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Energy-Landscape Optimization for Land use Planning. Application in the Barcelona Metropolitan Area

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Energy-Landscape Optimization for Land Use Planning. Application in the Barcelona Metropolitan Area

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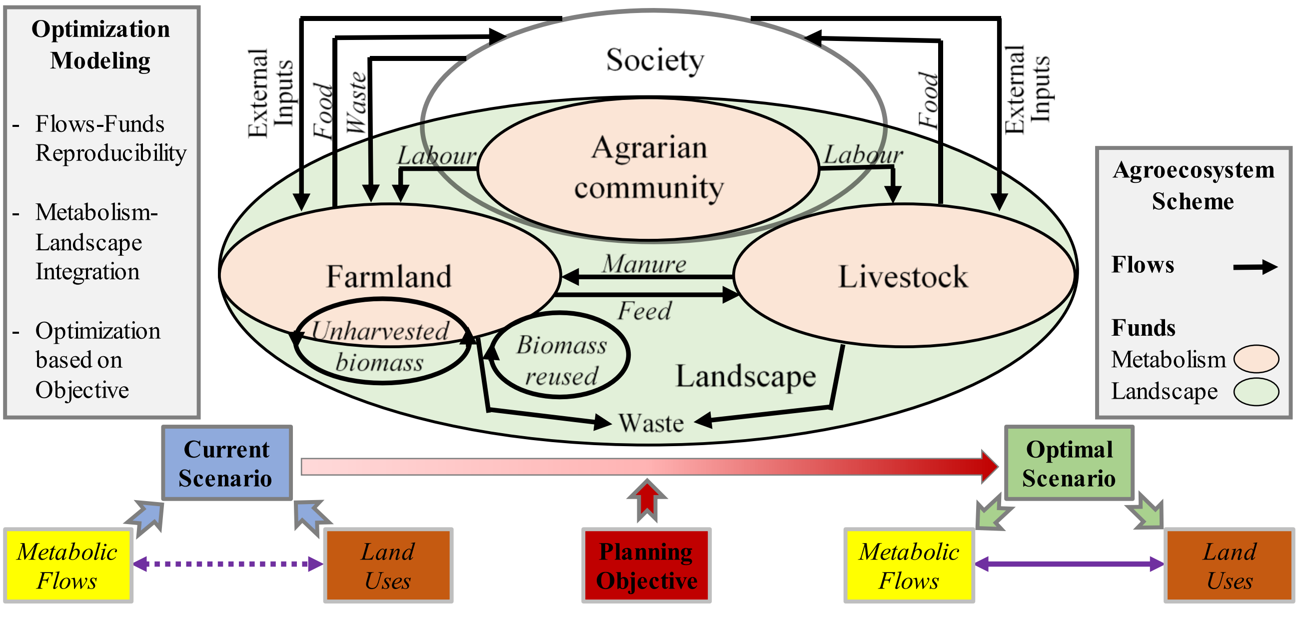
Graphical Abstract



Abstract

Rapid population growth and urban expansion in metropolitan areas have led to a dramatic increase in food demand. In most cases, urban sprawl occurs in unplanned ways, forcing peri-urban agriculture to adopt detrimental practices for biodiversity conservation and metabolic efficiency (i.e. landscape homogenization and dependence on non-renewable external inputs), facing the food-biodiversity dilemma. In order to ameliorate these negative effects over the metropolitan socioecological system, researchers have focused on developing comprehensive indicators to support sustainable urban expansion in metropolitan areas. In this paper, we use these indicators to develop an Energy-Landscape Optimization (E-LO), a nonlinear model designed for land use planning by means of considering biophysical constraints. Then, we test the model in a representative Mediterranean bio-cultural landscape in the Barcelona metropolitan area (Spain). The E-LO results allow us to propose different land use configurations for both conventional and organic agriculture, taking into account the associated socio-metabolic balances and the related landscape functional structures, with the aim to meet different societal objectives. We have fruitfully tested three settings: i) to increase conditions to host farm associated biodiversity, ii) to increase agricultural production, and iii) to minimize dependence on non-renewable external inputs. According to these socioecological objectives, we have obtained the best landscape-metabolism integration, which is a useful methodology for sustainable land use policy. This socioecological perspective is necessary for the new paradigm on agroecosystem management and landscape planning, and can help advancing towards functional green infrastructures in metropolitan areas, especially in the climate change and socioecological transition global context.

Key words

Energy-Landscape Integrated Analysis; Landscape Agro-ecology; Land Use Policy; Agro-ecological Transition; Optimisation Modelling.

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 2001). 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 (Sterling and Ducharne 2008; Ellis et al. 2008). The past century was witness to particularly severe LUCC, which affected habitat and biodiversity conservation (Newbold et al. 2015; UN-IPBES 2019). 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 (Tilman et al. 2002; Mayer et al. 2015).

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). Along with the growth in population, comes the increasing need for food. The main strategies to respond to this growing food demand are: i) to increase production per unit area of land, and ii) to increase the land used for production of food. One of the easiest and 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 external 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 some other reproductive characteristics of agroecosystems that we call "funds" (Giampietro 1997).

Sustainable agroecosystems are to be designed by optimizing their functioning with respect to the social aim driving them but constrained to their reproduction imperatives (Padró et al. 2019a). To solve this food-biodiversity dilemma (Cardinale et al. 2012) a 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. 2018). 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. 2020, Padró et al. forthcoming). To that aim, the objective of this paper is to develop an Energy-Landscape Optimization (E-LO) nonlinear modelling based on Energy-Landscape Integrated Analysis (ELIA) (Marull et al. 2016) 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 in relation with both conventional and organic agriculture. The E-LO is designed to help land-use policy-makers and agroecosystem managers to advance towards a socioecological transition taking into account societal priorities and environmental constrains in a human-transformed landscape.

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. 2016). The latter is a socio-metabolic and landscape ecology methodology that brings together landscape patterns and processes and how agrarian flows (such as energy, fertilizers or production) are distributed among the landscape. This tool is particularly useful to represent complex performances of cultural landscapes as human-nature co-evolutionary systems.

2.1. Energy-Landscape Integrated Analysis (ELIA)

2.1.1. Agroecosystem Energy Flows from a Landscape Ecology Standpoint

ELIA summarizes human coproduction with nature (Marull et al., 2016) through the connexion between energy flows (Fig. 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 (Fig. 1).

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 (Fig. 1).

Then *BR* splits into the 'livestock' subsystem (Fig. 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 (Fig. 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 (Marull et al. 2016).

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 (Ho and Ulanowicz 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 1966).

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.

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 (Fig. 1) is a metric of *E* and *I*, which contributes to the energy potentially available for trophic chains existing in agroecosystems.

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 1990). 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 (Fig. 1) entail that 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. 1):

Eq.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 (Fig 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 cultural 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.

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, 1996). 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. 2020). 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 2017). This work used a Shannon-Wiener Index adaptation over each pair of β_i's (Fig. 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. 2).

Eq. 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 (Tello et al. 2016).

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.

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. 2003) (eq. 3).

Eq. 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. 2012).

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 leads 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. 2016). 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. 2019) (eq. 4).

Eq. 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 impression 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. 2019). This calls for an integrated research of coupled human-natural systems aimed at revealing the functioning of complex structures and processes (Liu et al. 2007).

2.2. Energy-Landscape Optimization (E-LO)

2.2.1. Case Study Databases

This work uses data of land covers and the associated energy flows of Sant Climent de Llobregat (Fig. 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.

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 (https://www.creaf.uab.es/mcsc/). 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. 2020).

Metabolic flows are calculated from land cover and farming databases on agriculture, livestock, forestry and trade following the procedure described in Marco et al. (2017). Land surfaces are taken from DARPA (http://agricultura.gencat.cat/ca/inici), together with production and yields from DUN (http://agricultura.gencat.cat/ca/ambits/desenvolupament-rural/declaracio-unica-agraria/) and SIGPAC (https://www.mapa.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/default.aspx) databases. From MAPAMA (https://www.mapama.gob.es/) 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 (https://www.idescat.cat/?lang=es) data on agricultural machinery according to their ownership have been used. To simulate organic agriculture scenarios we have followed the CCPAE recommendations (http://www.ccpae.org/index.php?option=com_frontpage&Itemid=1&lang=en; see Table 1).

2.2.2. Energy Flows Definition

The energy flows are essentially the nodes of the ELIA graph previously seen in Fig. 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 (Fig. 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 ($l = 1, 2 \ldots 13$), $k_1, k_2, k_3, \gamma_F, \gamma_L, \alpha_F, \alpha_L$, the indicators *E*, *I*, *L* and finally *ELIA*.

2.2.3. Formulation

Departing from the variables x_i (land covers; $i = 1, 2\ldots 13$), e_j^1 (primary energy flows; $j = 1, 2\ldots 13$), e_k^2 (secondary energy flows; $k = 1, 2\ldots 10$), β_l (incoming-outgoing coefficients; $l = 1, 2 \ldots 12$), 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

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

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

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

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

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

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

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

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

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

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

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

For the nonlinear models, there are boundary constraints considered in the implementations. The general form for these constraints are $LowerBound_i \leq x_i \leq UpperBound_i$. 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, $LandChange_i$ can be specified according to the properties of x_i, but with the available data these $LandChange_i$ values are considered. Later on, a parametric analysis is conducted, in which we change $LandChange_i$ (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 ($d_{i,j}$).

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): General Algebraic Modelling System (GAMS) (https://www.gams.com/), Constrained Optimization BY Linear Approximation (COBYLA) (Powell 2007) and Improved Stochastic Ranking Evolution Strategy (ISRES) (Lones 2011). C library for nonlinear programming is used. 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 by GAMS, and considering the fact that GAMS is much faster than running the C program using COBYLA, we can say the results obtained by GAMS are acceptable.

Second Setting: maximize Final Produce (e^2_{10}), 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 ($e^1_6 + e^1_8$), 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 GAMS tool is used in the research (Torabi 2019), because the starting points in COBYLA are random and may affect the results, as well as the small difference with COBYLA in the objective function, and the execution of GAMS being faster than the C program using COBYLA. In this paper, we aim at analysing the effects that changing the parameters, specifically $LandChange_i$, may have on the results of each setting. We recall that so far in this study, 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 Annex C we present an example of the model syntax (Table 4C).

3. Results and Discussion

In order to see the effect of $LandChange_i$ on the optimization scenarios, Fig. 3a and Fig. 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 A3 and B3. 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 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. Fig. 3b and Fig. 4b show the results of S1, S2 and S3 in terms of *ELIA*, *FP* and *EInr* in conventional and organic agriculture. Tables A1 and B1 show the energy flows and *E*, and Tables A2 and B2 show the energy coefficients and *I*.

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 (Fig. 3b), passing from 1.0% to 2.7%, for a land cover change of 10% and 50% respectively (Fig. 5). All land cover categories increase their area in percentage (Table A3), 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 (Fig. 3b).

This increase in *ELIA* values is higher in organic agriculture (Fig. 4b), passing from 2.4% to 5.3%, for a land cover change of 10% and 50% respectively (Fig. 5). Again, all land cover categories increase their area in percentage (Table A3), 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 (Fig. 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 (Fig. 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* (Fig. 3b and 4b), rather than reducing *E* and *I* –see Tables A1, B1, A2 and B2-, 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 (Fig. 5), and therefore it underlines the importance of an agro-ecological transition for biodiversity conservation.

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* (Fig. 3b), passing from 7.6% to 37.8%, for a land cover change of 10% and 50% respectively (Fig. 5). All land cover categories increase their area in percentage (Table A3), 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 A3).

The increase in *FP* values is much higher in organic agriculture (Fig. 4b), passing from 95.1% to 157.0%, for a land cover change of 10% and 50% respectively (Fig. 5). All land cover categories increase their area in percentage (Table B3), 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 A1, B1, A2 and B2). 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.

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* (Fig. 3b), passing from -9.9% to -49.3%, for a land cover change of 10% and 50% respectively (Fig. 5); all land cover categories decrease their area in percentage (Table A3), 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 (Fig. 4b) passing from 26.9% to 58.8%, for a land cover change of 10% and 50% respectively (Fig. 5); all land cover categories increase their area in percentage (Table B3), 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 more 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 (Fig. 5), in organic agriculture *FP* passes from an increase of 64.3% to 2.6%, for a land cover change of 10% and 50% respectively (Fig. 5). Consequently, there is room for an agro-ecological transition and climate change mitigation and adaptation without compromising the socio-economic viability of farm systems in metropolitan areas.

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 other metropolis of the world. The application of E-LO in specific land use policies combined with an agroecological 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 this 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 socioecological 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 agro-ecological transition for biodiversity conservation. However, it results as well in an increase of non-renewable external inputs (*EInr*), and it should be corrected in the model. 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 more 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 (e.g. using cellular automata modelling) 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.

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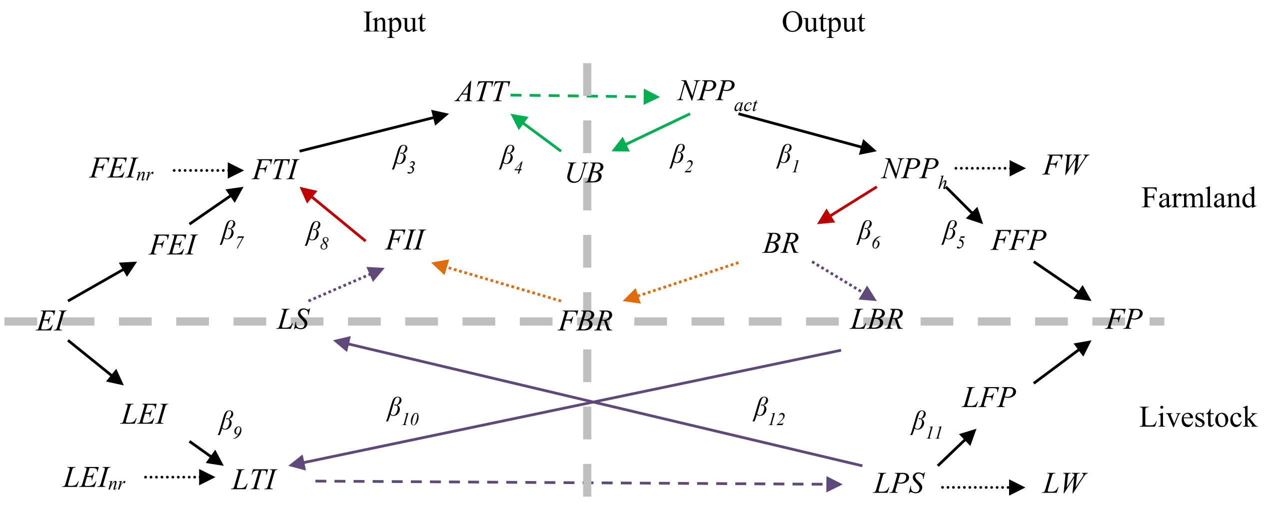
Figures

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

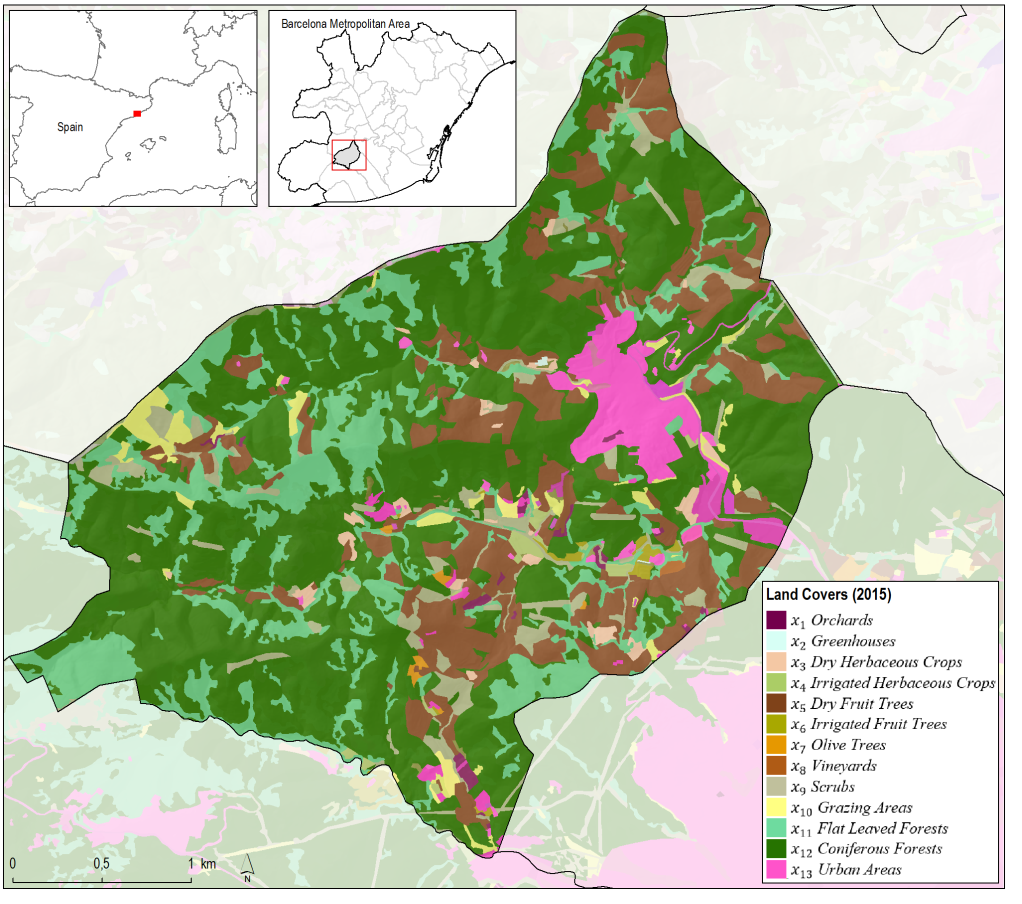


Variables: Actual Net Primary Production (*NPP_{act}*); Unharvested Biomass (*UB*); Harvested Net Primary Production (*NPP_h*); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); 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*). *nr* means no-renewable. β_i's are the incoming-outgoing coefficients.

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

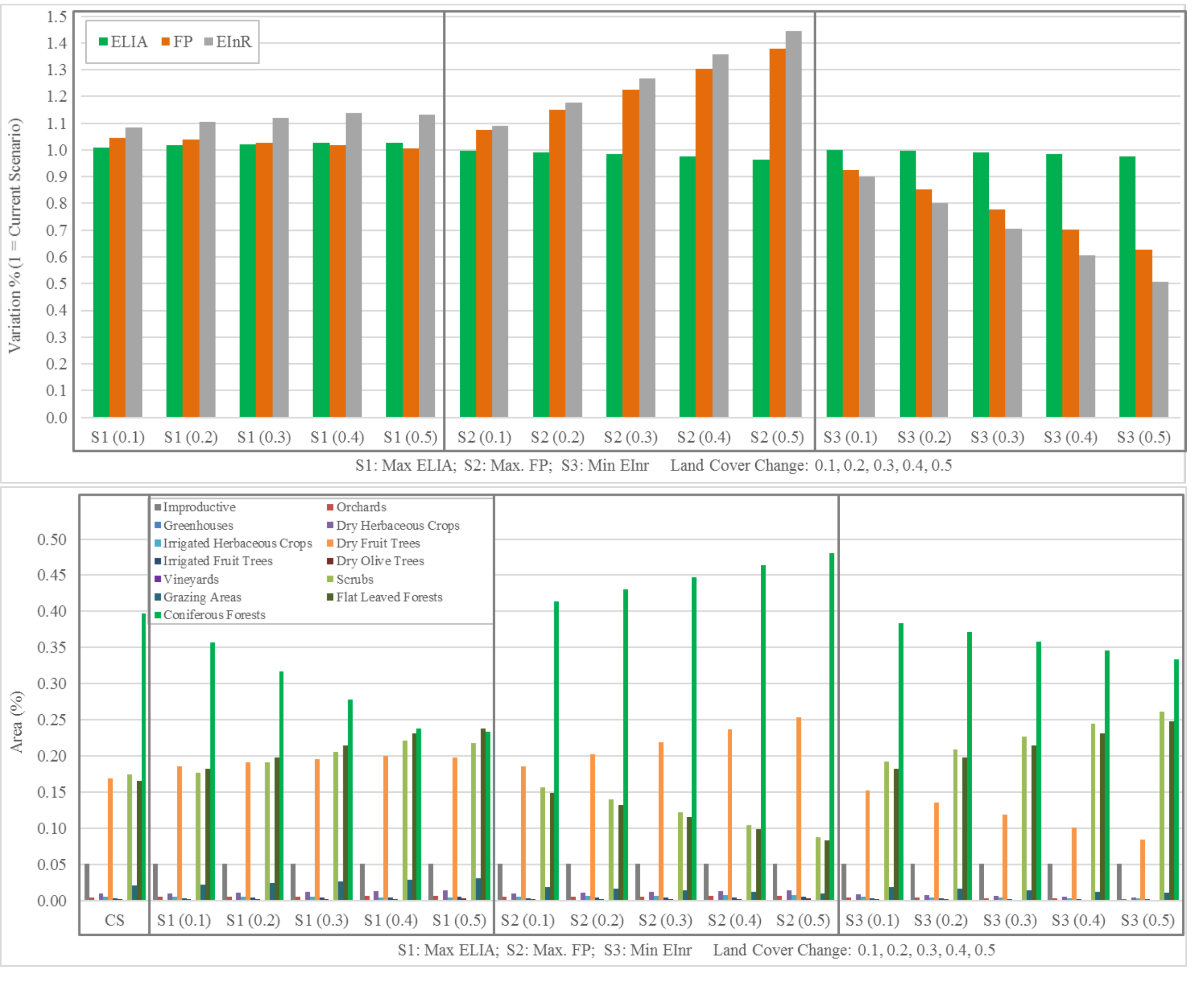
Note: [1] The colours of the arrows represent the 'natural' (green), 'farmland' (red) or 'livestock' (purple) subsystems.

Figure 2. Land covers in 'Sant Climent de Llobregat' municipality, Barcelona Metropolitan Area, Spain.



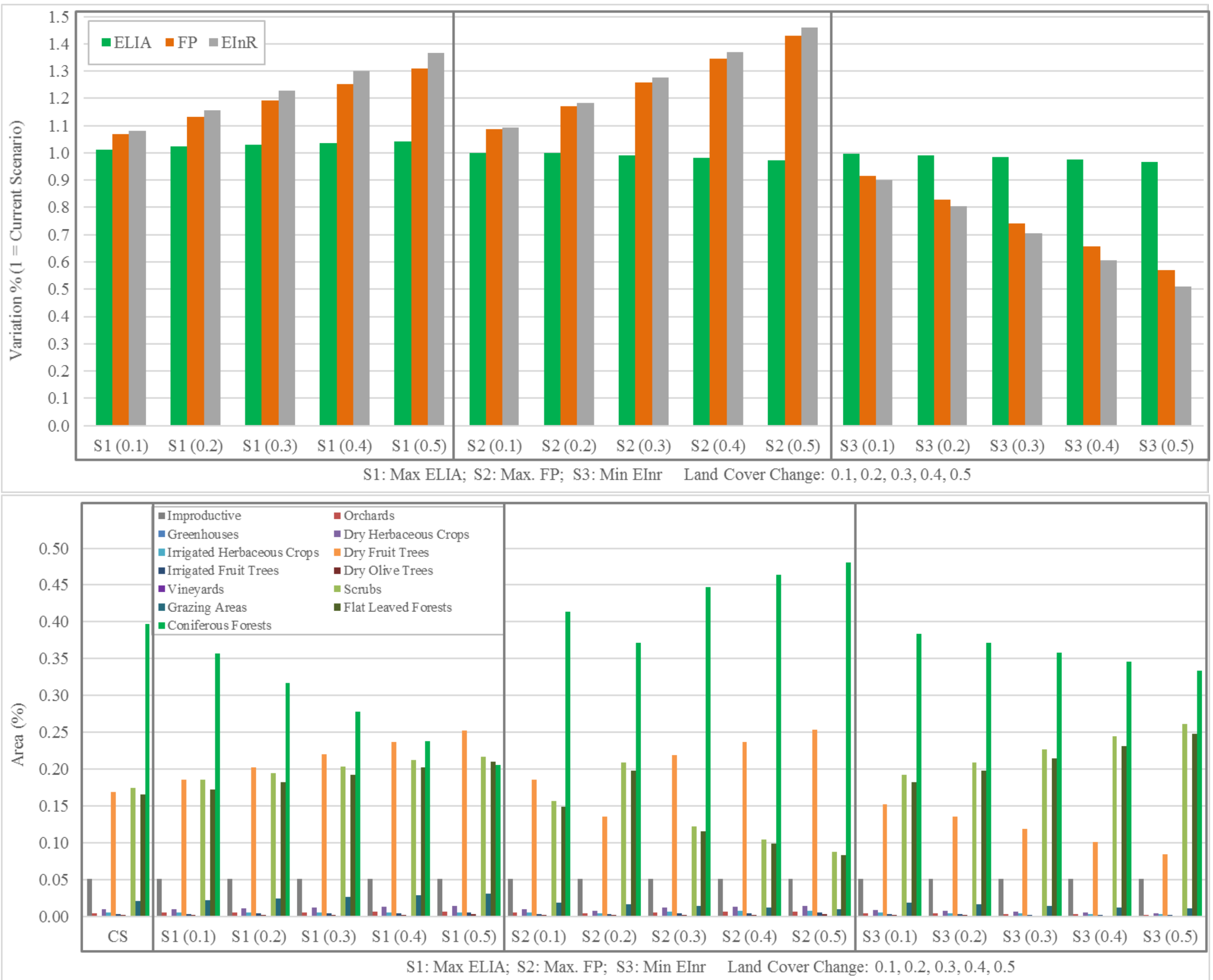
Source: Centre for Ecological Research and Forestry Applications (CREAF, https://www.creaf.uab.es/mcsc/).

Figure 3. Optimization scenarios for conventional agriculture in ‘Sant Climent de Llobregat’municipality.



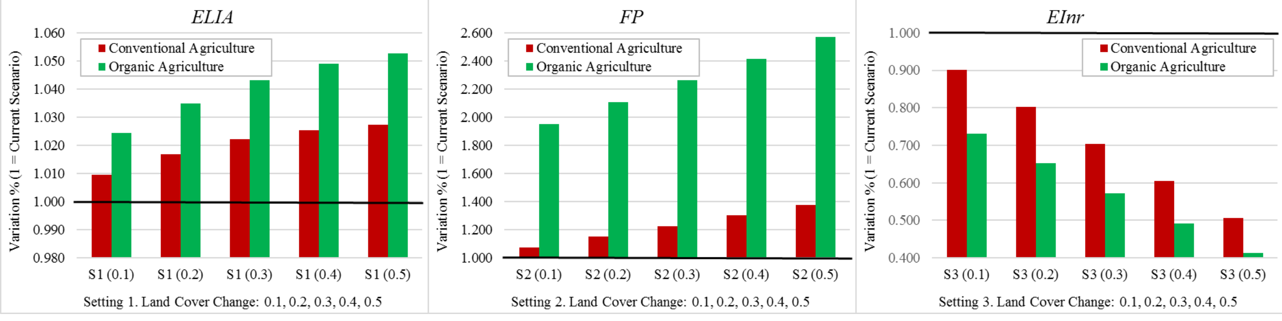
Note: CS is the Current Scenario; S1 is the First Setting (maximizing *ELIA* while maintaining at least 90% of *FP*); S2 is the Second Setting (maximizing *FP* while *E* and *I* do not decrease more than 10% of the current amount); S3 is the Third Setting (minimizing *EInr* while the indicator *L* is 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.

Figure 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.

Figure 5. 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.



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.

Tables

Table 1. Conditions and assumptions for the modeling of conventional and organic scenarios

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

Source: Our own

Supplementary Material

A. Optimization scenarios for conventional agriculture

Table A1. 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 A2. 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 A3. 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)
Improductive	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.

B. Optimization scenarios for organic agriculture

Table B1. 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 B2. 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 B3. 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.

C. 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 C1 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 C2 we present the different values for conventional management and for the organic in Table C3. 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 C1. 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 C2. 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 C3. 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

Table C4. 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
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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
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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+curr
entenergy1FW));
```

```
	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*(currentbeta10+currentbeta12));
	currentI = (-1/6)*(currentbeta1*log2(currentbeta1)+currentbeta2*log2(currentbeta2)+currentbeta3*log2(currentbeta3)+currentbeta4*log2(currentbeta4)+currentbeta5*log2(currentbeta5)+currentbeta6*log2(currentbeta6)+currentbeta7*log2(currentbeta7)+currentbeta8*log2(currentbeta8)+currentbeta9*log2(currentbeta9)+currentbeta10*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')/totLand)/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('FlatLeavedForest')+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('Greenhouse
s')/totLand)*(log(covers('Greenhouses')/totLand)/log(12))+(covers('DryHerbaceousCrop')/tot
Land)*(log(covers('DryHerbaceousCrop')/totLand)/log(12))+(covers('IrrigatedHerbaceousCro
p')/totLand)*(log(covers('IrrigatedHerbaceousCrop')/totLand)/log(12))+(covers('DryFruitTree
s')/totLand)*(log(covers('DryFruitTrees')/totLand)/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('FlatLeavedFore
st')+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;
```