were obtained from the GIS dataset of the Institute of Social Ecology at the Vienna University of Natural Resources and Life Sciences (Krausmann et al., 2013, available at http://www. uni-klu.ac.at/socec/inhalt/5605.htm).

Our methodology presents an advance in the level of detail for calculating NPP_{act} since previous studies used aggregated data at the country or continental level, representing a degree of generalization that would obviate relevant NPP specificities at the farm or landscape levels. This calculation was carried out using data from the National Agricultural Census (DANE, 2014), considering the disaggregated information at the farm level. We built a primary production database for each land cover for this calculation, where nearly 240 species of plants reported by the census were re-categorized into the land cover categories. These figures were contrasted with the municipal reports of the Ministry of Agriculture for the year 2014. We estimate above and belowground biomass for each agricultural land cover based on plant-specific converters for different crops and pastures following (Guzmán-Casado et al., 2014), as well as the adventitious flora coefficients contributing to the unharvested NPP (Oerke, 2006), a value often disregarded on large scale analysis, but determinant for farm and landscape levels analysis (Guzmán-Casado et al., 2014). To obtain HANPP for each unit of analysis, each land cover HANPP value was multiplied by a coefficient w_i that represents the proportion (P) of land cover i in the unit of analysis j:

Eq. 2.7. $HANPP_{hex} = \sum_{i=1}^{k} wiPi$

Thus, HANPP depends not only on variations of P but also on variations of w. HANPP units are reported in tons of C / ha. Detailed inputs and methodology are presented in Table A3.

2.2.4.3 Intermediate Disturbance Complexity (IDC) model

The IDC model analyses how the interplay between different farming disturbances exerted across land covers create diverse combinations of landscape heterogeneity (H’) and ecological connectivity (ECI). Jointly, they become a crucial mechanism for biodiversity maintenance in human-transformed landscapes (Loreau et al., 2003a) and the provision of ecosystem services to society (Tscharntke et al., 2005). The IDC model considers integrating both the Landscape complexity (L) and the HANPP for each unit of analysis (Marull et al., 2015, 2018).

Eq. 2.8. $IDC = L\,(1 - HANPP/100)$

Eq. 2.9. $L = (H' + ECI/10)/2)$

where L expresses an integrated measure of the land cover pattern (H') and process (ECI) and is given by L. The expression 1-HANPP accounts for the NPP that remains in the system and is available for other species of the trophic chain after human appropriation.

2.2.5 Statistical analysis

2.2.5.1 Farm system typologies

A Principal Component Analysis (PCA) was used to reduce the dimension of the 83 standardized variables from the NAC (see section 2.3). The resulting factors were used to perform a Cluster Analysis (CA). A hierarchical, agglomerative clustering algorithm (Ward's method) was used to define the number of k groups in RSudio (Kuivanen et al., 2016). Then, a non-hierarchical partitioning algorithm was employed to refine these k-groups in SPSS. Finally, a discriminant analysis was done to compare k-means groups.

2.2.5.2 Landscape ecology assessment

Based on the proposed metrics and indicators (see section 2.4), we performed a PCA to identify the main factors characterizing the landscapes of the UCRV. An Exploratory Factor Analysis (EFA) was built to visualize the relationships among the principal components and the farm systems typologies and land covers, including each hexagon’s land cover distributions and the relative frequency of each farm system typology on them. Finally, we applied a Multiple Regression Analysis (MRL) to evaluate the relative contribution of each farm system typology and land covers to the PCA factors.

2.3 Results

We present the results according to three scales of analysis: First, a local analysis, resulting from the farm system typology. At this scale, the relationship of the different agricultural production systems and land use patterns was evaluated. Second, a landscape ecology assessment based on the 502 sample units (hexagons) was used to identify the ecological implications of different landscape patterns. Finally, an integrated regional analysis assessed the role of biocultural landscapes and land-use intensification on the sustainability and ecological functioning of the UCRV socio-ecological system.

2.3.1 Farm systems typologies

The CA resulted in five identified farm systems typologies (T*n*) and two residual clusters (see a complete report on the typology analysis in Table A4**)**. The five typologies represent a spatial distribution consistent with the geographic and socio-cultural characteristics of the UCRV (Figure 2.2). Table 2.1 provides a complete description of the typologies based on their representativeness, extension, land use, elevation, demography, land tenure, and market destination. General and relevant observations are described below.

Table 2.1 Description of farm systems typologies of the Upper Cauca River Valley.

Typology	**Short description**	**Percentage of the total sampled units**	**Percentage of the total agricultural area**	**Mean APU size (± SD ha)**	**Main land use[1]**	**Elevation (m.a.s.l)**	**Demography and land tenure**	**Agricultural type**	**Market destination**
T1	Mixed coffee and plantain farms	24.4 %	10 %	2.76 ± 4.9	Coffee and plantain polycultures	940 – 3600	Peasant, indigenous, and afro communities	Subsistence or small-scale agriculture	Local
T2	Cattle raise farms	9.4 %	7 %	22.8 ± 66.3	Pastures	940 – 3800	Not specified	Bovine livestock for both milk and meat production	Not specified
T3	Irrigated polyculture farms	7.1 %	29 %	8.22 ± 15.9	Polycultures (fruits, vegetables) and rice and pineapple	950 - 3800	Predominantly afro Colombian and peasant communities. Natural persons. Leased properties	Irrigated polycultures	Subsistence agriculture, barter, and local markets
T4	Indigenous farms	18.0 %	6 %	3.44 ± 4.17	No particular crop associated	950 – 3800	Indigenous communities	Polycultures	Not specified
T5	Sugarcane plantations	5.1 %	41 %	37.5 ± 54.7	Sugarcane	941 – 1510	Not associated with any ethnicity. Legal persons	Specialized, high intensity, and sugarcane plantations	National and international markets and industrial markets
Residuals	NA	36.0 %	7 %	4.6 ± 10.7	NA	939 – 4200	NA	NA	NA

[1] Referes to the predominant land use or crop reported.

APU: Agricultural Production Unit

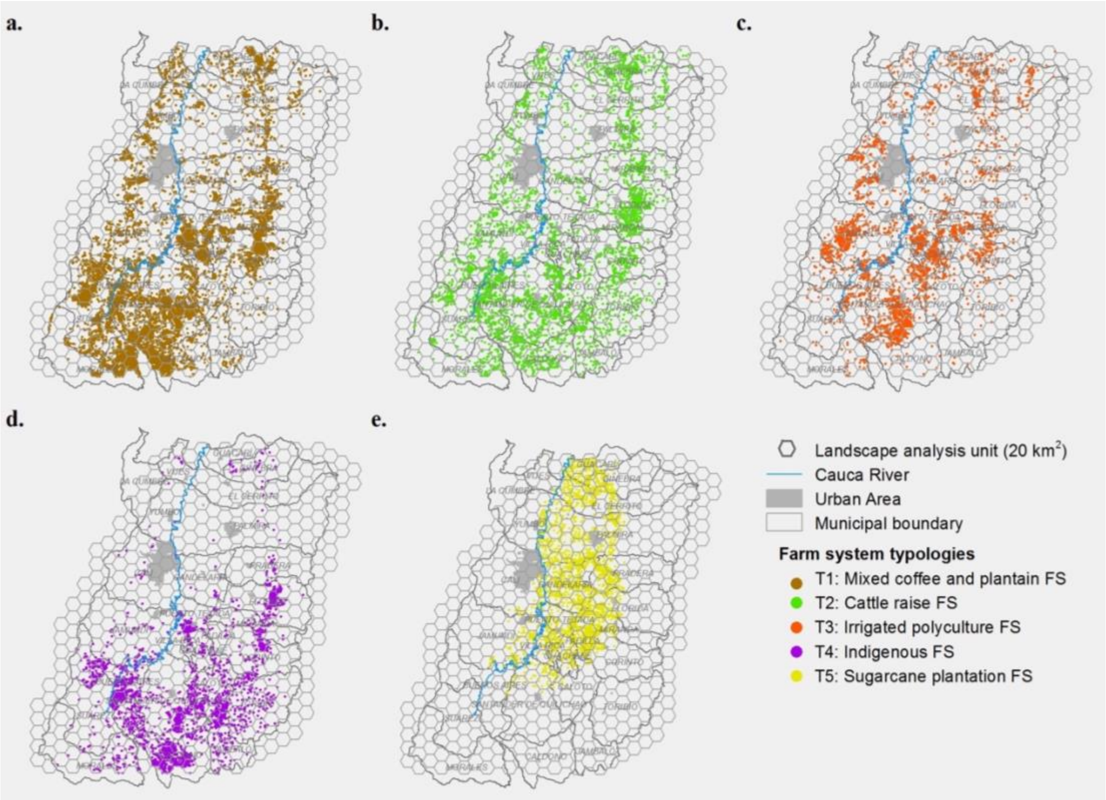


Figure 2.2 Geographic distribution of farm system typologies of the Upper Cauca River Valley.

a) Mixed coffee and plantain farms; b) Cattle raise farms; c) Irrigated polyculture farms; d) Indigenous farms; e) Sugarcane plantations.

T1 ('mixed coffee and plantain farms') is the most common farm system typology widely distributed along the UCRV (Figure 2.2A). It refers to traditional small-holder farms where the coffee-plantain are the leading products; however, they are often embedded in a polyculture setting. The highest density of this typologies is found towards the southern portion of the valley, in municipalities (Suarez, Buenos Aires, Santander de Quilichao, and Caldóno) with a predominant presence of peasant, indigenous, and afro communities that practice subsistence or small-scale agriculture.

T2 ('cattle raise farms') is a farm system typology with predominant pasture land use and bovine livestock for dairy and meat production. T2 are also widely distributed along the region, between the 900 – 2,300 m of elevation, although they may be present up to 3,800 m (Figure 2.2B).

T3 ('irrigated polyculture farms') represents diverse irrigated crops of fruits and vegetables, as well as rice and pineapple plantations. T3 is present in all the UCRV, mostly below 1,500 m, in the municipalities (Santander de Quilichao, Guachené, Jamundí, and Caloto) of the southern valley section where rural afro and peasant communities are predominant (Figure 2.2C).

T4 ('indigenous farms') refers to the collective (i.e., indigenous reserves) or individual indigenous-owned lands, located on the south-eastern part of the valley, on the outskirts of the Central Andes Cordillera, in traditionally indigenous municipalities (Caldono, Toribio, Corinto, Buenos Aires, and Jambaló) (Figure 2.2D). Within these territories, family and subsistence agriculture is common; therefore, no single crop species predominate, and crop diversity is relatively higher than the other typologies.

T5 (‘sugarcane plantations’) are monocultures located on the valley's flat plain, below 1,000 m (Figure 2.2E). T5 plot size is significantly larger than other typologies. The production is destined for the sugar and ethanol industry, and there is a significant association with the use of chemical fertilizers. Although T5 only comprises 5.1% of the sample units, it represents 41% of the declared crop area of the UCRV (DANE, 2014).

2.3.2 Landscape ecology assessment

Landscape metrics (described in section 2.4.1) allowed the distinction of at least three landscape zones (Figure 2.3 A-F). The first zone (Z1) is the valley's flat area, where landscapes are characterized by high LPI (Figure 2.3A); single large patches of non-urban coverages mainly corresponding to monoculture plantations of sugarcane. Large patches occupy between 51 % to 100 % of the landscape units' total surface. These single large polygons consequently reflect low PD and low ED (Figure 2.3B and 2.3C). H’ is considerably low, mirroring the loss of landscape heterogeneity (Figure 2.3E) as sugarcane land cover becomes predominant. EMS also depicts a high level of fragmentation (Figure 2.3D). The main cities and rural centres, as well as industrial complexes, are in Z1.

The second zone (Z2) is located on the foothills of the western and southern flanks of the Andes Mountains and the southern area of the study region. Z2 is described by medium LPI (Figure 2.3A) and high PD (Figure 2.3B), as well as more heterogeneous landscapes where the agricultural mosaic is predominant (Figure 2.3E). These areas show relatively medium to low levels of landscape fragmentation (Figure 2.3D).

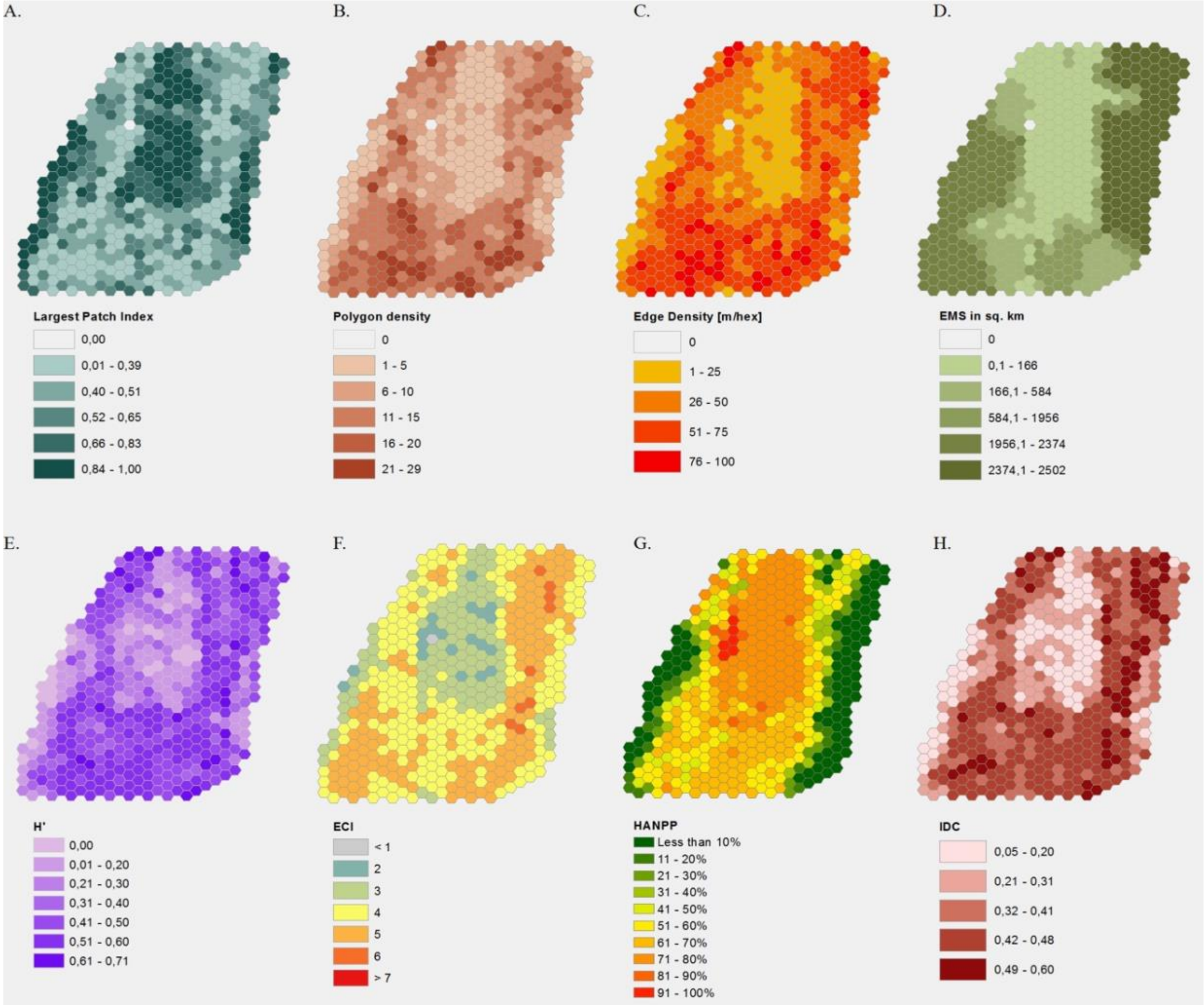


Figure 2.3 Landscape ecology assessment of the Upper Cauca River Valley.
a) Largest Patch Index (LPI); b) Polygon Density (PD); c) Edge Density (ED); d) Effective Mesh Size (EMS); e) Shannon Index (H'); f) Ecological Connectivity Index (ECI); g) Human Appropriation of Net Primary Production (HANPP); h) Intermediate Disturbance Complexity (IDC) model.

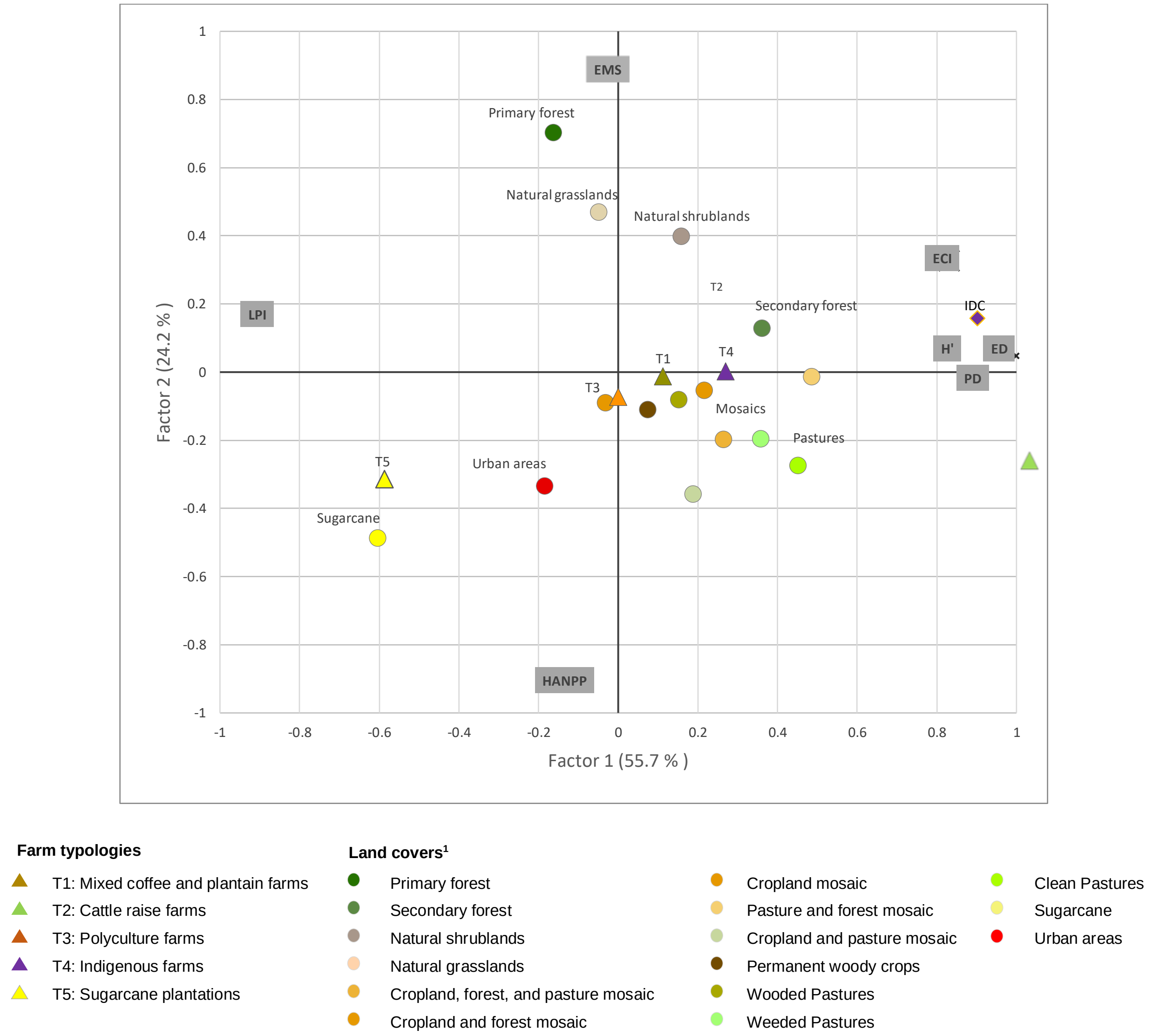
The third zone (Z3) is located at high elevations of the West, and Central Andes Cordillera (above 2,800 m), where natural land covers include primary forest, shrublands, grasslands, and paramo vegetation are predominant. Z3 reflects high LPI and EMS that at the scale of this analysis do not comprise highly fragmented natural areas; therefore, land cover diversity (Figure 2.3E) is relatively low compared to the agricultural mosaic areas of Z2, but similar to Z1, both characterized by few large patches, but of different land covers (i.e., sugarcane vs. forests).

ECI (Figure 2.3F) indicates a landscape ecological connectivity disruption between the western and eastern flanks of the valley, with the lowest values found in the flat plain of the river basin (Z1). The ecological connectivity improves as elevation increases in the Z2 and Z3.

HANPP (Figure 2.3G) reaches the highest values (60 – 100 %) through Z1, which correspond with the urban, suburban, and industrial land covers and the presence of intensive agriculture. Z2 presents an intermediate disturbance strip (40 – 70 %), and finally, Z3 is characterized by low HANPP (0 – 40 %).

2.3.3 Integrated regional analysis

An Exploratory Factor Analysis (EFA) (Figure 2.4, Table 2.2, and Table A5) allows a further understanding of the landscape spatial patterns (described in section 3.2) by identifying two principal factors characterizing the UCRV. Factor 1 ('landscape complexity') explains 55.7 % of the variance and is positively associated with H', ED, PD, and ECI, and inversely associated with LPI. Therefore, Factor 1 would be accounting for the structural functionality of the landscapes. Here, positive values would be associated with heterogeneous and well-connected landscapes (i.e., land cover mosaics). Factor 2 ('anthropogenic disturbance') explains 24.2 % of the variance and is positively associated with EMS (as the inverse of fragmentation) and negatively associated with HANPP. This factor describes human-transformed landscapes in their degree of fragmentation and disturbance and characterizes the UCRV along with a range of "natural and continuous" and "anthropogenic and fragmented" landscapes.



[1]Land covers "others," "timber plantations," "water bodies," and "nude soils" are not shown given the low surface representativeness on the study area (<0,5%)

Figure 2.4 Exploratory Factor Analysis (EFA) of the Upper Cauca River Valley. Shaded grey-squares represent the Principal Component Analysis (PCA) variables: Largest Patch Index (LPI); Polygon Density (PD); Edge Density (ED); Effective Mesh Size (EMS); Shannon Index (H'); Ecological Connectivity Index (ECI); Human Appropriation of Net Primary Production (HANPP); Intermediate Disturbance Complexity (IDC, purple rhomboid). Circles represent different land covers, and triangles represent the farm systems typologies of the Upper Cauca River Valley.

According to the MLR analyses (Table A6), Factor 1 (‘landscape complexity’) can be predicted to a significant degree ($R^2 = 0.76$; $p<0.05$) by the percentage of sugarcane, primary forest, grasslands, crop-pasture-forest mosaics, urban areas, weeded pastures, water bodies, and shrubland land covers-from highest to lowest (see Table A6.b for ß and p values). Farm systems typologies have a significant but lower capacity to explain Factor 1 ($R^2 = 0.47$; $p<0.05$). In this case, T5 (‘sugarcane plantations’) are the strongest negative predictors of landscapes’ structural functionality, while T2 (‘cattle raise farms’), T4 (‘indigenous farms’), and T1 (‘mixed coffee and plantain farms’) relate positively with it -from highest to lowest. T3 (‘irrigated polyculture farms’) showed no significant association to this dimension (see Table A6.a for ß and p values).

Factor 2 (‘anthropogenic disturbance’) is inversely related to the primary and secondary forests, grasslands, shrublands, and mosaics ($R^2 = 0.86$; $p<0.05$). Landscape units of analysis positively associated with Factor 2 reflect lower anthropogenic disturbance (Table A5.b). Complimentary, T5 (‘sugarcane plantations’) are the strongest predictors of anthropogenic (Table A5.a).

2.4 Discussion

2.4.1 Regional land use, anthropogenic disturbances, and ecological functionality

Our findings reveal a gradient in landscape composition, configuration, and land-use intensity along the UCRV, associated with the region's long-term social metabolism. The current landscapes reflect an ongoing socio-ecological transition from organic-based agriculture to an industrial one that began in the first half of the 20th century (Delgadillo-Vargas, 2014; Delgadillo-Vargas et al., 2016). However, this process has not occurred homogeneously along the region. As (Delgadillo-Vargas, 2014; Marull et al., 2017) described it, it began in the vicinity of the municipality of Palmira (with the first sugarcane plantation). It spread towards the south of the valley, finding two limits: first, at the 1,000 m of elevation (natural productive limit of sugarcane) and second, a socio-cultural encounter with various indigenous, peasant, and afro-descendant communities practicing traditional small-scale agriculture (Vélez-Torres and Varela, 2014a).

To our knowledge, this is the first empirical report of the implications of this transition on the ecological functioning of this region. Our results support social sciences narratives that anticipated the implications of these land-use and land-tenure conflicts (Rincón-García and Machado, 2014; Uribe-Castro, 2014a, 2014b, 2017). In this sense, the conversion of small farms practicing low-intensity agriculture and pasturelands into large-scale sugar plantations has been transformed in less than a century the UCRV’s flat area into an isolated and fragmented area with potentially severe effects on the ecological functionality of all the region. Parallelly, the displacement of peasant agriculture towards higher elevations has expanded the agricultural frontier. While the agricultural mosaics still show appropriate levels of ecological functionality, their quality and composition would be determinant to assure the support of biodiversity and ecosystem services for long-term sustainability (Chapter 3; La Rota Aguilera et al., forthcoming).

The most evident consequence of this transformations is how large sugarcane patches have homogenized the agricultural land matrix and disrupted the basin’s ecological connectivity, a trend seen in other Tropical Andes regions undergoing a similar process of agricultural industrialization (Shaver et al., 2015). Despite being located at its core, the UCRV flat area (Z1) depicts a severely disconnected zone from the rest of its biogeographic unit in ecological functioning terms. This highly homogeneous zone, mainly cover by sugarcane plantations (T5), is characterized by elevated anthropogenic disturbances (i.e., fragmentation and land-use intensification). This area will unlikely be able to maintain the critical ecosystem process needed for the maintenance of human (e.g., food, clean water, climate regulation) and biodiversity populations (e.g., food, habitat, pest control) (Matson et al., 1997; Tilman et al., 2002a).

On the contrary, Z2, located at mid-elevations along the UCRV, is a distinguishable agricultural mosaic zone, configured by diverse farm system typologies that provide crucial configurational and compositional heterogeneity for the region, both key drivers of metacommunity structuring (Cisneros et al., 2015; Duelli and Obrist, 2003; Grass et al., 2019; Massa et al., 2020; Wilson, 1992). This zone supports ecological connectivity for the region, especially in the southern part of the valley where afro, peasant, and indigenous agriculture seem to be configuring well-connected landscapes within interstitial spaces of sugarcane plantations and in conjunction with pasture land covers. In this sense, while extensive cattle production systems have been identified as a substantial driver of deforestation and global change, and in Colombia, (Garcia Corrales et al., 2019a) found associations between pastures and poverty and irregular land tenure, many pasture land covers in the UCRV include live fences and scattered trees, potentially enhancing the structural diversity of this land cover, contributing to maintaining the biocultural landscape mosaic (Leon and Harvey, 2006).

The third zone (Z3) describes the high-elevation ecosystems characterized by natural land covers such as mature and secondary forests and natural shrublands and grasslands. The zone harbours critical ecosystems such as 'paramos' and high Andean Forest, not only valuable for their biodiversity but also because they are the natural water reservoirs of the UCRV. This zone is not distinctively occupied by any farm typology, although there is some peasant and indigenous presence. Many of these populations have migrated from lower elevations after the land and productive transformations triggered by agro-industrial models. While these migrations have resulted in environmental conflicts due to overgrazing and high elevation crop expansion (e.g., potatoes), our results showed high ecological connectivity and low fragmentation values for this zone at the scale of the analysis (1:100000). However, sub-basin and local studies are needed to understand the impacts of agricultural expansion on its capacities to provide ecosystem services for the metropolitan region and its vulnerability to climate change (Cresso et al., 2020)

2.4.2 The role of biocultural landscapes in regional sustainability

The integrated landscape-metabolism assessment suggest that agricultural industrialization and intensification contribute to the loss of landscape ecological functionality due to the interplay between increased anthropogenic disturbance intensity and the loss of landscape complexity. On the contrary, agricultural mosaics support landscape complexity and present low anthropogenic disturbance intensities (Figure 2.4). This association was also observed in a preliminary multitemporal study on a section of the UCRV, where IDC values fell as the intensity of human disturbance increased between 1943 (the beginning of the sociometabolic transition) and 2010 (Marull et al., 2017).

Our findings support the hypothesis that biocultural landscapes characterized by agrosilvopastoral significantly contribute to the ecological functionality of this inter-Andean metropolitan system. The presence of intermediate intensity agricultural activities reflects a social metabolism linked to traditional, small to medium-scale agriculture practiced by the indigenous, peasant, and afro farm systems (T1, T3, and T4 farm systems typologies). These typologies shape heterogeneous agricultural landscapes in space (by providing different land cover patches of various sizes) and, in time, offer a diversity of crop phenologies and crop rotation regimes that contribute to local agricultural diversity. By maintaining a balance between space devoted to crops, grazing land, and forested areas, these mosaics could ultimately provide a complex, integrated patchwork of landscapes with the potential to support biodiversity (Brüning et al., 2018; Fahrig et al., 2011).

However, while these mosaics might be critical structural and functional components of biocultural landscapes (Marull et al., 2015, 2016b), their agronomic management holds the key to facing the sustainability implications of the socio-ecological transformations (Cattaneo et al., 2018; Perfecto et al., 2009; Perfecto and Vandermeer, 2008). For example, it has been increasingly reported that agricultural diversification promotes multiple ecosystem services (Lovett et al., 2005; Palomo-Campesino et al., 2018; Tamburini et al., 2020); but this capacity strongly depends on the management practices followed (e.g., conventional, organic or agroecological) (Jeanneret et al., 2021; Kremen and Miles, 2012b; Wezel et al., 2014).

The results invite us to think about the sustainability of the food system of the metropolis of Cali. One of the main contributions of Tropical Andes biocultural landscapes to sustainability is their crucial role as food providers (Altieri and Toledo, 2011; Perfecto and Vandermeer, 2008). In this work, we have shown high HANPP values for sugar and ethanol production surrounding the city of Cali and its spatial and functional implications for the whole region. The reduction of traditional small-scale agriculture due to large-scale schemes of monoculture plantations, the impact of agrochemical pollution(Hurtado and Vélez-Torres, 2020) and hydrological changes (Hurtado and Vélez-Torres, 2020; Pérez-Rincón et al., 2011) has resulted in incipient impacts on the communities that maintain the biocultural mosaic, and therefore, on food security (Hurtado-Bermúdez et al., 2020; Vélez-Torres et al., 2011). On a regional scale, small-scale farm systems in the UCRV produce various crops where coffee, bananas, and fruit predominate, playing a fundamental role in the region and country's food system.

2.4.3 Socio-ecological implications for land planning and rural political agendas

This work shows that the economic logic that has defined land planning in the UCRV over the last 70 years has led the region to a state of socio-ecological vulnerability. Currently, there is no administrative definition nor a land planning instrument for the integrative management of UCRV as a metropolitan region. From a socio-ecological perspective, our results suggest the usefulness of considering this region as a socio-ecological system and supports -to an extent worth further exploration- the consolidation of an administrative entity to manage the metropolitan region of Cali in the face of its current sustainability challenges.

We suggest that the metropolitan area of Cali should include not only the municipalities of the flat zone (Z1) but must necessarily be linked through an ecological structure to the mosaic areas (Z2), potential providers of goods and services for the metropolitan people and its biodiversity. Likewise, it is strongly advised to include high-altitude ecosystems (Z3) and promote hydrological and ecological connectivity given its role as an ecosystem service provider and secure the livelihoods of communities who rely on their services and have been heavily affected by land intensification and transformations along the region.

Our results support the approaches that subscribe to the importance of conserving the natural habitats that still exist in the URCV (*land-sparing*) and preserving the agrosilvopastoral mosaics characteristic of biocultural landscapes (*land-sharing*) maintained by traditional agricultural systems. Combining the two strategies (*land-sparing* and *land-sharing*) is essential for the territorial sustainability of the Tropical Andes, especially in metropolitan regions; with the potential to alleviate rural poverty, improve food security, crop diversity, landscape heterogeneity, and biological conservation (Dahlquist et al., 2007; Perfecto and Vandermeer, 2008; Tscharntke et al., 2012).

Despite holding some of the most biodiverse territories on the planet, the land in Colombia has played a critical social and political role. Land use and land tenure in the country are the outcome of violent territorial control dynamics (Garcia Corrales et al., 2019a) exerted by diverse armed groups, drug cartels, and political mafias, that have contributed to a prolonged civil war and one of the most unequal societies in the world (Fajardo, 2015). This context has already had tremendous consequences for biodiversity (Baptiste et al., 2017). In this sense, our analyses provide a useful integrative view of the land-use and socioeconomic and cultural dimensions

Faced with the post-conflict scenario, there are still many questions to be resolved about how to develop the field in Colombia (Torres-Rodríguez et al., 2020). Proposals such as the Peasant Reserve Zones (Law 160 of 1994) and the "Planes de Vida" (life plans) of afro or indigenous communities can contribute to this task by providing a socio-ecological vision of the territories where agroecology has promoted a strategy to protect biodiversity and promote sustainable, fair, and dignified livelihoods. Agroecological mosaics have been associated with land democratization processes (Rosset & Torres, 2016). In this context, an orderly, fair, and sustainable use of the territory in which these actors interact and articulate, is necessary to avoid the occurrence of a myriad of intercultural and environmental conflicts that have affected the region for decades (Duarte Torres, 2015; Hurtado and Vélez-Torres, 2020; Hurtado-Bermúdez et al., 2020; Pérez-Rincón et al., 2018). In this sense, the elements contributed by our approach can complement the post-conflict local and regional development debates elucidating the synergistic interactions between human land use, ecological functionality, and local livelihoods.

2.4.4 Scope and limitations of this research

The socio-political context of the UCRV has been dominated by contrasting and virtually irreconcilable narratives between political, economic, and social actors. However, these narratives have been backed up by inconsistent and ambiguous scientific research, specifically regarding the biophysical and socio-ecological dimensions. In that sense, we recognized the study of socio-ecological systems as a complex and challenging task involving multiple analytical dimensions that no single indicator could account for, claiming for the need to integrate interdisciplinary methodologies.

The opportunity to use the national census data to account for the HANPP offered a valid indicator of the level of human disturbances in the UCRV and a spatial expression of the farm systems typologies. The various forms of appropriation of biomass by different agricultural systems and communities result in distinctive landscapes that merit an in-depth study. In this sense, our experimental design contributes to understanding multiscale agricultural transition dynamics along space gradients. Its relatively simple application can allow future scalability, knowledge transfer to other tropical regions, and methodological improvements. However, the use of HANPP at farm and landscape levels might have limitations (Tello and González de Molina, 2017a), given the standardized definition of the NPP_o. We acknowledge these limitations and the fact that the method does not account for social or environmental externalities. However, HANPP analysis can be relevant for land planning studies, especially when combined adequately with other social, ecological, and economic indicators in regions where socioeconomic forces could be more determinant for biomass extraction (Wrbka et al., 2004).

Despite these limitations, we argue that socio-ecological research is fundamental to understanding local sustainability challenges in contexts where historical political powers and geography have hindered the configuration of long-term, reliable baseline data to perform robust analyses. In this regard, our results provide empirical evidence supporting the environmental history narratives of the UCRV ((Delgadillo-Vargas and Valencia, 2020; Giraldo Díaz, 2014). The implications of this coupling between environmental history and integrated landscape-metabolism methodologies are valuable considering that long-term studies have demonstrated the weight of legacy effects on current landscape-level ecological assessments (Wimberly, 2006). Furthermore, our results can be analysed from a space-for-time perspective (Blois et al., 2013), in which today's spatial gradient of land-use intensity and the landscapes' patterns and processes illustrate the gradual effects of agricultural transformations on ecological functioning.

2.5 Conclusions

This research proposes an integrated landscape-metabolism approach for assessing human-transformed landscapes of the Tropical Andes. We hypothesize that biocultural landscapes configured by indigenous, peasant, and afro traditional farm systems significantly contribute to the ecological functionality of the metropolitan region of Cali (Colombia). The region's current landscapes reflect an ongoing transition from organic-based agriculture to an industrial one. This transition has happened within a complex socio-cultural context where rural livelihoods are at a crossroads with regional agroindustry development. We propose a landscape-metabolism model based on georeferenced farm systems typologies (local scale) and land cover data (landscape scale) of the region to test our hypothesis. The results show that industrial plantations have homogenized the territorial matrix and deteriorated the ecological connectivity of the region, a trend seen in many other Tropical regions (Shaver et al., 2015).

An important conclusion that emerged from applying the proposed approach is that this landscape-metabolism assessment offers an opportunity to enrich intersectoral land policy formulation for highly biological and culturally diverse regions. Conversely, the contribution of different biocultural landscapes to the region's ecological functionality was evidenced, supporting our hypothesis, and stressing that agroforestry and agroecological systems can offer promising contributions to biodiversity conservation and ecosystem services provisioning.

Furthermore, and especially relevant for the tropical Andes, these results can contribute to local environmental and social movements discourses that have denounced the effects of the sugarcane monoculture on local livelihoods and ecosystems for decades, despite persecution and even costing them their lives. Given the confluence of the Colombian post-conflict implementation agenda, the global (un)sustainability crisis, and the UN sustainable development goals, there is a need to bring biocultural landscapes into a broader interdisciplinary dialog and evaluate the sustainability, political feasibility, and social desirability of current agricultural development.

2.6 References

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3 New criteria and methods for sustainable land use planning of metropolitan green infrastructures in the tropical Andes.

This chapter is based on the following submitted journal paper: **LaRota-Aguilera, M. J.,** Zapata-Caldas, E., Buitrago-Bermudez, O., and Marull, J. New criteria and methods for sustainable land use planning of metropolitan green infrastructures in the tropical Andes. Submitted to: *Land Use Policy*. (Q1: Forestry).

3.1 Introduction

The relationship between urban centres and peri-urban and rural areas has been vital for the development of our societies. Historically, farmland and natural ecosystems have played a central role as a food and material providers for the cities (Steel, 2008). However, the Industrial Revolution triggered two substantial socioecological changes that altered this relationship: urbanisation and agricultural intensification (Krausmann et al., 2008b; Swyngedouw and Heynen, 2003). Together with current economic and technological development models, population growth is related to a considerable increase in the consumption of resources in the metropolis (e.g., water, energy, materials, food) (Balatsky et al., 2015; Krausmann et al., 2009). Land use and land cover changes from natural and low-intensity agricultural areas to urban and high-intensity agriculture ones have been linked to biodiversity and ecosystem services losses (Elmqvist et al., 2013), water flow interruptions (Hibbs and Sharp Jr, 2012) and the global increase in greenhouse gas emissions (IPCC, 2014; Vermeulen et al., 2012b).

At local levels, urbanisation and agricultural intensification could affect ecosystems and their ability to provide services for society and life support systems on the planet (Brondizio et al., 2019). Moreover, under current global climate change scenarios, biodiversity and ecosystem services loss can increase the societies' vulnerability to climate change (Burak Güneralp et al., 2013; IPCC, 2014; McDonald et al., 2013).

Even so, the global population will keep growing; it is forecasted that by 2050 it will reach 9.8 billion people, where 68% of us will live in urban areas (United Nations, 2019a). Although this situation is global, its impacts will be disproportionately absorbed by low- and lower-middle-income regions of the world for which the pace of urbanisation is projected to be fastest, and high poverty and inequality rates could limit resilience and adaptation capacity (IPCC, 2014).

The above scenario presses unprecedented challenges for the urban-rural relationships and land-use planning of metropolitan regions and demands the adoption of integrative perspectives to face them (Yacamán-Ochoa et al., 2020). The concept of green infrastructure has gained significant importance over the last decade by providing a comprehensive socioecological understanding of the role of metropolitan open spaces in maintaining their sustainability (Benedict and McMahon, 2002). However, there are still gaps in knowledge on how to consolidate green infrastructure that truly meets its objectives of maintaining and promoting biodiversity and providing ecosystem services that benefit society (Chatzimentor et al., 2020; Demuzere et al., 2014; Vásquez et al., 2019).

The main advances in this subject have been developed in the Global North (Chatzimentor et al., 2020; European Commission, 2013; Slätmo et al., 2019). However, for regions such as the Global South, its development is even more incipient (Pauleit et al., 2021). Conversely, in Latin America, specifically in the tropical Andes, land use change and land use intensity dynamics are particularly difficult phenomena to manage. These changes are primarily driven by a productivist development model associated with agricultural intensification and the outrageous exploitation of natural resources (Aide et al., 2019). This development model often leads to rural migration to cities (Canales and Canales Cerón, 2013). Furthermore, the contexts of political instability, the corruption established in society, and even the internal armed conflicts have dissipated political attention from ecosystem protection (Angotti, 1996). These factors contribute to a highly disorganised metropolitanization process lacking solid urban and territorial planning with a biophysical and social basis.

Therefore, Tropical Andes' nations are at a difficult crossroads between following the current economic development model or protecting their natural ecosystems to ensure ecosystem services for their societies. In all its complexity, this situation is presented in the metropolitan region of Cali (Colombia), a territory that has experienced drastic socioeconomic and land use changes since the beginning of the 20th century (Delgadillo-Vargas, 2014). These dynamics have been mainly associated with agro-industrial metabolisms (Marull et al. 2017) based on the consumption of land and non-renewable resources and combined with critical migratory flows consequence of rural poverty and the internal armed conflict (Martínez-Toro and Patiño-Gómez, 2015; Rincón-García and Machado, 2014; Uribe-Castro, 2017). Today's scenario presents a growing metropolitan region, the epicentre of a myriad of socioecological conflicts and highly vulnerable to climate change.

Therefore, it is essential to understand the relationship between the different landscape-metabolic configurations of metropolitan systems and their ability to offer ecosystem services to society. This article presents an integrated evaluation of the ecological functionality of the metropolitan green infrastructure of Cali through a landscape-metabolism model (Marull et al., 2018, 2019). The study has three main objectives: first, to assess impacts of agricultural intensification and urbanisation on the ecological functions and services of the metropolitan green infrastructure; second, to analyse the relationship between these configurations and their capacity to supply ecosystem services, and third to guide future land use policy in this region targeted to the planning and implementation of a functional metropolitan green infrastructure.

The following section presents a brief contextualisation of the case study and a description of the methodologies. Followed by that, we present the results of the landscape-metabolic assessment and discuss the emerging opportunities and challenges offered by agricultural landscapes for the sustainability of the metropolitan region of Cali. Then we review the relevance of our results and the potentials of adopting a green infrastructure framework to guide future land use policies for the tropical Andes. And finally, conclude this analysis.

3.2 Methodology

3.2.1 Case study

Currently, the metropolitan region of Cali is not considered an official administrative entity. There have been some initiatives to consolidate a metropolitan area, mainly based on capital criteria dictated by the predominant role of agribusiness in the region; however, they have not thrived (Martínez-Toro and Patiño-Gómez, 2015; Urrea-Giraldo and Candelo-Álvarez, 2017). Therefore, this study considers the Upper Cauca River Valley (henceforth UCRV) as the territorial reference for the metropolitan region and the study area. The UCRV limits were defined based on three criteria: i) the third metropolitan crown (Martínez-Toro and Patiño-Gómez, 2015); ii) the limits of the hydrographic sub-basins in which the urban centres of the third metropolitan crown are located; and iii) the areas of influence of sugarcane cultivation, given their economic importance for the region (Figure 3.1). The population in the UCRV is approximately 3'635.573 people, and 2'172,527 people live in the urban area of the city district of Cali (DANE, 2019).

The UCRV is located within the geographic valley of the Cauca River (448,000 ha), between the Central and Western Mountain ranges of the Andes, in southwest Colombia (Figure 3.1). The study area occupies 1'004,000 hectares and includes elevations between 800 and 5,000 meters above sea level. The study area presents a bimodal tropical climate characterised by average temperatures of 24°C uniform throughout the year. Average annual precipitation ranges between 800 and 1,500mm. Originally, this biogeographic unit was made up of various ecosystems, including tropical dry forests, tropical pastures, high Andean forests, and paramos. However, currently, 19.2% of the UCRV is covered by sugar cane monocultures (192,742 ha); 31,1% by mixed crops that include coffee, banana, and fruit trees, in mosaics with natural areas and pastures (312,682 ha); 13% by natural and planted open pastures (130,547 ha); 32.5% by forests and other natural areas -among which are the last enclave of tropical dry forest and paramos- (198,659 ha); and 2.4% by urban and suburban spaces built (23,954 ha) (Figure 3.1).

There are two primary land cover change dynamics in the UCRV: i) the transformation of clean pastures, cropland (some sugarcane) and seminatural transition areas into low-density urban areas, and ii) the expansion of sugarcane crops throughout the flat zone, previously a mosaic of pastures and mixed crops; a phenomenon observed since the mid-19th century that has driven a radical productive transformation in the territory (Delgadillo-Vargas, 2014). Additionally, three socioeconomic and political dynamics contribute to making Cali the third most populated and growing city in Colombia: first, the designation of Cali as the capital of the Valle del Cauca department (1910), leading to the concentration of public services such as education, health and justice; second, the consolidation of the industrial conglomerate (Vásquez, 2018) and third, more than 50 years of violence and the internal political conflict that have turned the city and its fringes into one of the leading receptor centres of internal refugees (140,751 people between 1985 and 2014; (Comisión Nacional Memoria Histórica, 2015).

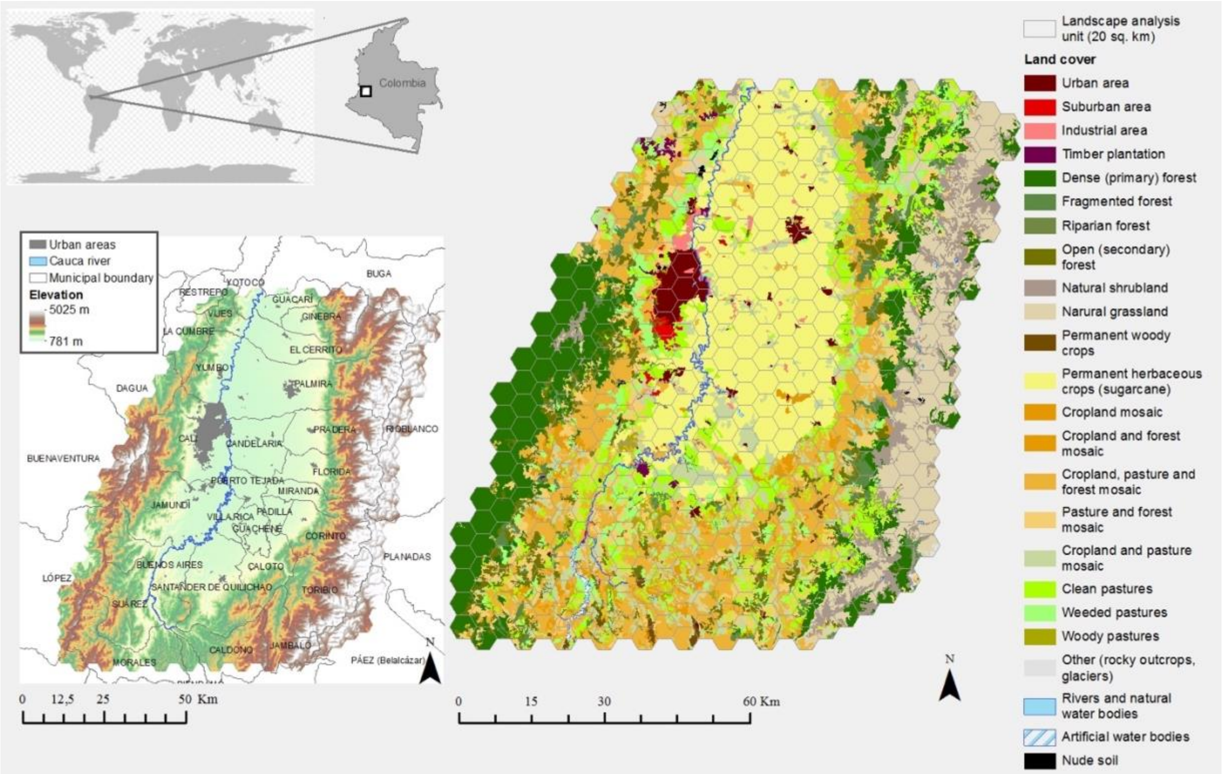

Figure 3.1 Location, administrative limits, and land cover map of the metropolitan region of Cali.

Source: Corine Land Cover Map for Colombia 2012 (level 3 legend).

3.2.2 Landscape ecological metrics

The landscape's functional structure evaluation was based on the adaptation of the Corine Land Cover map of land cover at a scale of 1:100,000 for Colombia, considering level 3 of the legend (Figure 3.1). The reference year is 2015 since it is the most recent year with relevant information. This map was updated with supervised classification and interpretation of aerial photographs for 2013 and 2016 by the authors to correct areas with high cloudiness. The final coverage legend includes 22 classes and is shown in Table 3.1.

The study area was divided into 502 analysis units (hexagons), each of 20 km^2 (2,000 ha) (Figure 3.1), for which four indicators were calculated: i) the Shannon Index ii) the Ecological Connectivity Index iii) the Human Appropriation of Net Primary Productivity; and iv) the Intermediate Disturbance Complexity (IDC) model. Each of these landscape metrics is described below.

Table 3.1 Land cover and surface distribution in the metropolitan region of Cali.

Typology	Land cover	Reclassification	Area (ha)	%
Forest and seminatural areas	Rocky outcrops	Others (rocky outcrops, glaciers)	257.81	0.0%
	Natural sandy areas	Others (rocky outcrops, glaciers)	287.51	0.0%
	Glacial and snow zones	Others (rocky outcrops, glaciers)	66.12	0.0%
		Total others	*611.44*	*0.1%*
	Natural shrublands	Natural shrublands	39627.44	3.9%
	Natural grasslands (Paramo)	Natural grasslands (Paramo)	87665.07	8.7%
	Dense forest	Dense forest	117687.3	11.7%
	Riparian forest	Riparian forest	2487.41	0.2%
		Total primary forest	*120174.7*	*12.0%*
	Fragmented forests	Secondary forest	29330.82	2.9%
	Secondary vegetation or in transition	Secondary vegetation or in transition	48542.91	4.8%
		Total secondary forest	*77873.73*	*7.8%*
		Total forest and seminatural areas		*32.5 %*
Agricultural land	Permanent woody crops	Permanent woody crops	3635.33	0.4%
	Permanent herbaceous crops	Sugarcane plantations [1]	192742.2	19.2%
		Total permanent crops	*196377.5*	*19.6%*
	Pasture and forest mosaic	Pasture and forest mosaic	75165.72	7.5%
	Cropland mosaic	Cropland mosaic	1922.57	0.2%
	Cropland and forest mosaic	Cropland and forest mosaic	18478.08	1.8%
	Cropland, forest, and pasture mosaic	Cropland, forest, and pasture mosaic	152551.3	15.2%
	Cropland and pasture mosaic	Cropland and pasture mosaic	64564.77	6.4%
		Total agricultural mosaics	*312682.5*	*31.1%*
	Wooded pastures	Wooded pastures	4673.74	0.5%
	Weeded pastures	Weeded pastures	41797.32	4.2%
	Clean pastures	Clean pastures	84076.29	8.4%
		Total pastures	*130547.3*	*13.0%*
	Timber plantations	Timber plantations	3238.40	0.3%
		Total agricultural land		*64.0 %*
Bodies of water	Rivers (50m)	Rivers and natural water bodies	2569.59	0.3%
	Artificial water bodies	Artificial water bodies	1637.38	0.2%
	Lagoons, lakes, swamps, and natural swamps	Rivers and natural water bodies	527.56	0.1%
		Total water	*4734.54*	*0.5%*
Build-up areas	Continuous urban fabric (Urban areas)	Urban areas	16228.67	1.6%
	Discontinuous urban fabric (Suburban areas)	Urban areas	3447.70	0.3%
	Industrial or commercial areas (Industrial area)	Urban areas	4278.26	0.4%
		Total urban and industrial areas	*23954.63*	*2.4%*
Other	Nude and degraded soils	Nude soils	854.29	0.1%
Total			1004000	100.0%

Source: Own elaboration based on the Corine Land Cover Map for Colombia.

Shannon index (H') (Shannon and Weaver, 1948). Characterises the landscape structure as a function of the land cover heterogeneity.

$H' = \sum_{i=1}^{j=k} pj \ \cdot Log\ pi$

For its calculation, eight land covers (*j*) considered potential habitats for biodiversity (forest, shrubland, grassland, heterogeneous crops, sugarcane, pastures, bodies of water, rocky outcrops, sandy areas) and one "no habitat" category grouping urban and industrial areas, degraded land, and road infrastructure, were defined. Thus, Pji is the proportion of land cover j in hexagon *i.* The H' values range from 0 to 1, with 0 being a homogeneous landscape with a single predominant cover and 1 being a theoretical landscape with many land cover classes distributed equitably.

Ecological Connectivity Index (ECI) (Marull and Mallarach, 2005). Assesses the functionality of the landscape in terms of the ecological connectivity between related land covers (Pino and Marull, 2012). ECI was calculated through a cost-distance model based on an affinity matrix considering 7 types of 'functional ecological areas' (i.e., forest, shrubland, grassland or paramo vegetation, agroforestry mosaics, crops, pastures, and sugar cane), and an impact matrix considering the 'anthropogenic barriers' (i.e., urban areas, infrastructures). The selection criteria for functional ecological areas, the coefficients and the type of anthropogenic barriers were obtained from a review of the literature and local experts' knowledge. Ecological connectivity is calculated for each of the different functional ecological areas:

$$ECI_b = 10\text{-}9 \ln (1+X_i)/\ln (1+X_t)^3$$

where X_i is the value of the sum of the cost distance per pixel and X_t is the maximum theoretical cost distance.

The total ecological connectivity values are calculated from the values obtained for each type of functional ecological area:

$$ECI = \sum ECIb\ /m$$

where *m* is the absolute number of functional ecological areas considered. The highest values, in a range of 0 to 10, represent high ecological connectivity.

Human Appropriation of Net Primary Production (HANPP). Measures the disturbance exerted by society on a particular ecosystem (Haberl et al., 2007) as a function of the degree to which humans modify the amount of NPP available to other species, fundamentally through two processes: the removal of a portion of the NPP as food., fibre and material of use for society (NPPh) and the change in land cover (ΔNPPLu) (Haberl et al., 2007a; Krausmann et al., 2013). Recent studies suggest that the indicators associated with HANPP provide key information for planning and evaluating ecosystem services (Mayer et al., 2021). HANPP considers NPP as the net amount of biomass produced by autotrophic organisms, in this case, plants, which constitute the primary energy source for the rest of the food chain for one year. In this sense, HANPP measures the

$$\text{HANPP}_i = \underline{\Delta}\,\text{NPP}_{lu} + \text{NPP}_h$$

$$\Delta\text{NPP}_{Lu} = \text{NPP}_0 - \text{NPP}_{act}$$

In turn, ΔNPP_{Lu} is the difference between the potential NPP (Krausmann et al., 2013; available at https://www.aau.at/blog/global-hanpp-2000/) and the actual NPP (NPP_{act}) based on disaggregated agricultural production data for the region obtained from the 3rd National Agricultural Census (2014) and based on (Guzmán-Casado et al., 2014).

To obtain the HANPP value per unit of analysis (hexagon), HANPP values (P) for each land cover i were multiplied by a w_i coefficient representing the proportion of land cover i in each hexagon. HANPP units are presented in Tons of C / ha.

$$\text{HANPP}_{hex} = \sum_{i=1}^{k} wiPi$$

Intermediate Disturbance Complexity (IDC).

The IDC model proposed by Marull et al. (2016) transfers the concept of intermediate disturbance in natural ecosystems (Cornell, 1978) to human transformed landscapes (e.g., agroecosystems). The IDC argues that heterogeneous and well-connected land covers, with intermediate levels of agricultural activity, reflect an interaction between landscape complexity and energy availability that constitutes an agroecological matrix capable of harbouring great biodiversity (Loreau, 2000; Tscharntke et al., 2012). Therefore, the IDC measures the landscapes' capacity to host biodiversity and provide ecosystem services (Marull et al., 2016b, 2018, 2019).

The IDC model is calculated from the biomass available for other species (1-HANPP / 100) and the complexity of the landscape (Le). Le describes in a combined way the patterns (L) and processes (ECI) of the landscape (Marull et al., 2018).

$$\text{Le} = (aL + b\,\frac{ECI}{10})\,1\,/(a + b)$$

where *a* and *b* are the canonical coefficients for the ortorthogonalization of the indices.

$$IDC = Le\ (1\text{-}HANPP\ /\ 100)$$

3.2.3 Ecosystem services

The UCRV landscapes' supply and demand of ecosystem services were assessed from Tabares-Mosquera et al. (2020) and based on the Common International Classification of Ecosystem Services (CICES) v.4.3 typology (Haines-young et al., 2013), which is associated with the defined ecosystem service categories: provisioning, regulation and cultural, of the Millennium Ecosystem Assessment (2005). Twenty-one ecosystem services were selected that appropriately fit the spatial scale of the Cali metropolitan phenomenon (Table 3.2).

Since the land cover pattern is one of the most critical factors affecting the ability of a landscape to provide ecosystem services (Burkhard et al., 2009), the land cover map was used as the basis for quantifying multifunctionality and the capacity to provide ecosystem services of the landscapes that make up the UCRV. Ecosystem services were assessed using an expert-knowledge approach, given the region's incipient developments of ecosystem service mapping (Jacobs and Burkhard, 2017). An interdisciplinary group of 27 experts was selected to evaluate the capacity to supply and demand ecosystem services for each land cover category (Tabares-Mosquera et al., 2020). The experts had to: i) be specialists in at least one of the following groups of land use: agricultural production areas, forests and seminatural areas, humid areas, or artificial areas; ii) be knowledgeable about the study area; and iii) be affiliated with public administrative institutions (mayors and governments), universities or private research centres.

Table 3.2 Ecosystem services considered in the analysis.

Section	Division	Code	Group
Provisioning	Nutrition	1.1.1	Biomass
		1.1.2	Water
	Materials	1.2.1	Biomass
		1.2.2	Water
		1.2.3	Metallic and non-metallic abiotic materials
	Energy	1.3.1	Biomass
		1.3.2	Renewable abiotic source
		1.3.3	Non-renewable abiotic source
Regulation and support	Regulation of waste, toxic substances, and other nuisances	2.1.1	Mediation by living systems
	Flow regulation	2.2.1	Mass flows
		2.2.2	Liquid flows
		2.2.3	Gas/air flows
	Maintenance of physical, chemical, and biological conditions	2.3.1	Maintenance of the life cycle, habitat, and protection of the gene pool
		2.3.2	Control of pests and diseases
		2.3.3	Soil formation and composition
		2.3.4	Maintenance of the chemical composition of water
		2.3.5	Atmospheric composition and climate regulation
Cultural	Physical and intellectual interaction	3.1.1	Physical experience
		3.1.2	Intellectual and representative
	Symbolic and spiritual interaction	3.2.1	Spiritual or emblematic
		3.2.2	Existence and natural intrinsic value

Source: Tabares-Mosquera et al., 2020, adapted from Haines-Young and Potschin, 2013.

The experts qualitatively evaluated the capacity of land covers to supply or demand ecosystem services, based on a six-class Likert scale: not relevant (0); very low (1); low (2); medium (3); high (4); very high (5) (Albert et al., 2016; Koschke et al., 2012). Experts' responses were averaged to obtain the supply and demand matrices. Finally, two criteria were established to evaluate the ecosystem function of each land cover. The first criterion, 'capacity', is defined as the long-term ability to provide different ecosystem services (Jacobs and Burkhard, 2017). Capacity was calculated from the difference between ecosystem services supply and demand and can take values between -5 (very low capacity) and 5 (very high capacity) (Burkhard et al., 2014, 2009). The second criterion, 'multifunctionality', accounts for the number of ecosystem services of various categories (i.e., provisioning, regulation and cultural) offered by each land cover class(Tabares-Mosquera et al., 2020). The Multifunctionality can take values from 0 (minimum) to 5 (maximum). The Ecosystem Services Capacity (ESC*j*) and Multifunctionality of Ecosystem Services (MF*j*) for each hexagon (*j*) were calculated as the sum of each land cover capacity or multifunctionality within *j*, and weighted by the proportion of land cover *I in j* (*Pij)*.

$$\mathrm{ESC}j = \sum_{j=1}^{k} ESCi \bullet Pij$$

$$\mathrm{MF}j = \sum_{j=1}^{k} MFi \bullet Pij$$

3.2.4 Statistical analyses

A linear regression analysis was performed to explore the relationship between IDC and the ESC based on the results obtained for each unit of analysis (hexagons; n =502). Additionally, to assess the contribution of the different land covers to the expression of the IDC, a step-wise multiple regression model (MRM) was performed where IDC was the dependent variable, and the 22 land cover classes of the area were the predictor variables.

3.3 Results and discussion

3.3.1 Ecological functions and services of the metropolitan green infrastructure

3.3.1.1 Landscape metrics

The results indicate the highest levels of anthropogenic disturbance in the flat zone of the UCRV, where the main urban and industrial centres, road infrastructure and sugarcane monoculture are located (HANPP> 61%; Figure 3.2c). HANPP shows the existence of a gradient in the intensity of agricultural land use, which decreases with elevation and as we move to the southern zone of the metropolitan region. This spatial pattern of anthropic disturbance would be associated with a disruption of ecological connectivity (ECI) in the flat zone of the study area (Figure 3.2a). This area is also characterised by low landscape heterogeneity (H') (Figure 3.2b). On the contrary, a strip of higher connectivity (Figure 3.2a) and heterogeneity (Figure 3.2b) stands out on the slopes of both mountain ranges, which also coincide with intermediate levels of anthropic disturbance (Figure 3.2c).

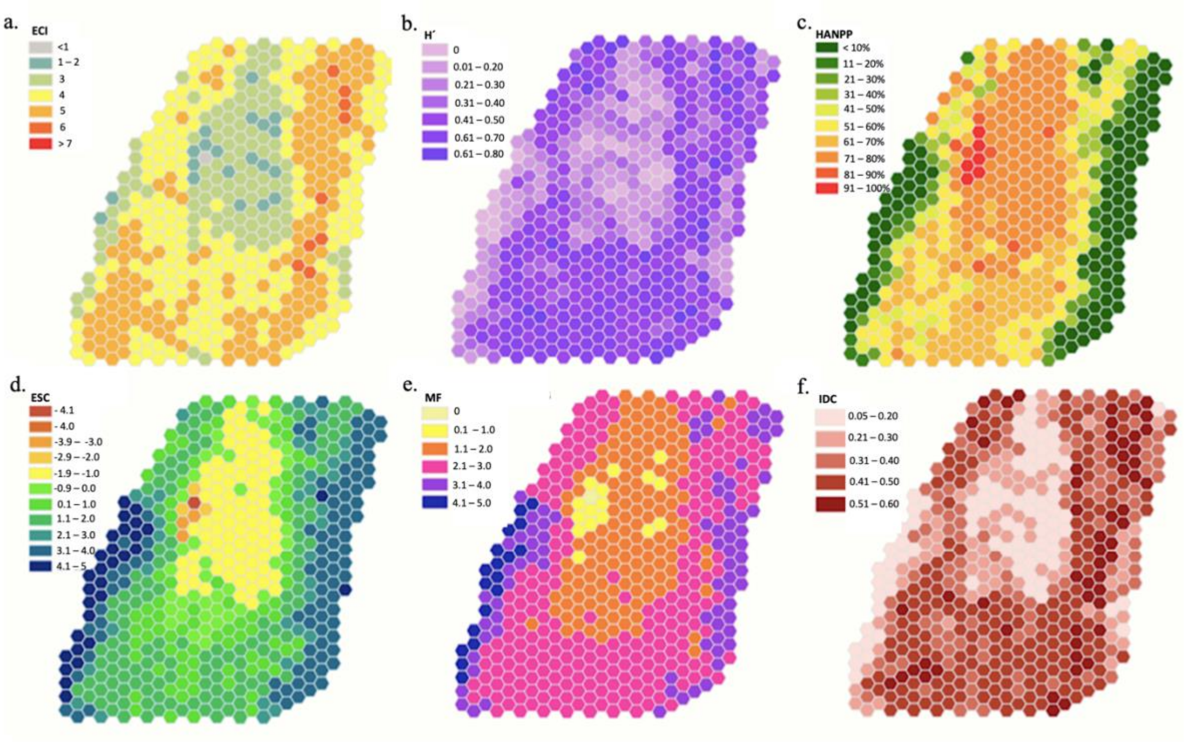

Figure 3.2 Ecological functions and services of the metropolitan region of Cali.
Ecological Connectivity Index -ECI (a); Shannon Index -H' (b); Human Appropriation of Net Primary Production -HANPP (c); Ecosystem Services Capacity -ESC (d); Multifunctionality of Ecosystem Services -MF (e), and Intermediate Disturbance Complexity -IDC (f).

The ECI levels reflect an overall ecological disconnection between the valley and key natural areas (i.e., forests, natural shrubs, natural grasslands; Figure 3.1) mainly located at high elevations of both Andean mountains (Figure 3.3). Even though the model considers the hydrological network a fundamental element for ecological connectivity, the connective function exerted by rivers, especially the Cauca river, is very subtle. This situation contrasts with the one found in other metropolitan regions of the world, where riparian ecosystems play a key role in maintaining ecological connectivity even within highly anthropogenized areas (Dupras et al., 2016; Padró et al., 2020a). In the UCRV, this situation stresses the critical ecological state of the metropolitan region.

We suggest that low connectivity associated with the hydrological network (Figure 3.3) might explain the low ecological affinity between forests and pasture land covers. Especially pastures might be playing a critical and controversial role in the landscape functioning of this region and the socioecological sustainability. For instance, many clean pastures adjacent to rivers result from deforestation driven by extensive cattle ranching and land speculation (Garcia Corrales et al., 2019b; Rodríguez Eraso et al., 2013; Zuluaga et al., 2021). The land cover changes associated with pastures establishment is a phenomenon risking homogenising the UCRV and overall mountain landscapes in the tropical Andes. Similarly, riparian natural land covers have also been pushed to the limits by sugarcane monoculture (Ayala-Osorio, 2019; Delgadillo-Vargas, 2014; Río et al., 2019). Additionally, although beyond the scope of this work, illegal human settlements and resulting water pollution are critical issues for the Cauca river (Holguin Gonzalez and Goethals, 2010). All these conditions have limited the river's ecological connectivity potential. The results complement previous research at local and sub-basin scales reporting desertification, high scarcity indexes (Pérez-Rincón et al., 2011) and river reversion (Delgadillo-Vargas, 2014; Marull et al., 2017). In addition, the above situation represents an essential water use conflict between agricultural and human consumption (Pérez-Rincón et al., 2011).

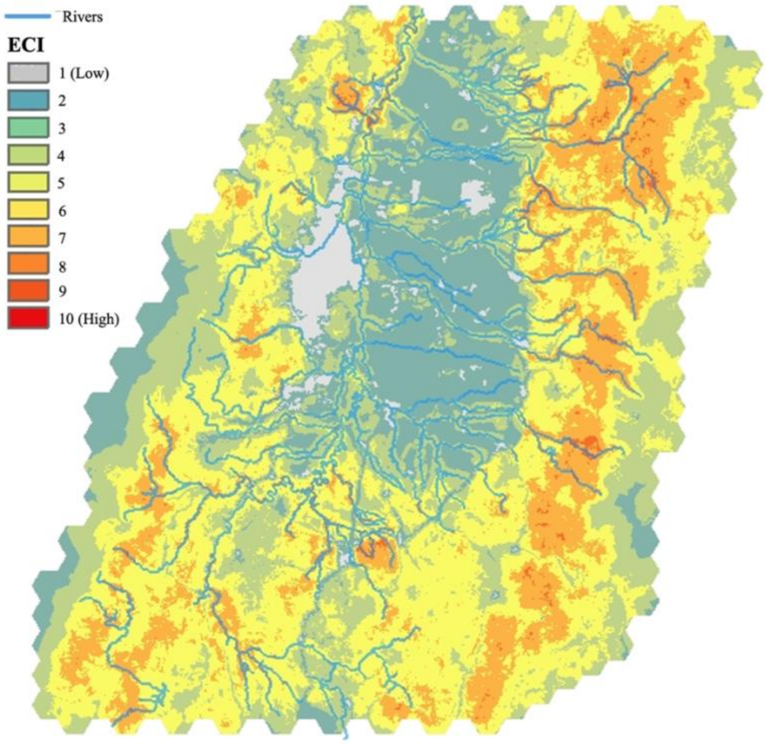

Figure 3.3 Ecological Connectivity Index (ECI) of the metropolitan region of Cali.

3.3.1.2 Landscape-metabolism model (IDC)

The different levels of ecological disturbances exerted by various agricultural practices of the region result in a land cover and land-use intensity spatial gradient (Figure 3.2f). The IDC revealed the existence of at least three types of territorial metabolic configurations of the UCRV landscapes (Figure 3.2h). The first type (*anthropic*) is defined by a very low IDC (0,05< IDC < 0,3). This type depicts landscapes resulting from an industrial agriculture metabolism and are mainly concentrated along the river valley's flat area. The second type (*natural areas*) is defined by low-to-moderate IDC, low anthropogenic activity, low land cover heterogeneity, predominantly dense forests and paramos. These areas are located mainly above the 3000 masl, where population density and activity are very low, usually associated with subsistence agriculture. A high IDC defines the third type of landscape-metabolic configuration (mosaics). It reflects heterogeneous landscapes with less intensive agricultural activities (intermediate disturbance levels). These landscapes are found at mid-elevations (1,200 masl. to 2,800 masl.) on the slopes of the Andean Mountain ranges. This area comprises agricultural, agroforestry, and agropastoral mosaics (Figure 3.1), reflecting different agricultural practices, including traditional peasant, Afro and indigenous agroecological models (Duarte Torres et al., 2018).

Seventy-four per cent (74%) of the IDC variance is explained by the land covers of this metropolitan region (Table 3.3). Specifically, sugarcane plantations, urban areas, natural areas (dense forest, natural grasslands) have a significant negative relationship with the IDC. Natural shrublands, cropland and pasture mosaics, rives and water bodies and clean pastures significantly contribute to higher IDC values (Table 3.3).

Table 3.3 Step-wise multiple regression model of the relationship IDC and land covers of the metropolitan region of Cali.

Residuals:	**Min**	**1Q**	**Median**	**3Q**	**Max**
	-0.17760	-0.04293	-0.00521	0.02989	0.21350

Variables/Coefficients	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	**Significance** (< 0.050)
Intercept	0.43586	0.007971	54.683	$< 2e^{-16}$	*
Sugarcane plantations	-0.26907	0.010776	-24.970	$< 2e^{-16}$	*
Dense forest	-0.24005	0.014356	-16.721	$< 2e^{-16}$	*
Urban areas	-0.40903	0.027881	-14.671	$< 2e^{-16}$	*
Natural grasslands (Paramo)	-0.14953	0.016800	-8.901	$< 2e^{-16}$	*
Natural shrublands	0.24755	0.031203	7.934	$< 1.45e^{-14}$	*
Cropland and pasture mosaic	0.13680	0.031376	4.360	$< 1.58e^{-05}$	*
Rivers and natural water bodies	0.90214	0.256902	3.512	0.000486	*
Clean pastures	0.06582	0.027501	2.394	0.017062	*
Weeded pastures	-0.07655	0.042348	-1.808	0.071252	
Cropland mosaic	0.25399	0.175123	1.450	0.147594	

Note 1: Dependent variable: IDC. Predictive variables: 22 land covers. n: 502. Multiple R-squared: 0.0.7433. Adjusted R-squared: 0.7381. Residual standard error: 0.06372 on 491 degrees of freedom. F-statistic: 142.2 on 10 and 491 DF. p-value: $< 2.2e^{-16}$.
Significance codes: * < 0.050

The conceptual basis of the land-sharing and land-sparing paradigms can be helpful to understand the implications of these landscape-metabolic configurations on the socioecological sustainability in the region and their relevance for green infrastructure and land use planning in this and other Tropical Andean metropolitan regions (Fischer et al., 2014a, 2008c; Grass et al., 2019). In this case study, the *anthropic* landscape-metabolic configuration is characteristic of a productive paradigm that has often been associated with land-sparing strategies to balance biodiversity conservation and agricultural production (mainly for food, but see Anderson-Teixeira et al. (2012)). This strategy operates under the assumption that intensive agricultural production is concentrated in a large extension of intensive monocultures, sparing aside land to protect biodiversity actively (Fischer et al., 2008). Secondly, the natural landscape-metabolic configurations concentrated in protected areas host critical ecosystems and perform essential functions and services for natural and societal communities. However, as previously observed, these areas are highly disconnected, possibly affecting the effectiveness of a land-sparing strategy (Cannon et al., 2019; Edwards et al., 2021). Finally, the areas with mosaic landscape-metabolic configuration would be reflecting a land-sharing strategy for food production and biodiversity conservation (Perfecto et al., 2009; Perfecto and Vandermeer, 2008). These areas are increasingly demonstrated to provide suitable habitats for species, host higher biodiversity and provide multiple ecosystem services (Loreau et al., 2003; Marull et al., 2019; Margalef, 1973; Tscharntke et al., 2005). The ECI shows that these areas play a crucial role in ecological connectivity (Figure 3.3).

While the nuances on the effectiveness of the land-sharing or land-sparing strategies go beyond the purpose and scope of this study and have already been widely revised in the literature (Fischer et al., 2014, 2017; Grau et al., 2013, Kremen, 2015; Scariot, 2013), their postulates can complement our analysis. Assuming that the UCRV reflects the necessity of a combined land-sharing and land-sparing strategies, our integrative assessment exposes that the effectiveness of these two strategies would be highly compromised by the poor ecological connectivity of the area. Metropolitan green infrastructure must contain different interrelated and connected elements to provide a structure that provides the different functions and services (Basnou et al., 2020; Hansen and Pauleit, 2014). To illustrate this, we explore the relationship between the IDC and the capacity of metropolitan landscapes to supply ecosystem services (ESC) (Figure 3.4). The results indicate that landscape-metabolic configurations related to agro-industrial activity have a lower capacity to supply ecosystem services for the metropolitan population (yellow dots on Figure 3.4). On the contrary, the agricultural mosaic revealed a higher capacity to supply ecosystem services (orange dots on Figure 3.4). Since the IDC is based on the theoretical assumption that agricultural landscapes can retain more farm-associated biodiversity at intermediate levels of human net primary production appropriation (Loreau et al., 2003; Marull et al., 2015; Montero et al., 2021), the IDC predictive power decreases as non-anthropogenic land covers (i.e., natural forest, shrublands, pasturelands and paramos) increases, as seen in Figure 3.3. The ESC of landscapes is expressed along the land-use intensity gradient, with the lower capacity index where urban and sugarcane land covers are predominant (Figure 3.2d). This is expected, as this land covers have a high demand for ecosystem services while offering none (i.e., urban) or very few (i.e., sugarcane monocultures) ecosystem services, for instance, the capacity to provide energy in the form of biomass. In contrast, the strip of intermediately disturbed and well-connected and heterogeneous landscapes (higher IDC values) shows higher capacity and multifunctionality to supply ecosystem services.

Our assessment reveals an important emerging category of metropolitan open spaces: the agrosilvopastoral mosaics. These biocultural landscapes hold a high capacity to supply ecosystem services and high ecological connectivity and help structure a well-connected, multifunctional green infrastructure (Table 3.4 and Table 3.5). Therefore, land use planning policies should consider the socioecological impacts of maintaining large agricultural areas with low levels of provision of ecosystem services (i.e., intensive sugarcane cultivation) at the cost of losing the ecological quality of the Cauca valley by decreasing the provision of other essential ecosystem services and condemning the most populated area of the UCRV to ecological isolation and environmental degradation (Kremen and Miles, 2012a).

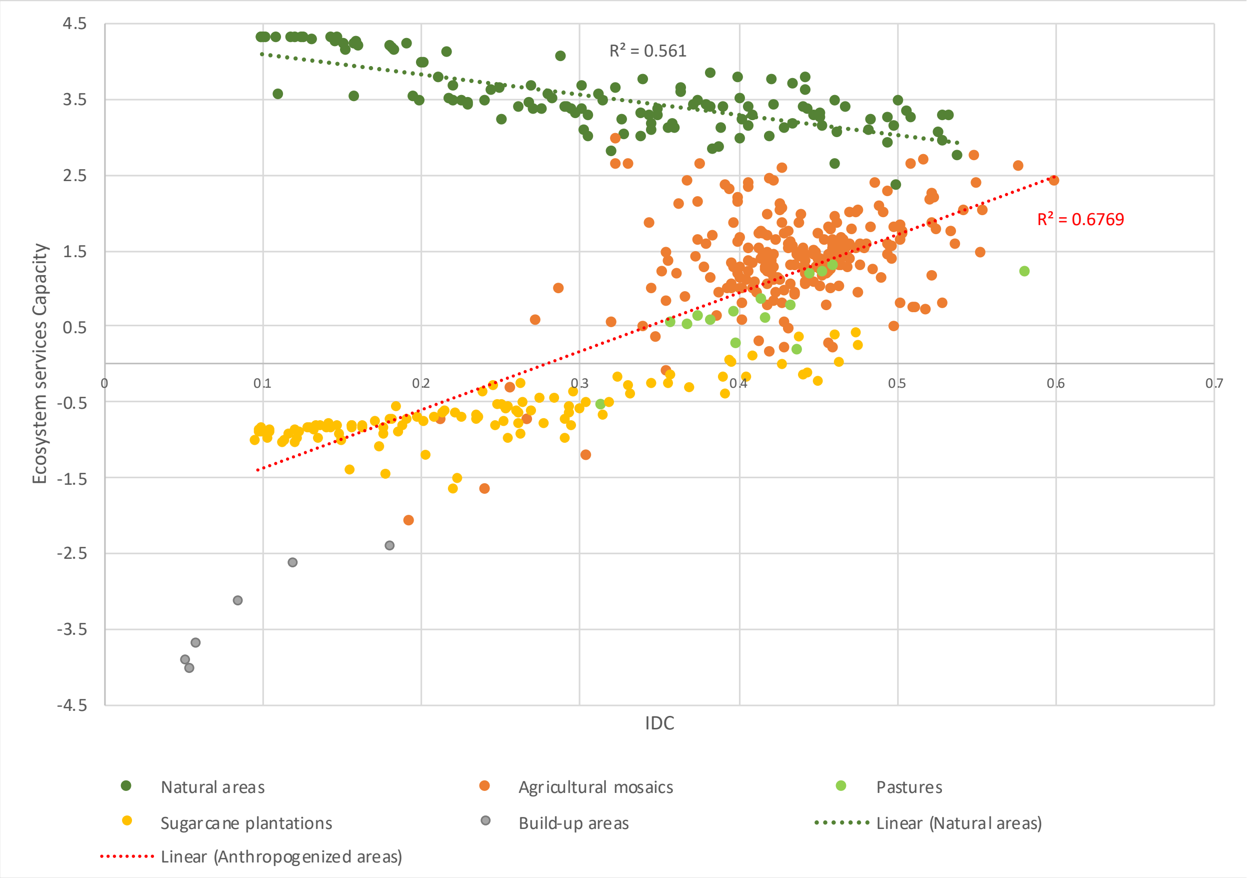

Figure 3.4. Relationship between the Intermediate Disturbance Complexity (IDC) model and the Ecosystem Services Capacity (ESC) in the metropolitan region of Cali.

Note: The points represent each of the 502 landscape-scale analysis units. Anthropogenized areas: pastures, agricultural mosaics, sugarcane plantations, built-up areas. Natural areas: forests, grasslands and shrubs. Colours indicate the predominant land cover in each unit of analysis (i.e., those occupying more than 50% of the total hexagon area): Natural areas (i.e., forests, grasslands and shrublands), Agricultural mosaics, sugarcane plantations and build-up areas (i.e., urban, suburban and industrial).

Our results show that the ecological rupture affects essential ecosystem flows between the paramos and high Andean Forest. This situation jeopardises the delivery of vital ecosystem services from these areas to the metropolis, including collecting, regulating, and providing water for human consumption and agriculture in the entire region (Table 3.4). Therefore, our results support the importance of considering metropolitan green infrastructure as a system (Padró et al., 2020a) and not as independent functionally independent patches only spatially connected. Only when considering the green infrastructure as a systemic, functional unit, the different functions and services will be delivered, and properties, such as connectivity and complementarity, will emerge.

Table 3.4 Ecosystem Service Capacity of the land covers of the metropolitan region of Cali.

			Land cover class																									
			Continuous urban fabric	Discontinuous urban fabric	Industrial or commercial areas	Urban green areas*	Recreative areas*	Cropland mosaic	Sugarcane plantations	Permanent woody crops	Clean pastures	Wooded pastures	Weeded pastures	Cropland, forest and pasture mosaic	Cropland and forest mosaic	Cropland and pasture mosaic	Pasture and forest mosaic	Dense forest	Fragmented forests	Riparian forest	Timber plantations	Natural grasslands (Paramo)	Natural shrublands	Secondary vegetation or in transition	Rocky outcrops	Natural water bodies	Artificial water bodies	Nude and degraded soils
Ecosystem services	Provisioning	1.1.1	-4.2	-3.8	-2.7	2.8	-0.2	3.7	1.7	2.7	1.9	2.3	2.3	2.7	2.7	2.7	1.9	3.4	2.9	2	1	2	2.05	2.1	0.6	3.4	2.3	0.3
		1.1.2	-5	-4.5	-4.2	2.3	-1.8	0.2	-0.3	0.7	0	1.6	1.6	2.2	2.2	2.2	2.6	5	3.4	4	1.4	4.3	3.5	2.7	0.9	3.4	4	0.3
		1.2.1	-4.5	-4	-4.7	1.9	-0.6	0.9	1.2	1.3	0.6	2.2	2.2	2.5	2.5	2.5	2.5	4.9	3.6	3.4	2.8	2.9	2.8	2.7	0.4	2.5	1.5	0.1
		1.2.2	-4.3	-4	-4.8	0.3	-2.5	-3.2	-4.1	-1.2	-1.7	-0.3	-0.3	-0.3	-0.3	-0.3	0.2	4.7	3.9	3.9	-0.8	4.3	3.45	2.6	0.4	3.6	0.2	0.1
		1.2.3	-4.7	-4.3	-4.7	1.2	-0.4	-0.5	-0.7	-0.1	-0.2	0.2	0.2	0.7	0.7	0.7	1	1.4	1.3	1.7	0.7	1.7	1.55	1.4	2.6	2.8	1.8	1.6
		1.3.1	-2.7	-2.5	-3.5	1.9	0	1.4	1.8	2.5	1.3	2.1	2.1	1.9	1.9	1.9	2.3	3.4	3	2.9	4.5	1.9	2.3	2.7	0.3	2.6	1.7	0.4
		1.3.2	-2.8	-3	-3.3	1.8	-0.2	0.7	0.2	1.4	0.5	1.2	1.2	1.1	1.1	1.1	1.5	3.9	3	3.1	1.6	3.1	2.5	1.9	2.1	2.8	2.3	0.9
		1.3.3	-4.3	-4	-4.2	-0.5	-1.7	-1.6	-1.5	-0.8	-0.8	0.2	0.2	-0.1	-0.1	-0.1	0.2	1.9	1.4	1.6	0.6	1.1	1.05	1	1.4	1.9	1	1.1
	Regulation and support	2.1.1	-4.5	-4.3	-4.2	1.1	-0.5	-0.3	-0.9	0.2	-0.3	0.6	0.6	1.1	1.1	1.1	1.3	4	3.1	3.6	-0.3	2.6	2.6	2.6	0.6	3.4	1.2	0.1
		2.2.1	-4.2	-4	-3.7	1.7	-0.2	-0.1	-0.9	1.1	-0.6	1	1	1.6	1.6	1.6	1.7	4.9	3.7	3	0.9	3.3	3.3	3.3	1	3.2	1.7	0.1
		2.2.2	-4.7	-4.3	-4.7	1.7	-0.8	-1	-1.9	0	-0.5	0.9	0.9	1.3	1.3	1.3	1.6	5	3.9	3.7	0.9	4.3	3.65	3	0.4	3.5	1.2	0.1
		2.2.3	-4.5	-3.8	-4.7	2	-0.5	0.2	-1.5	1.2	-0.1	1.5	1.5	2.1	2.1	2.1	2.4	4.7	3.4	3.9	1.9	3.4	3.15	2.9	1	2.6	0.8	0.1
		2.3.1	-3	-3.2	-3.2	1	-0.5	-0.9	-2	-0.1	-1.8	-0.6	-0.6	0.6	0.6	0.6	0.6	5	3.4	4.1	-1.4	4.4	3.7	3	1	3.9	-0.3	0.1
		2.3.2	-4.3	-4.5	-4	0.1	-1.9	-1.7	-2.7	-0.8	-2	-0.4	-0.4	0.8	0.8	0.8	0.7	3.9	3	3	-1.3	2.9	2.75	2.6	0.7	2.3	0.2	0.3
		2.3.3	-2	-2.3	-1.8	1.4	-0.1	-1.6	-2.2	-1.2	-2.1	-1	-1	-0.3	-0.3	-0.3	0.2	4.9	3.9	4	-1.1	4.7	4.05	3.4	0.9	3.8	1.2	0
		2.3.4	-4.8	-5	-4.7	-0.2	-2.6	-2.1	-2.5	-1.4	-1.6	-0.4	-0.4	-0.4	-0.4	-0.4	-0.1	4.9	3.7	4	-1.2	4.7	3.65	2.6	0.6	3.6	-0.5	0.1
		2.3.5	-4.7	-4.7	-4.5	1	-0.8	-1.9	-2.6	-0.6	-1.5	-0.4	-0.4	0	0	0	0.3	5	3.7	4.1	-0.5	4.9	4	3.1	0.4	3.7	0	0.1
	Cultural	3.1.1	-4.7	-4.7	-2.8	0.8	-0.8	1.3	0	2	0.9	1.9	1.9	2.8	2.8	2.8	2.7	4.7	3.4	3.7	0.4	4	3.45	2.9	3.3	4.0	0.2	0.6
		3.1.2	-4.3	-4.3	-3.3	0.8	-0.1	1.7	0.9	2.6	0.7	2	2	3.3	3.3	3.3	3.3	5	3.6	3.9	1.7	4.6	3.75	2.9	3.3	3.8	1.5	0.4
		3.2.1	-4.2	-4.2	-2.2	1.1	0.5	1.6	0.3	1.6	0.6	2.3	2.3	3.1	3.1	3.1	2.7	4.9	3.1	3.3	0.2	4.7	3.5	2.3	3.4	3.9	0.5	0.6
		3.2.2	-4.2	-4	-2.8	0.8	0.3	1.2	-0.6	1.5	-0.7	1	1	2.5	2.5	2.5	2	5	3.4	4	-0.4	4.9	3.75	2.6	3.3	3.7	0.2	0.4
		Mean	-4.1	-4	-3.7	1.2	-0.7	-0.1	-0.9	0.6	-0.3	0.9	0.9	1.4	1.4	1.4	1.5	4.3	3.2	3.4	0.6	3.6	3.1	2.6	1.4	3.3	1.1	0.4

* These classes were not mapped given their low representation in the study area.

Table 3.5 Ecosystem Services Multifunctionality of the land covers of the metropolitan region of Cali.

			Continuous urban fabric	Discontinuous urban fabric	Industrial or commercial areas	Urban green areas*	Recreative areas*	Cropland mosaic	Sugarcane plantations	Permanent woody crops	Clean pastures	Wooded pastures	Weeded pastures	Cropland, forest and pasture mosaic	Cropland and forest mosaic	Cropland and pasture mosaic	Pasture and forest mosaic	Dense forest	Fragmented forests	Riparian forest	Timber plantations	Natural grasslands (Paramo)	Natural shrublands	Secondary vegetation or in transition	Rocky outcrops	Natural water bodies
Multifunctionality	Provisioning	1.1.1	0.0	0.0	0.0	2.3	1.1	3.3	1.7	3.3	1.7	2.5	2.5	3.0	2.9	2.9	2.3	3.4	2.4	2.0	1.4	2.0	2.3	1.8	0.0	3.0
		1.1.2	0.0	0.0	0.0	2.3	0.7	0.7	0.5	1.7	0.6	2.0	2.0	2.5	1.8	1.3	2.9	5.0	2.9	4.0	1.5	4.3	3.2	2.3	0.0	4.1
		1.2.1	0.0	0.0	0.0	2.2	0.8	1.7	2.0	2.5	0.9	2.4	2.4	2.7	2.3	2.0	2.6	4.9	3.0	3.4	3.3	2.9	2.6	2.3	0.0	2.2
		1.2.2	0.0	0.0	0.0	2.2	0.7	0.7	0.6	1.9	0.8	1.7	1.7	2.1	1.9	1.2	2.4	4.7	3.2	3.9	1.7	4.3	3.0	2.1	0.0	4.1
		1.2.3	0.0	0.0	0.0	1.8	0.9	0.2	0.1	0.6	0.1	0.6	0.6	0.8	0.6	0.4	1.1	1.4	1.1	1.7	0.8	1.7	1.2	1.2	0.3	3.3
		1.3.1	0.0	0.0	0.0	1.8	0.8	1.7	2.8	3.1	1.0	1.9	1.9	2.3	2.1	1.8	2.0	3.4	2.5	2.9	3.9	1.9	1.9	2.3	0.1	2.1
		1.3.2	0.0	0.0	0.0	2.2	1.3	1.1	1.3	2.1	0.8	1.4	1.4	2.1	1.8	1.3	1.9	3.9	2.5	3.1	1.8	3.1	2.3	1.5	0.1	3.8
		1.3.3	0.0	0.0	0.0	0.7	0.5	0.5	0.9	1.4	0.5	1.3	1.3	1.2	0.8	0.9	1.4	1.9	1.2	1.6	1.8	1.1	1.2	0.8	0.2	1.8
	Regulation and support	2.1.1	0.0	0.0	0.0	2.2	1.2	1.3	1.0	2.4	1.1	2.1	2.1	2.7	2.0	1.7	2.9	4.0	2.6	3.6	2.1	2.6	2.4	2.1	0.0	2.8
		2.2.1	0.0	0.0	0.0	2.8	1.2	1.2	1.0	2.7	1.0	2.4	2.4	3.0	2.2	1.8	3.1	4.9	3.1	3.0	2.9	3.3	2.8	2.7	0.0	2.6
		2.2.2	0.0	0.0	0.0	2.8	1.3	1.2	1.0	2.5	1.1	2.4	2.4	2.7	2.2	1.8	3.0	5.0	3.2	3.7	2.4	4.3	3.3	2.5	0.0	3.4
		2.2.3	0.0	0.0	0.0	3.5	1.5	1.2	1.1	2.4	1.0	2.4	2.4	2.9	2.0	1.8	3.1	4.7	2.9	3.9	3.2	3.4	2.9	2.4	0.0	2.6
		2.3.1	0.0	0.0	0.0	3.2	1.9	1.7	1.3	2.9	1.0	2.4	2.4	3.5	2.3	2.0	3.5	5.0	2.9	4.1	2.1	4.4	3.4	2.5	0.0	4.3
		2.3.2	0.0	0.0	0.0	2.8	0.9	1.4	0.8	2.4	0.8	2.1	2.1	3.5	2.0	1.8	3.1	3.9	2.5	3.0	1.4	2.9	2.5	2.1	0.0	2.4
		2.3.3	0.0	0.0	0.0	2.7	0.9	1.6	1.4	2.5	1.0	2.3	2.3	3.1	2.4	1.9	3.3	4.9	3.2	4.0	2.1	4.7	3.5	2.9	0.0	3.7
		2.3.4	0.0	0.0	0.0	2.3	0.9	1.1	0.9	2.0	1.2	2.6	2.6	2.7	2.1	1.9	2.9	4.9	3.1	4.0	1.9	4.7	3.7	2.1	0.0	4.0
		2.3.5	0.0	0.0	0.0	3.5	2.0	1.5	1.2	3.0	1.3	2.6	2.6	3.3	2.3	2.1	3.5	5.0	3.1	4.1	2.7	4.9	3.7	2.6	0.0	3.4
	Cultural	3.1.1	0.0	0.0	0.0	4.0	2.7	1.6	0.7	2.6	1.2	2.4	2.4	3.3	2.2	2.0	3.1	4.7	2.9	3.7	1.5	4.0	3.2	2.4	0.1	4.2
		3.1.2	0.0	0.0	0.0	3.8	2.1	1.8	1.2	3.0	1.1	2.5	2.5	3.6	2.4	2.2	3.6	5.0	3.0	3.9	2.3	4.6	3.5	2.4	0.1	4.3
		3.2.1	0.0	0.0	0.0	3.8	2.5	1.7	0.8	2.1	1.0	2.6	2.6	3.5	2.2	2.2	3.0	4.9	2.6	3.3	0.8	4.7	3.7	1.9	0.1	4.2
		3.2.2	0.0	0.0	0.0	4.0	2.5	1.8	0.6	2.5	0.8	2.4	2.4	3.6	2.3	2.1	3.2	5.0	2.9	4.0	1.0	4.9	3.6	2.1	0.1	4.1
		Mean	0.0	0.0	0.0	2.7	1.4	1.4	1.1	2.4	1.0	2.1	2.1	2.8	2.0	1.8	2.7	4.3	2.7	3.4	2.0	3.6	2.8	2.1	0.1	3.4

* These classes were not mapped given their low representation in the study area.

This result support previous research showing that productively heterogeneous landscapes (polycultures) play a fundamental role not only in supplying food, material and fibres to metropolitan areas but also contributing to the regulation of ecosystem functions such as supporting life cycle, protecting habitat and gene pool, controlling pest and disease, and forming healthy soils (Bennett and Radford, 2008; Grass et al., 2019; Kennedy et al., 2013; Tscharntke et al., 2012). These findings are relevant within the land scarcity debates and can provide important elements to analyse land conflicts around the production of biofuels, food, and biodiversity protection (Fischer et al., 2014a; Lambin and Meyfroidt, 2011c). In this sense, it is crucial to study further different agricultural practices and management types at the farm and landscape scales (e.g., conventional, organic or agroecological) since they can potentially influence agroecosystem functioning and their overall contribution to sustainability and ecosystem service provisioning (Padró et al., 2020a).

3.3.2 Importance of the metropolitan green infrastructure for land use planning

The results show the emergence of landscape-metabolic configurations of the metropolitan green infrastructure that can offer key functions and services for society. They show that the sustainability of metropolitan systems transcends the limits of urbanised territories. For instance, the COVID-19 pandemic made evident the food sovereignty challenges of a metropolitan region isolated in sugarcane monocultures. It becomes evident that this homogeneous territorial set-up reduces the ecosystem service supply, and ultimately, the resilience of the entire metropolitan system.

Based on these results, we propose five reflections that we believe can guide land use planning discussion for the UCRV and other metropolitan regions of the tropical Andes, facing the challenges imposed by land-use changes and intensification.

i) *Adopting a landscape approach:* Adopting the landscape scale for urban and territorial planning in metropolitan systems is increasingly relevant for land planning. In the first place, many of the ecosystem functions and services of the metropolises occur at this scale, which is key to overcoming the methodological difficulties of their evaluation, monitoring and incorporation into public policy. The landscape-scale allows closing metabolic cycles (water, energy, food, waste, etc.) necessary to move towards a more circular economic model, which implies fostering interactions between built and open spaces, relationships of great relevance to society (Bennett and Radford, 2008; Tello et al., 2017). Finally, considering the landscape as one of the essential background elements for the sustainability of the metropolitan system allows, under the right conditions, the reproduction of biophysical flows essential for its sustainability, such as those related to the agri-food system (Cattaneo et al., 2018; Marull et al., 2016a).

ii) Re-establish the functional structure of the landscape: Restoring landscape complexity (i.e., heterogeneous, and well-connected land covers) would imply a substantial and long-term productive transformation of the valley. However, interstitial spaces in the flat plain can be a starting point for reconfiguring the territory and promoting an agricultural mosaic with a high capacity to provide ecosystem services. In particular, improving the ecological structure of pasture land covers (i.e., promoting wooded pastures) would be crucial because of their affinity with agroforestry mosaics and heterogeneous crops, serving as steppingstones for ecological processes.

iii) Enhancing ecological connectivity and protecting high mountain nature: Altitudinal gradients are associated with highly endemic biodiversity (Larsen et al., 2009). Therefore, a well-connected network of natural areas should facilitate the altitudinal migration of species threatened by global warming, anthropogenic habitat loss and degradation (Balthazar et al., 2015; Cresso et al., 2020; Lambin et al., 2003c). For instance, despite occupying less than 8% of the study area, the land covers associated with the Páramos ecosystem (i.e., grasslands and natural grasslands) have a high capacity to supply essential ecosystem services. A region with good connectivity at the macro-basin scale (Cauca river) will likely counteract the impact suffered by the hydrological system of the UCRV.

iv) Configure mosaic landscapes following agroecological management: The results show the great weight that the agrosilvopastoral mosaic area exerts on the provision of ecosystem services and the ecological connectivity of the metropolis. However, these values may vary depending on the type of agriculture practised (e.g., conventional, organic, agroecological) (Font et al., 2020b; Marull et al., 2020; Padró et al., 2020c). Given this condition, the international consensus points to a necessary global agroecological transition, for which Latin America plays a fundamental role (Altieri and Nicholls, 2012; Altieri and Toledo, 2011; Jeanneret et al., 2021; Perfecto and Vandermeer, 2008). The priorities should focus on improving the metropolitan areas' capacity to close metabolic cycles (Billen et al., 2021; Cattaneo et al., 2018) and providing multiple ecosystem services. This can be achieved in combination with promoting highly multifunctional land uses, where crop and livestock systems are integrated. The potential of agricultural mosaics for sustainable land use planning and management in metropolitan regions is critical (Tscharntke et al., 2021).

v) Define and implement a metropolitan green infrastructure: Based on the five previous elements, both the needs and the opportunities to adopt a conceptual and methodological green infrastructure framework to face the sustainability challenges of the UCRV are evident. The results are in line with cutting-edge studies on urban and territorial planning of metropolitan areas, which increasingly reinforce the need to include agricultural open spactmoes as fundamental elements for the sustainability of the metropolitan system given its multifunctional character (Basnou et al., 2020; Slätmo et al., 2019; Yacamán-Ochoa et al., 2020). This implies defining a network of interconnected open spaces, including peri-urban and rural spaces and natural spaces, capable of providing diverse ecological services, goods, and functions for society. The agrarian elements of this green infrastructure are fundamental, and, therefore, it is recommended to include them in the landscape and urban planning of metropolitan regions.

3.4 Conclusions

This article proposes an integrated landscape-metabolism assessment of the impacts of urban growth and agricultural intensification on the socioecological functionality of a tropical Andean metropolitan region. The different landscape-metabolic configurations along a land use gradient were related to the landscapes capacity to supply ecosystem services. The results show that the metropolis current land use planning model, associated with agricultural intensification and industrialisation, has transformed the territory to the point of degrading the metropolitan socioecological quality, jeopardising desirable sustainable progress in urban and rural areas. The landscape-metabolism model proposed in this study aims to support the decision-making processes to reverse this situation, both concerning land use planning and the management of the metropolitan territory, to promote its sustainability, as well as multifunctionality of the prevailing biocultural landscapes and their capacity to provide ecosystem services to the metropolis.

Future studies should focus on evaluating the potential synergies and trade-offs of territorial planning to respond to multiple socioecological challenges, for example, the ecological functioning of the hydrological network of the valley as a fundamental factor to improve ecological connectivity and also mitigate conflicts over water for human consumption and agriculture. Likewise, since inequality and poverty are some of the main characteristics of tropical Andes metropolitan regions and, in general, throughout Latin America, future socioecological studies must include the dimension of environmental justice in their evaluations and purposes.

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PART II Applications of the Socio-ecological Integrated Analysis model to land use public policy

4 Assessing the sustainability of contrasting land use scenarios through the Socio-ecological Integrated Analysis (SIA) of the metropolitan green infrastructure in Barcelona

This chapter is based on the following journal paper: Padró, R., **LaRota-Aguilera, M.J.**, Giocoli, A., Cirera, J., & Coll, F. (2020). Landscape and Urban Planning Assessing the sustainability of contrasting land use scenarios through the Socio-ecological Integrated Analysis (SIA) of the metropolitan green infrastructure in Barcelona. *Landscape and Urban Planning*, *203*(April), 103905. https://doi.org/10.1016/j.landurbplan.2020.103905

4.1 Introduction

Creating metropolitan areas capable of conciliating population rise and the landscape ecological functioning should be a priority for planning cities and communities, in accordance to the 2030 UN Sustainable Development Goals (SDG). Building sustainable cities requires achieving the targeted objectives of participatory, integrated, and sustainable human settlement planning and management (United Nations, 2019b). 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; Tratalos et al., 2007). Simultaneously, this metropolitan growth has often increased administration costs to maintain basic functions of the open spaces for the provisioning of ecosystem services required by society (Benedict and McMahon, 2002, Tzoulas et al., 2007, Sandifer et al., 2015).

In order to overcome these trends towards a more sustainable economy, one of the main challenges of future cities and their metropolitan communities is how to provide close, sustainable, and safe food for their population while contribute to a more circular economy (FAO, 2011). Along the decades of the green revolution, western agrarian activities simplified their complex socio-ecological functioning resulting in a loss in territorial and resource use efficiency (Gingrich et al., 2018a; Marull et al., 2019a) . This affected both landscape functioning and metabolism in open spaces. Hence, although there is a growing trend advocating for the need of an agro-ecological transition (FAO, 2018; IFOAM, 2019), it is necessary to develop methodologies aiming to understand its feasibility and impacts from a multi-criterial perspective to better understand its potentials and shortcomings beyond its economic viability (Duru et al., 2015; Magrini et al., 2019; Wezel et al., 2020). In this sense, planning towards this socio-ecological transition of agriculture towards more sustainable management should aim, at least, at four objectives. The first one would imply to reduce the external inputs needed for agriculture (i.e., fertilizers, animal feed, seeds) (Tello et al., 2016). The second, to optimize material and energy flows between food production and animal husbandry (i.e., closing energy and material cycles at landscape scale (Tello and González de Molina, 2017b). The third, to improve the autonomy of farms by promoting functional diversification and biodiversity by implementing more integrated and complex types of farming (Marull et al., 2016b). And the last but not least, to strengthen climate change adaptations and contributing to net-zero emissions policies (Aguilera et al., 2015). Accordingly, a quantification of energy and matter flows inside agricultural systems is essential to understand how sociometabolic 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 (Martínez-Alier et al., 1998; Thomas and Littlewood, 2010). Then, only when the biophysical benefits to the metropolis are valued with a multi-criterial perspective, the socioeconomic pressures to the green infrastructure can be reduced (Thomas and Littlewood, 2010). Also, this process would allow understanding some issues that often remain out of focus with the classical cost-benefit analysis: the environmental externalities, the asymmetry of information, and the of open spaces as public goods in a wider perspective (Bastian et al., 2012; 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, 1998). 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 socio-ecological 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 biocultural landscape where its different elements (both social and natural) interact, through innumerable processes that characterize the functioning of the territory as a system as a result of a relation between nature and society in a given site-specific context (Agnoletti, 2006; Marull et al., 2010).

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 socio-ecological approach, currently there is a lack of models to assess the land planning on the multifunctionality of the green infrastructure (Maruani and Amit-Cohen, 2007). In order to guarantee a meaningful land Planning for Sustainability and advance in the knowledge of the metropolitan systems and the complexity of the decisions making processes, multi-criteria and multi-scale analysis are needed to facilitate the necessary deliberative processes (European Commission, 2013). This strategy is also an imperative by current policy roadmaps in order to identify the role of the green infrastructure in providing ecosystem services, nature-based solutions, climate change mitigation and adaptation, and maintaining natural capital (European Commission, 2013; Hansen and Pauleit, 2014).

In this paper, we use an improved version of the Socio-ecological Integrated Analysis (SIA) (Marull et al., 2021a), a particularly comprehensive model of the landscape-scale social metabolism that includes its main structural, functional, and managerial dimensions, to integrate social metabolism variables into land planning, through the quantification of the metabolic flows of the green infrastructure land uses. The work has two specific objectives. First, it aims to explore alternative but feasible horizons of the Barcelona Metropolitan Area (BMA) by applying the SIA to different theoretical land use scenarios defined by the Land Use Master Plan (PDU for its acronym in Catalan) of the BMA. Second, it aims to particularly assess the socio-ecological implications of a transition in the agrarian system from the current conventional management to an organic one.

4.2 Methodology

4.2.1 Case study

The Barcelona Metropolitan Area (BMA) is comprised of 36 municipalities in a total area of 63,611 ha (Figure 4.1) and has a population of 3.3 million people (IDESCAT, 2020). According to the newest Land Cover Map of the BMA (CREAF, 2015), open spaces are still the predominant land covers (55%) distributed among forests and scrublands (42%), croplands (8%), pastures (3%) and other open spaces (2% water corridors and bare soil). The remaining 45% of the surface are built-up areas including compact and spread urban areas, urban parks, roads, and other infrastructures. Agriculture is concentrated along the lower valley and the Delta of the Llobregat River, although some patches of arable land, vineyards and arboriculture still form mosaic patterns with forests in the Vallès plain and the slopes between sparsely populated areas.

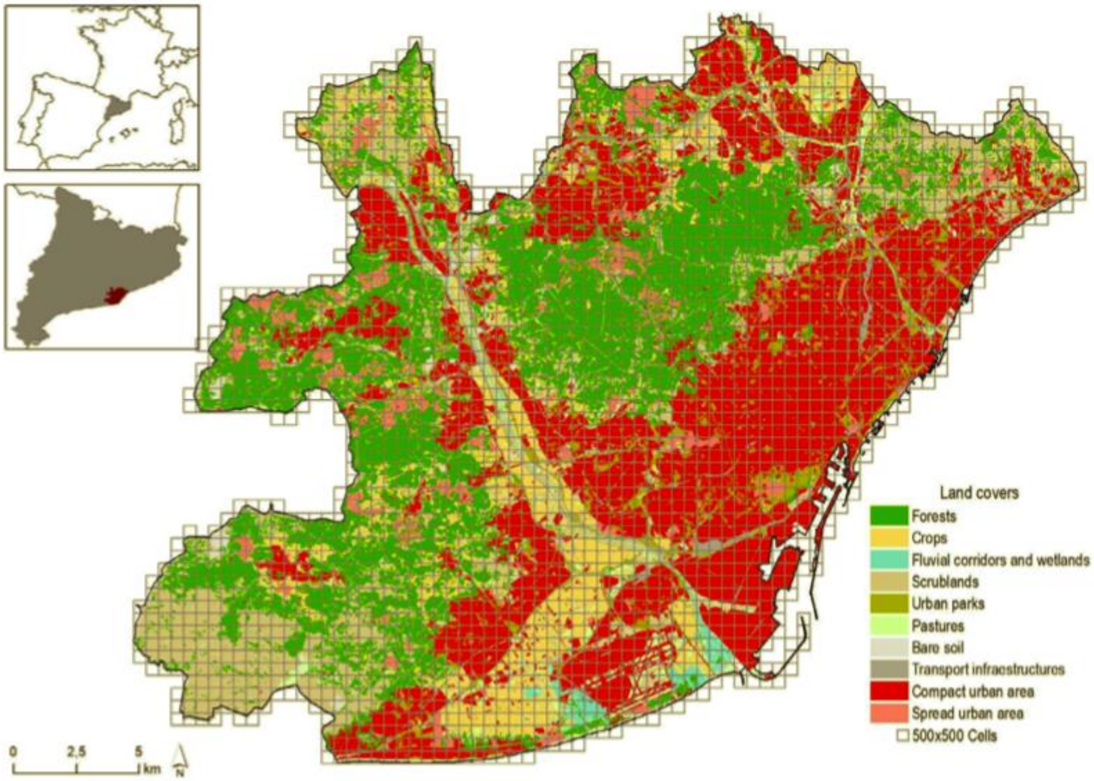


Figure 4.1 Land cover map of the Barcelona Metropolitan Area (BMA).
Source: CREAF, 2015.

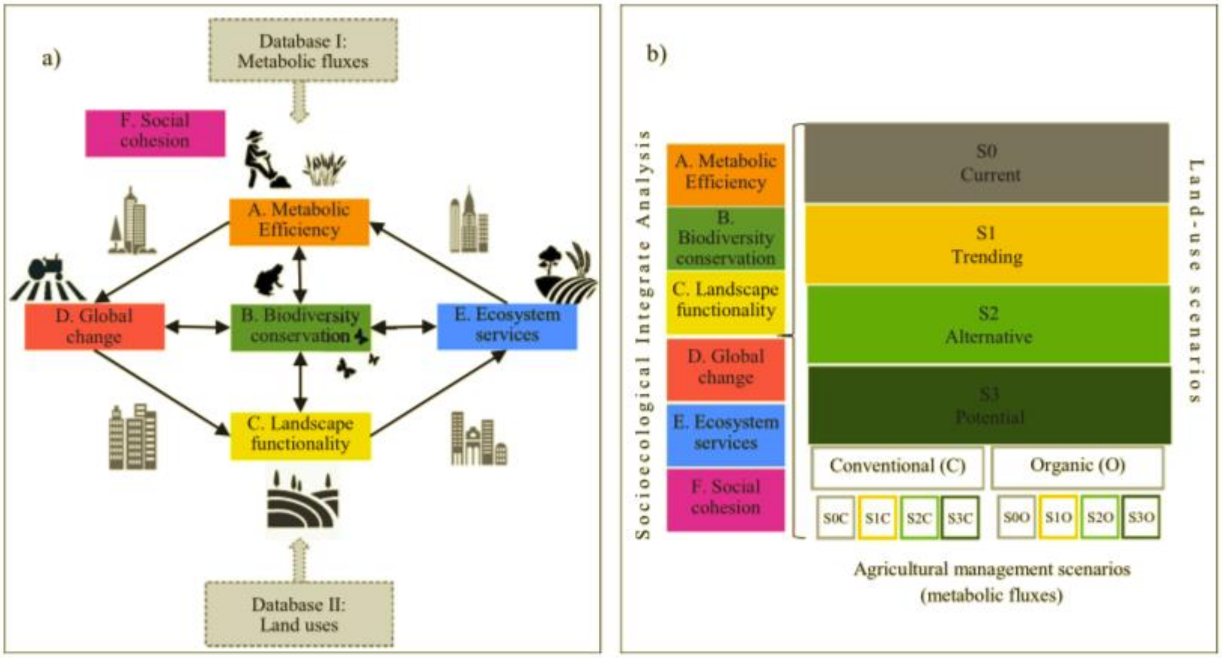


Figure 4.2 Conceptual framework and experimental design for the evaluation of land cover and agricultural practices scenarios with the Socio-ecological Integrated Analysis (SIA). Conceptual framework (a) and experimental design (b) for the evaluation of land cover scenarios and agricultural practices (conventional vs organic). Source: Our own modified from Marull et al. 2020.

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; (United Nations, 2015). The General Metropolitan Plan from 1976 set the foundations of land use planning basis for the urban expansion up to 2014. After 38 years a new process was launched to achieve a new consensus under the Urban Master Plan (PDU). The Action Plan for the PDU considers 3 structural elements that constitute the socio-ecological 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 socio-ecological system. To this aim, the SIA model can be an effective tool.

4.2.2 Socio-ecological Integrated assessment

The Socio-ecological Integrated Assessment (SIA) (Marull et al., 2021a) is a metabolic-territorial model that evaluates the contribution of the green infrastructure to the whole socio-ecological system of the BMA considering six interrelated dimensions (Figure 4.2A): 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 4.1): 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 selection of socio-ecological indicators has been done according to the main objectives for the green infrastructures' planning in the PDU Action Plan. The conceptual definition of these indicators was done through a semantic categorization together the technicians in charge of the redaction of the PDU so as to ensure its usefulness of the multicriteria assessment in the deliberative processes (Giampietro et al., 2009). The model is fed with land use digital maps and regional statistical data on inputs and products of agricultural systems. It considers the whole relevant biophysical fluxes that circulate within the agroecosystems and assesses its functioning based on four balances: phytomass, energy, animal feeding and biogeochemical cycles (Marco et al., 2018).

This means the model accounts whether nutrients or the feed flows circulating through the case study are enough to ensure reproduction of soil fertility and livestock. If not, it is estimated the amount of feed or soil amendments that has to be imported from outside and all the corresponding implications on the indicators. This biophysical framework is also related to a set of landscape ecology models that account for patterns and processes considering the green infrastructure as a system (Marull et al., 2008). All together make up a set of interrelated models which allow to calculate the set of socio-ecological indicators. Thus, changes on management or on land use composition, would result in different values for the eight principal SIA indicators.

Table 4.1 Socio-ecological 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)

4.2.3 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 4.2B) 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 (Figure 4.1). Land cover composition for each scenario is detailed in Table 4.2 and changes from the current to the trending (S1), alternative (S2) and potential (S3) scenarios are shown in Figure 4.3. The trending scenario (S1) corresponds to business-as-usual situation, with the full implementation of the current municipal urbanistic land plans, characterized by a general increase in the built-up areas and urban parks and leading to a decrease in forests, scrublands, and agricultural areas. In the alternative scenario (S2), change from planned urban parks to productive agricultural areas is proposed. Finally in the potential scenario (S3) an important recovery of the pre-existing agricultural areas in the BMA is set (identified through an historical land cover map of 1956). Land uses, specifically crop surface and structure, were adjusted accordingly to the land cover distribution changes between scenarios (i.e., when herbaceous crop surface increased in S3, specific crop surface increased depending on the original distribution).

The trending scenario (S1), supposes an increase in the built-up areas of 5500 ha (considering as well the urban parks) (Figure 4.3). The most affected categories are the forest and the scrublands (1500ha and 1330 ha respectively), but it is also relevant the loss of around 25% of current agricultural surface (1150 ha). The effect of the urban development in S1 is partially reverted in the alternative scenario (S2) where a large part of the urban park area considered in S1 is transformed into agroforestry activities (more than 80%). Also, around 520ha and 600 ha, respectively, of compact and lax urban areas are reconsidered, increasing agricultural areas in the BMA from 4200 ha in S1 to 6950 ha in S2. In the potential scenario (S3), the increase in the agricultural surface is very important: up to 12,600 ha as all the agricultural areas from 1956 are recovered except for those already built-up areas (Giocoli, 2017). New transport infrastructures, which heavily impact on the fragmentation processes, increase in more than 720 ha in S1, 430 ha in S2 and few more than 320 ha in S3.

Each land cover scenario was analysed under two different agricultural management practices: conventional and organic (Figure 4.2B). The first corresponds to the current agrarian management activities, and is mainly based on the 2009 agricultural census and updated with the statistical sources using the year 2015 as reference. This allows estimating the metabolic fluxes of the current agrarian activities and, by extension, of the complete green infrastructure (Marull et al., 2021).

Table 4.2 Land planning scenarios of the Land Use Master Plan of the Barcelona Metropolitan Area (BMA) considered in the Socio-ecological 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%

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

To simulate organic agricultural management scenarios, we followed the guidelines for certified organic animal and food production stablished by the European Commission legislation (834/2007, 889/ 2008, and 1235/2008) and the Catalan Council of Ecological Agricultural Production (CCPAE, 2017). Given the many possible crop management practices under the official certification of CCPAE (i.e., fertilizing techniques, pest control management, crop rotations), for the specific purpose of this study, we defined organic agriculture management as: i) the complete removal of chemical non-mineral fertilizer use; ii) the complete removal of chemical pesticides and herbicides use; and iii) the limited and regulated use of external inputs (i.e., animal feed and seeds). Under those definitions, organic agricultural practices were assumed to comply with the minimum CCPAE certifying criteria (Table A11).

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 A11). In summary, three main assumptions were made: i) crop and animal yields decrease (de Ponti et al., 2012; Seufert et al., 2012); ii) labour requirements per product unit increase, as well as the intensity of machinery use (DAAR, 2006); iii) all biomass and manure are properly reused (nutrient cycles are closed) and there is no waste flow (biomass discard); and iv) crop species composition and crop structure remained the same between organic and conventional managements.

4.2.4 Cartographic and statistical analyses

To assess the implications of a potential territorial (land cover scenarios) or/and metabolic (management scenarios) transition in the BMA, each SIA indicator was calculated for each scenario at 500x500m sample cell and metropolitan (aggregated) scope. First, the SIA assessment at cell level 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 (Section 3.1). Then, in order to compare the overall impact of scenarios, a multicriterial assessment is performed through aggregate values (this is, the absolute value for the whole BMA), which allow to have the big picture on the overall functioning (Section 3.2). Finally, a Principal Component Analysis (PCA) was performed to assess the synergies and trade-offs among SIA dimensions through a statistical Exploratory Factorial Analysis (EFA). Finally, we used results at cell level to identify how the relation among dimensions and scenarios shifts and how changes in the landscape structure are associated with changes in the metabolism (Section 3.3).

4.3 Results and discussion

4.3.1 Contrasting land planning scenarios and management practices

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

Results show that, in general, the energy efficiency indicator (A1) is higher for all conventional scenarios compared with the same scenarios with organic agricultural practices, with the lowest A1 value found in the organic trending scenario (S1), although it is not statistically significant (Table 4.3). Scenarios of conventional management with larger agricultural land cover (S2 and S3), have significantly higher A1 values than S0 and S1 scenarios of the same management type.

The energy-landscape integration indicator (B1), has an overall higher and significant values when the agroforestry mosaic is recovered (S2 and S3) and when there is a transition towards organic management in each land cover planning scenario, despite those effects remain around 5% (Table 4.3). 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 (Table 4.3). There are no significant changes between the alternative and potential scenarios, but they both present relatively low differences compared to changes in other dimensions.

Regarding the non-renewable energy inputs (D1), the transitions from conventional into organic management generally resulted in lower non-renewable energy inputs, although these differences were not significant (Table 4.3). As organic farming maintains machinery or greenhouses, which are an important part of external energy inputs, the exclusion of pesticides, herbicides and chemical fertilizers is not enough to significantly affect total external inputs. However, like A1, the indicator was especially sensitive to the substantial agricultural area increase of the potential scenario (S3).

In terms of nutrient recirculation (E1A), regardless of the land planning scenario, mean indicator values under conventional management were always lower than under organic management (Table 4.3). These differences are significant for the current (S0), trending (S1) and alternative (S2) scenarios. However, the greater the agricultural surface the lower the system's ability to provide enough nutrients to close the nutrient cycles at local level. The carbon stock indicator (E1B) reveals higher values in the current scenario (S0).

With respect to agricultural production (E1C), values are always significantly higher for conventional management mainly due to the lower yields considered for organic management. These sustained differences (an overall drop in production of 17%), are also affected by the increase in agricultural area that makes the average value of production per cell increase significantly in the potential scenario (S3) in relation to the current scenario (S0).

Finally, the agricultural jobs indicator (F1) showed for all land cover scenarios higher labour intensities in organic production (Table 4.3). This difference was significant for the current, trending, and alternative scenarios (S0, S1 and S2 respectively). Additionally, the shift from the current scenario into the potential scenario (S3), where agricultural land cover considerably increased, would imply an increase in the average amount of work in relation to any of the other scenarios.

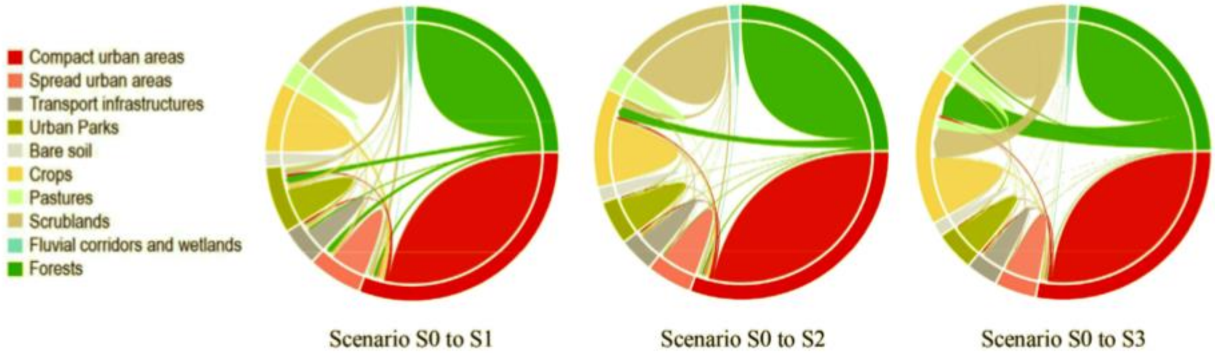
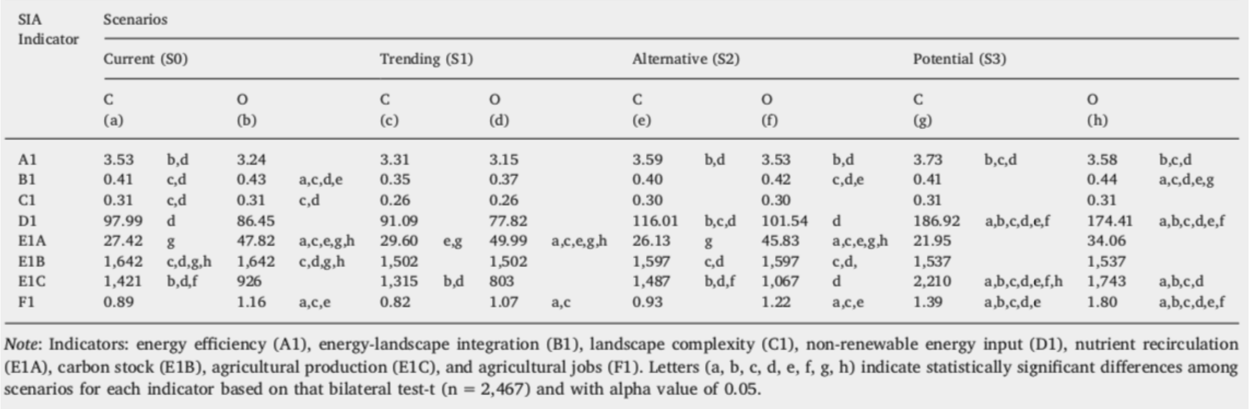


Figure 4.3 Land cover changes among land planning scenarios in the Barcelona Metropolitan Area (BMA).

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

Table 4.3 Results of the Socio-ecological 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.

4.3.2 Multi-criteria assessment of the scenarios and practices

4.3.2.1 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 4.4). This loss of complexity, together with the increase of urban sprawl, would also worsen the conditions for biodiversity conservation (B1). In general, all fluxes are reduced in the trending scenario, resulting in less production (E1C), lower job provision (F1) but less external entries as well (D1), as a counter-effect.

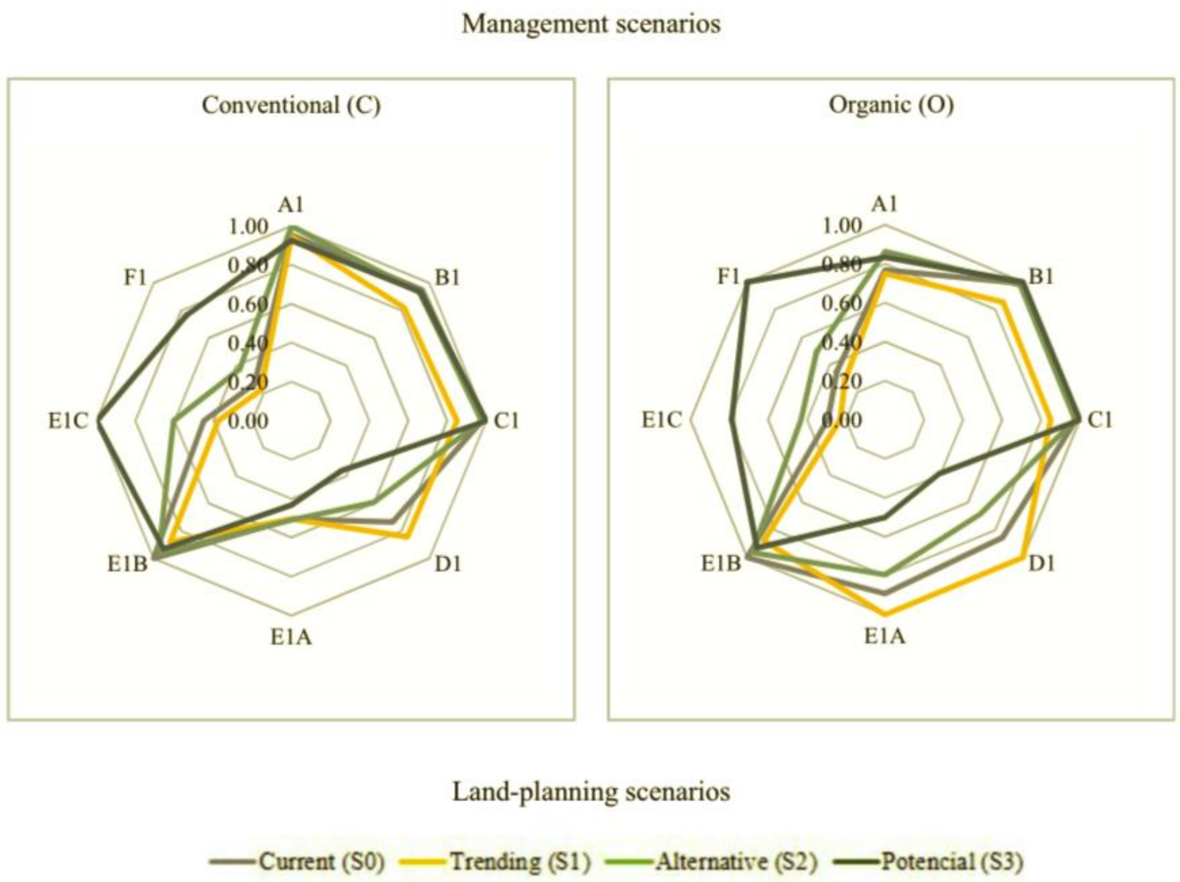


Figure 4.4 Multi-criteria Analysis of the land planning and management scenarios in the Barcelona Metropolitan Area (BMA) evaluated with the SIA .

SIA results for the 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). Socio-ecological 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).

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) (Figure 4.4). This means that S0 has more stock than the trending scenario (S1) but also compared to the potential scenario (S3).

In terms of the alternative (S2) and potential (S3) scenarios, regarding the soil nutrients recycling (E1A), an increase in the agricultural surface causes a drop in the ability to close the nutrient cycles, because nutrients are lost through sewage sludge and are not recycled to agricultural areas (Padró et al., 2017) (Figure 4.4). This makes difficult to close the nutrient cycles, increasing the heavy reliance on imports as seen in the D1 results, regardless of the type of fertilizer imported (manure or chemical).

The transition between S1 to S2, where the agroforestry land recovered, shows the potential to mitigate the impacts of the trending scenario (S1), although its effects would not be even equal to the situation in 2015 (S0) (Figure 4.4). This agroforestry recovering in the alternative and potential scenarios, has also potential benefits for biodiversity conservation (B1), which can go hand in hand with the increase of total agricultural production (E1C), the later with a 2.2-fold increase from the current (S0) to the potential scenario (S3). This synergy found in the SIA indicators supposes an interesting trend that should be corroborated in further studies, supported under the hypothesis of a land sharing strategy (Fischer et al., 2014b; Marull et al., 2019b), so that increasing agricultural production by increasing cropland cover while maintaining intermediate levels of human disturbance can hold greater levels of biodiversity than intensifying the already existing cropped surface.

4.3.2.2 Management practices, a socio-ecological transition towards organic production

A transition to organic farming (Figure 4.4) meeting the CCPAE criteria (Table A11) is particularly favourable facilitating a greater degree of autonomy closing the nutrient cycles (E1A) and providing agricultural jobs (F1). But this process is associated with a decrease of agricultural production (E1C) and energy efficiency (A1). A reduction on agricultural yields was expected considering the yield factors estimated in the model (De Ponti et al., 2012, Seufert et al., 2012). Despite the decrease of external fertilizers use and the complete elimination of herbicides and pesticides, a significant decrease on energy efficiency under organic practices could be explained by the elevated use of external inputs: in this particular case the feed, imported from regional organic sources when the local production did not satisfy the requirements, as well as machinery use also slightly increased.

The effect of an organic transition would significantly reduce aggregate agricultural production (E1C), with an average drop of 17% (Figure 4.4). Indeed, this decline in productivity per hectare is not as much as the decline in productivity, even though the total amount of inputs per hectare decreases. Thus, energy efficiency of agriculture falls between 9% and 20% at the aggregate level. On the contrary, the average difference among agricultural practices in terms of nutrient recirculation (E1A) is a relevant 30% increase between the conventional and the organic management, as following the legal criteria livestock is mainly feed with local sources trying to maximize the circular functioning and limiting external imports of grains and hay.

A similar effect is observed with the slight reduction in the dependence on external inputs (D1) or the energy-landscape interaction (B1), but in this case the increase is much more restrained as they only improve on average between 10 and 5% respectively when compared to the conventional production (Figure 4.4). Those two aspects are probably showing the biophysical limits of an organic management versus an agroecological one (Tello and González de Molina, 2017), challenging the transition and the goals of a sustainable management.

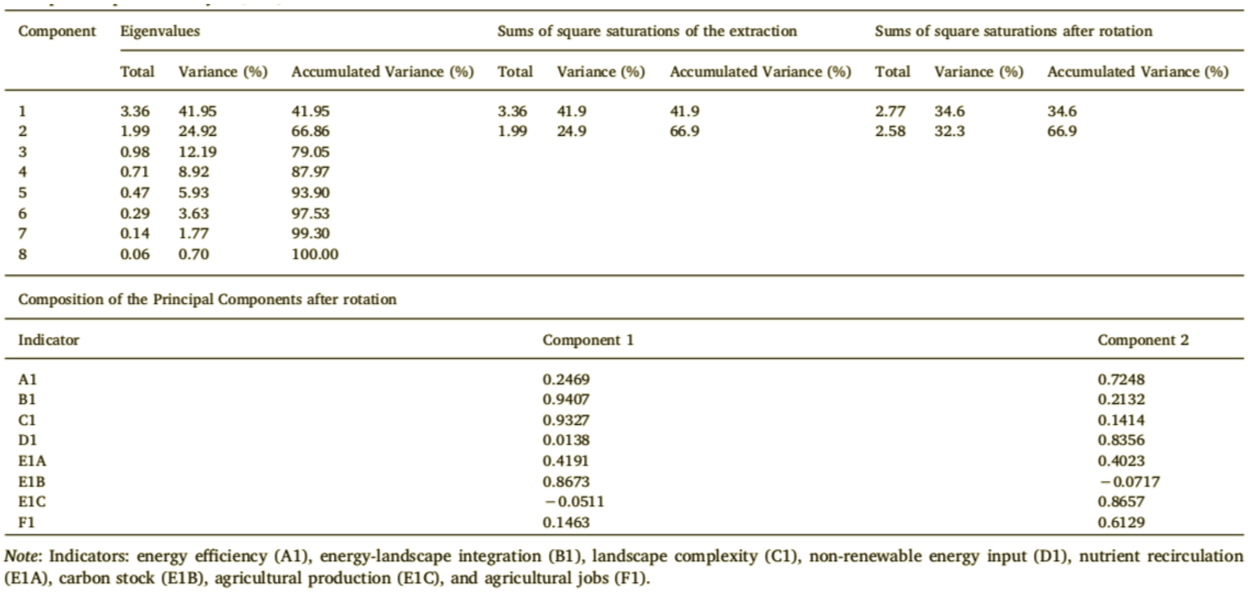
Finally, the average agricultural job provisioning (F1) increased 24% Agrarian Working Units (AWU) (Figure 4.4). An ecological transition would increase the current estimated 640 to almost 2,400 AWU in the potential land cover scenario (S3). This increase of 3.7 times in the volume of workers is explained mainly by the increase of surface, but by the shift to organic farming as well as by the agricultural expansion towards cropping areas with productivities below the average.

4.3.3 Trade-offs and synergies on the socio-ecological functioning

The Principal Component Analysis (PCA) results in the identification of 2 components with eigen values over 1 that represent around 66.9% of the total variance in the case study and have very different composition (Table 4.4). The first component mostly includes energy-landscape integration (B1), landscape complexity (C1) and carbon stock (E1B). Then, it is more related to the landscape structure and functioning, reflecting a classical perspective on the land covers from a landscape ecology viewpoint. On the contrary, the second component is a good proxy of the biophysical flows circulating through the landscape. The variables of agricultural production (E1C), use of non-renewable inputs (D1), and energy efficiency (A1) or agricultural labour (F1) to a lesser extent, represent the material flows that occur in the green infrastructure. This gives prominence to the agricultural metabolic dimensions when considering the approach that must be considered for a land Planning for Sustainability. It is worth noting that while component 1 explain 42% of the total variance, component 2 accounts for the 25%. This means that while land use planning for sustainability cannot set aside the metabolic flows, the landscape patterns and processes play a fundamental role to understand variability along the territory.

It is also relevant to bring to light the shared contribution of the E1A indicator (soil nutrient recycling) to both components, suggesting that this is an important aspect to be considered in land planning given its ability to integrate metabolic and territorial aspects of the socio-ecological system (Table 4.4). From a conceptual perspective means that this indicator is affected by both the landscape funds and the metabolic flows and gives relevance to the reproductive processes needed by the green infrastructure to keep its socio-ecological functioning. In this sense, the recirculation of nutrients, as a fundamental regulating 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 biocultural landscape capital (such as terraces or the selective management of forests).

Table 4.4 Principal Component Analysis (PCA) for the Socio-ecological Integrated Analysis (SIA) of the Barcelona Metropolitan Area (BMA)



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).

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 4.5). As can be seen, scenarios are much more affected by changes in component 2 (‘metabolic flows’) than component 1 (‘landscape ecology’). For this case study, the trending scenario is the only land use scenario that supposes a relevant change on the landscape component, with an average loss of 0.31 points in component 1, while for the rest of land use scenarios are practically null with an average change around 0.02 points. On the other hand, the performance of component 2 is much more sensible to land use scenarios, with an average loss of

0.14 points in the trending scenario, a gain of 0.25 for the alternative and a much more greater 0.87 increase in the potential compared with the current one. The observed low and high sensitivity of land cover scenarios to landscape pattern and metabolic flows variables, respectively, lead us to a draw a relevant statement for policy making in this study: land use planning is much more affecting the agricultural metabolic flows than traditionally expected. Finally, organic farming scenarios compete with conventional ones in terms of the metabolic flows (component 2) but also result in a better performance in relation to sustainability objectives of the landscape in an average increase of 0.11 points. Something that, again, reinforces this crossed effect of land use planning on metabolic performance and vice versa (the effect of metabolic changes on landscape performance).

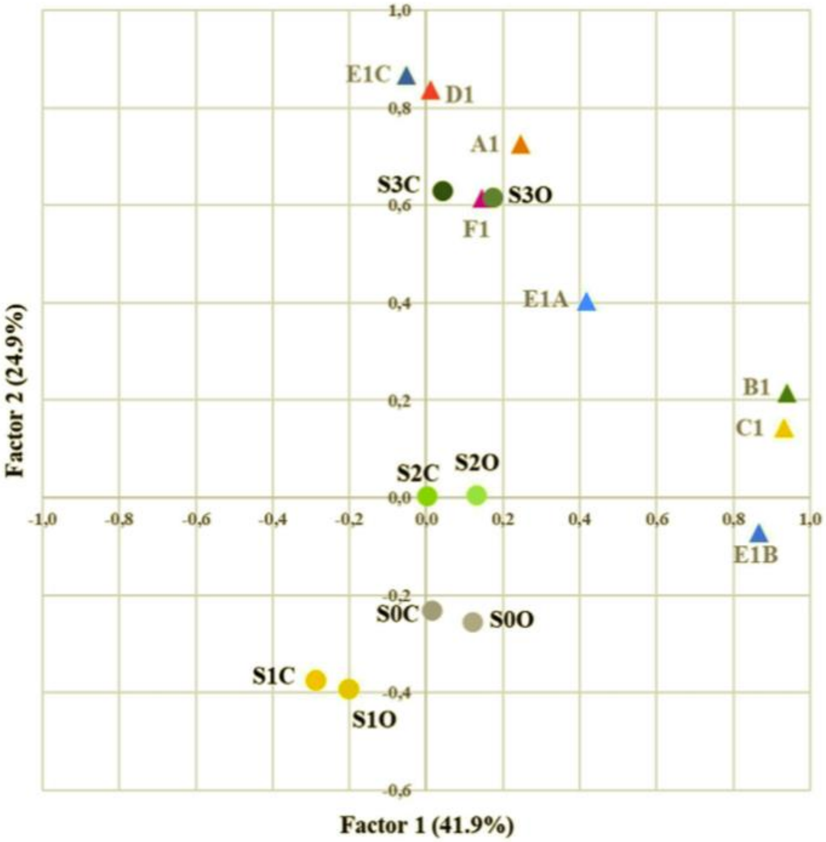


Figure 4.5 Exploratory Factor Analysis (EFA) of the Socio-ecological Integrated Analysis (SIA) for the Barcelona Metropolitan Area (BMA).

Land planning scenarios are represented with coloured circles and dark text (S0 = current scenario, S1 = trending scenario, S2 = alternative scenario, S3 = potential scenario), under conventional (C) and organic (O) managements. The Socio-ecological Integrated Analysis (SIA) indicators are represented with triangles and grey text: 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).

4.3.4 Strengths and limitations of the model

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

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

Metropolitan agricultural landscapes can become the greenbelts needed for a closer agri-food supply in line with the Milan Urban Food Policy Pact (Moragues-Faus and Morgan, 2015), as well as for the delivery of many ecosystem services (Haines-young and Potschin, 2010). The proposed SIA model has proven to be a useful assessing tool for this new sustainability-driven approaches to urban planning, remarking the need to redirect and take care of the biophysical flows that shape these horticultural and agroforest landscapes within metropolitan areas. It confirms the relevance of the FAO's 2018 Scaling Up Agroecology Initiative that claim to leap forward from current organic farming to more integrated agroecology territories able to ensure the provision of all kinds of ecosystem services to society (FAO, 2018). Land-use planning can enhance all the ecosystem services delivered to citizens from the metropolitan green infrastructures by driving towards socially desired scenarios these farming matter-energy flow that shape the agroforest landscape mosaics. Thus, land-use policy can do it through incentives and regulations which set in motion positive synergies with farmers.

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

4.4 Conclusions

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

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

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 socio-ecological functioning on metropolitan areas during a possible organic transition should be carefully accounted. Strict compliance with ecological regulations might not necessarily translate into overall improvements, and might not be enough to face challenges such as the decrease on the use of external inputs or on the increase on the energy efficiency improvement.

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

In summary, the challenge of sustainable land planning and circular economy in metropolitan areas could be addressed by adopting an integrated view that allows for the identification of both land uses and metabolic flows changes. A socio-ecological transition towards organic agriculture should be evaluated on a case-by-case level, considering the specific socio-ecological 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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5 Energy-Landscape optimization for land use planning. Application in the Barcelona metropolitan area

This chapter is based on the following journal paper: Marull, J., Torabi, P., Padró, R., Alabert, A., **LaRota-Aguilera, M.J**., & Serrano, T. (2020). Energy-Landscape optimization for land use planning. Application in the Barcelona metropolitan area. Ecological Modelling, 431, 109182. https://doi.org/10.1016/j.ecolmodel.2020.109182

5.1 Introduction

Global human-driven Land Use and Cover Change (LUCC) have spread the so-called ‘anthropogenic habitats’ in many regions of the world thus determining biodiversity and ecosystem functioning in human-transformed landscapes for centuries, as in the Mediterranean(Grove and Rackham, 2003). However, increasing landscape transformation linked to fuel energy consumption (Giampietro et al., 2013)have driven to unprecedented levels of affectation of ecosystem functioning at landscape and regional scales (Ellis et al., 2010; Sterling and Ducharne, 2008). The past century was witness to particularly severe LUCC, which affected habitat and biodiversity conservation (Brondizio et al., 2019; Newbold et al., 2015). These effects lead to biotic homogenization in most-human transformed regions like metropolitan areas (McKinney, 2006). In any case, human-transformed landscapes are the outcome of a shifting interplay between spatial patterns of land-use types, their associated ecological processes and their socio-metabolic energy flows driven by human activity (Haberl, 2001; Wrbka et al., 2004). The human population has continued growing in the last decades, and the huge increase in global food production through increasingly industrialized and globalized production systems has provoked many serious socio-ecological impacts and conflicts (Mayer et al., 2015; Tilman et al., 2002b).

The dilemma that land-use planners and agroecosystem managers are facing today is between increasing the “efficiency” of land trying to provide the demanded food and products at the cost of losing important features of landscape, and trying to keep the sustainability of the agroecosystem, which means limiting the production per unit area of land (Nair, 2014). The main strategies to respond to the growing food demand are: i) to increase production per unit area of land; ii) to increase the land used for food production. One of the most common ways used in industrialized agriculture to increase the production per unit area of land or increasing the “efficiency” of the land, is using fertilizers, pesticides, and other non-renewable inputs. Although in the short run, these options seem desirable, the long-term effects are disastrous due to the loss in biodiversity, soil nutrition and other reproductive characteristics of agroecosystems that we call “funds” (Giampietro, 1997).

Hence, there is an urgent need for tools that support the designing of sustainable agroecosystems, where socio-ecological goals (i.e., food production, biodiversity conservation, ecosystem service provisioning) are optimized, while they operate within a framework of constrained reproductive imperatives (Padró et al., 2019). To solve this food-biodiversity dilemma (Cardinale et al., 2012b) deeper research on how landscape ecological functionality is kept in different land use patterns is required, according to the quantity and quality of the human disturbance that farmers carry out across the landscape (Marull et al., 2018a). The aim of this research is to find optimal scenarios for land use management in the Barcelona Metropolitan Area (BMA) that maximize key reproductive characteristics of agroecosystems (Padró et al., 2019) such are metabolic efficiency, landscape ecological functionality, biodiversity, and associated ecosystem services, and also climate change mitigation and adaptation (Marull et al., 2021a; Padró et al., 2020a). To that aim, the objective of this paper is to develop an Energy-Landscape Optimization (E-LO) nonlinear modelling based on the Energy-Landscape Integrated Analysis (ELIA) (Marull et al., 2016b) to find the optimal land uses that lead to a sustainable agroecosystem. Then, we test the E-LO model by applying three optimization scenarios in a Mediterranean bio-cultural landscape of the BMA, considering different LUCC under both conventional and organic agricultural practices. The E-LO is designed to help land-use policy-makers and agroecosystem managers to advance towards a socio-ecological transition considering societal priorities and environmental constrains in a human-transformed landscape.

5.2 Material and Methods

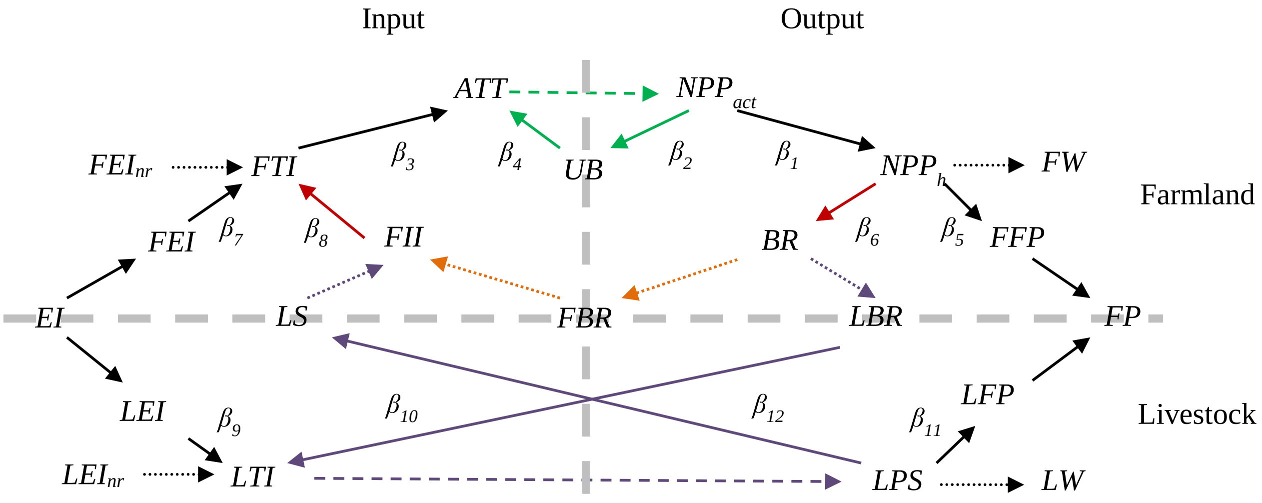
The methodology considered for the E-LO model is based on applying an optimization procedure to the ELIA (Marull et al., 2016b). The latter is a socio-metabolic and landscape ecology methodology that brings together landscape patterns and processes and describes how agrarian flows (such as energy, fertilizers, or production) are distributed among the landscape. This tool is particularly useful to represent complex performances of biocultural landscapes as human-nature co-evolutionary systems.

5.2.1 Energy-Landscape Integrated Analysis (ELIA)

5.2.1.1 Agroecosystem Energy Flows from a Landscape Ecology Standpoint

ELIA summarizes human coproduction with nature (Marull et al., 2016b) through the connexion between energy flows (Figure 5.1) coming from solar radiation through the photosynthesis (vertical axis) and coming from outside the landscape (left side of the horizontal axis). Both energy flows interact across a landscape functional structure to give rise to a final product extracted from it (right side of the horizontal axis). The ELIA graph expresses this network of energy flows across the agroecosystem, which are partially recirculating internally (to keep its own reproduction) and partially open externally (to sustain the agri-food chains of human society). β_i's are the incoming-outgoing energy flows coefficients.

The phytomass obtained from solar radiation through autotrophic production by plants is the *actual Net Primary Production* (NPP_{act}) (Vitousek et al., 1986). The biomass included in NPP_{act} that becomes available for heterotrophic species splits into *Unharvested Biomass* (*UB*) and the share of *Net Primary Production harvested* by farmers (NPP_h). *UB* generally remains in the same place where it has been originally growing and can feed farm-associated biodiversity. It becomes a source of *Agroecosystem Total Turnover* (*ATT*), which closes the cycle of the 'natural' subsystem Figure 5.1.



Variables: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_h); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input

Figure 5.1 Graph model of interlinked energy carriers flowing in a mixed-farming agroecosystem[1].

Relationships between variables: $NPP_{act} = UB + NPP_h$; $NPP_h = BR + FFP$; $BR = FBR + LBR$; $EI = FEI + LEI$; $LTI = LEI + LBR$; $LPS = LFP + LS$; $FP = FFP + LFP$; $ATT = FTI + UB$; $FTI = FII + FEI$; $FII = FBR + LS$.

Note: [1] The colours of the arrows represent the ‘natural’ (green), ‘farmland’ (red) or ‘livestock’ (purple) subsystems.

This ‘natural’ subsystem allows maintaining the farm-associated biodiversity and, in turn, the NPP_{act}, again through the trophic net of non-domesticated species either aboveground or in the soil (such as decomposer organisms). NPP_h splits into *Biomass Reused* (*BR*) inside the agroecosystem and *Farmland Final Produce* (*FFP*) that goes outside. *BR* is an important flow that remains within the agroecosystem as the farmers’ investment directly or indirectly addressed to maintain two basic fund elements: livestock and soil fertility. Hence, *BR* closes the ‘farmland’ subsystem Figure 5.1.

Then *BR* splits into the ‘livestock’ subsystem (Figure 5.1) that goes to feed and bed the domesticated animals as *Livestock Biomass Reused* (*LBR*), which is added to the *Livestock Total Inputs* (*LTI*), and *Farmland Biomass Reused* (*FBR*). In turn, these flows add up to *Farmland Total Inputs* (*FTI*) as seeds, green manure, and other vegetal fertilizers. These energy linkages in the ELIA graph enable us to see to what extent the land use management is integrated or not within the surrounding agroecosystem. Afterwards, domestic animals perform bioconversions and then the *LTI* is converted into *Livestock Final Produce* (*LFP*) and internal *Livestock Services* (*LS*). *LFP* includes a wide range of food and fibre products, and *LS* services include manure. Together they make up *Livestock Produce and Services* (*LPS*).

The ‘farmland’ and ‘livestock’ subsystems are partially closed within the agroecosystem, since they offer a *Final Produce* (*FP*) to be consumed outside—as well as receive *External Inputs* (*EI*). Therefore, *UB, BR* and *LS* regulate the internal flows that lead to a higher or lower internal circularity in the pattern of energy networks of the agroecosystem (Figure 5.1.). They constitute important flows of recirculating biomass that contribute to the maintenance of the agroecosystem funds: landscape processes and associated biodiversity, soil fertility and livestock (M.W Ho and Alkanoic, 2005; Marull et al., 2016b).

The internal circularity of energy flows is kept within the agroecosystem because the outputs of one subsystem serve as inputs for the next subsystem, allowing the storage of energy carriers and information within its dissipative structure (M.W Ho and Alkanoic, 2005). There is an exception to this rule though, when some energy carriers circulating inside the agroecosystem imply losses as opportunity costs, because of farmers' mismanagement, into what (Odum, 1993) named a 'resource out of place'—i.e., a waste. We consider wastes as energy flows that cannot be integrated by farm systems, either because they exceed the carrying capacity, or they are not correctly disposed for the agroecosystem funds according to societal goals (Douglas, 2003).

Sometimes a fraction of NPP_{act} can be wasted, such as crop stubble or tree pruning that are burnt on the field instead of being used, as it often was in the past, for bedding (straw), home heating (branches), or animal feed (leaves). The same may happen with a fraction of the *LPS*, such as dung slurry coming from agro-industrial feedlots that is spread out in excess of cropland carrying capacity and finally contaminates the water table. If they exist, *Farmland Waste* (*FW*) and *Livestock Waste* (*LW*) do not contribute to the renewal of the agroecosystem's funds; they neither enhance its reproduction, nor meet human needs.

5.2.1.2 Agroecosystem Energy Flows and Landscape Ecology Integration

ELIA combines three indicators: the energy storage performed through the internal cycles of agroecosystems – 'energy reinvestment' (*E*), the information embedded in the energy network of flows – 'energy redistribution' (*I*), and the landscape functional structure – 'energy imprint' (*L*). The circularity of energy carriers driven by farmers through *UB*, *BR* and *LS* flows Figure 5.1 is a metric of *E* and *I*, which contributes to the energy potentially available for trophic chains existing in agroecosystems.

5.2.1.2.1 Measuring Energy Storage as Reinvestment of Energy Cycles (E)

We understand agroecosystem complexity as the differentiation of dissipative structures (metabolic cycles) allowing for diverse potential ranges in their behaviour (Tainter, 1988). The more complex the space-time differentiation of these structures, the more energy is stored within a living system (Ho and Ulanowicz, 2005). Hence, higher mean values of even β_i's (Figure 5.1) entail those agroecosystems are increasing in complexity because the different cycles are coupled to each other, and the residence time of the stored energy increases thanks to a greater number of interlinked energy transformations circulating inside. Accordingly, our way of calculating the *Energy Stored* (*E*) to keep the agroecosystem's funds functioning goes as follows (Eq. 5.1):

Eq.5.1

$$E = \frac{\beta_2 + \beta_4}{2} k_1 + \frac{\beta_6 + \beta_8}{2} k_2 + \frac{\beta_{10} + \beta_{12}}{2} k_3.$$

$$k_1 = \frac{UB}{UB + BR + LS}, k_2 = \frac{BR}{UB + BR + LS}, k_3 = \frac{LS}{UB + BR + LS},$$

Where the coefficients k_1, k_2, k_3 account for the share of reusing energy flows that are circulating through each of the three subsystems (Figure 5.1), which allows differentiating the agroecosystems' fund composition and making their energy patterns comparable. *E* remains within the range $[0,1]$. *E* close to 0 implies low reuse of energy flows—usually associated with industrial farm systems, which are highly dissipative and dependent on external inputs. *E* close to 1 implies the existence of internal cycles only, usually translating into land abandonment (i.e., loss of biocultural landscapes) or to a simple extractive use of the land (i.e., foraging or hunting).

E assesses the amount of all the energy flows that go back inside the agroecosystem. When we account for the three subsystems altogether (natural, farmland and livestock), we are adopting a landscape agroecology standpoint. This allows linking farming energy analysis with landscape ecology assessment.

5.2.1.2.2 Measuring Information as Complexity of Energy Flow Patterns (I)

Agroecosystems have a quantity of information embedded in the network structure through which their reproduction takes place over time. This way of information accounting can be seen as a measure of uncertainty, or the degree of freedom for the system to behave and evolve (Prigogine and Stengers, 1997). It is called 'information-message' and registers the likelihood of the occurrence of a pair of events (Passet, 1996; Ulanowicz, 2001). The *Energy Information* (*I*) is always site-specific, which becomes an important trait from a cultural standpoint (Barthel et al., 2013; Font et al., 2020c). In general, when a balanced agroecosystem registers a decrease of *I*, some important parts of the agroecosystem functioning are then no longer controlled at the landscape level, but linked to increasingly globalised agri-food chains (McMichael, 2011; Tello and González de Molina, 2017b). This work used a Shannon-Wiener Index adaptation over each pair of β_i's (Figure 5.1), so that this indicator shows whether the β_i's pairs are evenly distributed or not. This measure of *I* accounts for the equi-proportionality of pairwise energy flows that exit from each node in every sub-process (Eq. 5.2).

Eq. 5.2

$$I = -\frac{1}{6}\left(\sum_{i=1}^{12} \beta_i \log_2 \beta_i\right)(\gamma_F + \gamma_L)(\alpha_F + \alpha_L),$$

$$\gamma_F = \frac{UB + NPP_h}{2(UB + NPP_h + FW)}, \gamma_L = \frac{LS + LFP}{2(LS + LFP + LW)}$$

$$\alpha_F = \frac{FEIr}{2(FEIr + FEInr)}, \alpha_L = \frac{LEIr}{2(LEIr + LEInr)}$$

Base 2 logarithms are applied as the probability is dichotomous. The introduction of the information-loss coefficients γ_F, γ_L ensures that *I* remains lower than 1 when the agroecosystem presents farm and/or livestock waste. The coefficients α_F, α_L act as a penalization for the use of non-renewable external inputs, which entail an internal information loss given that the agroecosystem functioning is no longer self-reproductive. *I* values close to 1 are those with an equi-distribution of incoming and outgoing energy flows, where the 'information-message' embedded in the agroecosystem structure is high, whereas *I* values close to 0 mean patterns of probability far from equi-distribution which endow less information. These lower *I* values correspond to an industrialised farm system; or, by contrast, to an almost 'natural' turnover with no external inputs and no harvests. Conversely, agroecosystems with *I* equal to 1 are the ones with equi-distributed incoming and outgoing energy flows in each sub-process, that probably correspond to a mixed farming in which external inputs play a balanced role integrated with local energy recirculation

Therefore, *E* measures the energy reinvested and temporarily stored in the agroecosystem and *I* assesses how the farmers redistribute this energy in the landscape. Needless to say, the more complex (i.e., internally differentiated and interlinked) an agroecosystem is, the greater the farming information required to manage it.

5.2.1.2.3 *Measuring Energy Imprint as Landscape Structure (L)*

In order to measure the *Energy Imprinted* (*L*) in the landscape, we introduce a land metric. We use *L* to account for landscape heterogeneity, which reveals the capacity of differentiated land cover mosaics to circulate the energy flows and offer a range of habitats that sustain biodiversity (Harper et al., 2005). The underlying assumption is that species richness associated with agricultural landscapes depends on both energy availability and landscape heterogeneity, measured at scales larger than the farm level (Loreau et al., 2003b) (Eq. 5.3).

Eq. 5.3

$$L = -\sum_{i=1}^{k} p_i \log_{k+1} p_i$$

Where k is the number of different land covers (potential habitats), and there are $k+1$ possible land covers in each unit of analysis. We consider that the existence of urban land cover results in a loss of potential habitats. Thus, p_i is the proportion of land covers *i* into every unit of analysis. These L values can be seen as a proxy for the spatial insurance of farm-associated biodiversity, so that species whose populations are disturbed by agriculture can find safe haunts nearby by activating their own dispersal abilities (Tscharntke et al., 2012a).

5.2.1.2.4 Measuring the Energy-Landscape Integrated Analysis (ELIA)

After having defined the three ELIA indicators (E, I and L), we are going to analyse their relationship. We surmise that the interplay between E and I jointly lead to complexity, understood as a balanced level of intermediate self-organisation (Gershenson and Fernández, 2012). We assume that the agroecosystems' complexity of energy flows ($E \cdot I$) are related to more heterogeneous landscapes where the ecological patterns and processes that sustain farm-associated biodiversity become stronger (Marull et al., 2016b). Therefore, *ELIA* combines the agro-ecological landscape functional-structure with the complexity of the interlinking pattern of energy flows, as a proxy for the agroecosystem's biodiversity (Marull et al., 2019b) (Eq. 5.4).

Eq. 5.4

$$ELIA = \left(\frac{(E \cdot I)\, L}{max\{EI\}a}\right)^{1/3}$$

Where E is the energy storage, I is the information carried by the network structure of energy flows and L is the heterogeneity of land covers seen as the energy imprint in the landscape structure. The equilibrated $max\{EI\}e = 0.6169$ ($k_i = \frac{1}{3}$) –implies subsystems equilibrium and no waste. When there is no such equilibrium, the absolute $max\{EI\}a = 0.7420$ ($k_i = 1$) –even though this last combination is unlikely in an agroecosystem– it is possible in a theoretical mathematic case. Hence, *ELIA* theoretically ranges from 0 to 1 for any value of the parameters considered.

In order to understand the relationship between the stored energy (E), the information it contains (I) and its imprint on the landscape (L), we have to consider a three-dimensional model. ELIA can be interpreted in the sense that it is culture, which allows farmers to manage the energy entering the system to meet their needs and goals, while taking care of the agroecosystem funds' reproduction and biodiversity conservation (Marull et al., 2019b). This calls for integrated research of coupled human-natural systems aimed at revealing the functioning of complex structures and processes (Liu et al., 2007b).

5.2.2 Energy-Landscape Optimization (E-LO)

5.2.2.1 Case Study Databases

This work uses data of land covers and the associated energy flows of Sant Climent de Llobregat (Figure 5.2), a rural municipality of the BMA. This municipality has been chosen because it consists of a complex land matrix (land use mosaic) that can be a good representative of the Mediterranean bio-cultural landscapes.

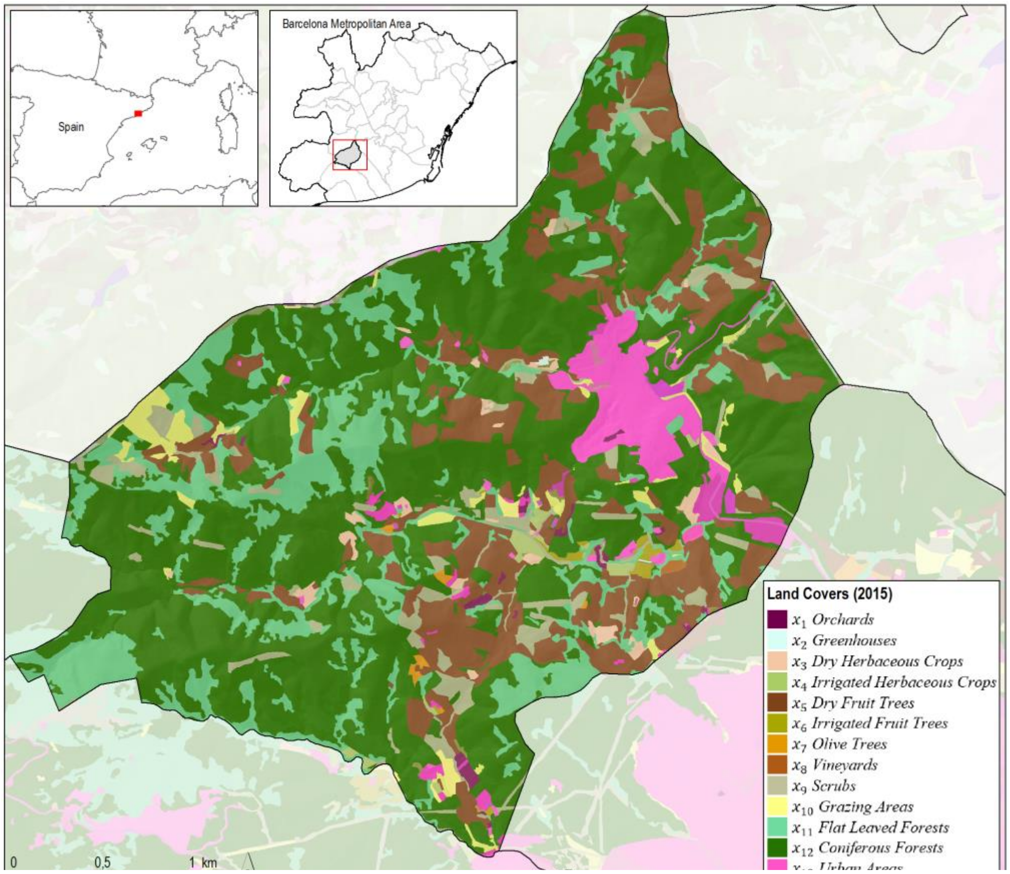


Figure 5.2 Land covers in 'Sant Climent de Llobregat' municipality, Barcelona Metropolitan Area, Spain.

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

Land covers are classified into 13 categories, namely *Orchards*, *Greenhouses*, *Dry herbaceous Crops*, *Irrigated Herbaceous Crops*, *Dry Fruit Trees*, *Irrigated Fruit Trees*, *Dry Olive Trees*, *Vineyards*, *Scrubs*, *Grazing Areas*, *Flat-leaved Forests*, *Coniferous Forests* and *Urban Areas*. The land cover thematic map (2015) used in this study have been provided by CREAF [5]. For each current land cover, the surface in hectares covered by each category is given. We call this parameter x_i *CurrentCover*, which is an array of size $i = 13$ and defines the input land use pattern to be modified. For each land cover there is a set of energy flows coming from the socio-metabolic pattern of the municipality (Marull et al., 2021a).

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[5] https://www.creaf.uab.es/mcsc/

Metabolic flows are calculated from land cover and farming databases on agriculture, livestock, forestry, and trade following the procedure described in (Marco et al., 2018). Land surfaces are taken from DARPA[6], together with production and yields from DUN[7] and SIGPAC[8] databases. From MAPAMA[9] we have taken provincial data from livestock surveys, statistics on dairy and eggs production, and wool, yearbook of annual statistics on crops, fertilizers, farm implements, and statistics on phytosanitary products consumed, as well as forestry statistics and annual management balances of cereals, and statistical data on fisheries. From IDESCAT[10] data on agricultural machinery according to their ownership have been used. To simulate organic agriculture scenarios, we have followed the CCPAE recommendations[11] (Table 5.1 Conditions and assumptions for the E-LO modelling of conventional and organic scenariosTable 5.1).

Table 5.1 Conditions and assumptions for the E-LO modelling of conventional and organic scenarios

Dimension	Theme	Conventional	Organic
General definition		Current agricultural management in the MAB defined from land uses, county 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 (CCPAE, 2017; de Ponti et al., 2012; Seufert et al., 2012).
Agriculture	Yields	Current crop yields (DARPA 2015).	Yields per hectare decrease up to 30%
	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-Casado et al., 2014)
	Crop losses due to herbivory	Conventional management factors (Oerke, 2006; Oerke et al., 2012)	Higher than in conventional Factors adjusted to Organic management records (Oerke, 2006; Oerke et al., 2012)
	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.

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[6] http://agricultura.gencat.cat/ca/inici

[7] http://agricultura.gencat.cat/ca/ambits/desenvolupament-rural/declaracio-unica-agraria/

[8] https://www.mapa.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/default.aspx

[9] https://www.mapama.gob.es/

[10] https://www.idescat.cat/?lang=es

[11] http://www.ccpae.org/index.php?option=com_frontpage&Itemid=1&lang=en

Dimension	Theme	Conventional	Organic
			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, county, 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 were adjusted to life cycles of each species under Organic management.
Labour	Human labour	Base data from the 2009 Agrarian census.	Overall increase of human labour (up to 20%) (DARPA, 2007).

Source: Our own

5.2.2.2 Energy Flows Definition

The energy flows are essentially the nodes of the ELIA graph previously seen in Figure 5.1. In fact, we have the values for 12 of the primary flows, while the values of the other 10 flows are calculated using the ELIA graph. For this reason, two sets of variables are considered for these flows; namely e_j^1 for the so-called primary flows and e_k^2 for secondary flows with $j = 1, ..., 13$ and $k = 1, ..., 10$. It could be confusing to see that j is ranging from 1 to 13 instead of 12. The reason is that in the data, there are two variables considered for *Livestock Biomass Reused*: *LBR1* and *LBR2*. The former is the biomass that 'farmland' subsystem makes available to be used in the 'livestock' subsystem (seen from the farmland standpoint as the share of *NPPh* devoted to livestock), while the latter is the biomass that is required for the 'livestock' subsystem (seen from the livestock standpoint as the share of total requirements coming from the agroecosystem). In this sense, it is useful to consider them separately, and as one of the possible constraints, make them have equal values, so that the amount of *Biomass Reused* (*BR*) requirements of livestock match with the production of farmland for this purpose.

From this socio-metabolic pattern, we calculate the metabolic flows (*j*) for each land use (*i*). This parameter is called $d_{i,j}$. Using this parameter, the variables e_j^1 can be obtained as $e_j^1 = \sum_{i=1}^{15} x_i \, d_{i,j}$. Also e_k^2 can be obtained using the relations seen in the ELIA graph (Figure 5.1.) from e_j^1. The summary of variables used in the model is as follows:

x_i Land covers	e_j^1 Primary flows	e_k^2 Secondary flows
x_1 *Orchards*	e_1^1 *FFP*	e_1^2 *EI*
x_2 *Greenhouses*	e_2^1 *LFP*	e_2^2 *FTI*
x_3 *Dry Herbaceous Crops*	e_3^1 *LBR1*	e_3^2 *LTI*
x_4 *Irrigated Herbaceous Crops*	e_4^1 *LBR2*	e_4^2 *ATT*
x_5 *Dry Fruit Trees*	e_5^1 *FEI*	e_5^2 *FII*
x_6 *Irrigated Fruit Trees*	e_6^1 *FEInr*	e_6^2 *NPPact*
x_7 *Olive Trees*	e_7^1 *LEI*	e_7^2 *BR*
x_8 *Vineyards*	e_8^1 *LEI*nr	e_8^2 *NPPh*
x_9 *Scrubs*	e_9^1 *FFP*	e_9^2 *LPS*
x_{10} *Grazing Areas*	e_{10}^1 *FW*	e_{10}^2 *FP*
x_{11} *Flat Leaved Forests*	e_{11}^1 *LW*	
x_{12} *Coniferous Forests*	e_{12}^1 *LS*	
x_{13} *Urban Areas*	e_{13}^1 *UB*	

The last set of variables we consider in our modelling are the constant values that measure the system (or subsystems) in one way or another, and in the end they all contribute to one of our main indicators. These variables include the coefficients β_l (*l = 1, 2 ... 13*), k_1, k_2, k_3, γ_F, γ_L, α_F, α_L, the indicators *E*, *I*, *L* and finally *ELIA*.

5.2.2.3 Formulation

Departing from the variables x_i (land covers; *i* = 1, 2… 13), e_j^1 (primary energy flows; *j* = 1, 2… 13), e_k^2 (secondary energy flows; *k* = 1, 2… 10), β_l (incoming-outgoing coefficients; *l = 1, 2 ... 12*), k_1, k_2, k_3 (reusing energy flows coefficients), γ_F, γ_L (information-loss coefficients) and α_F,

α_L (non-renewable external input coefficients), we can describe, as a summary, the following E-LO equations:

Eq.5.5

$$e_1^2 = e_6^1 + e_8^1 \,;\, e_2^2 = e_7^1 + e_6^1 + e_5^2 \,;\, e_3^2 = e_9^1 + e_8^1 + e_4^1 \,;\, e_4^2 = e_{13}^1 + e_2^2 \,;\, e_5^2 = e_{12}^1 + e_3^1$$

$$e_6^2 = e_{13}^1 + e_8^2 \,;\, e_7^2 = e_3^1 + e_4^1 \,;\, e_8^2 = e_7^2 + e_1^1 + e_{10}^1 \,;\, e_9^2 = e_{12}^1 + e_2^1 + e_{11}^1 \,;\, e_{10}^2 = e_1^1 + e_2^1$$

$$\beta_1 = \frac{e_8^2}{e_6^2};\, \beta_2 = \frac{e_{13}^1}{e_6^2};\, \beta_3 = \frac{e_2^2}{e_4^2};\, \beta_4 = \frac{e_{13}^1}{e_4^2};\, \beta_5 = \frac{e_1^1}{e_8^2};\, \beta_6 = \frac{e_7^2}{e_8^2}$$

$$\beta_7 = \frac{e_6^1}{e_2^2};\, \beta_8 = \frac{e_5^2}{e_2^2};\, \beta_9 = \frac{e_8^1}{e_3^2};\, \beta_{10} = \frac{e_4^1}{e_3^2};\, \beta_{11} = \frac{e_2^1}{e_9^2}\,;\, \beta_{12} = \frac{e_{12}^1}{e_9^2}$$

$$k_1 = \frac{e_{13}^1}{e_{13}^1+e_7^2+e_{12}^1};\, k_2 = \frac{e_7^2}{e_{13}^1+e_7^2+e_{12}^1};\, k_3 = \frac{e_{12}^1}{e_{13}^1+e_7^2+e_{12}^1}$$

$$\gamma_F = \frac{e_{13}^1+e_8^2}{e_{13}^1+e_8^2+e_{10}^1};\, \gamma_L = \frac{e_{12}^1+e_2^1}{e_{12}^1+e_2^1+e_{11}^1}$$

$$\alpha_F = \frac{e_6^1-e_7^1}{2e_6^1};\, \alpha_L = \frac{e_{12}^1-e_2^1}{2e_8^1}$$

$$E = \frac{\beta_2 + \beta_4}{2} k_1 + \frac{\beta_6 + \beta_8}{2} k_2 + \frac{\beta_{10} + \beta_{12}}{2} k_3$$

$$I = -\frac{1}{6}\left(\sum_{i=1}^{12} \beta_i \log_2 \beta_i\right)(\gamma_F + \gamma_L)(\alpha_F + \alpha_L)$$

$$L = -\sum_{i=1}^{k} p_i \log_{k+1} p_i$$

$$ELIA = \left(\frac{(E \cdot I)\, L}{max\{EI\}a}\right)^{1/3}$$

For the nonlinear models, there are boundary constraints considered in the implementations. The general form for these constraints is *LowerBound$_i$* ≤ *x$_i$* ≤ *UpperBound$_i$*. In principle, these bounds can have any value, according to the unique situations of land cover *i* (x_i), and if detailed studies are done in this regard, exact values can be used. We assume that each x_i with the specific characteristics that they have ($\sum_{i=1}^{15} x_i = \sum_{i=1}^{15} CurrentCover_i$) can be changed to a certain range with respect to the *CurrentCover$_i$*. Thus, we have considered these bounds to be of the form: *LowerBound$_i$= (1−LandChange$_i$)CurrentCover$_i$; UpperBound$_i$= (1+LandChange$_i$)CurrentCover$_i$.*

In addition, *LandChangeᵢ* can be specified according to the properties of x_i, but with the available data these *LandChangeᵢ* values are considered. Later on, a parametric analysis is conducted, in which we change *LandChangeᵢ* (except x_{13} *Urban Areas*) to analyse the way they might affect the optimization solution. Different objective functions that we consider for non-linear models are *ELIA* (First Setting), *FP* (Second Setting) and *EInr* (Third Setting). Then we implement the settings for both conventional and organic agriculture, which are characterized by different patterns of energy flows for each land use ($d_{i,j}$).

5.2.2.4 Implementation

Different optimization tools are tested to implement the model using data from the Sant Climent de Llobregat case study (Torabi, 2019): We have used the algorithms from the General Algebraic Modelling System (GAMS[12]), Constrained Optimization BY Linear Approximation (COBYLA) (Powell, 2007) and Improved Stochastic Ranking Evolution Strategy (ISRES) (Runarsson and Yao, 2005), the last two through its implementation in the open-source C library of nonlinear programming algorithms NLopt[13].

The CONOPT procedure in GAMS is essentially based in the Generalized Reduced Gradient method (Abadie, 1969; Fletcher, 1987), with some pre-processing that helps reducing the dimension of the model. COBYLA relies on linear approximations of objective function and constrains, combined with a trust region kind of step choice. Finally, ISRES is an evolutionary population-based heuristic algorithm.

We consider three different settings for objective functions and constraints, each one following a specific goal, while trying to consider other restrictions, in order to keep the balance between variables. To compare the results obtained from the different optimization tools, we observe the following for each setting:

First Setting: maximize ELIA, while maintaining at least a certain percentage of the current Final Produce, $e_{10}^2 \geq$ FPchange $e_{10,current}^2$. COBYLA algorithm results in a solution with the highest value for the objective function, as well as being feasible. However, the values for all the related variables in the best solution obtained by COBYLA are very close to the solution obtained

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[12] https://www.gams.com/

[13] https://nlopt.readthedocs.io

by GAMS. Considering the fact that GAMS is faster than running the C program using COBYLA, we can say the results obtained by GAMS are acceptable.

Second Setting: maximize Final Produce (e_{10}^{2}), while the indicators E and I do not decrease more than a certain percentage of the current amount, $E \geq$ Echange $E_{current}$, and $I \geq$ Ichange $I_{current}$. Contrary to the previous case, none of the methods have resulted in a superior solution in all aspects. On one side, in the sense of obtaining the most significant value for the objective function, it seems that ISRES produces best results. However, first and second constraints are not met in this solution, making it infeasible. On the contrary, the results obtained from COBYLA and GAMS are very close and are feasible.

Third Setting: minimize non-Renewable External Inputs (e_{6}^{1} + e_{8}^{1}), while the indicator L is maintained at least to a certain percentage of the current value, $L \geq$ Lchange $L_{current}$. The best solutions are given by COBYLA algorithm with the least value for objective function as well as being a feasible solution. The explanations given for the previous case about the differences between COBYLA and GAMS results hold here too.

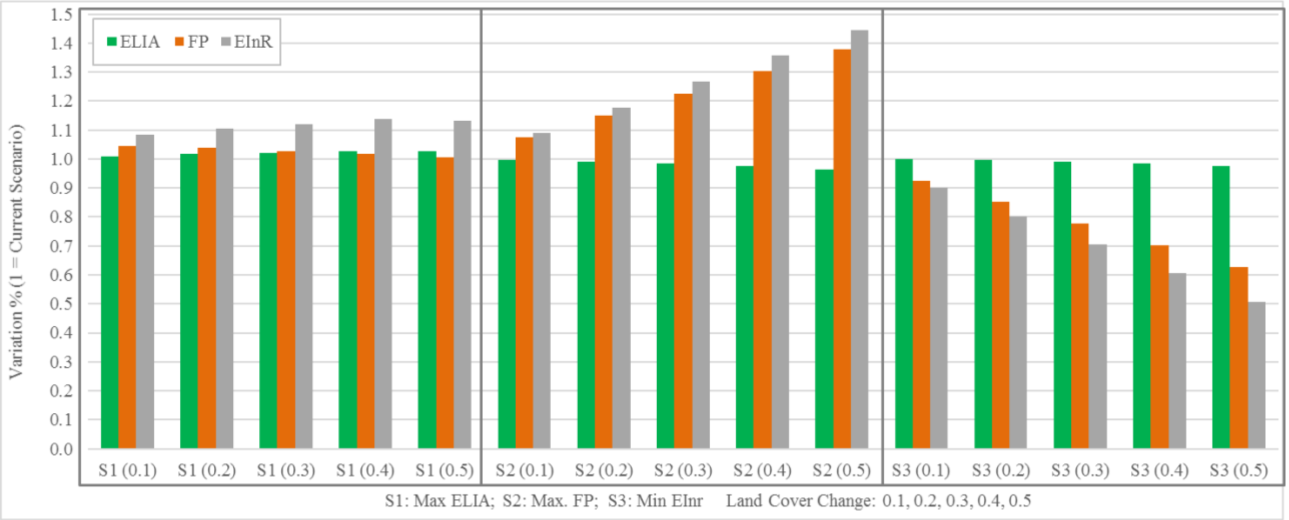
Considering this preliminary analysis, the CONOPT algorithm implemented in GAMS is used in the research (Torabi, 2019), because it was found that the supplying different initial point to COBYLA may lead to different final points, the difference between COBYLA and GAMS in the optimal values found is very small, and the execution of GAMS is faster than the C program using the COBYLA implementation of the NLopt library.

In this paper, we aim at analysing the effects that changing the parameters, specifically *LandChange$_i$*, may have on the results of each setting. The values of *LandChange$_i$* were considered to be 10%, 20%, 30%, 40% and 50% of land cover change for both conventional and organic agriculture typologies. In Appendix 4 we present an example of the model syntax.

5.3 Results and Discussion

In order to see the effect of *LandChange$_i$* on the optimization scenarios, Figure 5.3A and Figure 5.4A can be used as a reference for conventional and organic agriculture, respectively, showing how land covers have changed with respect to the *CurrentCover$_i$* in both agricultural typologies. These land cover changes and L can be seen in Tables A14 and A17. CS is the Current Scenario (conventional agriculture). S0 considers the same land cover structure than the Current Scenario but supposing a full organic agriculture transition (according to the CCPAE recommendations – Table 5.1). S1 corresponds to the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*). S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount). S3 is the Third Setting (minimizing *EInr* while *L* is maintained at least to a 90% of the current value). For all settings, E-LO applies to 10%, 20%, 30%, 40% and 50% of land cover change for both agricultural typologies. Figure 5.3B and Figure 5.4B shows the results of S1, S2 and S3 in terms of *ELIA*, *FP* and *EInr* in conventional and organic agriculture. Tables A12 and Tables A15 show the energy flows and *E*, and Table A13 and Table A16 show the energy coefficients and *I*.

a.



b.

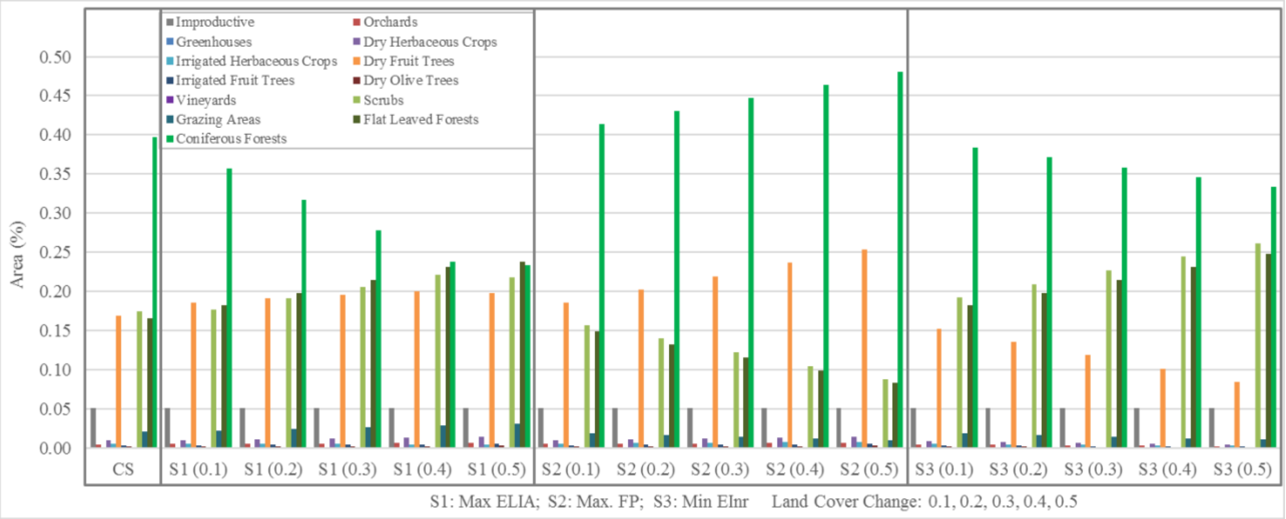


Figure 5.3 Optimization scenarios for conventional agriculture in 'Sant Climent de

Note: CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

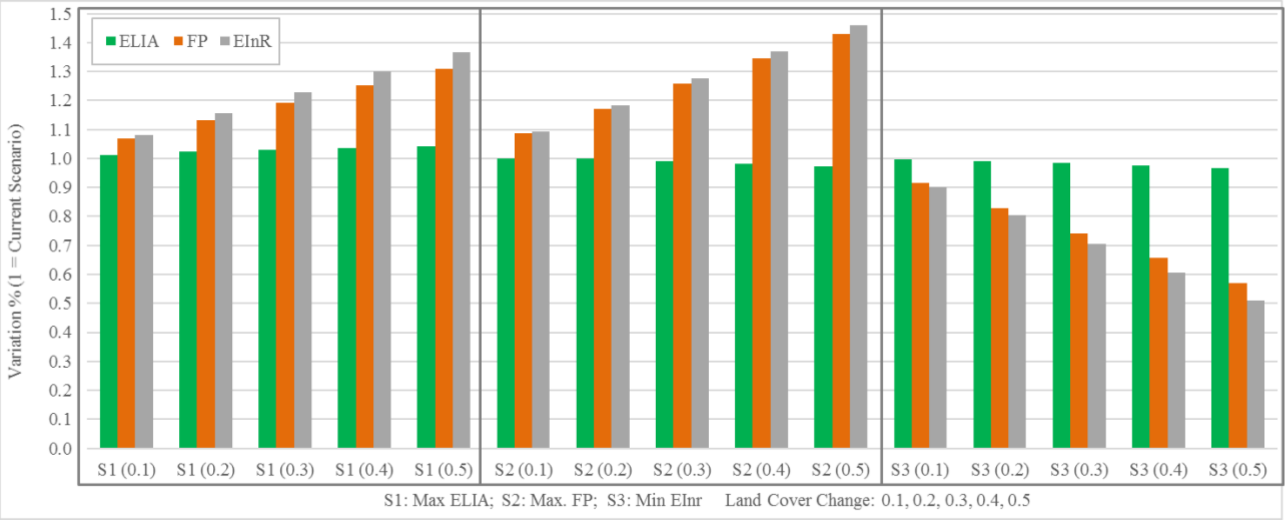
5.3.1 Optimizing biodiversity conservation

The First Setting (S1) is designed to maximize the energy-landscape integration (*ELIA*), variable that has been related recently with biodiversity (birds and butterflies) and associated ecosystem services in Mediterranean bio-cultural landscapes (Marull et al., 2019). In conventional agriculture, S1 shows a slight increase on *ELIA* values Figure 5.3B, passing from 1.0% to 2.7%, for a land cover change of 10% and 50% respectively **Error! Reference source not found.**. All land cover categories increase their area in percentage (Table A14), except *Coniferous Forests* (from 39.67% in CS to 23.35%) and, in less proportion, *Greenhouses* (from 0.03% in CS to 0.01%) and *Irrigated Herbaceous Crops* (from 0.51% in CS to 0.35%). The moderate increase in *ELIA* values first produces an increase and then a gradual reduction in *FP*, and a constant increase in *EInr*, when the model passes from 10% to 50% of land cover change (Figure 5.3B).

This increase in *ELIA* values is higher in organic agriculture (Figure 5.4B), passing from 2.4% to 5.3%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.). Again, all land cover categories increase their area in percentage (Table A14), except *Coniferous Forests* (from 39.67% in CS to 20.58%) and, in less proportion, *Greenhouses* (from 0.03% in CS to 0.01%). The increase in *ELIA* values produces an increase in *FP* and *EInr*, when the model passes from 10% to 50% of land cover change (Figure 5.3B).

The reason for the slight increase of *ELIA* values in S1 is because the 'Sant Climent de Llobregat' municipality represents a Mediterranean well-structured land cover mosaic (Figure 5.2) and then there is a limited potential to improve landscape complexity. Compared to the average value for the whole BMA, St Climent de Llobregat doubles the ELIA value (Marull et al., forthcoming). However, the model prioritizes the balancing of land covers (mainly reducing the more abundant *Coniferous Forests* category), in order to increase *L* (Figure 5.3B and Figure 5.4B), rather than reducing *E* and *I* –see Tables A12, A15, A13 and A16, and this is the reason that explains the increase of non-renewable external inputs (*EInr*). This agroecosystem dysfunction could be corrected including some constrains in the model (i.e., limiting the dependence on *EInr*). In this sense, it is interesting to note that organic agriculture practically doubles the increase of *ELIA* values of conventional agriculture in the different land cover change scenarios (Error! Reference source not found.), and therefore it underlines the importance of an ecological transition for biodiversity conservation.

a.



b.

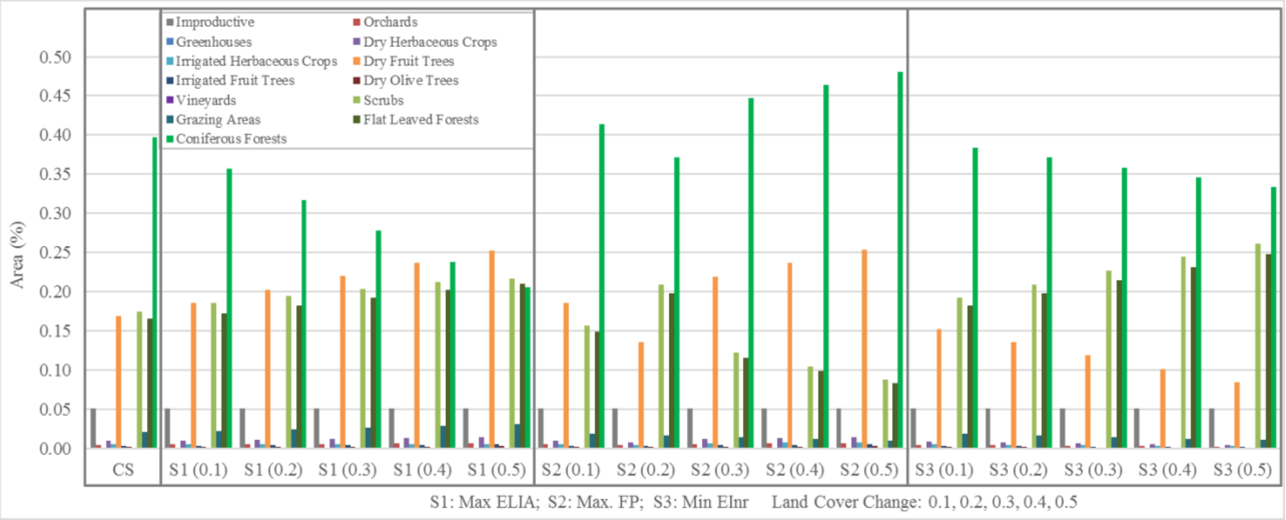
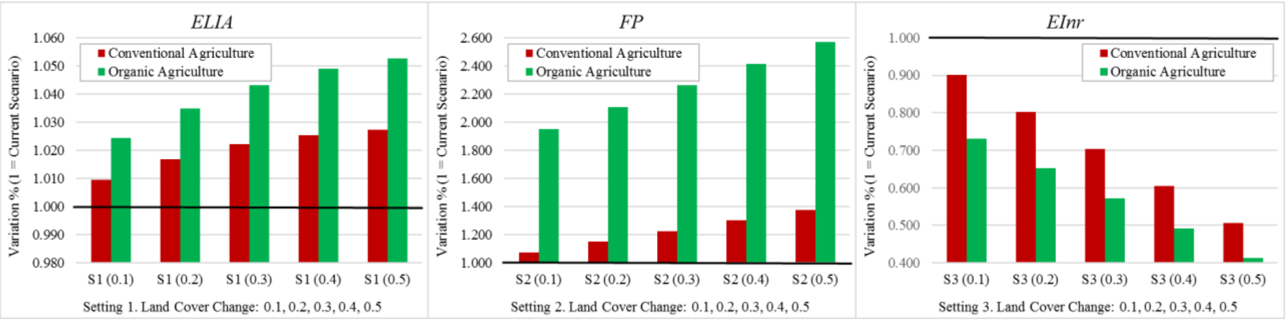


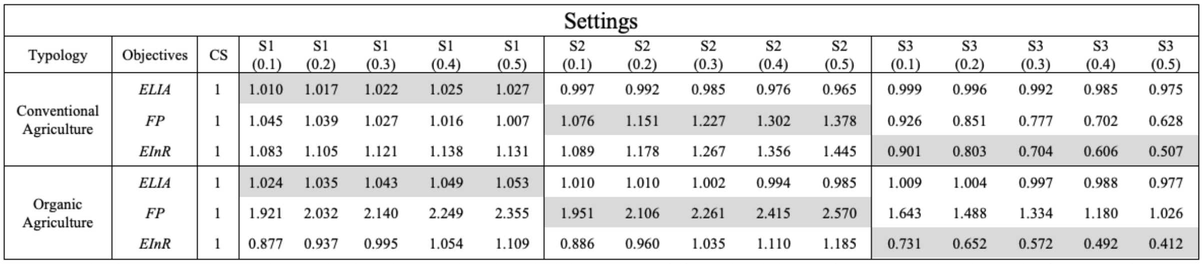
Figure 5.4 Optimization scenarios for organic agriculture in 'Sant Climent de Llobregat'municipality.

Note: CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

5.3.2 Optimizing agrarian productivity

The Second Setting (S2) is designed to maximize the agrarian productivity (*FP*), parameter that could attain higher values in organic than in conventional agriculture in Europe, even in economic terms (van der Ploeg et al., 2019). In conventional agriculture, S2 shows an important increase on *FP* (Figure 5.3B), passing from 7.6% to 37.8%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.). All land cover categories increase their area in percentage (Table A14), except *Scrubs* (from 17.42% in CS to 8.70%), *Grazing Areas* (from 2.03% in CS to 1.01%) and *Flat Leaved Forests* (from 16.52% in CS to 8.25%) that are those more extensive areas. The major increase in area is produced in *Dry Fruit Trees* (from 16.88% in CS to 25.31%) and *Coniferous Forests* (from 39.67% in CS to 48.03%), the latter being just the opposite trend than in S1 (Table A14).





			Settings														
Typology	Objectives	CS	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
Conventional Agriculture	*ELIA*	1	1.010	1.017	1.022	1.025	1.027	0.997	0.992	0.985	0.976	0.965	0.999	0.996	0.992	0.985	0.975
	FP	1	1.045	1.039	1.027	1.016	1.007	1.076	1.151	1.227	1.302	1.378	0.926	0.851	0.777	0.702	0.628
	EInR	1	1.083	1.105	1.121	1.138	1.131	1.089	1.178	1.267	1.356	1.445	0.901	0.803	0.704	0.606	0.507
Organic Agriculture	*ELIA*	1	1.024	1.035	1.043	1.049	1.053	1.010	1.010	1.002	0.994	0.985	1.009	1.004	0.997	0.988	0.977
	FP	1	1.921	2.032	2.140	2.249	2.355	1.951	2.106	2.261	2.415	2.570	1.643	1.488	1.334	1.180	1.026
	EInR	1	0.877	0.937	0.995	1.054	1.109	0.886	0.960	1.035	1.110	1.185	0.731	0.652	0.572	0.492	0.412

Note: CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* inputs while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

Figure 5.5 Summary of the Energy-Landscape Optimization (E-LO) results. Results expressed in relation to Current Scenario (1) for both conventional and organic agriculture. The objectives of Settings S1, S2 and S3 are to increase Energy Landscape Integrated Analysis (ELIA) to increase Final Produce (*FP*) and to reduce Non-renewable External Inputs (*EInr*), respectively.

Summary of the Energy-Landscape Optimization (E-LO) results (expressed in relation to

Current Scenario = 1) for both conventional and organic agriculture. The objectives of Settings S1, S2 and S3 are to increase Energy Landscape Integrated Analysis (*ELIA*), to increase Final Produce (*FP*) and to reduce Non-renewable External Inputs (*EInr*), respectively.

The increase in *FP* values is much higher in organic agriculture (Figure 5.4B), passing from 95.1% to 157.0%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.). All land cover categories increase their area in percentage (Table A17), except *Scrubs* (from 17.42% in CS to 8.70%), *Grazing Areas* (from 2.03% in CS to 1.01%) and *Flat Leaved Forests* (from 16.52% in CS to 8.25%), therefore behaving similarly to conventional agriculture. It is important to take into account that this increase in *FP* values is associated to the disappearing of waste (*FW*) in Fruit trees associated to the burning of pruning. Therefore, the greatest part of this change when it is compared to conventional scenarios is due to these woody by-products.

Probably the notable increase in *Dry Fruit Trees* guarantees the maximum *FP* in both conventional and organic agriculture, while *Coniferous Forests* contributes to maintain certain levels of energy reinvestment (*E*) and redistribution (*I*) (Tables A12, A15, A13 and A16). However, the *FP* increase in S2 is supported through an increase in non-renewable external inputs (*EInr*), which is not good news in terms of agrarian sustainability.

5.3.3 Optimizing climate change mitigation

The Third Setting (S3) is designed to minimize the dependence of non-renewable external inputs (*EInr*), parameter that is directly related with agrarian greenhouse gas emissions and then with climate change mitigation (Aguilera et al., 2015). In conventional agriculture, E1 shows an important decrease on *EInr* (Figure 5.3B), passing from -9.9% to -49.3%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.); all land cover categories decrease their area in percentage (Table A14), except *Scrubs* (from 17.42% in CS to 26.15%) and *Flat Leaved Forests* (from 16.52% in CS to 24.80%). For organic agriculture, the initial value for the current scenario (S0) is already 20%, being lower than for conventional. Then, the decrease in *EInr* values is higher in organic agriculture (Figure 5.4B) passing from 26.9% to 58.8%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.); all land cover categories increase their area in percentage (Table A17), except *Scrubs* and *Grazing Areas* in the same proportion than conventional agriculture.

The important decrease in *EInr* observed in S3 for conventional agriculture is comparable with the fall on *FP*, which means a non-desirable solution in socioeconomic terms and the claim for another model of agriculture. The good news is that for organic agriculture, the decrease in *EInr* is much higher than in conventional agriculture, but with an interesting difference: while in conventional agriculture *FP* passes from a decrease of -7.4% to -37.2%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.), in organic agriculture *FP* passes from an increase of 64.3% to 2.6%, for a land cover change of 10% and 50% respectively (Error! Reference source not found.). Consequently, there is room for an ecological transition and climate change mitigation and adaptation without compromising the socio-economic viability of farm systems in metropolitan areas.

5.3.4 Limitation of the model

The main purpose of the E-LO model is to assess how the capacity of the agricultural landscapes to provide regulatory and cultural ecosystem services can be improved while, at the same time, maintaining o increasing local agri-food production (a provisioning ecosystem service) and reducing agricultural dependence on non-renewable external inputs. This is a very useful assessment for land use planners to make decisions.

However, in its current version, the model has certain limitations that should be taken into account in future research. If changes in land use were not only incremental but more substantial, giving rise to a completely different agroecosystem, the assumption made about maintaining the same set of energy flows per land cover that in the current situation would no longer be acceptable. The E-LO optimization is not taking into account whether the land use changes arising from its optimization are feasible or adequate considering other constrains (e.g., slopes, soil textures and capacities or being placed in flood zones). For the same reason, E-LO modelling is not fit to explore the synergies and trade-offs involved in changing the pattern of energy and material flows interlinking the agroecosystem funds involved, accounting them in the appropriate different units. It does not allow to connect land and livestock uses with dietary changes in the consumers' food baskets. All these limitations means that, while being a useful tool to help land use planes to make better decisions aimed at improving the landscape capacity to provide ecosystem services to metropolitan areas, E-LO cannot deliver yet scenarios of systemic changes such as scaling up organic farming into agroecological territories.

5.4 Conclusions

The Energy-Landscape Optimization (E-LO) nonlinear model for land use planning developed in this paper can be of great importance for an agro-ecological transition in the Barcelona metropolitan area and, by extension, to another metropolis of the world. The application of E-LO in specific land use policies combined with an agro-ecological transition can contribute to reduce the dependence on non-renewable resources and therefore to climate change mitigation, as well as promoting the conservation of complex landscapes, maintained through a more circular economy, which can promote the preservation of biodiversity and associated ecosystem services.

The results of the E-LO modelling presented in this paper allow us to propose different land use configurations taking into account the associated socio-metabolic balances and the related landscape functional structures, with the aim of accomplishing different societal objectives. We have tested fruitfully three different objectives: i) to increase biodiversity and ecosystem services (S1), ii) to increase agricultural production (S2), and iii) to minimize dependence in non-renewable external inputs (S3). According to these objectives, and introducing several constrains in the settings, we have obtained the best land use/metabolism combinations, which is a useful method for calculating sustainable LUCC scenarios. This integrated analysis is appropriate for assessing complex socio-ecological systems to advance towards the new ‘green infrastructure’ paradigm, promoting alternative agroecosystem management and a systemic landscape planning in metropolitan areas.

The results of the E-LO modelling show: i) in S1, organic agriculture practically doubles the increase of energy-landscape integration (*ELIA*), as a proxy of biodiversity, compared with conventional agriculture in different land cover change scenarios, and therefore underlines the importance of an ecological transition for biodiversity conservation. However, it results as well in an increase of non-renewable external inputs (*EInr*). ii) In S2, the increase in agrarian production (*FP*) is also supported by an equivalent increase in *EInr*, which is not good news in terms of agrarian sustainability. iii) In S3, while the decrease in *EInr* for conventional agriculture is related with the fall on *FP*, in organic agriculture the decrease in *EInr* is much higher but with certain increase in *FP*. Consequently, there is room for an agro-ecological transition and climate change mitigation, without compromising the socio-economic viability.

The proposed methodology should be validated in the field and incorporate other constrains into the model, to be more site-specific and improve the model results, depending on the scope of study where it is intended to be applied (e.g., including slope, fertile areas for agriculture, protected natural spaces, or sectors with approved urban planning). In the parametric analysis, the scenarios could be considered in a more refined grid of values of land cover and metabolic changes, in order to see, for instance, in which point the direction of changes of some variables are altered taking into account the others. The transition costs of increasing land cover and metabolic changes should be considered to make more informative decisions about these parameters.

Finally, further research will improve the optimization model in a more geographical way, by means of the spatially implicit or explicit models (e.g., using cellular automata), in order to specify the best locations for land use change to maximize the closure of metabolic flows –circular economy. This research proposal would become a very important analytical advance, linking Ecological Economics (biophysical accounting) with Landscape Ecology (land use patterns and processes), in the design of metropolitan green infrastructures able to maintain biodiversity and provide ecosystem services to societies.

5.5 References

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PART IV Final remarks

6 Conclusions

This chapter will conclude the study by summarising the key findings in relation to the research aims and questions and discussing the value and contribution thereof. It will also review the limitations of the study and propose opportunities for future research.

6.1 Overall findings in relation to the research aims

This dissertation was aimed to evaluate the contribution of agriculture to the sustainability of metropolises from a systemic landscape-metabolism perspective. It was also intended to enrich our capacity to propose green infrastructure scenarios for sustainable land-use planning. It did it by taking on the challenge of studying two metropolitan areas, Cali (Colombia) and Barcelona (Spain). Based on the current land planning of these metropolises, the results indicate that agricultural landscapes are a key component of green infrastructure by contributing to maintaining its functions and services. The contributions of each chapter are presented next.

What is the contribution of biocultural landscapes to the ecological functionality of the Cali metropolitan region? (Chapter 2)

To approach this question, we proposed an integrated landscape-metabolism assessment based on georeferenced farm system typologies (local scale) and the region's land cover data (landscape scale). We hypothesised that biocultural landscapes configured by indigenous, peasant, and afro traditional agricultural systems significantly contribute to the ecological functionality of the metropolitan region of Cali. Our findings support the hypothesis and illustrate that the significant contribution of the biocultural landscapes relies on the connectivity exerted by agricultural mosaics. The results expose the rupture between society (socio-metabolic flows) and nature (ecological processes) in this metropolitan region driven by land-use intensification. We found that biocultural mosaic landscapes are characteristic of social metabolisms related to traditional and community agricultural practices and likely the product of a long-term traditional peasant, afro, and indigenous presence in the region. On the contrary, landscapes that are the product of decades of agroindustrial metabolisms, especially high-input sugarcane monocultures, have a detrimental impact on the ecological connectivity of these metropolitan areas. These results support environmental history narratives for the region and reflect an ongoing local transition from organic-based agriculture to an industrial one that began in the first half of the 20th century. This transition has happened within a complex socio-political and cultural context in which the rural livelihoods are at a crossroads with regional agroindustry development. This landscape-metabolism assessment offers an opportunity to enrich intersectoral land policy formulation for highly biological and culturally diverse world regions where agriculture is a fundamental pillar of the economy, the local culture, and rural livelihoods.

What is the relationship between the different metabolic configurations of the metropolitan biocultural landscapes with their capacity to provide ecosystem services? (Chapter 3)

A further assessment of the ecological functioning of the metropolitan region of Cali revealed key integrated landscape-metabolic configurations and their potential to enhance the region's socioecological sustainability. We applied the Intermediate-Disturbance Complexity (IDC) model to relate these configurations to the landscape's capacity to supply ecosystem services. Our findings highlighted the prevailing biocultural landscapes and their capacity to provide essential ecosystem services to the metropolis. The results showed how agricultural intensification and industrialisation, and the rapid and disorderly urban growth of the metropolis, have transformed the territory to threaten its sustainability. The IDC model showed potential to support land use planning and decision-making. Our research highlighted the relevance of adopting a green infrastructure framework to guide future territorial policies towards a more resilient metropolis. There is a need to rethink metropolitan land planning, especially regarding the opportunities and challenges offered by biocultural landscapes, to create a green infrastructure that supports essential ecosystem services and harnesses them to food sovereignty and rural livelihoods.

What could be the implications of an agricultural transition to organic management on the socioecological sustainability of metropolitan areas? And how can it guide future land policies on green infrastructure? (Chapter 4)

We proposed a Socioecological Integrated Analysis (SIA) to analyse four different land planning scenarios (current, trending, alternative and potential) under two agricultural management practices (conventional and a theoretical transition towards organic agriculture) to support the Land Use Master Plan in the Barcelona Metropolitan Area. The results showed cross effects between social metabolism and landscape ecology; land cover changes mainly affect the resource use efficiency, while management changes would affect the landscape ecological functioning. The potential implications of a farming transition to organic management on metropolitan agriculture would lead to a drop in agricultural yields while improving nutrient recirculation and increasing agricultural job provisioning. An organic transition based on input substitution (from synthetic inputs to organic ones) would surge non-renewable external inputs, ultimately translating into higher greenhouse gas emissions from agriculture and affecting the overall efficiency of agriculture in this metropolitan system. These findings stress the need for an agroecological transition and bring to the table the potential impacts of increasing input-substitution-based organic agriculture at the expense of integrated socioecological sustainability and climate change. The results suggest that future land planning should consider land use and metabolic flows to promote more sustainable agroecological transitions. The SIA model is an important conceptual and methodological step forward in conciliating urban development with the performance of surrounding open spaces and can guide the transition towards land use policies for sustainability.

What could be some optimal land use and management scenarios that maximise key reproductive characteristics of metropolitan landscapes? (Chapter 5)

We developed an Energy-Landscape Optimization (E-LO) to guide land use planning into ameliorating the negative effects of unplanned urban and agricultural areas in metropolitan contexts. The model explored optimal land use and management scenarios at the municipal scale in a representative Mediterranean bio-cultural landscape of the Barcelona Metropolitan Area. We fruitfully tested the model under three settings: i) to increase conditions to host farm associated biodiversity, ii) to increase agricultural production, and iii) to minimise agricultural dependence on non-renewable external inputs. The E-LO results allow us to propose different land use configurations for conventional and organic agriculture, considering the associated socio-metabolic balances and the related landscape functional structures intending to meet different societal objectives. This socioecological perspective is necessary for a context where population growth and disorganised city expansion have forced peri-urban agriculture to adopt detrimental practices for biodiversity conservation and metabolic efficiency. The E-LO can guide managers and land use planners to envision new agricultural paradigms and advance towards functional green infrastructures in metropolitan areas.

6.2 General contributions and conclusions

6.2.1 Conceptual and methodological contributions to different disciplines

The main contribution of this work relies upon its effort to apply the methodological and conceptual framework of social metabolism to present-day and future scenarios and approach the critical challenges of the current socioecological crisis from a systemic perspective. This is an important contribution to Sustainability Science. We present new standardised and comprehensive analytical tools with criteria derived from landscape-metabolism approaches: the Intermediate Disturbance Complexity (IDC), the Socioecological Integrated Analysis (SIA), and the Energy-Landscape Optimization (E-LO) models. These methodologies allow the characterisation and inclusion of diverse social metabolisms and their territorialisation. These territorialised metabolic analyses are fundamental to understanding how the reorganisation of spatial patterns in socioecological systems shapes ecosystems and cultural landscapes (Fischer-Kowalski and Haberl, 2007, chap. 5). These developments are important because they help understand to a better degree the complexity of metropolitan socioecological systems and their territorial expressions: a crucial element of sustainable land use planning.

We carried out integrated assessments of metropolitan green infrastructure in different geographical contexts (the tropical Andes and the Mediterranean) and scales (local, landscape, and regional), and the role of agricultural open spaces as key elements of this infrastructure. Therefore, the study offers a multiscalar vision beyond the usual product, plot, or farm agricultural sustainability analyses (Eichler Inwood et al., 2018; Velten et al., 2015). It also offers an Ecological Economics approach to the metropolitan green infrastructure assessment to overcome the limited productivity-led and chrematistic view of the neo-classical economics approach to food provisioning of cities (Gerber and Gerber, 2017; Gómez-Baggethun and Barton, 2013; Redondo et al., 2019).

Our findings contribute to socioecological transition studies, for which the characterisation of pre-industrial and traditional farm practices has been mainly done in historical contexts (Cunfer et al., 2018; Díez et al., 2018; Gingrich et al., 2018b; Gingrich and Krausmann, 2018; Marco et al., 2018; Parcerisas and Dupras, 2018). Here, we planted a seed to continue exploring current non-industrial agrarian metabolisms and their contributions to future sustainability transitions. This is why we talk about biocultural heritage, in line with FAO's program on Globally Important Agricultural Heritage Systems (Koohafkann and Altieri, 2011).

Finally, understanding green infrastructures as a system is a developing notion that can contribute to urbanism studies and applications. Through our methodological proposal, we have illustrated the systemic nature of the green infrastructure. These results invite us to consider green infrastructures as infrastructures that need different articulated functional and structural elements to act as one entity, and not a disconnected set of green patches. Only under this condition properties like connectivity and complementarity will emerge, and the green infrastructure will successfully deliver the different ecosystem functions and services.

6.2.2 Contributions to understanding the agroecological transition

This dissertation also aims to contribute to the knowledge about the multiscalar possibilities of more sustainable metropolitan agriculture proposals (e.g., agroecological, organic), ultimately leading to the implementation of an agroecological transition (FAO, 2019a, 2019b; Gliessman, 2016; Sinclair et al., 2019). It does so by linking agricultural social metabolism with landscape ecology assessment to understand and foresee how land use management gives rise to different agroecology landscapes that can either improve biodiversity and enhance ecosystem services or degrade them. This socioecological perspective is crucial to guide the change towards new socioecological paradigms regarding agroecosystem management and landscape planning, especially in the climate change and agroecological transition global context.

This Doctoral Thesis is the first attempt to join the landscape metabolic model (IDC) to socioeconomic data (i.e., farm system typologies in chapter 2) in a complementary approach to study European Mediterranean and Latin American green infrastructure. The results then made visible the contributions of small-scale, traditional agriculture to the current configuration of tropical Andean landscapes, as well as the importance of avoiding the disappearance of small family farms threatened by agro-industrial business in the Barcelona Metropolitan Area and overall, the globalised food system (Padró et al., 2017). This contributes to understanding the driving socioeconomic and cultural forces building the agricultural mosaics, which play a fundamental role in the ecological functioning of metropolitan areas. By incorporating socioeconomic information, this work also contributed to filling knowledge gaps about non-industrial agriculture practices, often overshadowed by the predominant industrial paradigm and its technocratic discourses, and labelled for many years as a remnant of backwardness. This also contributes to overcoming the limiting vision about agroecology mainly being a local or plot-level practice and moving towards landscape and regional agroecological horizons. This knowledge is helpful to explore the scalability of agroecological practices and ultimately support land use planning for sustainable cities and communities (United Nations, 2015).

The IDC, SIA, and ELO models give clues about the constraining dimensions of a socioecological transition, either towards intensive agro-industrial models as seen in Cali or towards organic agriculture, as modelled in Barcelona. The study of both cases has contributed to the understanding of these land-cover and land-use intensity changes phenomena in metropolitan areas, and either their benefits for to the earth social and ecological systems or their negative impacts regarding planetary boundaries, specifically related to global climate change, land-system changes, biosphere integrity, and biogeochemical flows (Li et al., 2021; Steffen et al., 2015).

6.2.3 Potential contributions to democratic and sustainable land use planning

These findings can be useful in real-world situations supporting metropolitan land use planning, agricultural development, and management plans at governmental, institutional, and community levels. The criteria and methodologies we propose provide comprehensive yet easy-to-use tools to support land-use planning and have proved to be conceptualised from different world contexts and transferable, including to regions where data availability can be scarce, such as in Latin America cases (Balvanera et al., 2020; Pauleit et al., 2021).

Our results support previous postulates highlighting the suitability of adopting a landscape scale to assess sustainability and implementing connected and multifunctional green infrastructures capable of providing the whole range of ecosystem services (Basnou et al., 2020; Tello et al., 2017; Yacamán-Ochoa et al., 2020; Marull et al., 2021). This reveals the need to overcome political-administrative divisions for land planning and advocate for supra-municipal, transversal governance for sustainable land planning and, eventually, climate change mitigation and adaptation.

The results on chapters 2 and 3 are at an incipient stage considering implementation; however, they provide scientific elements and systematic approaches to complement local farmers' processes and organisations' narratives regarding the defence of their territories, traditional livelihoods, food sovereignty, and cultural preservation in the metropolitan region of Cali (Hurtado-Bermúdez et al., 2020; Vélez-Torres et al., 2019, 2011; Vélez-Torres and Varela, 2014b). This is a crucial matter given the ongoing agendas for the Integral Agrarian Development of the Colombian peace agreement, aimed at reversing the effects of the conflict and ensuring the sustainability of peace (ACP and FARC-EP, 2016), as well as the UN Sustainable Development Goals, both directed towards the eradication of poverty and promoting equality (United Nations, 2019b).

Our interdisciplinary approach can enhance dialogue between environmental sciences and social processes and the different visions of the territory, especially regarding biodiversity conservation strategies and the implementation of nature-based solutions. Also, it can guide public policies consistent with the territory's socioecological needs and biophysical constraints. For instance, in the post-conflict context in Colombia, the silence of the rifles has revealed countless socio-environmental problems that demand a socioecological framework to be properly understood and addressed (Garcia Corrales et al., 2019a; Rincón-Ruiz et al., 2019; Rodríguez et al., 2020; Suarez et al., 2018).

Our results can align local livelihoods with global sustainability goals by bringing biocultural landscapes into a broader interdisciplinary dialogue to evaluate the sustainability, political feasibility, and social desirability of current agricultural development and support and enrich the construction of community planning agendas (i.e., "Planes de Vida" of indigenous and afro communities and Zonas de Reserva Campesina's communitarian development plans). In this sense, our results shed light on some preliminary yet inspiring possible horizons of agroecological landscapes in the tropical Andes. Furthermore, we highlighted the usefulness of our integrated analysis to assess and explain the environmental costs (externalities) of neo-extractive policies. This is an essential contribution to contemporary development political debates in Colombia and all regions of Latin America (Gudynas, 2013; Martínez-Alier and Walter, 2016; McKay et al., 2021; Urrego-Mesa, 2021b).

6.2.4 Ongoing research and applications of the SIA model:

The results of chapters 4 and 5 have already been a product of the collaborative work between the Metropolitan Laboratory of Ecology and Territory of Barcelona (LET) and the Urban Master Plan

(PDU) of the metropolitan area of Barcelona. We identified key elements of the green infrastructure systems and elucidated the potentials and pitfalls on the road towards a more circular economy in metropolitan areas. The SIA assessment on different land use scenarios is the basis for further collaborations with the Barcelona Metropolitan Area, including the ongoing LIFE Urban Greening Plans project (2021-2022), in which the SIA methodology will be applied to evaluate multi-actor proposals of land use scenarios.

- Support for strategic environmental assessment and drafting of the PDU (Role: Research group coordinator)
- PRIMA MA4SURE Mediterranean Agroecosystems for Sustainability and Resilience under Climate Change Project 2021-2024 (Role: Project manager and work-package No. 4 leader)
- Project LIFE UrbanGreeningPlans 2021-2022

6.3 Overall study limitations and scope

The relationship between society and nature is intricate; therefore, many of these results are highly context-dependent. While here we present a solid and rigorous analytical tool to support the decision-making process for land-use planning in anthropogenized landscapes, such as the metropolis of Barcelona and Cali, it is important to avoid a limiting positivist perspective, even while adopting a systemic view. It is crucial to remember that behind these values, there are complex social, ecological, and economic networks and processes not evaluated by this Thesis. Our results are a starting point to understand the sustainability challenges of metropolitan areas; they provide a helpful current snapshot of these socioecological systems grounded in model simulations based on secondary sources. The criteria and methods proposed and developed in this Doctoral Thesis aim to respond to complex socioecological questions. By adopting this complexity and socioecological paradigm, we acknowledge that no single study or model will respond to all inquiries; however, this study can lay the foundations for more comprehensive and integrative analyses in the future.

Specific limitations of the models are described in each chapter; however, below, we will enlist the overall limitations of the research done and draw some future research lines to further elaborate on our understanding of the contributions of agriculture as a critical piece of metropolitan green infrastructure and food systems.

6.3.1 Methodological limitations

The principal methodological limitations of this research are 1. The criteria and methods developed by this Thesis refer to the metropolitan green infrastructure; today, it does not directly assess energy, material, or information flows between urban and rural settings. 2. SIA cannot yet deliver scenarios of dynamic systemic changes such as scaling up organic farming into agroecological territories; however, some related models exist to start doing this in future, relying on the data provided by this Thesis. 3. Currently, the SIA does not connect the agricultural production of these metropolitan areas from crops or livestock with local diets, changes in the consumers' food baskets or the farming community (Padró et al., 2019, 2017). 4. The SIA and ELO models are based on national, regional, and local statistics and other sources; therefore, slight incongruences might exist. 5. Consistent data unavailability at different scales was another limitation; this is especially problematic for small-scale traditional agriculture; this general lack of up-to-date centralised information to feed the models will require collecting them through fieldwork interviews with farm communities in future research. 6. The lack of empirical data regarding ecosystem services supply; is a widely mentioned topic in the literature, especially for Latin American countries (Balvanera et al., 2020).

6.3.2 Conceptual limitations

Perhaps the major conceptual limitation of this research relies on its strengths. When providing a systematic and interdisciplinary analytical and evaluation framework, we consider a myriad of dynamics and dimensions, often complex to cover at the same depth. These approaches will ideally bring diverse visions, areas, and forms of knowledge into a dialogue. At its current version, this study offers a limiting view in this regard. Our aim is that the models presented here will show disconnections and disequilibrium in the relations between society and nature, and the result confirms that. Therefore, we provide tools that support rather than replace decision-making processes for land-use planning in metropolitan areas. However, we also aim at delivering in future a set of different feasible scenarios of scaling up current farming best practices into integrated agroecology landscapes and territories, each one stemming from the adoption of different societal goals, as a deliberative tool for evidence-based assessment in participatory processes of decision making (Padró et al., 2020). In this sense, our findings should be interpreted as a starting point.

6.4 Outlook for future research

To continue elaborating on the contribution of agriculture to the sustainability of metropolitan socioecological systems, it is necessary to undertake further interdisciplinary paths. The models presented here are iterative and can, and should, be tested in other contexts and bioregions; however, the work done in this dissertation may help envision some specific future research, as discussed below.

6.4.1 Expanding the Socioecological Integrated Analysis

Future research will focus on expanding the set of SIA indicators to include water metabolism by estimating the theoretical amount of water used by the metropolitan green infrastructure and the human biomass appropriation (Marull et al., forthcoming). Additionally, in this version of the model, we account for non-renewable external inputs to the system. Although the latest version of the SIA model already accounts for greenhouse gas emissions of the cropland subsystem, further studies should elaborate on this by incorporating livestock subsystem greenhouse emissions. This would provide a complete picture of the contributions of the agricultural system to climate change. Complementary, future studies should consider global change-driven land-use scenarios (e.g., crop migration; (Sloat et al., 2020) as well as agricultural yields alterations (Calzadilla et al., 2013; Müller et al., 2010), affecting socioecological sustainability.

Another SIA dimension that offers room for improvement is social cohesion. As has been widely argued, the agricultural workforce is one of the main pivotal factors of sustainable transitions (Font et al., 2020b). Depending on the context, agricultural labour demand can be an opportunity for the agroecological transition to reverse trends that increase the added value captured by big corporations that supply agro-industrial inputs at the beginning, and big wholesalers at the end of the agri-food chain, at the expense of the income retained by small and medium agricultural producers (IAASTD, 2009). The key point is that the new labour demand for a widespread agroecological transition is not only for gross labour but also for the know-how, seeds, livestock breeds and other site-specific knowledge that peasant family farms have treasured for centuries as a common-pool biocultural heritage (Tello & González de Molina, 2018).

Finally, the SIA could benefit from upscaling or linking the analysis to include the urban dimension. This will entail expanding the system boundaries and compartments to consider nutrient cycles associated with urban waste and water nutrient recovery (Li et al., 2019; Rufí-Salís et al., 2020). Similarly, since the SIA does not connect yet local agrarian production (from crops or livestock) with local population diets or changes in the consumers' food baskets of the metropolitan areas, adding these criteria to the model would eventually allow assessing food security and sovereignty. Those developments can be articulated with other Ecological Economics approaches (e.g., Urrego-Mesa, 2021; Urrego-Mesa et al., 2018, Giampietro et al., 2014, 2008) and provide, altogether, a comprehensive and multiscalar vision of the challenges faced by the agroecological transition under an urban-rural, and local-national lenses.

Finally, the ecological communities often reflect historical land-use processes (Dambrine et al., 2007; Maezumi et al., 2018). Similarly, research has shown that organic agricultural and even agroecological yields can be recovered and even increased several years after the transition (de Ponti et al., 2012; Schrama et al., 2018). Therefore, the answers to the questions approached by this Thesis would benefit from multitemporal analyses and simulations, which can be insightful in understanding current urban-rural relationships and future scenarios. Similarly, regarding ecosystem service supply, it would be helpful to assess ecosystem services offered empirically, mainly to elaborate from land-cover-based assessments and incorporate land-use management and practice types (e.g., agroecological, organic, conventional, regenerative, intensive).

6.4.2 Energy-Landscape Optimization

Based on the criteria modelled in chapter 5, we must continue to advance to answer the question about what distribution of land-uses would guarantee sufficient land for the closure of metabolic cycles on food, nutrients, and livestock. This is especially important to delve into the role of agricultural mosaics that are fundamental to the functional ecological structure of these landscapes.

Further research will improve the optimisation model making it more geographically bounded, using spatially explicit modelling (e.g., cellular automata) to specify the best locations for land-use change to maximise the closure of metabolic flows –the circular economy.

6.4.3 Research outlook for other disciplines

Further research in Ecological Economics could strengthen the Latin American approach to social metabolism and the socioecological transitions as a fundamental scientific task to address the critical question of how to start a new transition towards more sustainable and fair societies in the region (LaRota-Aguilera et al., 2021). This task requires developing new research that includes the different scales that make up the agricultural metabolism (i.e., from farm units to landscapes, from provincial areas to national level, and from entire Latin America to the global economy), bringing to light all the multidimensional flows and nexuses interconnecting them (i.e., energy, biomass, ores, land, worktime, income, financial debts) in order to understand better the current sociometabolic patterns and trends of this region and their unsustainability paths, as well as the possible alternatives to face the global socioecological crisis.

To contribute to this task and help understand the economic and cultural role of agriculture in countries like Colombia, it could be interesting to scale down the sociometabolic analysis to the farm and community levels and link them to our landscape and regional level results. An investigation at these lower scales could provide interesting information about the micro-structures producing the mosaic landscapes we have characterised and address upscaling paths for agroecological transition to higher levels. These links would bring to light the role of social movements resisting and challenging the prevailing extractivism dynamics of these territories (Amann et al., 2002).

Similarly, deepening our understanding of the metabolic performance of the different agricultural system typologies through methodological approaches models aimed at opening "the black box", such as the multi-EROI energy analysis (Galán et al., 2016; Martínez-Alier, 2011; Tello et al., 2016), will contribute to advance on the knowledge about agroecosystems and rural communities capable of self-reproduce while preserving biodiversity and maintaining ecosystem services. These analyses could also reveal the limiting factors for an agroecological transition at the base of the food system. In any case, material-energy balances and outcomes should articulate with comprehensive observations of the immaterial metabolism, considering long-term transformations, different scales and societal configurations, and the social ruling forces behind these changes (González de Molina & Toledo, 2014).

There is also an interesting opportunity to link this work with Political Ecology research agendas. Specifically, a necessary next step should be to answer how much local food production satisfies local diets. It will be crucial to explore the relationship between local food production and consumption within the Barcelona and Cali metropolitan systems and the links to national and global commodity trade. International trade analysis would account for possible environmental externalities projected by these metropolitan areas. In this sense, the consideration of North-South trade relationships could provide a more realistic view of the drivers of land-use and land intensity dynamics that currently perpetuate the prevailing agro-industrial ways of management in the territories.

Similarly, the sociometabolic analyses presented here can be linked to issues of food sovereignty, especially in Latin America, a region that plays a fundamental role as a global food and raw material supplier and where the food-fuel-biodiversity trilemma is decisive for their socioecological sustainability (Muscat et al., 2020; Pfeiffer, 2006; Tomei and Helliwell, 2016). Our research can contribute and would benefit from works studying the structures that perpetuate the different sociometabolic configurations of agricultural landscapes (i.e., extensive ranching and agriculture as a means of land grabbing, monoculture plantations, traditional and family agriculture). For example, in the Colombian case, an exciting and present-day line of research can be drawn regarding the current sustainability challenges, including the loss of biodiversity and ecosystem services, and the country's high inequality, by relating these sociometabolic studies to land tenure and distribution (Duarte Torres et al., 2018). In this sense, future research goals would also benefit from participatory feedback exercises with different stakeholders, including local communities and authorities.

Last but not least, besides the imperative need to incorporate different knowledge areas and disciplines into the sustainability studies, international cooperation among researchers from other regions of the world is also essential, especially promoting collaboration across the North-South divide would be fundamental to enrich common sustainability perspectives.

6.4.4 Final Remarks

Through this work, I have evaluated the contribution of agriculture to the sustainability of two metropolis, Cali, and Barcelona, that, while embedded in different ecological, social, and geographical contexts, they share present sustainability challenges imposed by a fast-growing population. I have examined through a systemic landscape-metabolism approach the potentialities and constraints for the possible paths, pitfalls, and bottlenecks of an agroecological transition in Latin America and Europe. Both of the study cases hold great potential to lead an agroecological transition in their regions. While there is still a long way to sustainability scenarios, agricultural systems are playing a fundamental role, yet under-explored and undervalued, in the everyday sustenance of metropolitan systems.

In the context of the current socioecological crisis, in which the figures of hunger, malnutrition, pollution, and increasing greenhouse emissions indicate that the paradigm of industrial agriculture has failed, it is urgent to move towards a new agroecological paradigm (Willett et al., 2019). It is clear that all land use public policy efforts for the next decades are decisive and must be focused on developing land-use and agricultural planning proposals that consider and prioritise the functionality of natural ecosystems. This involves creating and maintaining a healthy, multifunctional, and connected green infrastructure of agroecosystems.

I believe that the true potential of an agroecological scaling up relies not only upon adopting agroecological practices but also on the benefits that arise from a just and conscious relationship between nature and society; this relationship should therefore be attainable by all and reach the entire planet. This new paradigm entails significant changes in multiple dimensions and at multiple scales, which cannot be reduced to changes only in agronomic practices. In this sense, an actual agroecological transition must include changes in politics and institutions (González de Molina, 2013; González de Molina et al., 2019; Rosset and Altieri, 2018). Multi-criterial, multidimensional and multiscalar approaches, together with democratic deliberative processes, must support these changes, for which land-use planning tools are fundamental to support decision-making. We must read the present and future research on the agricultural contributions to metropolitan sustainability through interdisciplinary lenses, including local life histories, environmental history, and local, national, and global agricultural policies. Only in this way will it be possible to identify the true implications of the various forms of agriculture, livestock breeding and forestry on the sustainability of socioecological systems and fully understand the necessary steps to achieve a fair and genuine up-scaling of agroecological practices. This is the humble contribution that I have aimed to make in this Doctoral Thesis.

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7 Appendixes

7.1 Appendix 1: Supplementary Material for Chapter 2

Table A1. Land cover classes for the analysis of the Upper Cauca River Valley

	Corine Land Cover Level 3 Class (IDEAM, 2016)	**Reclassification**	**Area (ha)**	**% of total area**	**Included in the EFA**
Forest and seminatural areas	Rocky outcrops	Others (rocky outcrops, glaciers)	257.81	0.0%	
	Natural sandy areas	Others (rocky outcrops, glaciers)	287.51	0.0%	
	Glacial and snow zones	Others (rocky outcrops, glaciers)	66.12	0.0%	
		Total Others	**611.44**	**0.1%**	
	Natural shrublands	Natural shrublands	39627.44	3.9%	X
	Natural grasslands (Paramo)	Natural grasslands (Paramo)	87665.07	8.7%	X
	Dense forest	Primary forest	117687.30	11.7%	
	Riparian forest	Primary forest	2487.41	0.2%	
		Total Primary forest	**120174.71**	**12.0%**	X
	Fragmented forests	Secondary forest	29330.82	2.9%	
	Secondary vegetation or in transition	Secondary forest	48542.91	4.8%	
		Total Secondary forest	**77873.73**	**7.8%**	X
		Total Forest and seminatural areas		**32.5 %**	
Agricultural land	Permanent woody crops	Permanent woody crops	3635.33	0.4%	X
	Permanent herbaceous crops	Sugarcane plantations [1]	192742.21	19.2%	X
		Total Permanent crops	**196377.55**	**19.6%**	
	Pasture and forest mosaic	Pasture and forest mosaic	75165.72	7.5%	X
	Cropland mosaic	Cropland mosaic	1922.57	0.2%	X
	Cropland and forest mosaic	Cropland and forest mosaic	18478.08	1.8%	X
	Cropland, forest and pasture mosaic	Cropland, forest and pasture mosaic	152551.37	15.2%	X
	Cropland and pasture mosaic	Cropland and pasture mosaic	64564.77	6.4%	X
		Total Agricultural mosaics	**312682.52**	**31.1%**	
	Wooded pastures	Wooded pastures	4673.74	0.5%	X
	Weeded pastures	Weeded pastures	41797.32	4.2%	X
	Clean pastures	Clean pastures	84076.29	8.4%	X
		Total pastures	**130547.35**	**13.0%**	
	Timber plantations	Timber plantations	3238.40	0.3%	
		Total Agricultural land		**64.0 %**	
Bodies of water	Rivers (50m)	Rivers and natural water bodies	2569.59	0.3%	
	Artificial water bodies	Artificial water bodies	1637.38	0.2%	
	Lagoons, lakes, swamps and natural swamps	Rivers and natural water bodies	527.56	0.1%	
		Total water	**4734.54**	**0.5%**	X

Build-up areas	Continuous urban fabric (Urban areas)	Urban areas	16228.67	1.6%	
	Discontinuous urban fabric (Suburban areas)	Urban areas	3447.70	0.3%	
	Industrial or commercial areas (Industrial area)	Urban areas	4278.26	0.4%	
		Total urban and industrial areas	**23954.63**	**2.4%**	X
Other	Nude and degraded soils	Nude soils	854.29	0.1%	
Total			**1004000**	**100.0 %**	

[1] Sugar cane plantations are the only permanent herbaceous crop in the study region.

Table A2. Dimensions and variables for the farm system typologies of the Upper Cauca River Valley

Dimension	Variable name	Variable	Description
Geography	elevation	Elevation	Elevation of the APU (meters above sea level)
	near_dist	Distance to main town center	Distance of the AUP to the main town center (Km)
	ln_upa_ha	Agricultural production Unit (APU) area	Total area of the AUP (hectares)
	crop_varie	Crop variety	Number of different crops declared on the APU
	h2	Shannon index of land uses.	Shannon index for land uses of the APU
	lu_heterog	Land use heterogeneity	Number of different land-uses on the APU
Demography	dwelling_rel	dwelling_rel	Number of dwellings relative to the surface area of the APU.
	people_rel	people_rel	Agricultural unit population relative to the surface area of the APU.
	pers_natur	pers_natur	The interviewed is a natural person
	pers_legal	pers_legal	The interviewed is a legal person
	lndtnr_pro	lndtnr_pro	The interviewed owns the property
	lndtnr_arr	lndtnr_arr	The interviewed leases the property
	lndtnr_col	lndtnr_col	The APU is a collective property of ethnic communities
	prop_indig	prop_indig	The APU is an indigenous property
	prop_noetn	prop_noetn	The APU is a non-ethnic property
	InCoCo	InCoCo	The APU is located in non-titled collective territory of afro-Colombian communities
	etnia_indi	etnia_indi	The members of this household are indigenous
	etnia_afro	etnia_afro	The members of this household are afro-Colombian
	etnia_ning	etnia_ning	The members of this household do not have any ethnical affiliation
	etnia_othe	etnia_othe	The members of this household have other ethnical affiliation
	perma_labour_rel	perma_labour_rel	Ratio of permanent labour over the total yearly agricultural labour
	femlab_rel	femlab_rel	The ratio of permanent female labour over the total yearly agricultural labour
Production	hascrops	hascrops	The UPA has food crops
	hastimber	hastimber	The UPA has timber plantations
	totalyield_rel	totalyield_rel	Relative food crops yield (per UPA area)
Land cover and land use	agro_rel	agro_rel	% agricultural area (of the total AUP's area)
	pasture_rel	pasture_rel	% Pasture area (of the total AUP's area)
	forest_rel	forest_rel	% Forest area (of the total AUP's area)
	cropha_rel	cropha_rel	% Crop area (of the total AUP's area)
	polyha_rel	polyha_rel	% Polyculture area (of the total AUP's area)
	coffeeha_rel	coffeeha_rel	% Coffee area (of the total AUP's area)
	plantaha_rel	plantaha_rel	% Plantain area (of the total AUP's area)
	sugarha_rel	sugarha_rel	% Sugar area (of the total AUP's area)
	panelaha_rel	panelaha_rel	% Raw sugar (panela) area (of the total AUP's area)
	yucaha_rel	yucaha_rel	% Yuca area (of the total AUP's area)
	fruitha_rel	fruitha_rel	% Fruit trees area (of the total AUP's area)
	riceha_rel	riceha_rel	% Rice area (of the total AUP's area)
	pinaha_rel	pinaha_rel	% Pineapple area (of the total AUP's area)

Dimension	Variable name	Variable	Description
	timberha_rel	timberha_rel	% Timber area (of the total AUP's area)
	flowerha_rel	flowerha_rel	% Flowers area (of the total AUP's area)
	otrosha_rel	otrosha_rel	% Other crops area (of the total AUP's area)
Livestock	animales	Animals	The farm has animals
	livestock_farm	livestock_farm	It's a livestock farm
	livestock_present	livestock_present	There's livestock present in the farm
	livestock_meat	livestock_meat	Livestock purpose is for meat production
	livestock_milk	livestock_milk	Livestock purpose is for milk production
	poltry	poltry	It´s a poultry farm
Livestock management	poultry_meat	poultry_meat	Poultry purpose for meat production
	feed_conti	feed_conti	Livestock feeding is continuous
	feed_enclosed_past	feed_enclosed_past	Livestock feeding is enclosed
Crop management	withIrrigation	withIrrigation	The AUP has irrigation system
	noIrrigation	noIrrigation	The AUP has no access to irrigation
	aspersion_irri	aspersion_irri	Irrigation by aspersion
	grav_itti	grav_irri	Irrigation by gravity
	manual_irri	manual_irri	Manual irrigation
	pump_irri	pump_irri	Pump Irrigation
	dripGrav_irri	dripGrav_irri	Drip irrigation
	fert_org	fert_org	Uses organic fertilizers
	fert_chem	fert_chem	Uses chemical fertilizers
	fert_other	fert_other	Uses other fertilizers
	pest_manua	pest_manua	Uses Manual pest control
	pest_organ	pest_organ	Uses Organic pest control
	pest_chem	pest_chem	Uses Chemical pest control
	pest_biol	pest_biol	Uses Biological pest control
	pest_no	pest_no	Does not use pest control
	pest_other	pest_other	Uses another pest control
Infrastructure	e_grid	e_grid	UAP energy source: Electric national grid
	e_powerpla	e_powerpla	UAP energy source: Power plant
	e_renew	e_renew	UAP energy source: Renewable sources
	e_farm	e_farm	UAP energy source: Farm residues
	e_fuel	e_fuel	UAP energy source: Fuel
	e_none	e_none	UAP energy source: None
	e_biogass	e_biogass	UAP energy source: Biogas
	e_animal	e_animal	UAP energy source: Animal power
	noWater	noWater	No access to water.
Product destination/Purpose	crops_forHouse	crops_forHouse	Agricultural production: For the household
	crops_forMarket	crops_forMarket	Agricultural production: For comercialization
	all_market	all_market	Agricultural production: For any market
	ind_market	ind_market	Agricultural production: For industrial market (Agroindustry)
	nonind_market	nonind_market	Agricultural production: Not for industrial market
	local_market	local_market	Agricultural production: For Local markets

Dimension	Variable name	Variable	Description
	subsistance	subsistance	Agricultural production: Only for subsistence
	barter	barter	Agricultural production: For barter

Table A3. Assumptions for HANPP calculation for each land cover of the Upper Cauca River Valley

Land cover	**Definition**	**NPPo [t C/ha]**	**NPPact [t C/ha]**	**NPPh [t C/ha]**	**NPPuh**
Crop	Large crop plantations >25ha (Coffee, cacao, plantain, critics)	Haberl et al. 2014	NPPh + NPPuh	Bottom-up calculation from yield data (Product and byproducts harvested; Kg per ha) (NAC, 2014)	NPP of Associated Weeds (Guzman et al 2014) + Crop losses by herbivory (Oerke 2006) + Woods (Guzmán et al., 2014)
Crop Mosaics	Heterogeneous crops (polycultures fruits and vegetables) of less than < 25ha	Haberl et al. 2014	NPPh + NPPuh	Bottom-up calculation from yield data (Product and byproducts harvested; Kg per ha) (NAC, 2014)	NPP of Associated Weeds (Guzman et al 2014) + Crop losses by herbivory (Oerke 2006) + Woods (Guzmán et al., 2014)
Sugarcane	Sugar cane plantations	Haberl et al. 2014	NPPh + NPPuh	Bottom-up calculation from yield data (NAC, 2014)	None
Forest	Primary forests, non-unprofitable	Haberl et al. 2014	Equals to NPPo	Insufficient data. Non-extraction hypothesis.	Equals to NPPo
Timber plantation	Pine timber plantations for commercialize-tion purpose	Haberl et al. 2014	Plantations using production data in Tons/ha/yr	From theoretical yields by species.	
Natural pastures	Natural pastures and grasslands	Haberl et al. 2014	NPP grasses + NPP Weeds + NPP forage	None	
Planted pastures	Planted, managed pastures for livestock raising	Haberl et al. 2014	NPP grasses + NPP Weeds	Effective consumption from livestock feeding and requirement tables.	

Table A4. Cluster Analysis

A principal component analysis (PCA) was used to reduce the dimension of the 83 standardized variables from the Nacional Agrarian Census.

The PCA resulted in 12 components with eigenvalues larger than 1.4 explaining 49.57% of the variance. The component loadings for each rotated component were studied according to variable loads. Five final principal components (explaining 31.7% of the variance) were selected according to the interpretative power of the variables in the context of the current case study.

Factor	Eigenvalues			Sums of the squared saturations of the extraction			Sum of the squared saturations of the rotation		
	Total	% Variance	% Accm. Var.	Total	% Variance	% Accm. Var.	Total	% Variance	% Accm. Var.
1	9.259	11.156	11.156	9.259	11.156	11.156	7.513	9.052	9.052
2	7.460	8.988	20.144	7.460	8.988	20.144	6.274	7.559	16.611
3	4.435	5.344	25.487	4.435	5.344	25.487	5.426	6.537	23.147
4	4.090	4.928	30.415	4.090	4.928	30.415	4.320	5.205	28.353
5	2.680	3.229	33.644	2.680	3.229	33.644	2.830	3.410	31.762
6	2.222	2.677	36.321	2.222	2.677	36.321	2.368	2.854	34.616
7	2.115	2.548	38.869	2.115	2.548	38.869	2.366	2.851	37.466
8	2.041	2.459	41.328	2.041	2.459	41.328	2.292	2.761	40.228
9	1.822	2.195	43.523	1.822	2.195	43.523	2.090	2.519	42.746
10	1.732	2.087	45.610	1.732	2.087	45.610	2.017	2.430	45.177
11	1.684	2.029	47.639	1.684	2.029	47.639	1.824	2.198	47.374
12	1.600	1.928	49.567	1.600	1.928	49.567	1.820	2.193	49.567
13	1.403	1.691	51.258						

	Component											
	1	2	3	4	5	6	7	8	9	10	11	12
% Variance	9.052	7.559	6.537	5.205	3.410	2.854	2.851	2.761	2.519	2.430	2.198	2.193
% accum. Variance.	9.052	16.611	23.147	28.353	31.762	34.616	37.466	40.228	42.746	45.177	47.374	49.567
hascrops	0.853											
cropha_rel	0.842											
nonind_market	0.841											
local_market	0.840											
all_market	0.839											
crop_varie	0.725		0.503									
agro_rel	0.715									-0.301		
h2	0.671		0.460									
subsistance	0.603		0.331									
crops_forMarket	0.499											
ind_market	0.448	0.445										
plantaha_rel												
yucaha_rel												
otrosha_rel												
pest_biol		0.858										
e_fuel		0.826										
e_powerpla		0.811										
fert_other		0.759										
pers_natur		-0.708										
sugarha_rel		0.689										
pest_organ		0.573										
manual_irri	0.374	0.527										
pers_legal		0.465										
fert_org		0.379						0.344				
prop_indig			0.863									
prop_noetn			-0.840									
lndtnr_col			0.763									
etnia_indi			0.673									
noIrrigation	0.454		0.559		-0.363							
lu_heterog	0.305		0.553									
elevation			0.515							0.407	-0.322	
lndtnr_pro			-0.452								0.449	
hastimber			0.385									
livestock_farm				0.965								
livestock_present				0.953								
animales				0.869								
livestock_meat				0.815								
feed_conti				0.636								
feed_enclosed_past				0.571								
livestock_milk												
dripGrav_irri					0.878							
grav_itti					0.863							
withIrrigation	0.391	0.427			0.604							
riceha_rel					0.391							

aspersion_irri					0.356							
barter												
pinaha_rel												
fruitha_rel												
dwelling_rel						-0.810						
people_rel						-0.786						
ln_upa_ha						0.674						
totalyield_rel						-0.436						
timberha_rel												
etnia_othe							-0.709					
etnia_ning			-0.332				0.638					
e_grid		0.443					0.608					
e_none		-0.434					-0.525					
crops_forHouse	0.310						0.469					
noWater							-0.359					
pest_no								-0.706				
fert_chem								0.587				
pest_chem								0.565				
pest_manua		0.340						0.504				
perma_labour_rel								-0.393				
pest_other												
poutry									0.956			
poultry_meat									0.955			
near_dist										0.602		
forest_rel	-0.416									0.450		
panelaha_rel										0.368		
coffeeha_rel										0.337		
pasture_rel										-0.333		
pump_irri												
e_renew												
etnia_afro											0.638	
InCoCo											0.524	
lndtnr_arr												
femlab_rel												
polyha_rel												
e_farm												0.943
e_animal												0.852
e_biogass												0.397
flowerha_rel												

The selected five factors and their mean values are described in the following table:

	Component Name	1
		Description
1	Non- industrial agriculture	Groups variables related to crop production (relative area, agricultural area) Coffee and plantain farm systems Relative crop areas of coffee and plantain are significantly higher than in other groups. Presence of crops. Production is not associated with industrial markets but local.
2	Sugar plantations	Groups variables related to the size of the cropland and sugar production, use of biological pesticides, fuel as a main source of power as well as powerplants. Use of fertilizers, and negative associated to natural person land ownership.
3	Indigenous property	Groups variables describing ethnic properties and population: collective lands, ethnic background indigenous.
4	Livestock farms	Groups variables related to livestock farms (presence of livestock, production of meat and feeding systems)
5	Irrigation	Groups variables related to the type of irrigation, mostly drip irrigation and gravity irrigation, and crops with irrigation systems.

Based on the five principal components we perform a Cluster analysis, for which a hierarchical, agglomerative clustering algorithm (Ward's method) was used to define the number of *k* groups in RSudio (Kuivanen et al. 2016). Then, a nonhierarchical partitioning algorithm was employed to refine these k-groups in SPSS. Finally, a discriminant analysis was done to compare k-means groups.

The CA resulted in nine (9) groups (clusters) described below:

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Number of cases	22,646	17,194	6,658	1,999	5,003	684	12,683	344	3,370
% of cases	32.1%	24.4%	9.4%	2.8%	7.1%	1.0%	18.0%	0.5%	4.8%
Variance		11.156	4.928		3.229		5.344		8.988
Group mean		1.11698	2.86702		3.00261		1.61645		4.10615

Mean standardized value of each component among the nine clusters:

	Component description	**Original Clusters**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
		Mean	**Mean**	**Media**	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**	**Mean**
1	**Non- industrial agriculture**	-1.04829	**1.11698**	0.02053	-0.52500	0.57124	-0.33360	0.19757	0.08084	0.08419
2	**Sugar plantations**	-0.24342	-0.24110	-0.08423	-0.08640	-0.26375	0.07053	-0.16981	-0.06149	**4.10615**
3	**Indigenous property**	-0.39864	-0.61147	0.21999	0.05931	-0.33785	-0.30593	**1.61645**	0.21898	-0.21345
4	**Livestock farms**	-0.28960	-0.32259	**2.86702**	-0.06582	-0.15337	0.42652	-0.44750	0.17520	-0.22586
5	**Irrigation**	-0.14843	-0.44825	-0.16945	-0.12740	**3.00261**	0.00329	-0.21620	-0.34369	0.08524

* Highest mean value in bold describing the principal characteristic(s) of the cluster.

Clusters 1,4,6 and 8, do not group represent a clearly interpretable cluster, therefore were grouped as residual cluster with the 36,3% of sampling units in this category. The other 63.7% of the cases were distributed in clusters 2,3,6,7 and 9, and are described and analyzed on section 3 of the manuscript.

Table A5. Exploratory Factor Analysis

EFA - Rotated matrix for illustrative variables

	Variables	Dim.1	Dim.2
	IDC	0.9022497	0.1589268
Land covers	Primary forest	-0.1617665	0.7019907
	Secondary forest	0.3614606	0.1281658
	Natural shrublands	0.1596521	0.3987933
	Natural grasslands	-0.0488910	0.4683933
	Cropland, forest and pasture mosaic	0.2648251	-0.1981982
	Cropland and forest mosaic	0.2170398	-0.0537945
	Cropland and pasture mosaic	0.1891118	-0.3581011
	Pasture and forest mosaic	0.4868600	-0.0135231
	Cropland mosaic	-0.0312829	-0.0896911
	Permanent crops	0.0742199	-0.1099324
	Sugarcane plantations	-0.6032294	-0.4871451
	Clean pastures	0.4524499	-0.2742419
	Weeded pastures	0.3579215	-0.1955698
	Wooded pastures	0.1521732	-0.0817225
	Timber plantations	0.1141710	-0.1159375
	Others (rocky outcrops, glacials)	0.0168188	0.0736816
	Urban areas	-0.1845421	-0.3347914
	Water	0.0987060	-0.0309125
	Nude soils	0.0090910	-0.0390384
Farm system typologies	T1: Coffee and plantain farm systems	0.1121366	-0.0115183
	T2: Livestock farm systems	0.2496552	0.1991421
	T3: Polyculture farm systems	-0.0459003	-0.0728231
	T4: Indigenous communities farm systems	0.2703977	0.0018985
	T5: Sugarcane plantations farm systems	-0.5871604	-0.3128433
	T6: Other farm systems	0.0394852	0.1551448

Table A6. Multiple Linear Regression analysis for the (A) Landscape structural functionality and (B) Anthropogenic disturbances. Predictor variable: Farm systems typologies.

A)

Dependent Variable: Dim. 1 - Landscape Structural Functionality

Model Summary	Multiple R	R Square	Adjusted R Square			
	0.6975	0.4865	0.4728			
		Standardized Coe.		df	F	Sig.
Coefficients	Predictors	Beta	Std. Error	Beta	Std. Error	Beta
	T1	0.135	0.033	2	16.40	0.00*
	T2	0.241	0.035	3	46.79	0.00*
	T3	0.032	0.033	2	0.92	0.40
	T4	0.142	0.036	3	15.74	0.00*
	T5	-0.518	0.034	3	232.62	0.00*
		Sum of Squares	df	Mean Square	F	Sig.
ANOVA	Regression	244.231	13.000	18.787	35.567	0.000
	Residual	257.769	488.000	0.528		
	Total	502	501			

B)

Dependent Variable: Dim. 2. Anthropogenic disturbances

Model Summary	Multiple R	R Square	Adjusted R Square			
	0.6600	0.4356	0.4193			
		Standardized Coe.		df	F	Sig.
Coefficients	Predictors	Beta	Std. Error	Beta	Std. Error	Beta
	T1	-0.160	0.037	3	18.779	0.00*
	T2	-0.053	0.038	1	2.005	0.16
	T3	-0.223	0.039	2	33.495	0.00*
	T4	-0.194	0.038	4	25.848	0.00*
	T5	-0.546	0.036	4	225.238	0.00*
		Sum of Squares	df	Mean Square	F	Sig.
ANOVA	Regression	218.658	14.000	15.618	26.844	0.00*
	Residual	283.342	487.000	0.582		
	Total	502	501			

Table A7. Step-wise - Multiple Linear Regression analysis for the (A) Landscape structural functionality and (B) Anthropogenic disturbances. Predictor variable: Land covers.

A)

Dependent Variable: Dim. 1 - Landscape Structural Functionality

Model Summary	R	R Square	Adjusted R Square	Std. Error of the Estimate
	0.8754	0.7663	0.7625	0.4873

Coefficients	Standardized		95% Confidence Interval for B		Sig. Beta	
Predictors	**Beta**	**Std. Error**	**Zero-order**	**Partial**		
(Constant)		0.077	1.398	1.699	0.000	*
Primary Forest	-0.702	0.118	-2.895	-2.432	0.000	*
Nat. Grasslands	-0.517	0.136	-2.681	-2.146	0.000	*
Nat. Shrubland	0.080	0.246	0.269	1.236	0.002	*
Mosaics (crops, pastures and Forests)	-0.367	0.156	-2.038	-1.425	0.000	*
Weeden Pastures	-0.060	0.336	-1.452	-0.132	0.019	*
Sugarcane	-1.077	0.103	-3.384	-2.979	0.000	*
Water bodies	0.071	1.147	1.452	5.959	0.001	*
Urban areas	-0.319	0.222	-3.462	-2.587	0.000	*

ANOVA	Sum of Squares	df	Mean Square	F	Sig.
Regression	383.936	8.000	47.992	202.111	0.000
Residual	117.064	493.000	0.237		
Total	501	501			

B)

Dependent Variable: Dim. 2. Anthropogenic disturbances

Model Summary	R	R Square	Adjusted R Square	Std. Error of the Estimate
	0.9306	0.8660	0.8630	0.3702

Coefficients	Standardized Coe.		95% Confidence Interval for B		Sig.	
Predictors	**Beta**	**Std. Error**	**Zero-order**	**Partial**	**Beta**	
(Constant)		0.083	-1.280	-0.952	0.000	*
Primary Forest	0.785	0.101	2.781	3.178	0.000	*
Nat. Grasslands	0.522	0.121	2.201	2.674	0.000	*
Secondary Forest	0.199	0.228	1.904	2.798	0.000	*
Nat. Shrubland	0.202	0.197	1.507	2.282	0.000	*
Mosaic (Crops and forest)	0.106	0.346	1.274	2.632	0.000	*
Mosaics (Pastures and Forest)	0.135	0.216	0.836	1.685	0.000	*
Mosaics (crops, pastures and Forests)	0.119	0.134	0.299	0.825	0.000	*
Timber plantations	-0.039	0.739	-3.161	-0.256	0.021	*
Sugarcane	0.079	0.103	0.030	0.435	0.024	*
Urban areas	-0.092	0.184	-1.237	-0.514	0.000	*

Water bodies	0.115	0.876	4.259	7.700	0.000	*
ANOVA	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	
Regression	433.862	11.000	39.442	287.864	0.00	
Residual	67.138	490.000	0.137			
Total	501	501				

7.3 Appendix 2: Supplementary Material for Chapter 3

Parameters for Ecological Functional Areas (EFA)

For the selection of the coverage that can be AEF, the following criteria were taken into account: Representativeness in the total area of the study area (excluding urban, bare, industrial) is greater than 5% (approx. 48,000 ha) or there must be more than 10 Polygons / coverage patches within the study area.

Therefore, the covers glacial and snow zones, rocky outcrops and natural sandy areas are eliminated. And by not considering habitats, bare or degraded lands, clouds, continuous urban fabrics, industrial zones are also eliminated. The pre-selection procedure for hedges with potential AEF is illustrated in the following table.

Table A8. Definition of ecologically functional covers.

Code	AEF	AEF english	Land covers included
C'1	Forest	Forest	Dense, fragmented, gallery and riparian
C'2	Bushland	Natural shrubland	Secondary and transitional vegetation and natural shrubland
C'3	Grassland	Natural grassland	Grassland
C'4	Agroforestry Mosaic	Agroforest Mosaic	mosaics with natural areas
C'5	Crops	Cropland	Heterogeneous crops, permanent tree crops and grass crops
C'6	Cane	Sugar cane plantation	Herbaceous permanent crops
C'7	Pastures	Pastures	Clean, weedy and wooded pastures
C'8	Forest plantation	Forest plantation	Forest plantation
C'9	Discontinuous urban	Suburban areas	Discontinuous urban

Table A9. Extension and distribution of polygons of the EFA

Code	AEF	STUDY AREA				ECOLOGICAL FUNCTIONING AREAS						
		Total Patches 1	Mean patch size (ha)	C (total ha)	% of study area	Sr (ha)	N functional Patches	% of TP	Non-functional patches	C' (Functional area)	C` % on C	C ' % on Study Area

C'1	Forest	168	889.91	149,505.5	14.9%	200	60	35.7%	108	142,985.7	95.6%	14.2%
C'2	Shrubland	346	254.83	88 170.3	8.8%	100	161	46.5%	185	78510.0	89.0%	7.8%
C'3	Natural grassland	62	1,413.95	87,665.1	8.7%	200	21	33.9%	48	85643.6	97.7%	8.5%
C'4	Landscape mosaic	274	898.52	246 195.2	24.5%	150	107	39.1%	240	236,047.5	95.9%	23.5%
C'5	Cropland	264	265.62	70122.7	7.0%	100	159	60.2%	164	64647.4	92.2%	6.4%
C'6	Sugarcane plantations	23	8,380.10	192742.2	19.2%	400	eleven	47.8%	12	190457.5	98.8%	19.0%
C'7	Pastureland	493	264.80	130 547.2	13.0%	100	220	44.6%	273	117,535.4	90.0%	11.7%
NA	Others (Urban, bodies of water, etc)	196	NA	39,051.8	3.9%	NA	NA	NA	NA	NA	NA	NA
	TOTAL Study Area			1004000	100%							

[1]TP -Total number of patches on the study area

Table A10. Ecological Connectivity Index

A) **Barrier types and weights (Marull and Mallarach 2005)**

Code	**Barrier Type (*s*)**	**Source (example)**	**Weight (b_s)**	kS_{1}^{a}	kS_{2}^{a}
B1	Discontinuous urban fabric / Suburban areas	Land cover map (Discontinuous Urban Fabric)	*b* 1 = 30	$k\ 1_{1}$ = 16,657	$k\ 1_{2}$ = 0.167
B2	Secondary roads	Layer of roads Colombia IGAC 2012 Type 2, 4 and 5 (unpaved roads)	*b* 2 = 40	$k\ 2_{1}$ = 22,210	$k\ 1_{2}$ = 0.123
B3	Primary roads / Main roads	Colombia IGAC 2012 Type 1 and 3 road layer (paved roads)	*B* 3 = 80	$k\ 4_{1}$ = 44,420	$k\ 1_{2}$ = 0.063
B4	Continuous urban fabric / Urban and industrial areas	CLC 2012 Coverage (Continuous Urban Fabric) and (Industrial and Commercial Zones)	*B* 4 = 100	$k\ 5_{1}$ = 55,520	$k\ 1_{2}$ = 0.051
B5	Infrastructure	Coverage CLC 2012 (Salvajina Dam)	*B5 = 100*	$k\ 6_{1}$ = 55.520	$k\ 1_{2}$ = 0.051

Note: *b: barrier weight; a:* Constants for a logarithmic fall of 30% (*α*=0.3); *k1: Affectation coefficient in meters. k2: Affectation value (An = bs/an);* (see Marull and Mallarach 2005).

B) Affectation matrix

Land cover class	Type	Value	Affectation value An = b5/an = 100/an
Other	Neutral	10	0,1
Agricultural mosaics	Agriculture	13	0,13
Heterogeneous agricultural land	Agriculture	13	0,13
Sugarcane	Agriculture	13	0,13
Pastures	Agriculture	13	0,13
Forest plantations	Forest	15	0,15
Forests	Natural	20	0,2
Natural Shrubland and secondary vegetation	Natural	20	0,2
Natural grassland	Natural	20	0,2
Discontinuous urban fabric	Barrier	40	0,2
Secondary road	Barrier	40	0,4
Continuous urban fabric	Barrier	50	0,5
Infrastructure	Barrier	50	0.5
Main road	Barrier	50	0,5
Water body	Connector	10000	100
Artificial water body	Connector	10000	100

C) Impact Matrix for the calculation of the ECI in the Upper Cauca River Valley

Code	Type	Classes included	Affectation coefficient	Affectation value An = b5/an
V_1	Neutral	N_1 y N_2	$a_1 = 1000$ m	$A_1 = 0{,}10$
V_2	Agriculture	C_4, C_5, C_6	$a_2 = 750$ m	$A_2 = 0{,}13$
V_3	Natural	C_1, C_2, C_3	$a_3 = 500$ m	$A_3 = 0{,}20$
V_4	Barrier	B_1,B_2, B_3, B_4, B_5	$a_4 = 250$ m	$A_4 = 0{,}40$
V_5	Corridor	E_1, E_2	$a_5 = 1$ m	$A_5 = 100$

a: *Class description is found in Table 3.*
b: A_1 *defines the maximum significantly affected distance by each type.*

7.4 Appendix 3: Supplementary Material for Chapter 4

Table A11. 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. Crop yields are adjusted when literature suggested it.
Land use distribution		Land covers based on CREAF 2015 4 Scenarios of land use given by AMB 2019	Same as in conventional
Crop structure and crop species composition		Planted surface by species for 2015 (DARPA 2015a).	Same as in conventional
Agriculture	Yields	Municipal crop yields for the year 2015 (DARPA 2015a).	Yields per hectare decrease up to 30% (Seufert et al. 2012, 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. 1999)	Higher than in conventional Factors adjusted to Organic management records (Oerke et al. 1999).
	Fertilization	Chemical fertilization is allowed and unrestricted. (Data sources: MAPA 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 CCPAE. 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: MAPA 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 (2015b) 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. If local production cannot satisfy this requirement regional organic feed will be imported. 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 (CCPAE 2017).
	Manure management		Surplus use optimized according to agricultural nutrient requirements of local and organic production.
	Animal life cycles and productivity		Longer life cycles

Dimension	Theme	Conventional	Organic
			Meet, milk and eggs production was adjusted to life cycles of each species under Organic management.
Labour	Human labour	Base data from IDESCAT (2015a)	Overall increase of human labour (up to 20%) (DARPA 2007).
	Machinery	Base data from IDESCAT (2015b) and adapted with Aguilera et al. (2015)	Adapted from conventional following Aguilera et al. (2015) in machinery use.

Source: The authors based on cited references.

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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)

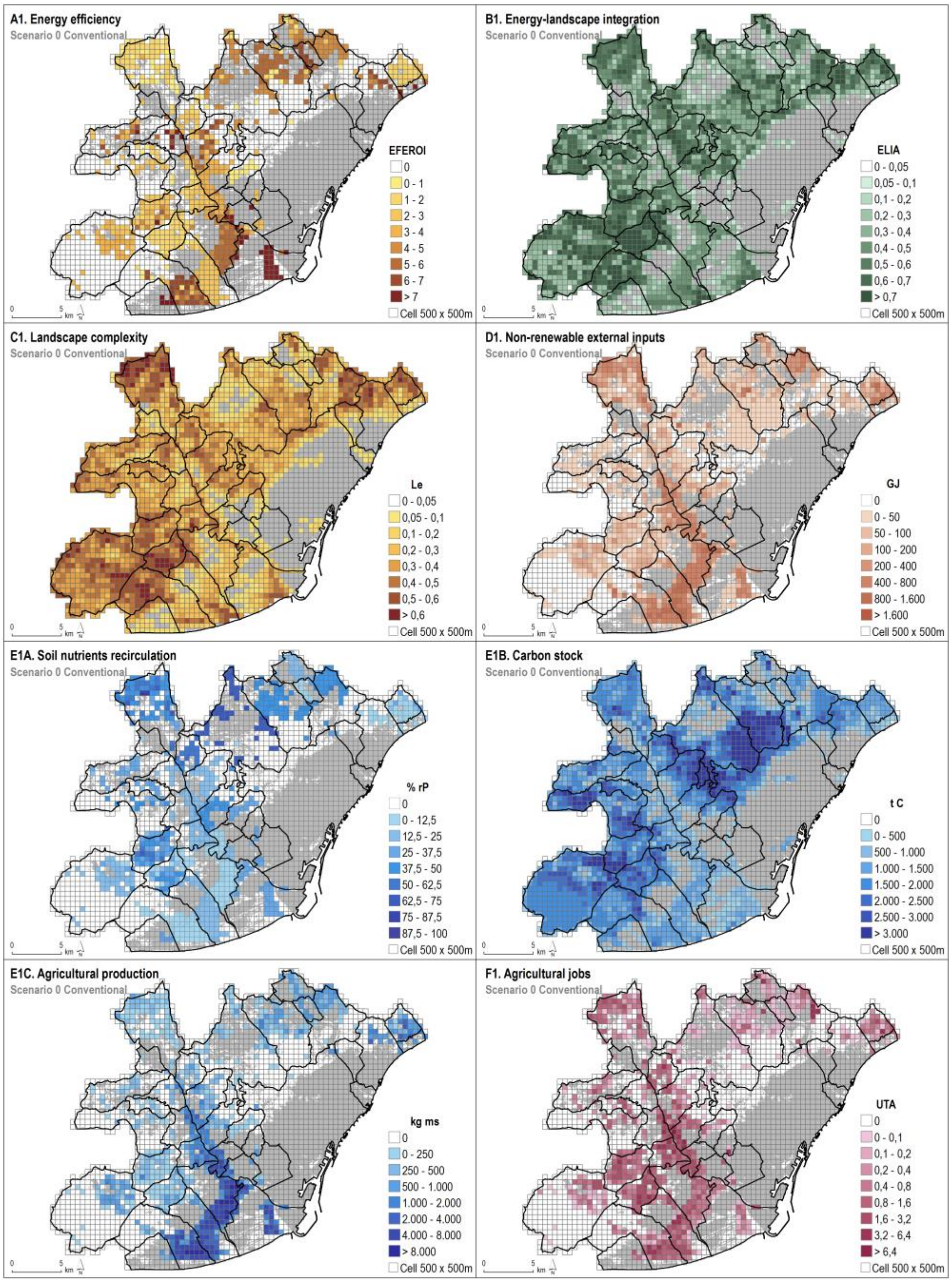


Figure A2 Territorialized Socioecological Integrated Analysis (SIA) indicators for the trending land planning scenario under conventional agricultural practices (S1C)

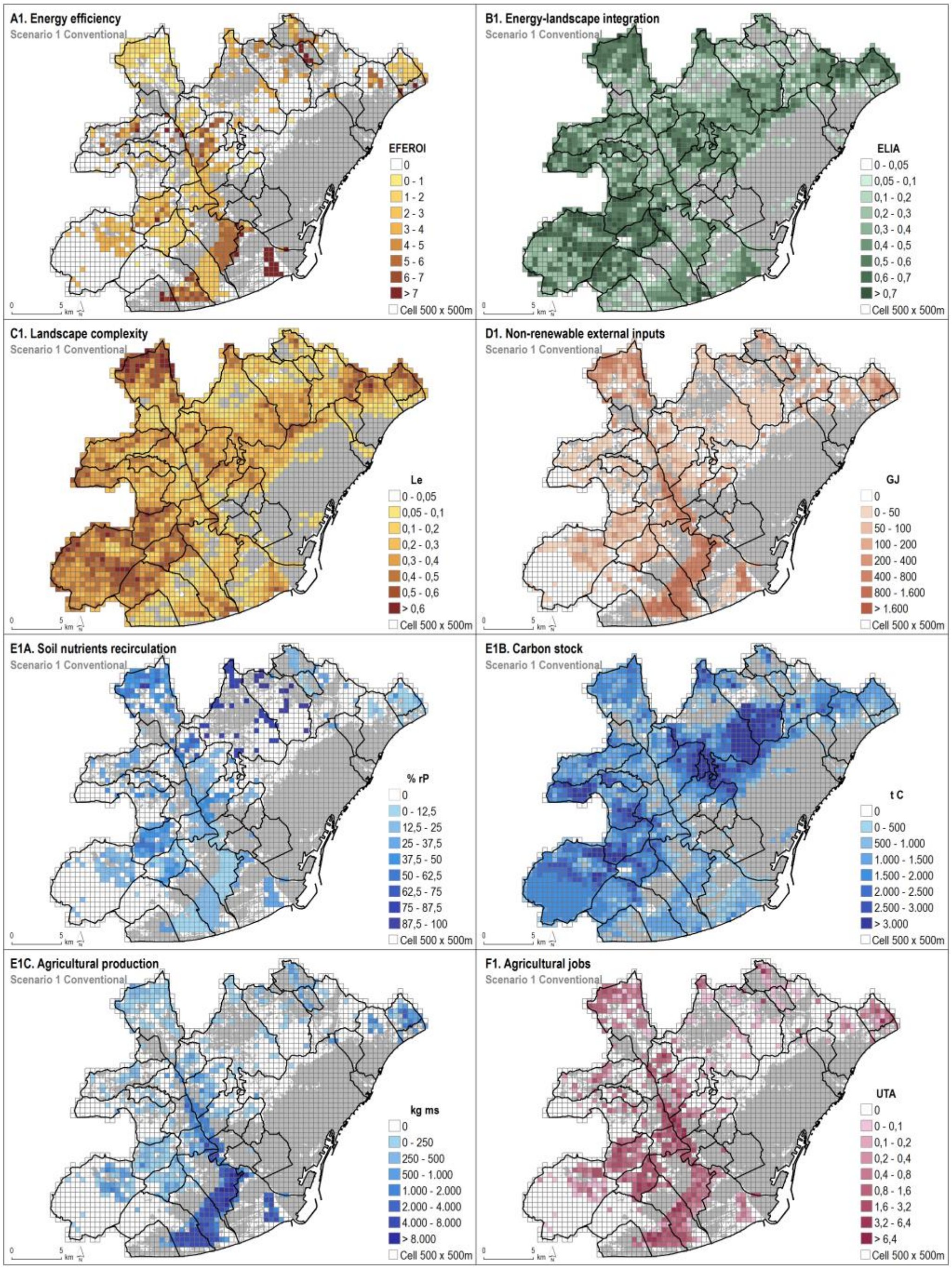


Figure A3 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario between current conventional (SC0) and trending conventional scenario (SC1).

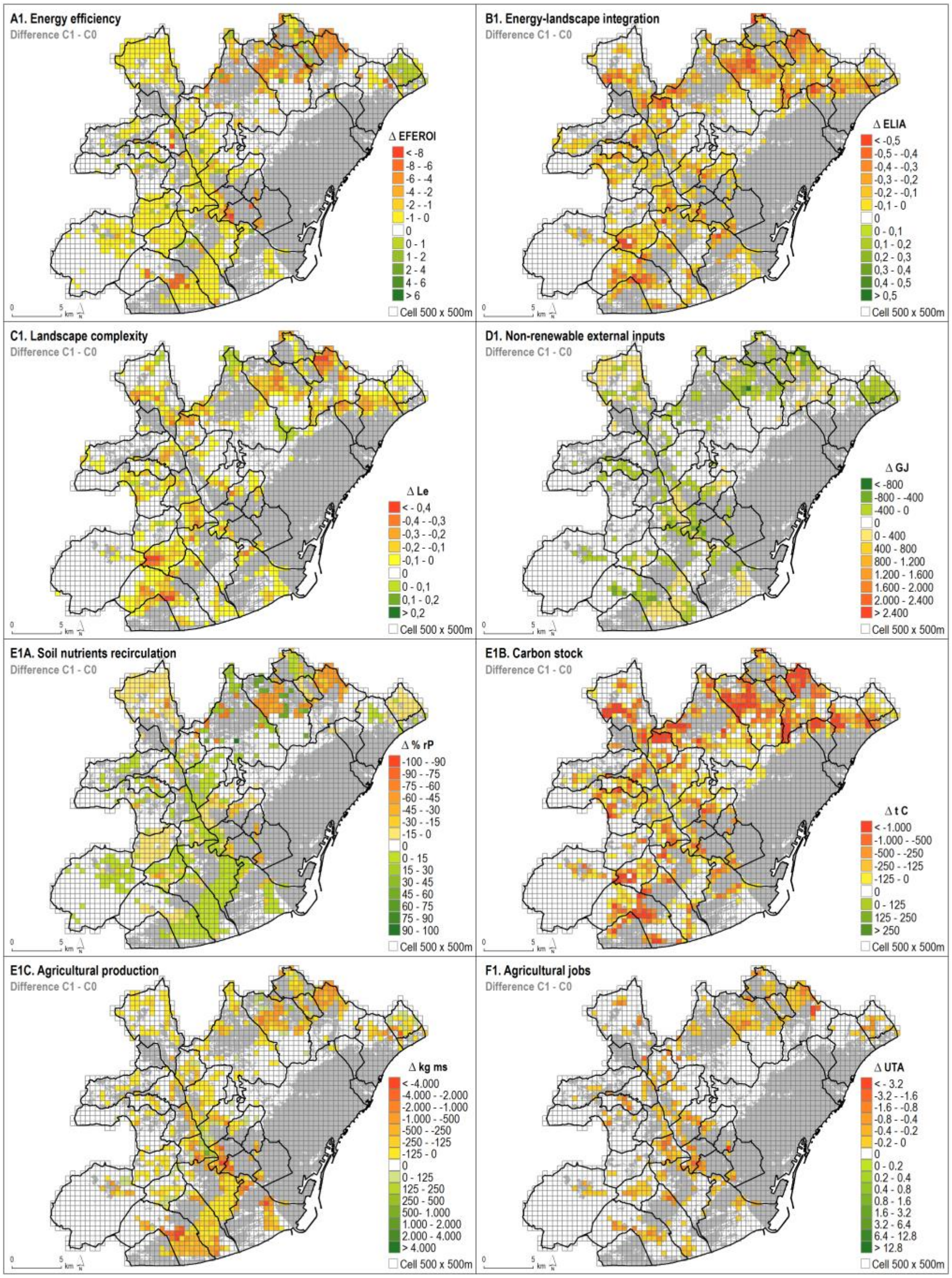


Figure A4 Territorialized Socioecological Integrated Analysis (SIA) indicators for the alternative land planning scenario under conventional agricultural practices (S2C)

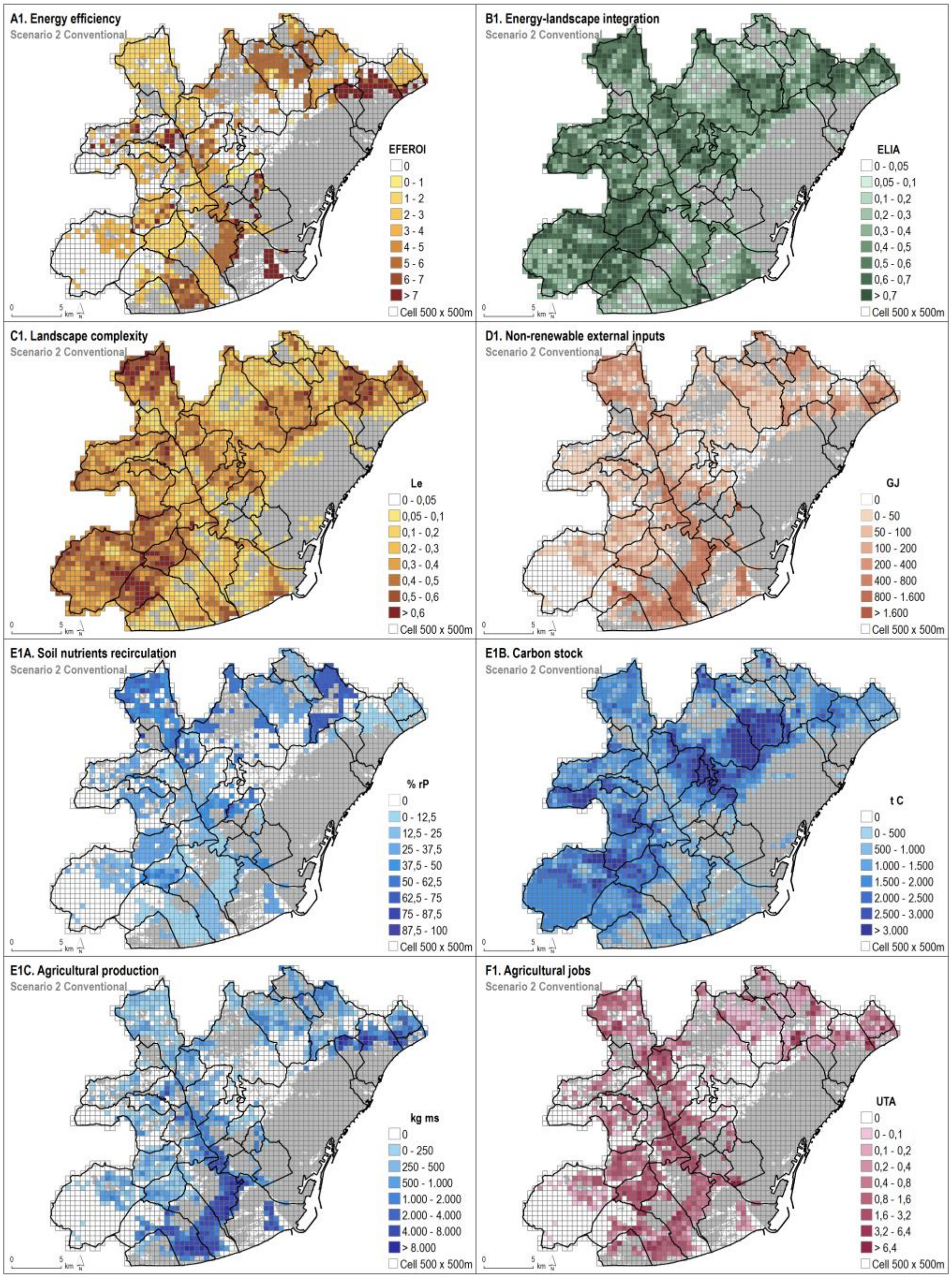


Figure A5 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario between current conventional (SC0) and alternative conventional scenario (SC2)

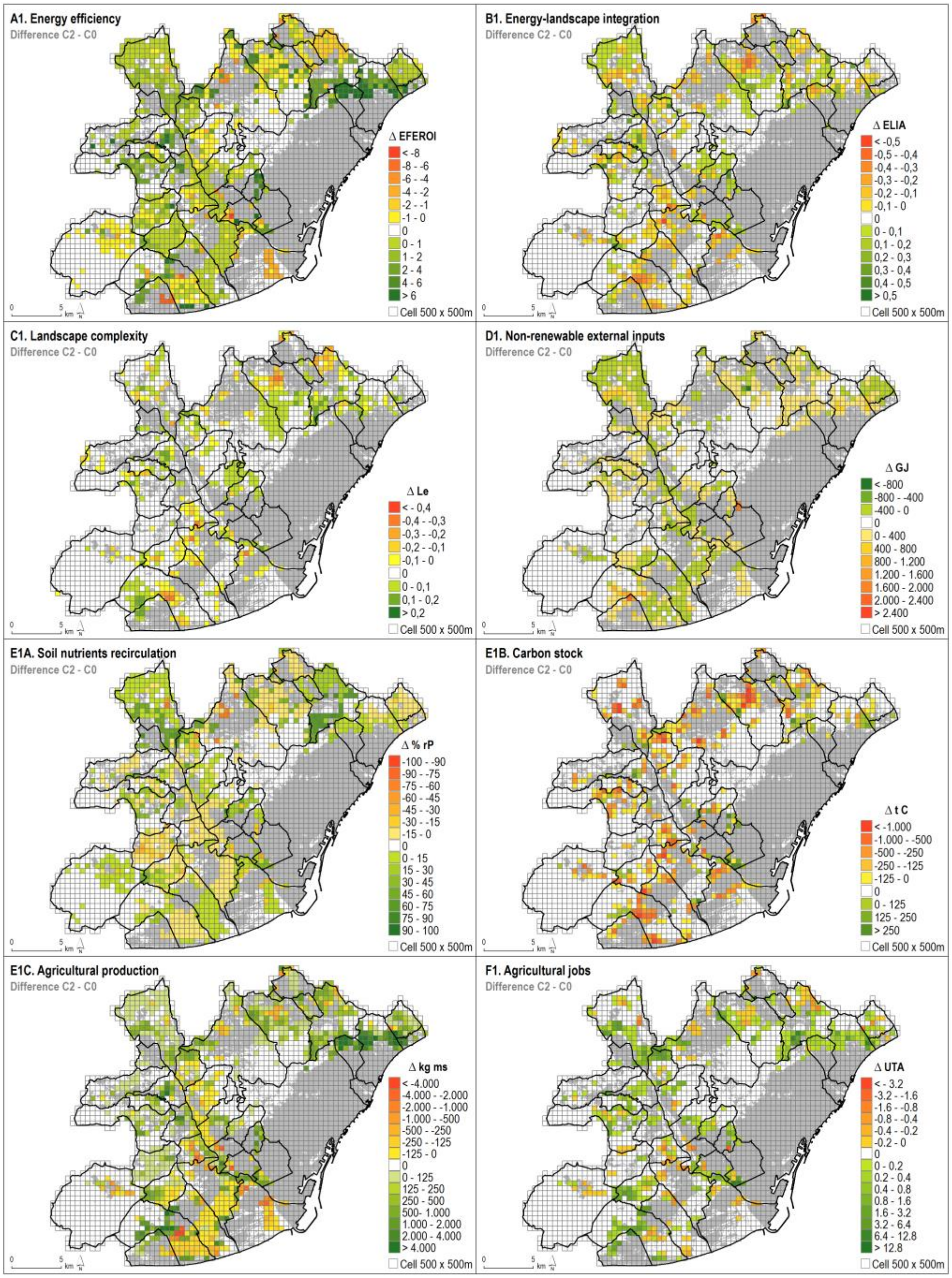


Figure A6 Territorialized Socioecological Integrated Analysis (SIA) indicators for the alternative land planning scenario under organic agricultural practices (S2O)

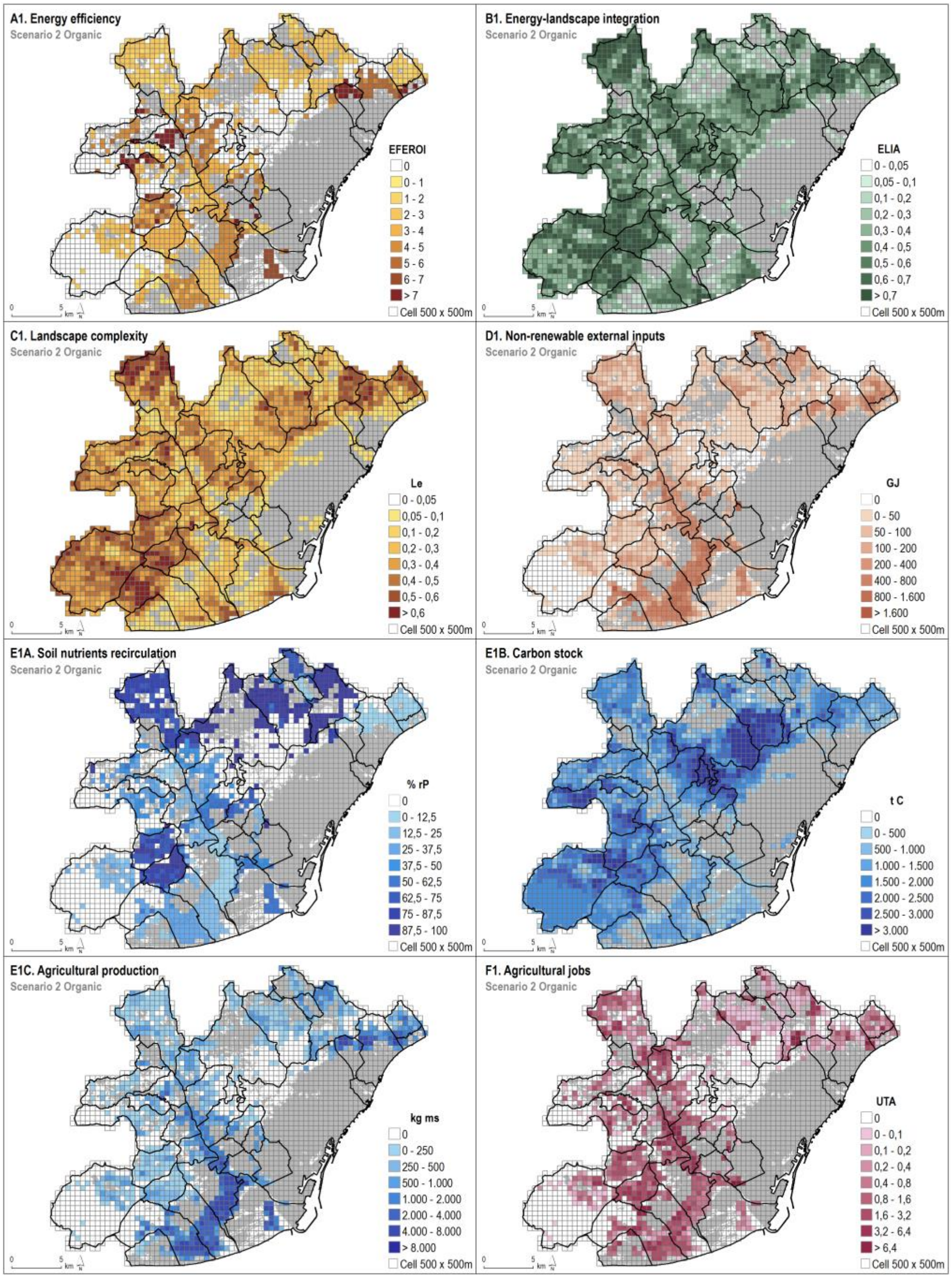


Figure A7 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario from the current conventional (SC0) to an alternative organic scenario (SO2)

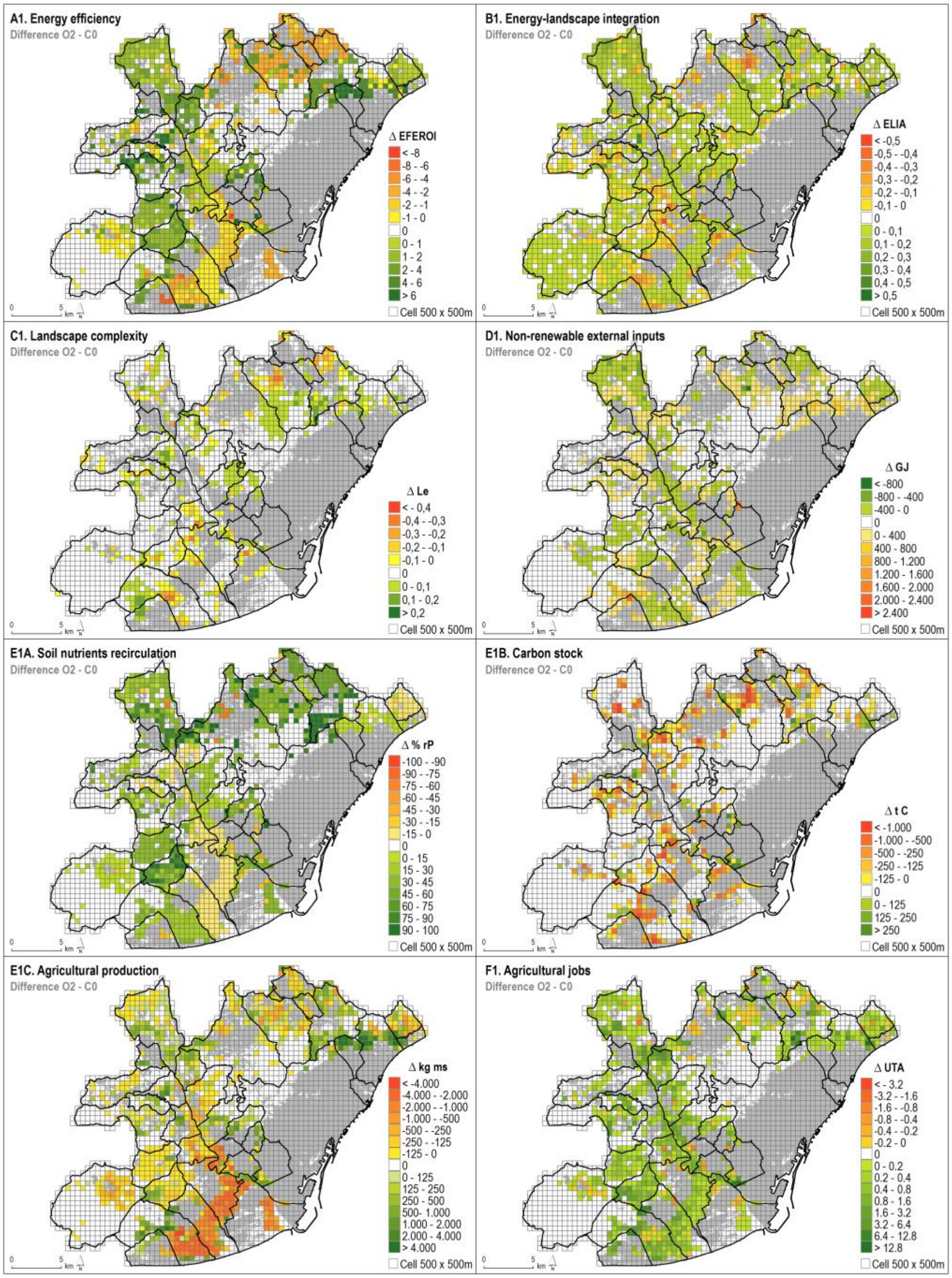


Figure A8 Territorialized Socioecological Integrated Analysis (SIA9 indicators for the potential land planning scenario under conventional agricultural practices (S3C)

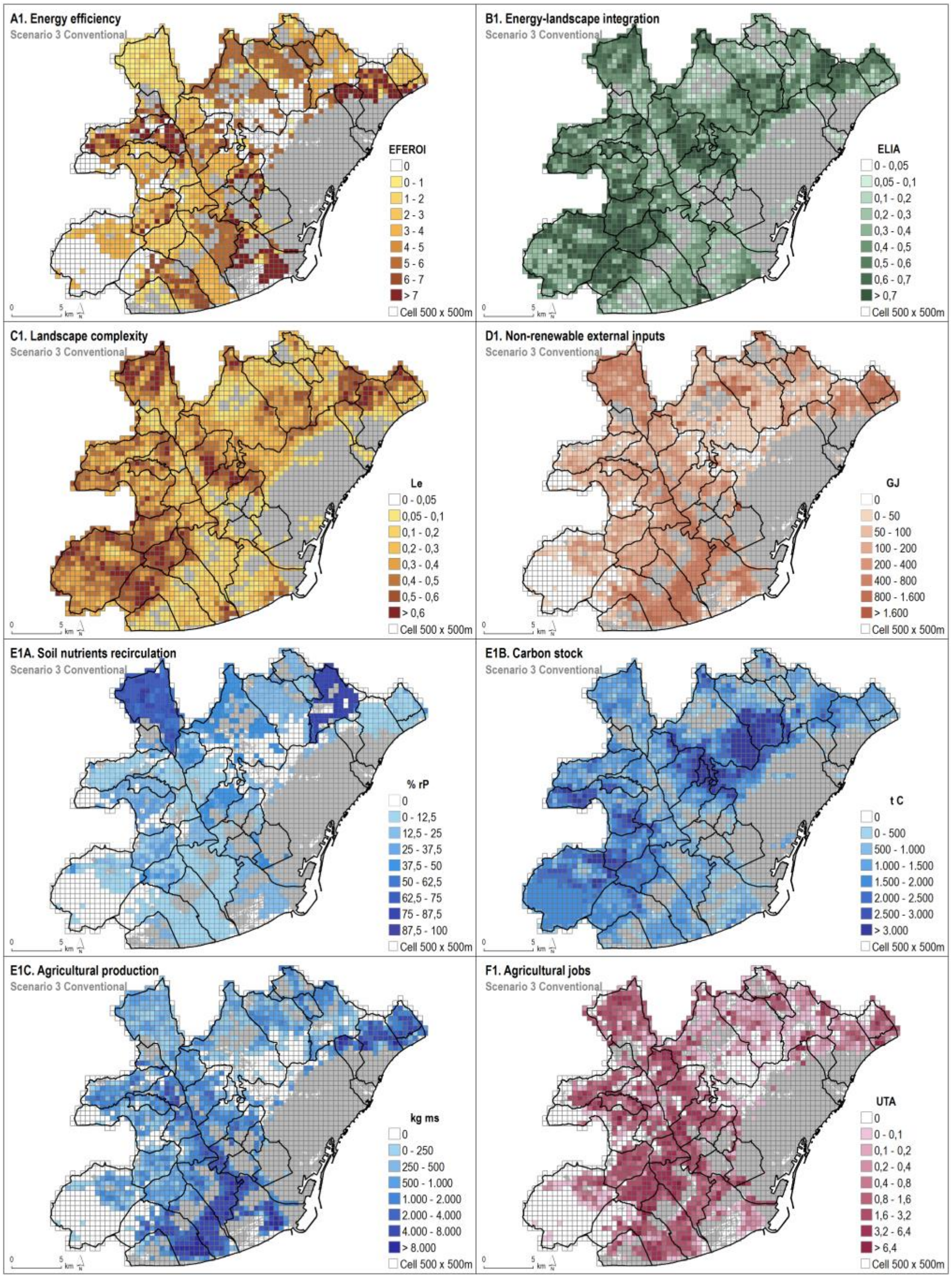


Figure A9 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario from the current conventional (SC0) to a potential conventional scenario (SC3)

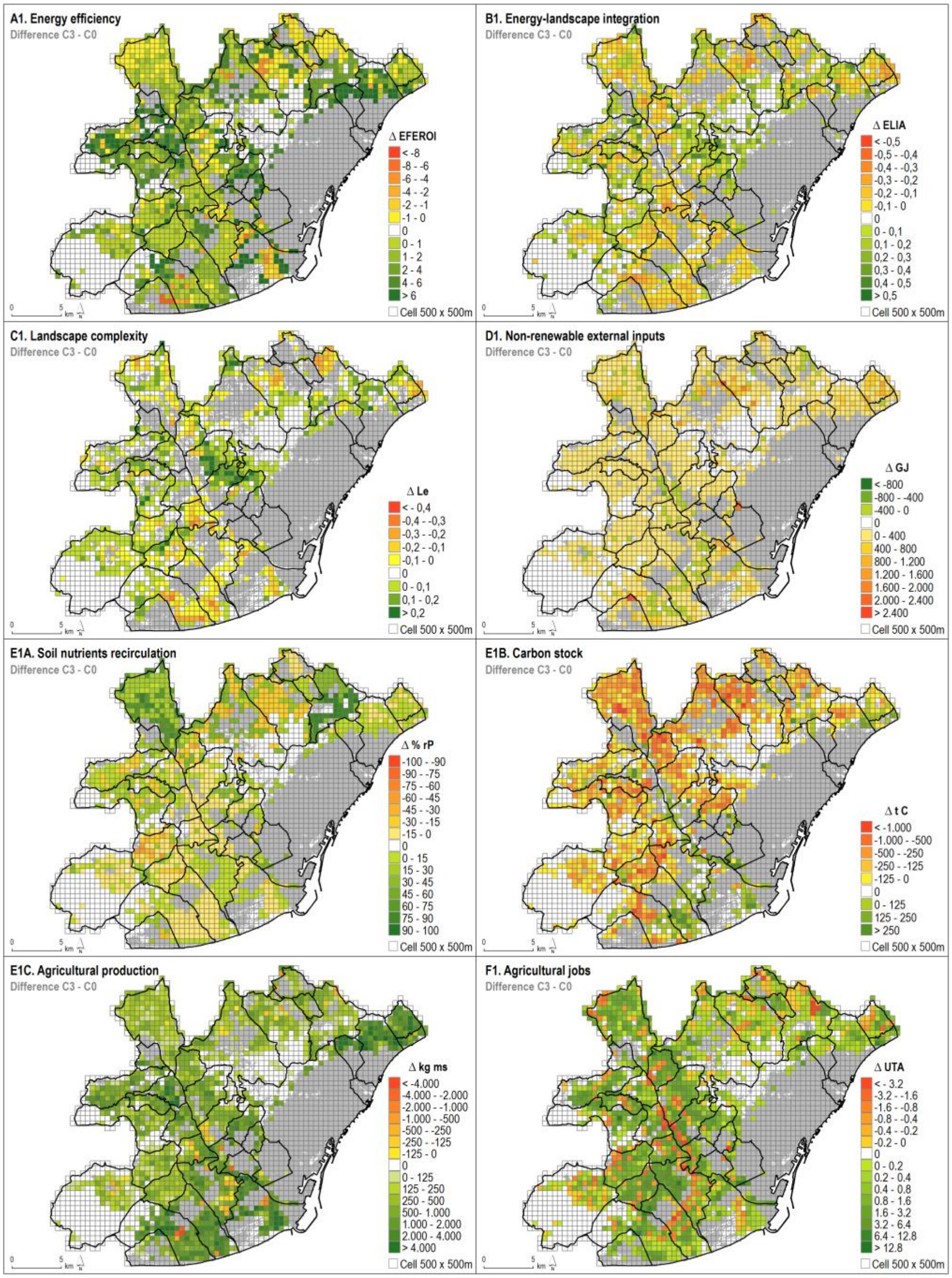


Figure A10 Territorialized Socioecological Integrated Analysis (SIA) indicators for the potential land planning scenario under organic agricultural practices (S3O)

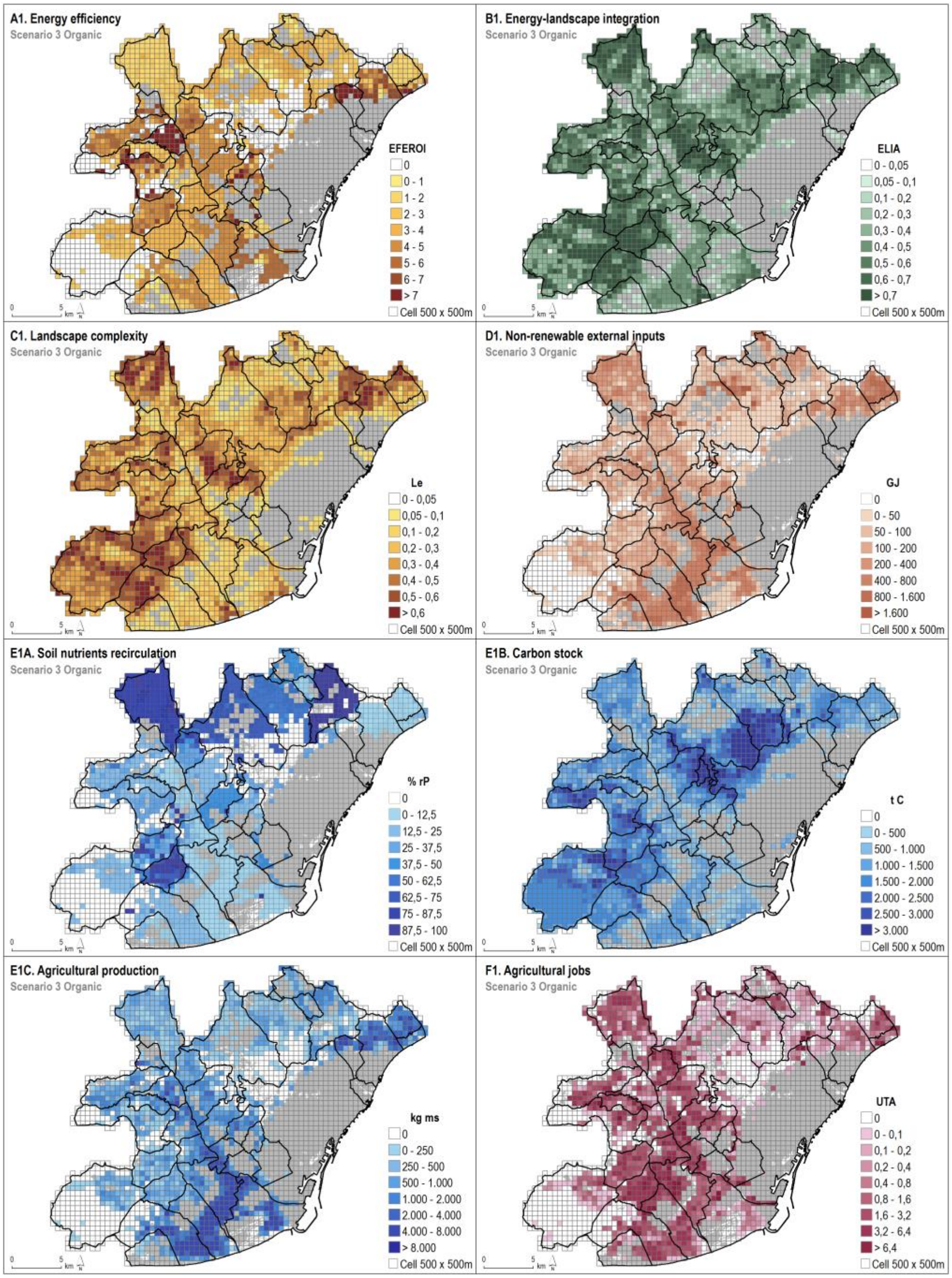
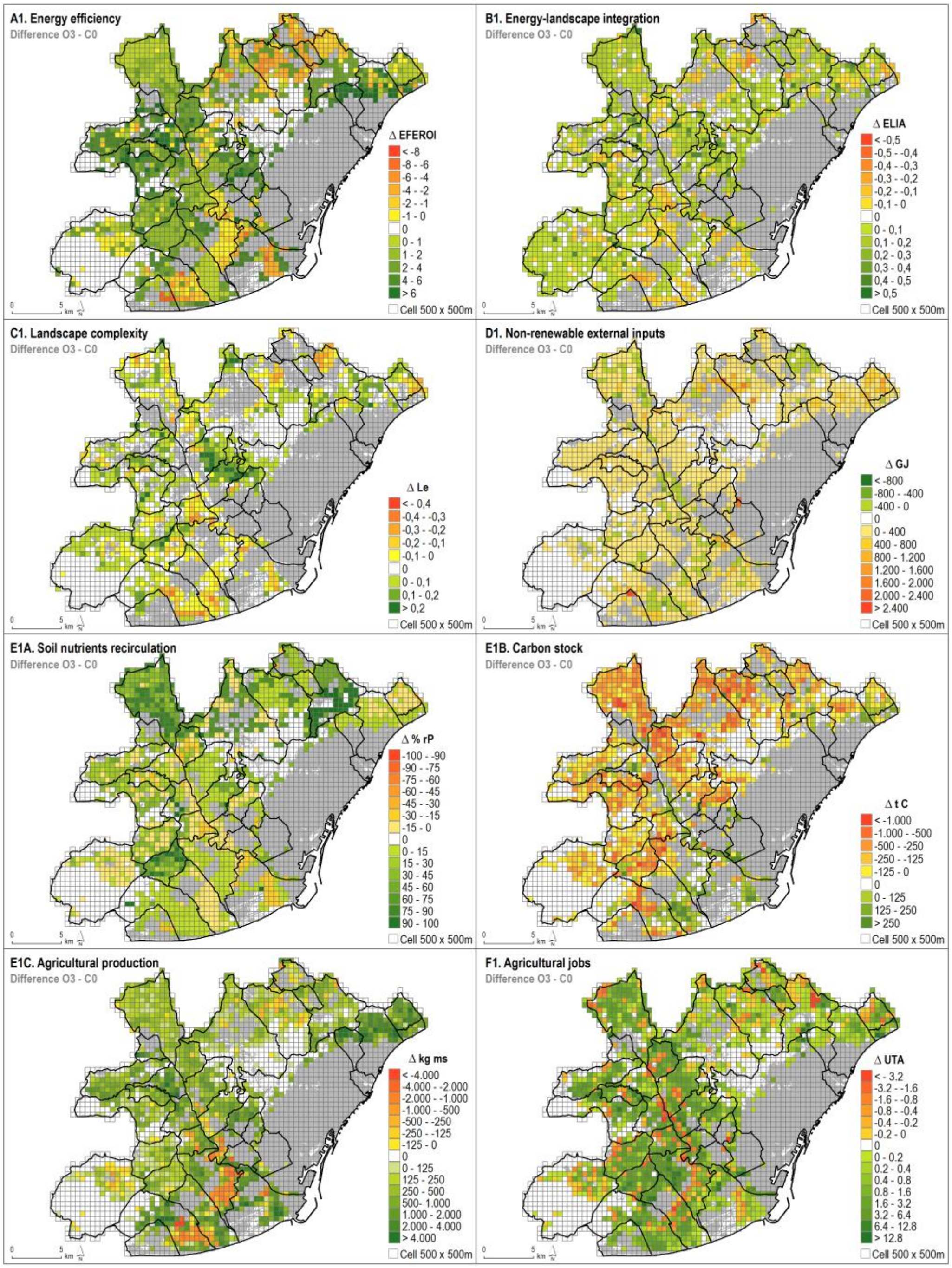


Figure A11 Differences on the Socioecological Integrated Analysis (SIA) indicators for a transition scenario from the current conventional (SC0) to a potential organic scenario (SO3)



7.5 Appendix 4: Supplementary Material for Chapter 5

7.5.1 Optimization scenarios for conventional agriculture

Table A12. Energy-Landscape Optimization (E-LO) results: Energy flows and the indicator of Energy Storage (E) for conventional agriculture.

Energy flows (GJ)															
Flows	CS	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
FEI	353453	387306	400612	412956	424791	424432	388716	423979	459242	494504	529767	318200	282947	247694	212441	177188
UB	75684700	73363870	71209004	69059666	66915758	66979457	75407966	75131233	74854499	74577766	74301032	76442848	77200996	77959143	78717291	79475439
FW	5710565	6264502	6476480	6673449	6861356	6841785	6281621	6852677	7423734	7994790	8565847	5139508	4568452	3997395	3426339	2855282
FBR	631636	690544	749453	808361	867270	926178	694799	757963	821126	884290	947454	568472	505309	442145	378981	315818
LBR	1491078	1640186	1668078	1669073	1679545	1687301	1564449	1637819	1711190	1784560	1857931	1341970	1192863	1043755	894647	745539
FFP	6125204	6388316	6346539	6273489	6202882	6139053	6593176	7061148	7529120	7997092	8465064	5674436	5223668	4772900	4322132	3871363
LEI	2979816	3278238	3333986	3335975	3356905	3372406	3126862	3273508	3420153	3566799	3713444	2682195	2384173	2086152	1788130	1490108
LW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LS	1802692	1983228	2016954	2018157	2030819	2040197	1891651	1980366	2069082	2157798	2246514	1622641	1442348	1262054	1081761	901467
LFP	208791	229701	233607	233747	235213	236300	219095	229370	239645	249920	260196	187937	167055	146174	125292	104410
Fnr	2022730	2182724	2229426	2268720	2306444	2286247	2221933	2421135	2620338	2819540	3018743	1823893	1625056	1426218	1227381	1028544
Lnr	481376	529585	538591	538912	542293	544798	505131	528821	552511	576201	599891	433297	385153	337009	288865	240720
NPP_{act}	89643183	88347418	86449555	84484038	82526811	82573774	90542012	91440841	92339670	93238498	94137327	89167235	88691286	88215338	87739390	87263441
NPP_{h}	13958483	14983548	15240551	15424372	15611053	15594317	15134045	16309608	17485170	18660733	19836295	12724387	11490291	10256195	9022099	7788003
ATT	80495211	78607672	76605448	74567861	72545083	72656511	80605065	80714676	80824287	80933899	81043510	80776054	81056655	81337255	81617856	81898457
LTI	4952270	5448009	5540655	5543960	5578743	5604505	5196442	5440148	5683854	5927560	6171266	4457462	3962189	3466915	2971641	2476368
LPS	2011484	2212930	2250561	2251904	2266032	2276497	2110745	2209736	2308727	2407718	2506709	1810579	1609403	1408228	1207053	1005877
FTI	4810511	5243803	5396444	5508195	5629324	5677054	5197099	5583443	5969788	6356133	6742478	4333207	3855659	3378112	2900565	2423018
FII	2434328	2673773	2766407	2826518	2898089	2966375	2586450	2738329	2890209	3042088	3193968	2191114	1947656	1704199	1460742	1217285
FP	6333996	6618017	6580147	6507236	6438095	6375352	6812271	7290518	7768765	8247013	8725260	5862374	5390724	4919073	4447423	3975773
FEROI	1.161	1.104	1.070	1.045	1.017	0.995	1.180	1.196	1.212	1.225	1.238	1.194	1.235	1.288	1.358	1.457
NPP-EROI	16.430	14.734	14.052	13.569	13.040	12.881	15.679	15.007	14.402	13.854	13.355	18.157	20.317	23.095	26.797	31.980
IF-EROI	2.984	2.839	2.722	2.627	2.528	2.439	3.015	3.043	3.068	3.090	3.110	3.069	3.174	3.311	3.492	3.746
EF-EROI	1.900	1.805	1.762	1.736	1.702	1.679	1.938	1.972	2.003	2.031	2.056	1.954	2.021	2.108	2.223	2.385
AE-EROI	0.078	0.083	0.085	0.086	0.088	0.087	0.084	0.090	0.096	0.101	0.107	0.072	0.066	0.060	0.054	0.048
E	0.871	0.858	0.852	0.846	0.840	0.840	0.861	0.853	0.844	0.835	0.827	0.882	0.893	0.905	0.917	0.929

Note: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_{h}); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agroecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*); Farmland Waste (*FW*): Livestock Waste (*LW*). CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

Table A13. Energy-Landscape Optimization (E-LO) results: Energy Coefficients and the indicator of Energy Information (I) for conventional agriculture.

Coefficients															
Coef.	CS	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
β_1	0.156	0.170	0.176	0.183	0.189	0.189	0.167	0.178	0.189	0.200	0.211	0.143	0.130	0.116	0.103	0.089
β_2	0.844	0.830	0.824	0.817	0.811	0.811	0.833	0.822	0.811	0.800	0.789	0.857	0.870	0.884	0.897	0.911
β_3	0.060	0.067	0.070	0.074	0.078	0.078	0.064	0.069	0.074	0.079	0.083	0.054	0.048	0.042	0.036	0.030
β_4	0.940	0.933	0.930	0.926	0.922	0.922	0.936	0.931	0.926	0.921	0.917	0.946	0.952	0.958	0.964	0.970
β_5	0.439	0.426	0.416	0.407	0.397	0.394	0.436	0.433	0.431	0.429	0.427	0.446	0.455	0.465	0.479	0.497
β_6	0.152	0.156	0.159	0.161	0.163	0.168	0.149	0.147	0.145	0.143	0.141	0.150	0.148	0.145	0.141	0.136
β_7	0.073	0.074	0.074	0.075	0.075	0.075	0.075	0.076	0.077	0.078	0.079	0.073	0.073	0.073	0.073	0.073
β_8	0.506	0.510	0.513	0.513	0.515	0.523	0.498	0.490	0.484	0.479	0.474	0.506	0.505	0.504	0.504	0.502
β_9	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602	0.602
β_{10}	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301
β_{11}	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104
β_{12}	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896	0.896
α_1	0.074	0.075	0.076	0.077	0.078	0.078	0.074	0.075	0.075	0.075	0.075	0.074	0.074	0.074	0.074	0.073
α_2	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430	0.430
γ_L	0.468	0.465	0.463	0.461	0.458	0.459	0.465	0.463	0.460	0.457	0.455	0.471	0.474	0.477	0.480	0.484
γ_B	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
k_1	0.951	0.944	0.941	0.939	0.936	0.935	0.948	0.945	0.942	0.939	0.936	0.956	0.961	0.966	0.971	0.976
k_2	0.027	0.030	0.032	0.034	0.036	0.036	0.028	0.030	0.032	0.034	0.035	0.024	0.021	0.018	0.016	0.013
k_3	0.023	0.026	0.027	0.027	0.028	0.028	0.024	0.025	0.026	0.027	0.028	0.020	0.018	0.016	0.013	0.011
I	0.334	0.339	0.342	0.344	0.346	0.347	0.337	0.340	0.343	0.345	0.347	0.330	0.326	0.321	0.315	0.309

Note: β_i's is the incoming-outgoing coefficient, when the energy flows enter or leave the agroecosystem's internal energy loops; γ_i's is the information-loss coefficient, when the agroecosystem present farm and/or livestock waste; α_i's is the penalization coefficient, when the farm system uses non-renewable external inputs; k_i's is the subsystem coefficient when the share of reusing energy are circling through each of the subsystems. CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

Table A14. Energy-Landscape Optimization (E-LO) results: Land covers and the indicator of Landscape Heterogeneity (L) for conventional agriculture.

Land Cover	Land covers (%)															
	CS	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
Unproductive	5.04%	5.04%	5.04%	5.04%	5.04%	5.04%	5.03%	5.03%	5.03%	5.03%	5.03%	5.04%	5.04%	5.04%	5.04%	5.04%
Orchards	0.44%	0.48%	0.52%	0.57%	0.61%	0.65%	0.48%	0.52%	0.57%	0.61%	0.65%	0.39%	0.35%	0.30%	0.26%	0.22%
Greenhouses	0.03%	0.03%	0.02%	0.02%	0.02%	0.01%	0.03%	0.03%	0.04%	0.04%	0.04%	0.03%	0.02%	0.02%	0.02%	0.01%
Dry Herbaceous Crops	0.91%	1.00%	1.09%	1.19%	1.28%	1.37%	1.00%	1.09%	1.18%	1.28%	1.37%	0.82%	0.73%	0.64%	0.55%	0.46%
Irrigated Herbaceous Crops	0.51%	0.57%	0.52%	0.46%	0.41%	0.35%	0.57%	0.62%	0.67%	0.72%	0.77%	0.46%	0.41%	0.36%	0.31%	0.26%
Dry Fruit Trees	16.88%	18.52%	19.06%	19.55%	20.01%	19.81%	18.57%	20.25%	21.94%	23.62%	25.31%	15.20%	13.51%	11.82%	10.14%	8.45%
Irrigated Fruit Trees	0.31%	0.34%	0.37%	0.41%	0.44%	0.47%	0.34%	0.37%	0.41%	0.44%	0.47%	0.28%	0.25%	0.22%	0.19%	0.16%
Dry Olive Trees	0.16%	0.18%	0.20%	0.21%	0.23%	0.24%	0.18%	0.20%	0.21%	0.23%	0.24%	0.15%	0.13%	0.11%	0.10%	0.08%
Vineyards	0.07%	0.08%	0.09%	0.10%	0.10%	0.11%	0.08%	0.09%	0.10%	0.10%	0.11%	0.07%	0.06%	0.05%	0.04%	0.04%
Scrubs	17.42%	17.65%	19.07%	20.55%	22.06%	21.80%	15.68%	13.93%	12.19%	10.45%	8.70%	19.17%	20.91%	22.66%	24.40%	26.15%
Grazing Areas	2.03%	2.23%	2.44%	2.64%	2.84%	3.05%	1.83%	1.62%	1.42%	1.22%	1.01%	1.83%	1.62%	1.42%	1.22%	1.02%
Flat Leaved Forests	16.52%	18.18%	19.83%	21.49%	23.15%	23.74%	14.87%	13.21%	11.56%	9.91%	8.25%	18.18%	19.83%	21.49%	23.15%	24.80%
Coniferous Forests	39.67%	35.71%	31.75%	27.78%	23.82%	23.35%	41.34%	43.02%	44.69%	46.36%	48.03%	38.40%	37.13%	35.86%	34.59%	33.32%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
L	0.565	0.581	0.594	0.603	0.609	0.612	0.560	0.552	0.542	0.530	0.514	0.563	0.559	0.552	0.543	0.532

Note: CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* inputs while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

7.5.2 Optimization scenarios for organic agriculture

Table A15. Energy-Landscape Optimization (E-LO) results: Energy flows and the indicator of Energy Storage (E) for organic agriculture.

Energy flows (GJ)															
Flows	S0	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
FEI	798871	878072	957193	1036299	1115405	1190948	878475	958080	1037684	1117288	1196893	719301	639730	560159	480589	401018
UB	87503621	85457976	83687058	81939222	80216748	78818681	88408780	89313939	90219097	91124256	92029414	87079877	86656133	86232388	85808644	85384900
FW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FBR	466945	509346	551585	593794	636003	678203	513639	560334	607028	653722	700417	420250	373556	326861	280167	233472
LBR	1134135	1247548	1316021	1376196	1436436	1494175	1171811	1209487	1247164	1284840	1322516	1020721	907308	793894	680481	567067
FFP	11175065	11939104	12629872	13306669	13983984	14645342	12148023	13120981	14093939	15066897	16039855	10219311	9263556	8307802	7352048	6396294
LEI	864926	951419	1003639	1049530	1095471	1139504	893659	922392	951125	979858	1008592	778434	691941	605449	518956	432463
LW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LS	3141819	3456001	3645686	3812385	3979264	4139215	3246190	3350562	3454934	3559306	3663678	2827637	2513455	2199273	1885091	1570909
LFP	205240	225764	238155	249044	259946	270395	212058	218876	225694	232512	239330	184716	164192	143668	123144	102620
Fnr	1836478	1982601	2120273	2256374	2392496	2521960	2017055	2197632	2378210	2558787	2739364	1656266	1476054	1295842	1115630	935418
Lnr	194490	213939	225681	236000	246330	256232	200951	207412	213872	220333	226794	175041	155592	136143	116694	97245
NPP_{act}	100279766	99153974	98184536	97215881	96273171	95636401	102242253	104204740	106167228	108129715	110092202	98740159	97200553	95660946	94121340	92581733
NPP_{h}	12776145	13695998	14497478	15276659	16056423	16817720	13833473	14890802	15948131	17005459	18062788	11660282	10544420	9428558	8312696	7196833
ATT	93747733	92283996	90961795	89638073	88339916	87349006	95064140	96380546	97696953	99013359	100329765	92703330	91658927	90614524	89570120	88525717
LTI	2193551	2412906	2545340	2661726	2778237	2889912	2266421	2339291	2412161	2485032	2557902	1974196	1754841	1535486	1316131	1096775
LPS	3347058	3681764	3883841	4061429	4239209	4409609	3458248	3569438	3680628	3791818	3903008	3012352	2677647	2342941	2008235	1673529
FTI	6244112	6826020	7274736	7698851	8123168	8530325	6655360	7066608	7477856	7889104	8300351	5623453	5002794	4382135	3761477	3140818
FII	3608763	3965346	4197271	4406178	4615266	4817418	3759829	3910896	4061962	4213028	4364094	3247887	2887011	2526134	2165258	1804382
FP	11380305	12164868	12868027	13555714	14243930	14915736	12360081	13339857	14319633	15299409	16279185	10404026	9427748	8451470	7475192	6498913
FEROI	3.486	3.392	3.361	3.342	3.325	3.313	3.575	3.654	3.726	3.791	3.850	3.540	3.609	3.696	3.813	3.977
NPP-EROI	30.715	27.647	25.646	23.969	22.476	21.239	29.570	28.547	27.626	26.793	26.036	33.600	37.205	41.840	48.016	56.659
IF-EROI	7.108	6.924	6.890	6.881	6.873	6.866	7.333	7.537	7.723	7.892	8.047	7.220	7.360	7.541	7.781	8.118
EF-EROI	6.840	6.649	6.563	6.499	6.443	6.400	6.975	7.094	7.200	7.295	7.381	6.947	7.080	7.251	7.479	7.797
AE-EROI	0.125	0.137	0.147	0.158	0.169	0.179	0.135	0.143	0.152	0.161	0.169	0.116	0.106	0.095	0.085	0.075
E	0.887	0.877	0.869	0.860	0.852	0.843	0.881	0.876	0.870	0.865	0.859	0.896	0.905	0.914	0.924	0.934

Note: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_{h}); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agroecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*); Farmland Waste (*FW*): Livestock Waste (*LW*). S0 is the same land cover structure than the Current Scenario but considering organic agriculture; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

Table A16. Energy-Landscape Optimization (E-LO) results: Energy Coefficients and the indicator of Energy Information (I) for organic agriculture.

Coefficients															
Coef.	S0	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
β_1	0.127	0.138	0.148	0.157	0.167	0.176	0.135	0.143	0.150	0.157	0.164	0.118	0.108	0.099	0.088	0.078
β_2	0.873	0.862	0.852	0.843	0.833	0.824	0.865	0.857	0.850	0.843	0.836	0.882	0.892	0.901	0.912	0.922
β_3	0.067	0.074	0.080	0.086	0.092	0.098	0.070	0.073	0.077	0.080	0.083	0.061	0.055	0.048	0.042	0.035
β_4	0.933	0.926	0.920	0.914	0.908	0.902	0.930	0.927	0.923	0.920	0.917	0.939	0.945	0.952	0.958	0.965
β_5	0.875	0.872	0.871	0.871	0.871	0.871	0.878	0.881	0.884	0.886	0.888	0.876	0.879	0.881	0.884	0.889
β_6	0.125	0.128	0.129	0.129	0.129	0.129	0.122	0.119	0.116	0.114	0.112	0.124	0.121	0.119	0.116	0.111
β_7	0.128	0.129	0.132	0.135	0.137	0.140	0.132	0.136	0.139	0.142	0.144	0.128	0.128	0.128	0.128	0.128
β_8	0.578	0.581	0.577	0.572	0.568	0.565	0.565	0.553	0.543	0.534	0.526	0.578	0.577	0.576	0.576	0.574
β_9	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394	0.394
β_{10}	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517	0.517
β_{11}	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061	0.061
β_{12}	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939	0.939
α_1	0.152	0.153	0.156	0.157	0.159	0.160	0.152	0.152	0.152	0.152	0.152	0.151	0.151	0.151	0.151	0.150
α_2	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408	0.408
γ_L	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
γ_B	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
k_1	0.949	0.943	0.938	0.934	0.930	0.926	0.947	0.946	0.944	0.943	0.942	0.953	0.958	0.963	0.968	0.973
k_2	0.017	0.019	0.021	0.022	0.024	0.026	0.018	0.019	0.019	0.020	0.021	0.016	0.014	0.013	0.011	0.009
k_3	0.034	0.038	0.041	0.043	0.046	0.049	0.035	0.035	0.036	0.037	0.037	0.031	0.028	0.025	0.021	0.018
I	0.339	0.347	0.353	0.359	0.365	0.370	0.343	0.347	0.350	0.353	0.355	0.334	0.329	0.323	0.316	0.308

Note: β_i's is the incoming-outgoing coefficient, when the energy flows enter or leave the agroecosystem's internal energy loops; γ_i's is the information-loss coefficient, when the agroecosystem present farm and/or livestock waste; α_i's is the penalization coefficient, when the farm system uses non-renewable external inputs; k_i's is the subsystem coefficient when the share of reusing energy are circling through each of the subsystems. S0 is the same land cover structure than the Current Scenario but considering organic agriculture; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

Table A17. Energy-Landscape Optimization (E-LO) results: Land covers and the indicator of Landscape Heterogeneity (L) for organic agriculture.

Land Cover	Land covers (%)															
	S0	S1 (0.1)	S1 (0.2)	S1 (0.3)	S1 (0.4)	S1 (0.5)	S2 (0.1)	S2 (0.2)	S2 (0.3)	S2 (0.4)	S2 (0.5)	S3 (0.1)	S3 (0.2)	S3 (0.3)	S3 (0.4)	S3 (0.5)
Improductive	5.04%	5.04%	5.04%	5.04%	5.04%	5.04%	5.03%	5.04%	5.03%	5.03%	5.03%	5.04%	5.04%	5.04%	5.04%	5.04%
Orchards	0.44%	0.48%	0.52%	0.57%	0.61%	0.65%	0.48%	0.35%	0.57%	0.61%	0.65%	0.39%	0.35%	0.30%	0.26%	0.22%
Greenhouses	0.03%	0.03%	0.02%	0.02%	0.02%	0.01%	0.03%	0.02%	0.04%	0.04%	0.04%	0.03%	0.02%	0.02%	0.02%	0.01%
Dry Herbaceous Crops	0.91%	1.00%	1.09%	1.19%	1.28%	1.37%	1.00%	0.73%	1.18%	1.28%	1.37%	0.82%	0.73%	0.64%	0.55%	0.46%
Irrigated Herbaceous Crops	0.51%	0.57%	0.57%	0.56%	0.56%	0.55%	0.57%	0.41%	0.67%	0.72%	0.77%	0.46%	0.41%	0.36%	0.31%	0.26%
Dry Fruit Trees	16.88%	18.57%	20.27%	21.96%	23.65%	25.26%	18.57%	13.51%	21.94%	23.62%	25.31%	15.20%	13.51%	11.82%	10.14%	8.45%
Irrigated Fruit Trees	0.31%	0.34%	0.37%	0.41%	0.44%	0.47%	0.34%	0.25%	0.41%	0.44%	0.47%	0.28%	0.25%	0.22%	0.19%	0.16%
Dry Olive Trees	0.16%	0.18%	0.20%	0.21%	0.23%	0.24%	0.18%	0.13%	0.21%	0.23%	0.24%	0.15%	0.13%	0.11%	0.10%	0.08%
Vineyards	0.07%	0.08%	0.09%	0.10%	0.10%	0.11%	0.08%	0.06%	0.10%	0.10%	0.11%	0.07%	0.06%	0.05%	0.04%	0.04%
Scrubs	17.42%	18.59%	19.48%	20.36%	21.21%	21.71%	15.68%	20.91%	12.19%	10.45%	8.70%	19.17%	20.91%	22.66%	24.40%	26.15%
Grazing Areas	2.03%	2.23%	2.44%	2.64%	2.84%	3.05%	1.83%	1.62%	1.42%	1.22%	1.01%	1.83%	1.62%	1.42%	1.22%	1.02%
Flat Leaved Forests	16.52%	17.18%	18.16%	19.17%	20.21%	20.95%	14.87%	19.83%	11.56%	9.91%	8.25%	18.18%	19.83%	21.49%	23.15%	24.80%
Coniferous Forests	39.67%	35.71%	31.75%	27.78%	23.82%	20.58%	41.34%	37.13%	44.69%	46.36%	48.03%	38.40%	37.13%	35.86%	34.59%	33.32%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
L	0.565	0.581	0.594	0.604	0.611	0.614	0.560	0.559	0.542	0.530	0.514	0.563	0.559	0.552	0.543	0.532

Note: S0 is the same land cover structure than the Current Scenario but considering organic agriculture; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* inputs while the indicator *L* is maintained at least to a 90% of the current value). For all settings, the optimization model applies 10%, 20%, 30%, 40% and 50% of land cover change.

7.5.3 Syntax for the Optimization Model

Below we present the Energy-Landscape Optimization (E-LO) syntax used to run the model with the GAMS program. In Table A18 we show the syntax lines for changing the interaction. For changing the objective function, shift the asterisk, and for the land cover change select the allowed change (from 0.1 to 0.5). Regarding the management scenario, in Table A19 we present the different values for conventional management and for the organic in Table A20. Finally, the Syntax corresponds to the case of optimization for ELIA maximization allowing a change in the land use pattern of 0.5 for organic management.

Table A18. Syntax lines to change the iteration and associated parameter.

Input change	Syntax Lines	Parameter
Objective function	530 – 532	–
Management scenario	10 – 205	d(i,j)
Municipality	208 – 222	$CurrentCover_i$
Land cover change	225 – 239	$LandChange_i$

Table A19. Land use energy flows (MJ/ha) for conventional management in Sant Climent de Llobregat.

Land cover	FFP	LFP	FBR	LBR1	LBR2	FEI	FnR	LEI	LnR	FW	LW	LS	UB
Orchards	49,243	6,203	69,787	0	70,639	4,743	26,497	141,988	23,260	0	0	87,238	12,187
Greenhouses	49,243	6,203	69,787	0	70,639	4,743	494,497	141,988	23,260	0	0	87,238	12,187
Dry Herbaceous Crop	2,938	3,317	14,898	44,956	10,547	936	1,976	21,199	3,473	0	0	13,025	7,809
Irrigated Herbaceous Crop	102,217	13,696	0	123,271	86,708	340	13,908	174,286	28,551	0	0	107,082	39,292
Dry Fruit Trees	17,479	220	0	0	2,511	1,729	8,519	5,047	827	29,245	0	3,101	14,212
Irrigated Fruit Trees	35,076	183	0	0	2,086	1,754	15,347	4,194	687	29,144	0	2,577	15,862
Dry Olive Trees	45,648	522	75,594	0	5,942	242	9,195	11,943	1,956	196,120	0	7,338	7,964
Olives Irrigated	0	0	0	0	0	0	0	0	0	0	0	0	0
Vineyard	41,076	632	13,267	0	7,199	726	15,916	14,471	2,371	12,070	0	8,891	4,393
Scrub	0	0	0	0	0	0	0	0	0	0	0	0	29,250
Grazing Areas	0	1,346	0	17,498	4,116	0	0	7,491	914	0	0	3,304	0
Flat Leaved Forest	1,353	0	0	0	0	1	29	0	0	0	0	0	113,847
Coniferous Forest	3,975	0	0	0	0	2	84	0	0	0	0	0	111,225
Forest Plantations	0	0	0	0	0	0	0	0	0	0	0	0	0
OtherForests	0	0	0	0	0	0	0	0	0	0	0	0	115,200

Table A20. Land use energy flows (MJ/ha) for organic management in Sant Climent de Llobregat.

Land cover	FFP	LFP	FBR	LBR1	LBR2	FEI	FnR	LEI	LnR	FW	LW	LS	UB
Orchards	48,614	0	70,416	0	0	11,317	25,318	0	0	0	0	110,761	44,185
Greenhouses	48,614	0	70,416	0	0	0	493,318	0	0	0	0	110,761	44,185
Dry Herbaceous Crop	2,195	4,770	11,057	27,609	27,609	112	1,128	21,663	4,520	0	0	10,712	5,650
Irrigated Herbaceous Crop	151,151	12,781	315	87,229	87,229	173	16,595	58,052	12,112	0	0	61,480	54,676
Dry Fruit Trees	42,693	0	0	0	0	4,030	7,534	0	0	0	0	8,070	77,061
Irrigated Fruit Trees	54,398	0	0	0	0	4,022	14,191	0	0	0	0	6,932	79,576
Dry Olive Trees	156,009	9,933	0	5,053	5,053	443	7,339	45,115	9,413	0	0	17,246	42,800
Olives Irrigated	0	0	0	0	0	0	0	0	0	0	0	0	0
Vineyard	38,427	812	12,070	493	493	1,331	12,659	3,688	770	0	0	25,014	21,082
Scrub	0	0	0	0	0	0	0	0	0	0	0	0	29,250
Grazing Areas	0	3,279	0	17,498	17,498	0	0	11,786	3,107	0	0	29,013	0
Flat Leaved Forest	1,353	0	0	0	0	3	29	0	0	0	0	0	113,847
Coniferous Forest	3,975	0	0	0	0	8	84	0	0	0	0	0	111,225
Forest Plantations	0	0	0	0	0	0	0	0	0	0	0	0	0
OtherForests	0	0	0	0	0	0	0	0	0	0	0	0	115,200

7.5.3.1 *Syntax example of the Energy-Landscape Optimization (E-LO) model in the Sant Climent de Llobregat case study. Case of optimization for ELIA maximization considering organic management and allowing land use pattern change of 0.5.*

```
Sets
        i Land Uses /Orchards, Greenhouses, DryHerbaceousCrop,
        IrrigatedHerbaceousCrop, DryFruitTrees, IrrigatedFruitTrees, DryOliveTrees,
        OlivesIrrigated, Vineyard, Scrub, GrazingAreas, FlatLeavedForest, ConiferousForest,
        ForestPlantations, OtherForests/
        j Primary Flows /FFP,LFP,FBR ,LBR1,LBR2,FEI,FnR,LEI,LnR,FW,LW,LS,UB/
        k Secondary Flows /EI,FTI,LTI,ATT,FII,NPPact,BR ,NPPh ,LPS, FP/
        m betas /1*12/;

Parameter d(i,j)
        /Orchards       .FFP    48614
        Orchards        .LFP    0
        Orchards        .FBR    70416
        Orchards        .LBR1   0
        Orchards        .LBR2   0
        Orchards        .FEI    11317
        Orchards        .FnR    25318
        Orchards        .LEI    0
        Orchards        .LnR    0
        Orchards        .FW     0
        Orchards        .LW     0
        Orchards        .LS     110761
        Orchards        .UB     44185
        Greenhouses     .FFP    48614
        Greenhouses     .LFP    0
        Greenhouses     .FBR    70416
        Greenhouses     .LBR1   0
        Greenhouses     .LBR2   0
        Greenhouses     .FEI    0
        Greenhouses     .FnR    493318
        Greenhouses     .LEI    0
        Greenhouses     .LnR    0
        Greenhouses     .FW     0
        Greenhouses     .LW     0
        Greenhouses     .LS     110761
        Greenhouses     .UB     44185
        DryHerbaceousCrop       .FFP    2195
        DryHerbaceousCrop       .LFP    4770
        DryHerbaceousCrop       .FBR    11057
        DryHerbaceousCrop       .LBR1   27609
        DryHerbaceousCrop       .LBR2   27609
        DryHerbaceousCrop       .FEI    112
        DryHerbaceousCrop       .FnR    1128
        DryHerbaceousCrop       .LEI    21663
        DryHerbaceousCrop       .LnR    4520
        DryHerbaceousCrop       .FW     0
        DryHerbaceousCrop       .LW     0
        DryHerbaceousCrop       .LS     10712
        DryHerbaceousCrop       .UB     5650
        IrrigatedHerbaceousCrop     .FFP    151151
        IrrigatedHerbaceousCrop     .LFP    12781
        IrrigatedHerbaceousCrop     .FBR    315
```

```
IrrigatedHerbaceousCrop     .LBR1   87229
IrrigatedHerbaceousCrop     .LBR2   87229
IrrigatedHerbaceousCrop     .FEI    173
IrrigatedHerbaceousCrop     .FnR    16595
IrrigatedHerbaceousCrop     .LEI    58052
IrrigatedHerbaceousCrop     .LnR    12112
IrrigatedHerbaceousCrop     .FW     0
IrrigatedHerbaceousCrop     .LW     0
IrrigatedHerbaceousCrop     .LS     61480
IrrigatedHerbaceousCrop     .UB     54676
DryFruitTrees       .FFP    42693
DryFruitTrees       .LFP    0
DryFruitTrees       .FBR    0
DryFruitTrees       .LBR1   0
DryFruitTrees       .LBR2   0
DryFruitTrees       .FEI    4030
DryFruitTrees       .FnR    7534
DryFruitTrees       .LEI    0
DryFruitTrees       .LnR    0
DryFruitTrees       .FW     0
DryFruitTrees       .LW     0
DryFruitTrees       .LS     8070
DryFruitTrees       .UB     77061
IrrigatedFruitTrees     .FFP    54398
IrrigatedFruitTrees     .LFP    0
IrrigatedFruitTrees     .FBR    0
IrrigatedFruitTrees     .LBR1   0
IrrigatedFruitTrees     .LBR2   0
IrrigatedFruitTrees     .FEI    4022
IrrigatedFruitTrees     .FnR    14191
IrrigatedFruitTrees     .LEI    0
IrrigatedFruitTrees     .LnR    0
IrrigatedFruitTrees     .FW     0
IrrigatedFruitTrees     .LW     0
IrrigatedFruitTrees     .LS     6932
IrrigatedFruitTrees     .UB     79576
DryOliveTrees       .FFP    156009
DryOliveTrees       .LFP    9933
DryOliveTrees       .FBR    0
DryOliveTrees       .LBR1   5053
DryOliveTrees       .LBR2   5053
DryOliveTrees       .FEI    443
DryOliveTrees       .FnR    7339
DryOliveTrees       .LEI    45115
DryOliveTrees       .LnR    9413
DryOliveTrees       .FW     0
DryOliveTrees       .LW     0
DryOliveTrees       .LS     17246
DryOliveTrees       .UB     442800
OlivesIrrigated     .FFP    0
OlivesIrrigated     .LFP    0
OlivesIrrigated     .FBR    0
OlivesIrrigated     .LBR1   0
OlivesIrrigated     .LBR2   0
OlivesIrrigated     .FEI    0
OlivesIrrigated     .FnR    0
OlivesIrrigated     .LEI    0
OlivesIrrigated     .LnR    0
OlivesIrrigated     .FW     0
OlivesIrrigated     .LW     0
OlivesIrrigated     .LS     0
OlivesIrrigated     .UB     0
```

```
Vineyard       .FFP    38427
Vineyard       .LFP    812
Vineyard       .FBR    12070
Vineyard       .LBR1   493
Vineyard       .LBR2   493
Vineyard       .FEI    1331
Vineyard       .FnR    12659
Vineyard       .LEI    3688
Vineyard       .LnR    770
Vineyard       .FW     0
Vineyard       .LW     0
Vineyard       .LS     25014
Vineyard       .UB     21082
Scrub    .FFP    0
Scrub    .LFP    0
Scrub    .FBR    0
Scrub    .LBR1   0
Scrub    .LBR2   0
Scrub    .FEI    0
Scrub    .FnR    0
Scrub    .LEI    0
Scrub    .LnR    0
Scrub    .FW     0
Scrub    .LW     0
Scrub    .LS     0
Scrub    .UB     29250
GrazingAreas       .FFP    0
GrazingAreas       .LFP    3279
GrazingAreas       .FBR    0
GrazingAreas       .LBR1   17498
GrazingAreas       .LBR2   17498
GrazingAreas       .FEI    0
GrazingAreas       .FnR    0
GrazingAreas       .LEI    11786
GrazingAreas       .LnR    3107
GrazingAreas       .FW     0
GrazingAreas       .LW     0
GrazingAreas       .LS     29013
GrazingAreas       .UB     0
FlatLeavedForest    .FFP    1353
FlatLeavedForest    .LFP    0
FlatLeavedForest    .FBR    0
FlatLeavedForest    .LBR1   0
FlatLeavedForest    .LBR2   0
FlatLeavedForest    .FEI    3
FlatLeavedForest    .FnR    29
FlatLeavedForest    .LEI    0
FlatLeavedForest    .LnR    0
FlatLeavedForest    .FW     0
FlatLeavedForest    .LW     0
FlatLeavedForest    .LS     0
FlatLeavedForest    .UB     113847
ConiferousForest       .FFP    3975
ConiferousForest       .LFP    0
ConiferousForest       .FBR    0
ConiferousForest       .LBR1   0
ConiferousForest       .LBR2   0
ConiferousForest       .FEI    8
ConiferousForest       .FnR    84
ConiferousForest       .LEI    0
ConiferousForest       .LnR    0
ConiferousForest       .FW     0
```

```
        ConiferousForest      .LW    0
        ConiferousForest      .LS    0
        ConiferousForest      .UB    111225
        ForestPlantations    .FFP   0
        ForestPlantations    .LFP   0
        ForestPlantations    .FBR   0
        ForestPlantations    .LBR1  0
        ForestPlantations    .LBR2  0
        ForestPlantations    .FEI   0
        ForestPlantations    .FnR   0
        ForestPlantations    .LEI   0
        ForestPlantations    .LnR   0
        ForestPlantations    .FW    0
        ForestPlantations    .LW    0
        ForestPlantations    .LS    0
        ForestPlantations    .UB    0
        OtherForests      .FFP   0
        OtherForests      .LFP   0
        OtherForests      .FBR   0
        OtherForests      .LBR1  0
        OtherForests      .LBR2  0
        OtherForests      .FEI   0
        OtherForests      .FnR   0
        OtherForests      .LEI   0
        OtherForests      .LnR   0
        OtherForests      .FW    0
        OtherForests      .LW    0
        OtherForests      .LS    0
        OtherForests      .UB    115200/;

Parameter CurrentCover(i)
        /Orchards 4.6
        Greenhouses 0.3
        DryHerbaceousCrop 9.7
        IrrigatedHerbaceousCrop 5.5
        DryFruitTrees 180.0
        IrrigatedFruitTrees 3.3
        DryOliveTrees 1.7
        OlivesIrrigated 0.0
        Vineyard 0.8
        Scrub 185.7
        GrazingAreas 21.6
        FlatLeavedForest 176.1
        ConiferousForest 422.9
        ForestPlantations 0.0
        OtherForests 1.6/;

Parameter LandChange(i)
        /Orchards 0.5
        Greenhouses 0.5
        DryHerbaceousCrop 0.5
        IrrigatedHerbaceousCrop 0.5
        DryFruitTrees 0.5
        IrrigatedFruitTrees 0.5
        DryOliveTrees 0.5
        OlivesIrrigated 0.5
        Vineyard 0.5
        Scrub 0.5
        GrazingAreas 0.5
        FlatLeavedForest 0.5
        ConiferousForest 0.5
        ForestPlantations 0.5
```

```
        OtherForests 0.5/;

Parameter energy1current(j);

scalar urbanAreas;
scalar totLand, currentenergy1FFP,currentenergy1LFP,currentenergy1FBR ,
        currentenergy1LBR1,currentenergy1LBR2,currentenergy1FEI,currentenergy1FnR,
        currentenergy1LEI ,currentenergy1LnR ,currentenergy1FW,currentenergy1LW ,
        currentenergy1LS,currentenergy1UB,currentenergy2EI,currentenergy2FTI,
        currentenergy2LTI,currentenergy2ATT,currentenergy2FII,currentenergy2NPPact,
        currentenergy2BR ,currentenergy2NPPh ,currentenergy2LPS, currentenergy2FP,
        currentbeta1,currentbeta2,currentbeta3,currentbeta4,
        currentbeta5,currentbeta6,currentbeta7,currentbeta8,currentbeta9,
        currentbeta10,currentbeta11,currentbeta12,currentk1,currentk2,currentk3,
        currentgamma_F, currentgamma_L, currentalpha_F, currentalpha_L,
        currentE,currentI,currentL, currentELIA,currentEInR;

        urbanAreas=53.68;
        totLand = sum(i,CurrentCover(i))+ urbanAreas;
        currentenergy1FFP = sum(i, d(i,'FFP')*CurrentCover(i));
        currentenergy1LFP = sum(i, d(i,'LFP')*CurrentCover(i));
        currentenergy1FBR = sum(i, d(i,'FBR')*CurrentCover(i));
        currentenergy1LBR1 = sum(i, d(i,'LBR1')*CurrentCover(i));
        currentenergy1LBR2 = sum(i, d(i,'LBR2')*CurrentCover(i));
        currentenergy1FEI = sum(i, d(i,'FEI')*CurrentCover(i));
        currentenergy1FnR = sum(i, d(i,'FnR')*CurrentCover(i));
        currentenergy1LEI = sum(i, d(i,'LEI')*CurrentCover(i));
        currentenergy1LnR = sum(i, d(i,'LnR')*CurrentCover(i));
        currentenergy1FW = sum(i, d(i,'FW')*CurrentCover(i));
        currentenergy1LW = sum(i, d(i,'LW')*CurrentCover(i));
        currentenergy1LS = sum(i, d(i,'LS')*CurrentCover(i));
        currentenergy1UB = sum(i, d(i,'UB')*CurrentCover(i));
        currentenergy2EI = currentenergy1FEI + currentenergy1LEI;
        currentenergy2FII = currentenergy1LS + currentenergy1FBR;
        currentenergy2FTI = currentenergy1FnR + currentenergy1FEI + currentenergy2FII;
        currentenergy2LTI = currentenergy1LnR + currentenergy1LEI + currentenergy1LBR1;
        currentenergy2BR = currentenergy1FBR + currentenergy1LBR1;
        currentenergy2NPPh = currentenergy2BR + currentenergy1FFP + currentenergy1FW;
        currentenergy2ATT = currentenergy1UB + currentenergy2FTI;
        currentenergy2NPPact = currentenergy1UB + currentenergy2NPPh;
        currentenergy2LPS = currentenergy1LS + currentenergy1LFP + currentenergy1LW;
        currentenergy2FP = currentenergy1FFP + currentenergy1LFP;
        currentbeta1 = currentenergy2NPPh/currentenergy2NPPact;
        currentbeta2 = currentenergy1UB/currentenergy2NPPact;
        currentbeta3 = currentenergy2FTI/currentenergy2ATT;
        currentbeta4 = currentenergy1UB/currentenergy2ATT;
        currentbeta5 = currentenergy1FFP/currentenergy2NPPh;
        currentbeta6 = currentenergy2BR/currentenergy2NPPh;
        currentbeta7 = currentenergy1FEI/currentenergy2FTI;
        currentbeta8 = currentenergy2FII/currentenergy2FTI;
        currentbeta9 = currentenergy1LEI/currentenergy2LTI;
        currentbeta10 = currentenergy1LBR1/currentenergy2LTI;
        currentbeta11 = currentenergy1LFP/currentenergy2LPS;
        currentbeta12 = currentenergy1LS/currentenergy2LPS;
        currentk1 = currentenergy1UB/(currentenergy1UB+currentenergy2BR+currentenergy1LS);
        currentk2 = currentenergy2BR/(currentenergy1UB+currentenergy2BR+currentenergy1LS);
        currentk3 = currentenergy1LS/(currentenergy1UB+currentenergy2BR+currentenergy1LS);
        currentgamma_F                                                             =
(currentenergy1UB+currentenergy2NPPh)/(2*(currentenergy1UB+currentenergy2NPPh+currentenergy1
FW));


```

```
        currentgamma_L =
(currentenergy1LS+currentenergy1LFP)/(2*(currentenergy1LS+currentenergy1LFP+currentenergy1LW
));
        currentalpha_F = (currentenergy1FEI)/(2*(currentenergy1FEI+currentenergy1FnR));
        currentalpha_L = (currentenergy1LEI)/ (2*(currentenergy1LEI+currentenergy1LnR));

        currentE =
0.5*(currentk1*(currentbeta2+currentbeta4)+currentk2*(currentbeta6+currentbeta8)+currentk3*(current
beta10+currentbeta12));
        currentI = (-
1/6)*(currentbeta1*log2(currentbeta1)+currentbeta2*log2(currentbeta2)+currentbeta3*log2(currentbeta3
)+currentbeta4*log2(currentbeta4)+currentbeta5*log2(currentbeta5)+currentbeta6*log2(currentbeta6)+c
urrentbeta7*log2(currentbeta7)+currentbeta8*log2(currentbeta8)+currentbeta9*log2(currentbeta9)+curr
entbeta10*log2(currentbeta10)+currentbeta11*log2(currentbeta11)+currentbeta12*log2(currentbeta12))
*(currentgamma_F+currentgamma_L)*(currentalpha_F+currentalpha_L);
        currentL = (-1)*
((CurrentCover('Orchards')/totLand)*(log(CurrentCover('Orchards')/totLand)/log(12))
+(CurrentCover('Greenhouses')/totLand)*(log(CurrentCover('Greenhouses')/totLand)/log(12))
+(CurrentCover('DryHerbaceousCrop')/totLand)*(log(CurrentCover('DryHerbaceousCrop')/totLand)/log
(12))
+(CurrentCover('IrrigatedHerbaceousCrop')/totLand)*(log(CurrentCover('IrrigatedHerbaceousCrop')/tot
Land)/log(12))
+(CurrentCover('DryFruitTrees')/totLand)*(log(CurrentCover('DryFruitTrees')/totLand)/log(12))
+(CurrentCover('IrrigatedFruitTrees')/totLand)*(log(CurrentCover('IrrigatedFruitTrees')/totLand)/log(12
))
+(CurrentCover('DryOliveTrees')/totLand)*(log(CurrentCover('DryOliveTrees')/totLand)/log(12))
+(CurrentCover('Vineyard')/totLand)*(log(CurrentCover('Vineyard')/totLand)/log(12))
+(CurrentCover('Scrub')/totLand)*(log(CurrentCover('Scrub')/totLand)/log(12))
+(CurrentCover('GrazingAreas')/totLand)*(log(CurrentCover('GrazingAreas')/totLand)/log(12))
+((CurrentCover('FlatLeavedForest')+CurrentCover('OtherForests'))/totLand)*(log((CurrentCover('FlatL
eavedForest')+CurrentCover('OtherForests'))/totLand)/log(12))
+(CurrentCover('ConiferousForest')/totLand)*(log(CurrentCover('ConiferousForest')/totLand)/log(12))
)*(1-(urbanAreas/totLand));
        currentELIA = (currentE*currentI*currentL/0.6169)**(1/3);
        currentEInR = currentenergy1FnR + currentenergy1LnR;


variables  E, Info, LanSt, ELIA, product, EInR Indicators;
Positive variables
        covers(i) Land Covers Associated to each Land Use
        energy1(j) Value of flows in Primary Flows
        energy2(k) Value of flows in Secondary Flows
        beta(m) beta's
        k1,k2,k3, gamma_F, gamma_L, alpha_F, alpha_L,W,livestock;

beta.l(m) = 1;
covers.l(i) = CurrentCover(i);
covers.up(i) = (1+LandChange(i))*CurrentCover(i);
covers.lo(i) = (1-LandChange(i))*CurrentCover(i);


Equations
        TotalLand
        TFFP
        TLFP
        TFBR
        TLBR1
        TLBR2
        TFEI
        TFnR
        TLEI
        TLnR
```

```
         TFW
         TLW
         TLS
         TUB
         Balance1
         Balance2
         Balance3
         Balance4
         Balance5
         Balance6
         Balance7
         Balance8
         Balance9
         Balance10
         F_L_Balance
         Defbeta1
         Defbeta2
         Defbeta3
         Defbeta4
         Defbeta5
         Defbeta6
         Defbeta7
         Defbeta8
         Defbeta9
         Defbeta10
         Defbeta11
         Defbeta12
         Defk1
         Defk2
         Defk3
         Defgamma_F
         Defgamma_L
         Defalpha_F
         Defalpha_L
         DefE
         DefI
         DefL
         DefELIA
         production
         nonRenewable
         Constraint1
         Constraint2
         Constraint3
         Constraint4
         LimE
         LimL
         LimI
         LimELIA
         Lvstock
         LimLvstockd
         LimLvstocku;

TotalLand..           sum(i, covers(i)) =e= totLand-urbanAreas;

TLFP..                energy1('LFP') =e= currentenergy1LFP*W;
TLBR2..               energy1('LBR2') =e= currentenergy1LBR2*W;
TLEI..                energy1('LEI') =e= currentenergy1LEI*W;
TLnR..                energy1('LnR') =e= currentenergy1LnR*W;
TLW..                 energy1('LW') =e= currentenergy1LW*W;
TLS..                 energy1('LS') =e= currentenergy1LS*W;

TFFP..                energy1('FFP') =e= sum(i, d(i,'FFP')*covers(i));
```

```
TFBR..              energy1('FBR') =e= sum(i, d(i,'FBR')*covers(i));
TLBR1..             energy1('LBR1') =e= sum(i, d(i,'LBR1')*covers(i));
TFEI..              energy1('FEI') =e= sum(i, d(i,'FEI')*covers(i));
TFnR..              energy1('FnR') =e= sum(i, d(i,'FnR')*covers(i));
TFW..               energy1('FW') =e= sum(i, d(i,'FW')*covers(i));
TUB..               energy1('UB') =e= sum(i, d(i,'UB')*covers(i));

Balance1..          energy2('EI') =e= energy1('FEI') + energy1('LEI');
Balance2..          energy2('FTI') =e= energy1('FnR') + energy1('FEI') + energy2('FII');
Balance3..          energy2('LTI') =e= energy1('LnR') + energy1('LEI') + energy1('LBR1');
Balance4..          energy2('ATT') =e= energy1('UB') + energy2('FTI');
Balance5..          energy2('FII') =e= energy1('LS') + energy1('FBR');
Balance6..          energy2('NPPact') =e= energy1('UB') + energy2('NPPh');
Balance7..          energy2('BR') =e= energy1('FBR') + energy1('LBR1');
Balance8..          energy2('NPPh') =e= energy2('BR') + energy1('FFP') + energy1('FW');
Balance9..          energy2('LPS') =e= energy1('LS') + energy1('LFP') + energy1('LW');
Balance10..         energy2('FP') =e= energy1('FFP') + energy1('LFP');
F_L_Balance..       energy1('LBR1') =e= energy1('LBR2');
Defbeta1..          beta('1')*energy2('NPPact') =e= energy2('NPPh');
Defbeta2..          beta('2')*energy2('NPPact') =e= energy1('UB');
Defbeta3..          beta('3')*energy2('ATT') =e= energy2('FTI');
Defbeta4..          beta('4')*energy2('ATT') =e= energy1('UB');
Defbeta5..          beta('5')*energy2('NPPh') =e= energy1('FFP');
Defbeta6..          beta('6')*energy2('NPPh') =e= energy2('BR');
Defbeta7..          beta('7')*energy2('FTI') =e= energy1('FEI');
Defbeta8..          beta('8')*energy2('FTI') =e= energy2('FII');
Defbeta9..          beta('9')*energy2('LTI') =e= energy1('LEI') ;
Defbeta10..         beta('10')*energy2('LTI') =e= energy1('LBR1');
Defbeta11..         beta('11')*energy2('LPS') =e= energy1('LFP') ;
Defbeta12..         beta('12')*energy2('LPS') =e= energy1('LS');
Defk1..             k1*(energy1('UB')+energy2('BR')+energy1('LS')) =e= energy1('UB');
Defk2..             k2*(energy1('UB')+energy2('BR')+energy1('LS')) =e= energy2('BR');
Defk3..             k3*(energy1('UB')+energy2('BR')+energy1('LS')) =e= energy1('LS');
Defgamma_F..                    gamma_F*2*(energy1('UB')+energy2('NPPh')+energy1('FW'))   =e=
(energy1('UB')+energy2('NPPh'));
Defgamma_L..                    gamma_L*2*(energy1('LS')+energy1('LFP')+energy1('LW'))   =e=   (
energy1('LS')+energy1('LFP'));
Defalpha_F..        alpha_F*2*(energy1('FEI')+energy1('FnR') )=e=  energy1('FEI');
Defalpha_L..        alpha_L*2*(energy1('LEI')+energy1('LnR')) =e= energy1('LEI');
DefE..              E  =e= 0.5*(k1*(beta('2')+beta('4'))+k2*(beta('6')+beta('8'))+k3*(beta('10')+beta('12')));
DefI..                                   Info   =e=   (-1/6)*sum(m   $   (beta.L(m)   >   0),
beta(m)*log2(beta(m)))*(gamma_F+gamma_L)*(alpha_F+alpha_L);
DefL..                                                                 LanSt     =e=     (-1)*
((covers('Orchards')/totLand)*(log(covers('Orchards')/totLand)/log(12))+(covers('Greenhouses')/totLand
)*(log(covers('Greenhouses')/totLand)/log(12))+(covers('DryHerbaceousCrop')/totLand)*(log(covers('Dr
yHerbaceousCrop')/totLand)/log(12))+(covers('IrrigatedHerbaceousCrop')/totLand)*(log(covers('Irrigate
dHerbaceousCrop')/totLand)/log(12))+(covers('DryFruitTrees')/totLand)*(log(covers('DryFruitTrees')/to
tLand)/log(12))
+(covers('IrrigatedFruitTrees')/totLand)*(log(covers('IrrigatedFruitTrees')/totLand)/log(12))
+(covers('DryOliveTrees')/totLand)*(log(covers('DryOliveTrees')/totLand)/log(12))
+(covers('Vineyard')/totLand)*(log(covers('Vineyard')/totLand)/log(12))
+(covers('Scrub')/totLand)*(log(covers('Scrub')/totLand)/log(12))
+(covers('GrazingAreas')/totLand)*(log(covers('GrazingAreas')/totLand)/log(12))
+((covers('FlatLeavedForest')+covers('OtherForests'))/totLand)*(log((covers('FlatLeavedForest')+covers
('OtherForests'))/totLand)/log(12))
+(covers('ConiferousForest')/totLand)*(log(covers('ConiferousForest')/totLand)/log(12))          )*(1-
(urbanAreas/totLand));
DefELIA..           ELIA =e= (E*Info*LanSt/0.6169)**(1/3);
production..        product =e= energy2('FP');
nonRenewable..      EInR =e= energy1('FnR')+ energy1('LnR');
Constraint1..       energy2('FP')=g=  0.9*currentenergy2FP;
Constraint2..       E =g= 0.9*currentE;
```

```
Constraint3..         Info =g= 0.9*currentI;
Constraint4..         LanSt =g= 0.9*currentL;

Lvstock..           livestock =e= W;
LimLvstockd..         W =g= 0;
LimLvstocku..         W =l= 2;


Model FirstSetting /TotalLand,Constraint1,Balance1,Balance2,
        Balance3,Balance4,Balance5,Balance6,Balance7,Balance8,Balance9,Balance10,
        TFFP,TLFP,TFBR,TLBR1,TLBR2,TFEI,TFnR,TLEI,TLnR,TFW,TLW,TLS,TUB,
        F_L_Balance,Defbeta1,Defbeta2,Defbeta3,Defbeta4,Defbeta5,
        Defbeta6,Defbeta7,Defbeta8,Defbeta9,Defbeta10,Defbeta11,Defbeta12,
        Defk1,Defk2,Defk3,Defgamma_F,Defgamma_L,Defalpha_F,Defalpha_L,DefE,DefI,DefL,
DefELIA, production,nonRenewable
        Lvstock,LimLvstockd,LimLvstocku/;
Model SecondSetting /TotalLand,production, Constraint2,Constraint3,Balance1,Balance2,
        Balance3,Balance4,Balance5,Balance6,Balance7,Balance8,Balance9,Balance10,
        TFFP,TLFP,TFBR,TLBR1,TLBR2,TFEI,TFnR,TLEI,TLnR,TFW,TLW,TLS,TUB,
        F_L_Balance,Defbeta1,Defbeta2,Defbeta3,Defbeta4,Defbeta5,
        Defbeta6,Defbeta7,Defbeta8,Defbeta9,Defbeta10,Defbeta11,Defbeta12,
        Defk1,Defk2,Defk3,Defgamma_F,Defgamma_L,Defalpha_F,Defalpha_L,DefE,DefI,DefL,
DefELIA, nonRenewable
        Lvstock,LimLvstockd,LimLvstocku/;
Model ThirdSetting /TotalLand, Constraint4,nonRenewable,Balance1,Balance2,
        Balance3,Balance4,Balance5,Balance6,Balance7,Balance8,Balance9,Balance10,
        TFFP,TLFP,TFBR,TLBR1,TLBR2,TFEI,TFnR,TLEI,TLnR,TFW,TLW,TLS,TUB,
        F_L_Balance,Defbeta1,Defbeta2,Defbeta3,Defbeta4,Defbeta5,
        Defbeta6,Defbeta7,Defbeta8,Defbeta9,Defbeta10,Defbeta11,Defbeta12,
        Defk1,Defk2,Defk3,Defgamma_F,Defgamma_L,Defalpha_F,Defalpha_L,DefE,DefI,DefL,
DefELIA, production
        Lvstock,LimLvstockd,LimLvstocku/;


Solve FirstSetting using NLP maximizing ELIA;
*Solve SecondSetting using NLP maximizing product;
*Solve ThirdSetting using NLP minimizing EInR;
```