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Energy–Landscape Integrated Analysis: A proposal for measuring complexity in internal agroecosystem processes (Barcelona Metropolitan Region, 1860-2000)

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Highlights

- The article proposes an energy-landscape integrated analysis of agroecosystems
- Nonlineal relation between energy-information storage, and landscape patterns
- Energy-landscape models can be used to design more sustainable farm systems

Manuscript

1. Introduction

1.1. Sustainable farm systems: the global food-biodiversity dilemma

Farm systems are facing a global challenge amidst a socio-metabolic transition (Muradian et al., 2012; Scheidel and Sorman, 2012; Schaffartzik et al., 2014) that places them in a dilemma between increasing land-use intensity to meet the growing demand of food, feed, fibres and fuels (Godfray et al., 2010; Lambin and Meyfroidt, 2011), while trying to avoid a dangerous biodiversity loss (Tilman, 1999; Schröter et al., 2005; Cardinale et al., 2012). The industrialization of agriculture through the 'green revolution' spread from the 1960s onwards has been a major driver of this loss (Matson et al., 1997; Tilman et al., 2002). However, it is increasingly acknowledged that well-managed agroecosystems can play a key role in biodiversity maintenance (Bengtsson et al., 2003; Tscharntke et al., 2005). From a land-sharing approach to biological conservation (Perfecto and Vandermeer, 2010; Tscharntke et al., 2012), there is a claim for a wildlife-friendly farming liable to provide complex agroecological matrices. An heterogeneous and well connected land matrix could maintain high species richness in cultural landscapes (Tress et al., 2001; Agnoletti, 2006, 2014; Jackson et al., 2007). Depending on land-use intensities and the type of farming, agricultural systems may either enhance or decrease biodiversity (Altieri 1999; Swift et al 2004). In turn, the adaptive capacities to farming disturbances and agroforestry land usages vary across species and biomes (Gabriel et al., 2013; Balmford et al., 2014).

Solving the global food-biodiversity dilemma requires a deeper research to know how species richness is kept or lost in different land-use patterns, according to the level (quantity) and character (spatiotemporal scale and quality) of the ecological disturbances that farmers carry out across the landscape (Fischer et al., 2008; Phalan et al., 2011). If human society wants to ensure all sorts of ecosystem services in the future, we need better operative criteria and indicators in order to assess when, where and why the energy throughput driven by farmers increases or decreases the mosaic pattern of cultural landscapes and their capacity to hold biodiversity (Gliessman, 1990; Pierce, 2014). This calls for an integrated research of coupled human-natural systems aimed at revealing complex structures and processes which are not apparent when studied by social or natural scientists separately (Liu et al., 2007; Marull et al., 2015a).

1.2. Aim and scope of this study

A growing consensus in conservation biology points to landscape heterogeneity as being a key mechanism that generates a dynamic biodiversity peak at intermediate levels of ecological disturbance in agroecosystems, thanks to the interplay between spatial diversity, ecosystem complexity and dispersal abilities of colonizing species either coming from less disturbed patches or the survivors in the most disturbed ones (Tilman, 1994; Elmqvist et al., 2003; Roxburgh et al., 2004; Harper et al., 2005; Perfecto and Vandermeer, 2010; Loreau et al., 2010). This opens a research field on how the complexity of energy flows driven by farmers shapes these types of heterogeneous landscapes that can offer a great deal of habitats, food chains and ecological connectivity required by the associated biodiversity of farm systems. The Energy–Landscape Integrated Analysis (ELIA) of agroecosystems proposed in this article aims to contribute to this task by bringing to light the link between the anthropogenic energy carriers flowing among the components of a farm system, the information held within this energy network, and the land-cover diversity of cultural landscapes that arises with the spatial imprint of these farming energy flows.

2. Theory

2.1. Towards an energy-landscape integrated analysis

Living systems are capable of using metabolic energy carriers in order to maintain or even increase their organization (Schrödinger, 1944), when they attain a far-from-thermodynamic equilibrium set up with the organized information that allows transferring energy while maintaining their complexity, reproducing themselves, and evolving (Ho, 1998; Gladyshev, 1999; Ulanowicz, 2003). Applying this approach to agroecosystems requires analysing 1) the energy throughput and closure degree of socio-metabolic cycles; 2) the information carried by the spatially differentiated shape of these energy fluxes flowing across the land-matrix; and 3) the land-cover diversity of the landscape to which the species are adapted (Ho and Ulanowicz, 2005). Like any other ecosystem, in agroecosystems the energy dissipated in space also leads to the emergence of self-organized structures that experience historical successions ruled by adaptive selection (Morowitz, 2002). Thanks to the internal biophysical cycles that link organisms one another, these agroecosystems can enhance their own complexity, increase temporal energy storage and decrease entropy. This set of emergent properties translates into integrated spatial heterogeneity and biodiversity of landscapes (Ho, 2013; Ulanowicz, 1986). Their sustainability is directly related to the information-complexity interplay, and inversely related to energy dissipation (Prigogine, 1996; Ulanowicz, 1997).

In this vein, agroecosystems are seen as the historically changing outcome of the interplay between sociometabolic flows (Haberl, 2001), the land-use patterns set up by farmers, and ecological functioning (Farina, 2000; Wrbka et al., 2004). Despite the long-lasting work done on energy analysis of farm systems, which revealed a substantial decline in energy returns of agro-industrial management brought about by the massive consumption of cheap fossil fuels (Odum, 1984, 2007; Giampietro and Pimentel, 1991; Pelletier et al., 2011; Giampietro et al., 2011, 2013), the role played by sociometabolic energy throughput as a driving force of contemporary Land Cover and Land-Use Change (LCLUC) is not yet well understood (Peterseil et al., 2004). ELIA intends to link these two lines of research, the agroecological accounting of energy flows (Guzmán and González de Molina, 2015; Tello et al., 2016) and the study of LCLUC from a landscape ecology standpoint (Marull et al., 2015a). This requires specifying and measuring the pattern of energy flows and the information held in agroecosystems.

2.2. Cultural landscapes as socio-metabolic imprint

Traditional organic farm systems with a solar-based metabolism, like the ones existing in Europe before the massive spread of the green revolution from the 1960s onwards, tended to organize their land usages according to different gradients of intensity, keeping an integrated management of the landscape because their whole subsistence depended on this. In order to offset the energy lost in the inefficient human exploitation of animal bioconversion –on which they had to depend to obtain the internal farm services of traction and manure (Guzmán and González de Molina, 2009)—, traditional organic farming kept livestock breeding carefully integrated with cropland, pasture and forest spaces (Krausmann, 2004). While the organic farm management strategy of closing cycles within an agroecosystem led to landscape mosaics, the socio-ecological transition to agro-industrial farm systems that rely on external flows of inputs coming from underground fossil fuels has enabled society to overcome the age-old energy dependency on bioconverters (Krausmann et al., 2003; Schaffartzik et al., 2014). As a result, integrated land-use management at a local or regional scale was no longer necessary—and overcoming this former necessity also led to losing its agroecological virtue (Cussó et al., 2006a, 2006b). The environmental damage caused worldwide by this lack of integrated management between energy flows and land usages urges societies to recover the former 'landscape efficiency' (the socioeconomic satisfaction of human needs while maintaining the healthiest landscape ecological patterns and processes) at present (Marull et al., 2010). Since the lack of an integrated management of energy flows and land-uses at different scales is part of the current global ecological crisis, its recovery becomes crucial for a more sustainable foodscape.

This line of research involves a wider and more complex approach to agroecosystems' energy efficiency. It requires not only accounting for a single input-output ratio between the final product and the external energy consumed, but looking at the harnessing of energy flows that loop within the system as well. The cyclical nature of these flows is important in order to grasp the emergent complexity and the information held within the agroecosystem, given that they involve an internal maximization of less-dissipative energy carriers—in the same vein as Ho and Ulanowicz (2005) explain the 'loopy' character of any living system. The temporal energy storage that these loops allow becomes a foundation for all sustainable systems (Ho, 2013). Hence, the usual methodology of energy flow analysis of social metabolism needs to be adapted and enlarged in order to give account of the cyclical character of agroecosystems' processes (Giampietro, 2004, 2011, 2013; Guzmán and González de Molina, 2015).

3. Method

3.1. Energy flows of an agroecosystem as a graph

Graph modelling is a well-known mathematical structure that allows us to chart natural phenomena as a set of 'nodes' and 'edges' (Urban et al., 2009). ELIA treats the pattern of flows in an agroecosystem as a graph where energy carriers are 'nodes' whose 'edges' represent their interaction. Fig. 1 shows how the total amount of phytomass obtained from solar radiation through the autotrophic production by plants, that accounts for the *actual Net Primary Production* (NPP_{act}) (Vitousek et al., 1986; Smil, 2011; Krausmann et al., 2013; Guzmán et al., 2014), is the natural energy source for all heterotrophs living there. From this starting point, we analyse the pattern adopted by the subsequent energy processes carried out, the internal loops they generate, the final product extracted or the external inputs introduced from outside the agroecosystem.

The whole biomass included in NPP_{act} that becomes available for all species is split into *Unharvested Biomass* (*UB*) and the share of *Net Primary Production harvested* (NPP_h) (Fig. 1). The *UB* remains in the same place where it has been primary produced to feed the populations of the farm-associated biodiversity. It becomes a source of the whole *Agroecosystem Total Turnover* (*ATT*) that closes the first cyclical subsystem called 'Natural' in Fig. 1a, because it allows for the production of NPP_{act} again through the trophic net of non-domesticated species either in the edaphic processes of the soil or aboveground. This does not mean, however, that the entire NPP_h which has been appropriated by farmers goes out of the agroecosystem. In turn, NPP_h is subdivided into *Biomass Reused* (*BR*) inside the agroecosystem and *Farmland Final Produce* (*FFP*) that goes outside to be consumed by humans (Fig. 1). The *BR* share is an important flow that remains within the agroecosystem as a farmer's investment addressed to maintain two basic renewable funds: livestock and soil fertility. Hence, *BR* closes the second basic loop called 'Farmland' subsystem in Fig. 1b.

Then *BR* is split into the share that goes to feed the domesticated animals as *Livestock Biomass Reused* (*LBR*), which is added to the whole amount of *Livestock Total Inputs* (*LTI*), whereas another share of *BR* is *Farmland Biomass Reused* (*FBR*) which adds up to *Farmland Total Inputs* (*FTI*) as seeds, green manure and other vegetal fertilizers (Fig. 1). In this way the 'Farmland' subsystem, which comes from the NPP_{act} in the 'Natural' one, becomes linked to the third 'Livestock' subsystem (Fig. 1c). These energy linkages in the graph enable us to make apparent how they relate to an integrated land-use management.

Afterwards, *LBR* flows to domestic animal bioconversion and then it splits into *Livestock Final Produce* (*LFP*) and internal *Livestock Services* (*LS*) obtained by farmers as draft power and manure (both make up *Livestock Produce and Services LPS*). In this way the two subsequent loops called 'Farmland' and 'Livestock' subsystems are partially closed within the agroecosystem, while offering a *Final Produce* (*FP*) to be consumed outside—as well as receiving a lower or higher amount of *External Inputs* (*EI*). Therefore, the amount of *UB*, *BR* and *LS* provide the internal flows that lead to a stronger or weaker 'loopiness' in the pattern of energy networks of agroecosystems (Fig. 2). Notice that when only the 'Natural' subsystem is in place, but some *Final Produce* (*FP*) is extracted, we are looking at a very simple gathering or forestry systems. If all the human-appropriated NPP_{act} is diverted towards livestock bioconversion, we are facing a purely pastoral system. In an agro-industrial monoculture of grains, almost all NPP_{act} would be appropriated, except some weeds or herbivores that survive pesticide application, while the greatest share of the energy carriers would flow from outside as *EI* or would go outside as *FP*, except some remnant *BR* like the stubble ploughed in the soil.

Once we have dissected the agroecosystem, Fig. 2 shows the three subsystems coupled in one that becomes an outline of a mixed farming that integrates cropping and forestry with livestock breeding. It goes without saying that the complexity reached and the information needed to run an integrated mixed farming like this is much higher than with forestry exploitation, a monoculture or a pastoral system carried out separately. This explains why we are going to use this graph model (Fig. 2) to calculate the level of energy storage within the agroecosystem provided by its ‘loopiness’, as well as the information embedded in this network of flows.

3.2. Energy carriers stored within agroecosystems

The agroecosystem can behave in a cyclical manner because the outputs of one subsystem (Fig. 1) become the inputs of the next one (Fig. 2). This, in turn, provides the base for its ‘loopiness’ that allows storing energy carriers and information within the dissipative structure (Ho and Ulanowicz, 2005). There is an exception to this rule though, when some energy carriers circulating inside the agroecosystem are turned into what Odum (1993) named a ‘resource out of place’. As seen in Fig. 2, sometimes a fraction of NPP_{act} can be wasted. The same may happen with a fraction of the *LPS*, such as dung slurry coming from agro-industrial feedlots that are spread in excess into cropland and end up contaminating the water table. If they exist, these *Farmland Waste* (*FW*) and *Livestock Waste* (*LW*) do not contribute to the renewal of the agroecosystem’s funds, neither to enhance its internal complexity, nor to meet human needs. Accordingly, the enthalpy of these energy carriers cannot be taken into account in our graph modelling as fluxes that contribute to keeping up the agroecosystem reproduction—although they have to be included as cost.

In the integrated graph (Fig. 2) we can identify six main subprocesses. In all of them the flow that exits from a node can be differentiated between the portion that remains within the agroecosystem and the other which goes to other subsystems or out of the system. Accordingly, there is always a pair of incoming-outgoing flows for each subprocess of the agroecosystem. Hence, we propose twelve coefficients (β_i) along the edges of the graph.

$$\beta_1 = \frac{NPP_h}{NPP_{act}}, \beta_2 = \frac{UB}{NPP_{act}}, \beta_3 = \frac{FTI}{ATT}, \beta_4 = \frac{UB}{ATT}, \beta_5 = \frac{FFP}{NPP_h}, \beta_6 = \frac{BR}{NPP_h},$$

$$\beta_7 = \frac{FEI}{FTI}, \beta_8 = \frac{FII}{FTI}, \beta_9 = \frac{LEI}{LTI}, \beta_{10} = \frac{LBR}{LTI}, \beta_{11} = \frac{LFP}{LPS}, \beta_{12} = \frac{LS}{LPS}.$$

These β_i’s account for the proportion in which every flow is split into two in each crossroads within the network. Then, we can differentiate between even and odd β_i’s, where the even ones account for the energy carriers looping inside the agroecosystem. Any pair of the same subprocess sum 1, except for those processes that have a third direction (waste). This is the case of NNP_{act} and *LPS*, which affects β_1, β_2, β_{11} and β_{12}. Another advantage of using β_i's is that they are bounded (between 0 and 1), which allows comparing different case studies or historical examples.

In Fig. 2 we differentiate between three shapes of arrows. Solid arrows show the energy flows we are most interested in, as they represent the internal and external exchange of energy carriers. Dashed arrows indicate fluxes that require biological conversion (i.e. photosynthesis). Finally, point-line arrows show energy carriers that are not diverted inside or outside but remain as 'resources out of place' (i.e. waste). Tables 1 and 2 give a complete description of an agroecosystem's energy carriers and coefficients.

3.3. Turning agroecosystems' energy graphs into spatially-explicit ones

Once we have the agroecosystem's energy network graph (Fig. 2), we are interested in the relationships of the evolving complexity of the internal energy loops with the information they contain and the diachronic LCLUC. The next step is converting the incoming-outgoing coefficients (β_i's) to their land-matrix expressions, by calculating the mean estimated values of energy fluxes flowing across each land-use (in $MJ \cdot ha^{-1}$).

In most of fluxes there are no difficulties when assigning a value for each land-use if they form part of the first two subsystems ('natural' and 'farmland'; Figs. 1 and 2). In the 'livestock' subsystem the key point is to set the weight of the whole internal loop which corresponds to each land-use, by taking into account that part of the animal bioconversion that goes to each type of farmland (see Tables A1 and A2 in the Annex). In order to allocate the full energy cost of livestock to different land-uses, we not only weighted the values of *LS* (manure and traction), but *LW* (dung wasted) as well. Moreover, we have to solve the problem of the energy carriers that flow from one land-use to another within farmland when we calculate spatially-specific values of biomass reuses included in *FBR* and *LBR*. We may have, e.g. a biomass flow coming from forest clearing that is buried into cropland, or the pruning of vineyards that is burnt and added to the soil of cereal-growing areas, etc. Although these fluxes cancel one another when they are accounted at aggregated level, for the land usages involved in these inter-farmland flows the values for *FBR* and *LBR* have to be differentiated depending on whether we are considering a flow entering or going out from each spatial unit of analysis.

Then, in order to link this network of energy flows with the land-matrix, we have to correlate both types of data (ingoing and outgoing flows) measured in the same spatial unit of analysis (sample cell). This also requires specifying and measuring the variables we are going to study. Recall that our aim is to analyse the agroecosystem's energy pattern of flows, as a dissipative structure (Prigogine, 1996). Hence, what is relevant here is not only the magnitude of each energy flow as such but two other things captured by our graph modelling: i) the specific part of this network of flows that provides negentropy by storing energy carriers within the agroecosystem and allows for the enhancement of its complexity; and ii) the increasing information embedded in this energy network. According to Ho and Ulanowicz (2005), the most relevant fluxes are the loop producers that have to be detached from the entropy producing flows. For this reason we will use as a first variable β_i^j defined as the quotient of the energy flow relation i associated with the land-use j.

$$\beta_1^j = \frac{npp_{h\,j}}{npp_{act\,j}}, \qquad \beta_2^j = \frac{ub_j}{npp_{act\,j}}, \qquad \beta_3^j = \frac{fti_j}{att_j}, \qquad \beta_4^j = \frac{ub_j}{att_j},$$

$$\beta_5^j = \frac{ffp_j}{npp_{h\,j}}, \quad \beta_6^j = \frac{br_j}{npp_{h\,j}}, \qquad \beta_7^j = \frac{fei_j}{fti_j}, \qquad \beta_8^j = \frac{fii_j}{fti_j},$$

$$\beta_9^j = \frac{fei_j}{lti_j}, \qquad \beta_{10}^j = \frac{lbr_j}{lti_j}, \qquad \beta_{11}^j = \frac{lfp_j}{lps_j}, \qquad \beta_{12}^j = \frac{ls_j}{lps_j}.$$

Here lowercase letters indicate we refer to coefficients, not to variables like was done previously. All the variables of the energy flow graph (Fig. 2) are expressed for each land-use j. Thus, for each sample cell we have β_i.

$$\beta_i = \sum_{j=1}^{k} \beta_i^j p_j,$$

where p_j is the proportion of the land-use j in the corresponding sample cell, and k is the number of different land-uses. Starting from this spatially-explicit β_i's we can then calculate the complexity and information carried with energy flows, so as to analyse its relationship with landscape patterns.

3.4. From the complexity of energy flows to landscape patterns through information

Once we have defined how to account for spatially-explicit energy flows, we can introduce the three indicators that we are going to use in ELIA. They are ordered hierarchically, according to the logical string that goes from the interplay between energy and information to landscape patterns. Energy storage can be seen as the harnessing of dissipation thanks to the farmers' efforts to generate and enhance energy loops (Ulanowicz, 2003). The intervention of farmers' labour also means that the looping of these biomass reuses is not produced randomly through space, because it is driven by information. Owing to the information delivered by farmers' labour the energy fluxes are directed in one or another way across the land-matrix with different intensities. It is precisely because energy carriers flow across different land-covers following a deliberate pattern that they imprint a specific mosaic that we recognize as a cultural landscape.

Therefore, energy reinvestement and storage driven by farmers' knowledge produces an effect on landscape patterns and processes. ELIA correlates the following three indicators: i) the complexity attained through the energy storage of loops (*E*); ii) the information embedded in the energy network of flows (*I*); and iii) the landscape functional structure (*L*). Acknowledging from the onset that to collect all the necessary data to analyse the whole environmental impact of the agroecosystem's energy cycles is not possible, we think that the use of the previously explained β_i's is a valuable proxy to give account of a looping rather than a linear set of energy transformations (Giampietro et al., 2011).

The 'loopiness' of energy carriers driven by farmers through *UB*, *BR* and *LS* flows (Fig. 2) can be adopted as a measure of *E* that expresses the energy potentially available for all food chains taking place in the agroecosystem. We are going to start measuring *E* as the quantity of energy remaining in the system, and then we will measure *I* that allows the farmers to reproduce the agricultural metabolism thanks to the information embedded in the system. *I* can be measured taking into account how evenly distributed the set of pairwise incoming-outgoing fluxes of the graph are. Both indicators, *E* and *I*, are assessing characteristics of human-made structures that allow us to dissect energy flows of agroecosystems and bring to light the energy-information interplay. These variables can then be related with *L*, considering them as the landscape 'imprint' of social metabolism.

3.5. Measuring Energy Storage (E) as the complexity of internal energy loops

We understand agroecosystem complexity as the differentiation of dissipative structures that allows for diverse potential ranges in their behaviour (Tainter, 1990). At the same time, the more complex the space-time differentiation is, the more coherent energy is stored within a system (Ho and Ulanowicz, 2005). Hence, higher mean values of even β_i's entail that agroecosystems are increasing in complexity because the different cycles are all coupled together and the residence time of the stored energy is enlarged thanks to a greater interlinked number of transformations looping inside. Accordingly, our way of calculating complexity is as follows:

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

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

where the coefficients k_1, k_2, k_3 account for the share of reusing energy carriers that are looping through each of the three subsystems (Fig. 2).

The formula used implies that *E* remains within the range [0,1]. *E* close to 0 implies low reusing of energy carriers—a behaviour that usually corresponds to an agro-industrial management highly dependent on external inputs and with maximum levels of *Human Appropriation of Net Primary Production* (*HANPP*). *E* close to 1 implies more internal energy loops, meaning that a high share of energy carriers harvested are reused within the agroecosystem—a behaviour usually associated with organic farming with lower dependence on external inputs, lower biomass extraction as *FP*, and also moderate levels of *HANPP*.

E assesses the amount of energy flows that go inside, relative to the whole energy flowing across each one of the three subsystems of the network structure of an agroecosystem. Hence *E* measures the proportion of energy stored on the land coming from each loop considered sequentially. That is, taking into account that a share of the flow stemming from the first loop can still be redirected inside again when flowing across the two subsequent loops. When we account for the three loops nested within one another, we are adopting a landscape standpoint that is focused on what happens with the energy flowing across different land units driven by farmers, and we name this value *Energy Storage (E).*

For some purposes it is also useful focusing the standpoint on what driving these energy throughputs means in terms of human labour allocation. Notice that from a labour cost point of view the ingoing flow of *UB* is the result of *not* doing anything (Tello et al., 2015), whereas *BR* and *LS* always require investing a farmer's labour. If we calculate this process of energy harnessing by adopting a labour-cost standpoint, we obtain *Ee*:

$$Ee = \frac{\beta_6+\beta_8}{2} k'_2 + \frac{\beta_{10}+\beta_{12}}{2} k'_3.$$

$$k'_2 = \frac{BR}{BR+LS}, k'_3 = \frac{LS}{BR+LS},$$

Indeed, what *Ee* accounts is only that part of the agroecosystem's energy throughput that involves a labour investment, leaving *UB* aside. Thus *Ee* expresses as a coefficient the reinvestment effort made by farmers relative to the energy flowing only across the agricultural and livestock subsystems (Fig. 2), and we name this value *Energy Reinvestment Effort* (*Ee*).

3.6. Measuring Energy Information (I) as shown in the energy flow pattern

The measuring of the information held in the network of energy flows draws on Information Theory (IT)—despite some common misunderstandings that we will try to avoid (Georgescu-Roegen, 1971; Ulanowicz, 2001; Vranken et al., 2014; Cushman 2014). In ELIA, IT is applied to the graph model of the network of energy fluxes that cross an agroecosystem (Figs. 1 and 2). The equidistribution of the energy carriers flowing across the binary strings that link the nodes of this graph assumes that the information they carry cannot be known beforehand. In this vein information can be seen as a measure of uncertainty, or the degree of freedom for the system to evolve (Prigogine, 1994). When energy flows concentrate in a specific sector of our graph model, the defined pattern tends to vanish. Conversely, the information embedded is the highest in an equidistributed pattern of energy fluxes.

This kind of 'information' is often called structuring information-message that only registers the likelihood of the occurrence of a pair of events (Passet, 1996; Ulanowicz, 2001). It differs from the meaningful content of the information farmers use to direct the fluxes of energy carriers according to a defined purpose, and also from the spatially organized information that can be measured in the land-cover diversity of a farmland mosaic—or even from the auto-reflexive information loop of considering the latter as an imprint of the former.

The information quantified in *I* has an important feature, though: It is always site-specific for the unit of analysis observed, which is a very important trait from a bio-cultural standpoint (Cocks, M., 2004; Robson and Berkes, 2011; Jackson et al., 2011; Gómez-Baggethun et al., 2012; Barthel et al., 2013; Agnoletti, 2014). When ELIA registers a decrease on *I*, we wonder to what extent the information running the system has been lost or transferred from the traditional agroecological knowledge of farmers located at landscape level towards higher hierarchical scales, where other people outside the place have taken control over some important parts of the agroecosystem functioning after being linked to increasingly globalized food chains (Johns and Sthapit, 2004; McMichael, 2011; Muradian et al., 2011).

Accordingly, we use a Shannon index (Shannon, 1948) adapted to be applied over each pair of β_i's, so that this indicator shows whether the β_i's pairs are evenly distributed or not. This measure of energy information (I) accounts for the equi-proportionality of pairwise energy flows that exit from each node in every sub-process:

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

$$\gamma_F = \frac{NPP_{act} - FW}{NPP_{act}} = \frac{UB + NPP_h}{UB + NPP_h + FW}$$

$$\gamma_L = \frac{LTP - LW}{LTP} = \frac{LS + LP}{LS + LP + LW}$$

Base 2 logarithms are applied as probability is dichotomous. Keeping in mind the definition of β_i's, we know that the pairs $\beta_1 - \beta_2$ and $\beta_{11} - \beta_{12}$ don't sum 1, as the rest of the pairs of β_i's do. This is because waste (*FW* and *LW*) can also be understood as a lack of information of the system. The introduction of γ_F, γ_L ensures that I remains lower than 1 when the system presents this information loss.

I values close to 1 are those with an equidistribution of incoming or outgoing flows of the agroecosystem's network structure where the structuring information-message is high, whereas values close to 0 means patterns of probability far from equidistribution. I values close to 0 correspond to a low site-specific information content in agroecosystem functioning, which may be related to an industrialized farm system with high *HANPP* and low relevance of traditional peasant knowledge; or, by contrast, to an almost 'natural' turnover with slight *HANPP* that may also correspond to rural abandoned forest or pastoral areas at present. Conversely, agroecosystems with I equal to 1 are the ones with equidistributed incoming and outgoing energy flows in each sub-process, as well as with intermediate levels of *HANPP* (Marull et al., 2015a), that correspond to an organic mixed farming deeply embedded in local knowledge.

3.7. Measuring Energy Imprint (L) in the landscape functional structure

In order to correlate the above explained energy-information interplay with landscape functional structure we need to introduce a landscape metric (L) as proxy of biodiversity. A focus on landscape functionality stresses the spatial dimension of biodiversity, focuses on the interplay between disturbances and land-cover heterogeneity, and the role of agroecological land management in ecosystem service provision (Tscharntke et al., 2005). This perspective relies on the interplay between patch disturbance and land-cover diversity as the key mechanism that actually matters in biodiversity maintenance (Loreau et al., 2010). This also brings to light the capacity of agro-forest mosaics to offer a range of habitats that sustain many species (Harper et al., 2005). Much of this biological diversity is apparent at scales larger than plot or farm level, and depends on landscape-wide heterogeneity of land covers.

We use a modification of the Shannon index commonly used in ecology to account for landscape heterogeneity (Vranken et al., 2014). In this land-cover dimension, Shannon index is not used for looking at agroecosystems as dissipative structures, but as the spatial 'imprint' of their social metabolism—therefore, without any thermodynamic meaning. We calculate L to capture the equidiversity of land-covers into sample cells:

$$L = \left(-\sum_{i=1}^{k} p_i \log_k p_i \right) (1 - p_u)$$

where k is the number of different land-covers (potential habitats) (Fig. 1). We consider that the existence of urban land-cover $p_u$results in a loss of potential habitats. Thus, p_i is the proportion of non-urban land-covers i into every cell. L can be improved, when data is available, i.e. using the following algorithm:

$$Le = \left(a\,L + b\,\frac{ECI}{10} \right) 1/(a + b)$$

In this way we obtain a new indicator *Le* as proxy of biodiversity (Marull et al., 2015c), capturing landscape patterns (L, heterogeneity) and landscape processes (*ECI*, connectivity), using Principal Component Analysis –PCA (where a and b are the empirical PCA coeffitients).

After having defined all the 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-organization (Gershenson and Fernández, 2012). Finally, we assume that the complexity of socio-metabolic fluxes and L are related to landscape ecological processes and biodiversity (Giampietro, 1997; Marull et al., 2015a).

3.8. Interplay of energy storage with information

Which configuration is adopted by the whole set of possible values that the interaction between *E* and *I* can take? As a first option, we compute some possible combinations of β_i's, and then perform the values of *E* and *I* for them, supposing $\gamma_L = \gamma_F = \frac{1}{2}$, $k_1 = k_2 = k_3 = \frac{1}{3}$ (see in Table 2 a complete description of energy coefficients). But *E* differentiates between the different distribution of β_i's values into the system, while *I* does not.

$$I(\beta_1, \beta_2, \dots, \beta_{12}) = I\left(\beta_{\sigma(1)}, \beta_{\sigma(2)}, \dots, \beta_{\sigma(12)}\right),$$

where σ is a permutation of β_i's. *I* provides seven types of zeros. To study these zeros we must look at each pair β_i and β_{2i} (see Fig. 2), for $i = 1, 3, 5, 7, 9, 11$, as $I\ (\beta_i, \beta_{2i}) = 0$ both when $\beta_i = 1$ or $\beta_{2i} = 1$. So we find seven possible combinations that imply $I = 0$, these are $(\beta_2, \beta_4, \beta_6, \beta_8\ \beta_{10}\ \beta_{12})$: $(0, 0, 0, 0,0,0)$, $(1, 0, 0, 0,0,0)$, $(1, 1, 0, 0,0,0)$, $(1, 1, 1, 0,0,0)$, $(1, 1, 1, 1,0,0)$, $(1, 1, 1, 1,1,0)$, $(1, 1, 1, 1,1,1)$, and any permutation over them. Furthermore, some of these β_i's combinations are unlikely, due to the fact that they do not maintain any equilibrium among loopiness.

Following Tello et al. (2015, 2016), we assume that if the energy amount of *BR* in an agroecosystem is greater than the energy content of its *EI* (*BR* > *EI*), then the ratio of *FP* over the *Total Inputs Consumed* (*TIC*) grows more for any improvement of *FP/BR* than for *FP/EI* (i.e. if we wish a greater *FP*/*TIC*, we can to some extent increase *EI* in order to reduce *BR* taking advantage of their substitutability, given that *TIC* = *BR* + *EI*). Hence we can argue, from the above example, that any increase of *EI* will imply the corresponding increase of 'non loop-producers' β_i's relations. Accordingly, we suppose that some coherence can be established between the loop-producing β_i's (i.e. not all possible beta-combinations are equally likely).

Fig. 3 shows the theoretical representation of interactions between *E* and *I* components. $c_i = (i - 1)/6$, represent the *E* values corresponding to $(\beta_2, \beta_4, \beta_6, \beta_8, \beta_{10}, \beta_{12})$ configurations that make *I*=0 and all its permutations. We can see an arc that reaches its maximum value on the vertical axis (*I*) for intermediate values of *E*, in the horitzontal axis—a figure that can suffer some variances for other β_i's. This figure highlights that our way of measuring the interplay between the information held in agroecosystems fluxes and the complexity of their internal energy loops makes sense. We have maximum information (*I*) for an intermediate level of complexity provided by the storage of energy carriers looping inside—which for the sake of simplicity we will call henceforth a 'sustainable' agroecosystem.

In the peak point of *I* (Fig. 3) we found an equi-proportionality of incoming and outgoing energy flows, a property that not only is coherent with our way of capturing the information embedded in agroecosystems but also fits with the vector directions of optimal paths found by Tello et al. (2015, 2016) for improving their joint energy efficiency (*FP/TIC*), depending on whether $BR > EI$ or the opposite. Low levels of site-specific information are found in the landscape either when the agroecosystem tends towards an agro-industrial management by increasingly relying on *EI*, or towards rural abandonment when farmers' labour and knowledge are withdrawn from it (i.e. either in highly 'intensive-industrialized' farm systems, or in former agroecosystems that presumably are being 'renaturalized'). More information embedded in cultural landscapes becomes a key resource for the future of sustainable farming that seeks to balance agricultural production with biodiversity conservation.

3.9. Energy imprint and landscape pattern modelling

The relationship between *E, I* and *L* is shown in Fig. 4. The values have been obtained from theoretical coefficients for two extreme agroecosystems' typologies (from 'natural' to 'intensive-industrialized' scenarios) listed above (Table 3). We propose β_i's for 'natural' (T_1), 'balanced' (T_3) and 'intensive-industrialized' (T_5) agroecosystems. T_1 is similar to an ecosystem (i.e. low or null *HANPP*; even β_i's are equal to one, while odd β_i's are equal to zero). T_3 has been defined as one with equal proportion of incoming or outgoing energy flows (i.e. intermediate *HANPP*; all β_i's are ½). T_5 is defined as having given up internal reuses (i.e. high *HANPP*; odd β_i's are equal to one and even β_i's to zero). In the three typologies waste has not been considered, so $\gamma_L = \gamma_B = 0.5$. Regarding (k_1, k_2, k_3), in the case of T_1 $k_1 = 1$ and $k_2 =$

$k_3 = 0$, which means that all the reuse comes from *UB*; in T_2 it is considered that $k_1 = k_2 = k_3 = \frac{1}{3}$; and in T_3 $k_2 = 1$ and $k_1 = k_3 = 0$.

In addition, two other agroecosystems' typologies have been introduced to show the results for intermediate values between the two extreme scenarios taken into account. Lastly, the points shown in Fig. 4 come from a probabilistic approximation by considering all possible land-use combinations in a cell. The first form is obtained using the values of the 'natural', 'balanced' and 'intensive-industrialized' agroecosystems (T_1, T_3 and T_5), while in the second also the intermediate agroecosystems have been considered (T_1, T_2, T_3, T_4 and T_5). As a result Fig. 4 reveals the relationship between complexity of energy flows (*E*), the information carried in them (*I*), and their joint spatial imprint in agroecosystems (*L*). This ELIA modelling allows us to test the relationship we deem to exist between the simultaneous loss in energy throughput and landscape efficiency (Marull et al., 2010), going a step forward from previous explorations of the links between intermediate levels of sociometabolic disturbance as assessed with *HANPP* and ecological functioning of cultural landscapes (Marull et al., 2015a).

ELIA is the energy–landscape integrated analysis resulting from the model. In order to improve its application, we propose a simplified indicator that combines the landscape functional structure with the complexity of the interlinking pattern of energy flows and the information carried by them, as a proxy of biodiversity in agroecosystems:

$$ELIA = 2\,(E * I)\,L$$

were *E* is the energy storage, *I* is the information carried by the network structure of energy flows and *L* is the energy imprint in the landscape structure (*L* can be substituted by *Le*; i.e. including functional attributes of the landscape).

3.10. Case study application

Many traditional Mediterranean agroecosystems had kept complex land-use mosaics, which were later turned into homogeneous land-covers –increasingly polarized between intensive monocultures and spontaneous afforestation of abandoned lands— as a result of the industrialization of farm systems fuelled by cheap fossil fuels that began in the 1960s (Gerard et al., 2010; Parcerisas et al., 2012; Marull et al., 2014). This historical process can be taken as a natural experiment for comparative analysis (Odum, 1984; Gliessman, 1990; Tscharntke et al., 2005). At the same time, the conservation of cultural landscapes has to take into account the human role in shaping their present ecological features (Gustavsson et al., 2007; Henle et al., 2008). ELIA looks at these landscape changes as the 'imprint' of the energy carriers driven by farmers, and highlights the bio-cultural role performed by the changing complexity-information interplay in the energy profiles of agroecosystems.

ELIA is applied to a case study that comprises four municipalities (Caldes de Montbui, Castellar del Vallès, Polinyà and Sentmenat) in the Vallès County of the Barcelona Metropolitan Region (Fig. 5), located westward in the Mediterranean biodiversity hotspot (Myers et al., 2000). Some authors have been studying this site from a long-term socio-ecological perspective (from c.1860 to the 2000s), by reconstructing the energy balances of farm systems (Cussó et al., 2006a, 2006b) and the ecological functioning of cultural landscapes (Marull et al., 2010). This led us to integrate the study of sociometabolic profiles of energy flows with the landscape ecology performance that existed in past organic farming, or characterize agro-industrial systems at present.

In mid-nineteenth century the Vallès County (Fig. 5) reached a population density of 65 inhab./km^2 close to the highest level that an organic rain-fed farming system could maintain in the Mediterranean bioregion in past times. This challenge drove peasants to combine as a response an export-led winegrowing specialization with traditional agro-forest mosaics (Garrabou et al., 2010; Badia-Miró and Tello, 2014). Maintaining and reproducing this poly-cultural landscape entailed a tight integration between cropland and livestock breeding, by means of a labour-intensive mixed farming (Olarieta et al., 2008, 2011; Tello et. al., 2012). Fodder and feed crops occupied 14% of cropland area in the organic case study c.1860, while livestock was also grazing pastures in 7% of farmland area, or in the grass layers below open forests and other uncultivated land. While all these links between diverse land-covers through livestock feeding helped to maintain agroforest mosaics, the energy flows of draught power and manure provided by these animals returned again to cropland. Especially in solar-based agroecosystems that practically only depend on a single type of external inputs (labour), this integration among cycles involves the well-known stiffness in societal land-use patterns due to the simultaneous need for food (cropland), firewood (forest) and animal feeding (pasture) (Guzmán and González de Molina, 2009). These were common features of late organic farm systems at the eve of the socio-ecological transition towards industrial agricultures in Europe (Krausmann, 2004).

4. Results

4.1. Land-use changes and landscape patterns from the 1860s to 2000s

Between the 1860s and 1950s the area allocated to vineyards was reduced in favour of cereals, hazelnut trees, irrigated orchards, woodland and pasture (Fig. 5). Cropland acreage fell from 58% to 34% of the total area, while urban expansion remained modest and the agrarian landscape mosaic was kept on the lowlands. Then, from the 1950s to the 2000s, cropland area shrunk to 19% due to a wide-scale adoption of the 'green revolution'. On the one hand 1,947 ha were devoted to urban expansion (16% of the useful area, two thirds at the expense of arable land and the rest of woodland and pastures). On the other hand, 646 ha of abandoned cropland were reforested (5%). The former agro-forest mosaics tended to vanish, which led to a significant decrease of spatially organized heterogeneity: Land-cover diversity fell from L = 0.72 in the 1860s, to L = 0.38 in 2000s (Table 4). Hence, our study area underwent an important reduction in the kind of landscape hetrogeneity that it is increasingly related to farm- associated biodiversity worldwide (Perfecto and Vandermeer, 2010).

4.2. Energy transition of agroecosystems from the 1860s to 2000s

The metabolic profile of the case study in the 1860s shows a solar-based agriculture that followed the strategy currently known as Low External Inputs Technology (LEIT) with strong reuse of biomass addressed to maintain the underlying funds—mainly soil fertility, and also the associated biodiversity probably as a side effect (Marull et al., 2014, 2015b). Conversely, in the 2000s chemical fertilizers and tillage mechanization following the massive spread of the green revolution allowed land and labour productivity to increase, rendering the effort of keeping internal reuses unnecessary. This combined with huge imports of animal feed consumed in industrial livestock breeding. Meat became the main component of *FP*, and relegated arable land to the role of provider of fodder, feed and straw to feedlots. At the same time woodland grew with the withdrawal of farming and grazing in the steepest areas, while its human use shrunk due to the ongoing rural abandonment (Cussó et al., 2006a, 2006b).

The use of graph modelling as an analytical tool (Fig. 6) allows us to reveal how the agroecosystem c.1860 was indeed highly dependent on internal energy loops and relied on a low amount of external energy fluxes. To obtain *FP* with very few *EI* (a LEIT strategy), it had to bear a high 'sustainability cost' of *BR* while a significant amount of *UB* available for the farm-associated biodiversity was still kept (Guzmán and González de Molina, 2009). In turn, the graph model for the 2000s also reveals the deep transformation that has taken place in farming strategy, currently addressed to industrial livestock breeding as shown by the enormous amount of *LTI*, combined with a subsidiary monoculture of animal feeding crops.

A key component in agroecosystem analysis is to determine which part of the energy flowing is redirected again towards the land matrix, in order to keep the underlying renewable funds. Accordingly, we propose three indicators calculated from the graph modelling (*E*, *Ee* and *I*): *E* assesses the entire proportion of energy stored in the agroecosystem throughout the successive nested loops, either by means of farming activity or not, relative to its whole energy turnover (*E* = 0.618 in 1860 and *E* = 0.622 in 2000). *Ee* expresses as a coefficient, relative only to the agricultural and livestock turnover, the labour investment made by farmers to maintain the farm system (*Ee* = 0.754 in 1860 and *Ee* = 0.361 in 2000; Table 2). In turn, the network structure of these energy flows and loops provides us with a measure of the information (*I*) they contain (*I* = 0.639 in 1860 and *I* = 0.587; Table 4).

4.3. *Complexity and information of energy flows in the 1860s and 2000s*

We calculated *E* and *I* over energy carriers of agroecosystems' flows, and their specific coefficients (Tables 1 and 2). These results are consistent with what has been discussed in previous sections. Circa 1860 a traditional organic farm system was closer to what we have considered a 'balanced' agroecosystem typology than to the agro-industrial management adopted in the 2000s, which fits with what we have considered as 'industrialized-intensive' farm systems. We also expected that a LEIT strategy would have scored higher information (*I*) values combined with moderately high energy reinvestment (*Ee*) and storage (*E*) indices, as shown by the results. Conversely, resorting to industrial feedlots and cereal monocultures has led to a decrease of the information embedded in the local agroecosystem in the 2000s.

Seen at aggregate level the results show comparable energy storages for the two time-points, although these similar *E* values conceal that those ingoing energy flows followed very different paths across the three subsystems interlinked in the corresponding graph models (Fig 6): c.1860 a great deal of them were biomass reused into farmland in a way that entailed many interconnections between cropland, forest and livestock, and showing an even distribution of energy flows among them; conversely, in 2000s these incoming energy flows turned out to be mainly unharvested biomass left in abandoned woodlands after forest transition. *Ee* values highlight these differences by showing that c.1860 the efforts that farmers made in energy reinvestment were much higher than in 2000s, while the energy storage that takes place in current industrial farm systems is an unintended result of the withdrawal of farmer's activity ensuing rural abandonment. Indeed, it concentrates in woodlands kept unexploited which have no bonds with cropland tillage and animal husbandry. Whereas in traditional organic farm systems the incoming flows were nesting all the three loops of the agroecosystem, in current industrial farm systems they stay either accumulated in forests, or they appear as dung slurry stemming from feedlots where animal intake comes from abroad (Table A2 in the Annex). The splitting among subsystems that we observe in 2000s, and the disconnection between energy flows crossing land covers, is coherent with the decrease of the average farmers' energy reinvestment (*Ee*) and with the lower values of information (*I*) found in the agroecosystem's network structure compared with c.1860.

The disaggregated results in Table 1 also show a noteworthy decrease in NPP_h from 503 GJ in the 1860s to 216 GJ in the 2000s driven by rural abandonment and spontaneous reforestation of the study area (Table 4). Although this entailed an increase of *UB*, from 295 GJ to 561 GJ respectively, this did not translate into a potentially higher farm-associated biodiversity due to the simultaneous decrease in land-use complexity and the loss of information embedded in the cultural landscape (Marull et al., 2015a; Tello et al., 2015; Galán et al., 2015). Just making more biomass available to ecological food chains, while the number of habitats is reduced in a more homogeneous landscape, instead of enhancing biodiversity probably only increases the populations of some better adapted species (Tello et al., 2014; Marull et al., 2014).

4.4. Energy-landscape modelling applied in the 1860s and 2000s

To run the ELIA model we have to work with spatially-explicit energy carriers and coefficients (as measured in 1x1 km^2 sample cells, Fig. 5; see also Table A1 and Table A2). Looking at the relationships between land-covers and the three variables $E - I - L$ (Fig. 7) we see that in the traditional organic agroecosystem *E* and *I* values ranged from 0.4 to 0.7, whereas in the current agro-industrial management there exists much more variability. Circa 1860 higher *E* and *I* can be found independently of the land-cover type considered, which suggests that they were tightly interlinked with one another through sociometabolic energy fluxes. In the 2000s, *E* is clearly related to the role *UB* is playing in unmanaged woodland, while *I* is kept at intermediate-low levels only in dry cropland and some forests. The aggregated Energy-Landscape Integrated Analysis results show ELIA = 0.568 in 1860 and ELIA = 0.278 in 2000.

Fig. 8 shows both the theoretical and the empirical $E - I - L$ relationships in the Vallès County in a two dimensional projection of a three dimensional figure (see also Fig. 4). Lowest theoretical values of *L* correspond to lowest values of *I* for each *E*; furthermore, for intermediate values of *E*, *I* attains its maximum (Fig. 8a). This phenomenon is less evident in the empirical case of the 1860s, where points are closer than in 2000s (Fig. 8b). This is due to the fact that in the 1860s the cells' land-cover distribution is similar, being tightly integrated to one another and having all of them higher energy complexity and higher information embedded. Conversely, in the 2000s there is more diversity among the cells' land-cover distribution, owing to the simultaneous loss of landscape functional structure, energy complexity and site-specific information. This means that by applying ELIA to the selected size of cells we are capturing the socio-ecological role of the typical Mediterranean agro-forest mosaics that existed c.1860, and tended to vanish in the 2000s.

To sum up, the higher values found in 'energy storage-reuse' (*E*) and 'energy message-information' (*I*) in the 1860s (Fig. 8b) correspond to a lower dissipative structure, which was imprinted in the agro-ecological landscape (*L*) according to the typical mosaic shape of a 'mixed-farming' system. Instead of that, cells in the 2000s show a more polarized pattern, where some 'natural' landscapes (involved in forest transition) have low dissipative structures, while most 'industrial-intensive' landscapes (intensified cropland, feedlots that rely on imported feed and urbanized areas) are highly dissipative structures. These results highlight the bio-cultural role that the information embedded in the land matrix (*I*) plays as a crucial link between socio-metabolic energy looping fluxes (*E*) and landscape functioning (*L*) in agroecosystems (Marull et al., 2015c).

5. Conclusions

The main aim of this paper has been to test the hypothesis that what lies behind the deterioration in the energy yield of agroecosystems, as a result of the current crisis of the rural world that is losing its age-old capacity to keep an integrated land-use management, is a considerable decrease of landscape efficiency, related to a misplacing of information held by energy fluxes (local farmers' knowledge) and its mutual interplay with energy-loop complexity. We have built an Energy-Landscape Integrated Analysis (ELIA) that allows us to measure both the energy storage as the complexity of internal energy loops, and the energy information held in the whole network of sociometabolic energy fluxes, in order to correlate both with the energy imprint in the landscape functional structure. The case study shows how landscape heterogeneity of Mediterranean land-use mosaics, created by traditional organic mixed-farming, tended to vanish as a result of simultaneous reduction in the complexity of the interlinking pattern of energy carriers flowing across the land-matrix and the quantity of information carried by them. From this case study we draw two main provisory conclusions, and a future research agenda:

Firstly, that the path followed by 'industrialized-intensive' agroecosystems which get rid of internal reuses to rely on increasing external fossil inputs has led to a loss of habitats in a simplified and monotonous landscape, in spite of the simultaneous 'land sparing' effect of steep land abandonment and forest transition that has taken place in the meantime. Land-use intensification and abandonment have been the joint outcome of giving up the former integrated multiple-use of farm systems. Both have entailed a reduction in land-cover diversity and ecotones. Even if the amount of unharvested biomass free to feed ecological food chains has increased as a result of land abandonment, this has probably only enlarged the population of some species because of the lack of habitat differentiation in the land-matrix. Recent studies in Mediterranean cultural landscapes reveal that the conservation of a heterogeneous and well-connected land matrix with a positive interplay between human disturbances and land-cover/land-use complexity are able to hold high species richness at regional scale (i.e. birds; Marull et al. 2015a), landscape scale (i.e. orchids; Marull et al. 2014) and local scale (i.e. butterflies; Marull et al. 2015b). Hence, the apparent land-use polarization experienced in the 2000s (Fig 8b) has entailed an interlinked decrease in energy complexity, site-specific information held and land-cover richness, leading to a likely loss of landscape capacity to host biodiversity.

Secondly, we infer that the opposite strategy of more 'sustainable' agroecosystems, which consists of saving external inputs by replacing them with internal reuses, also requires achieving a balance between human appropriation of net primary production and keeping high biodiversity in the landscape. By reinvesting as reuses a relevant share of the harvested biomass, and maintaining an integrated land-use management, organic farmers seek to balance human pressure on the land with the increasing complexity, information and resilience of agroecosystems. This strategy will also have an upper limit though, given that up to a point increasing harvested phytomass, either reused by farmers or consumed outside, will decrease the unharvested share let free for the associated biodiversity. We deem that beyond a threshold land-use intensification will no longer be 'sustainable' even in organic agriculture.

In the same vein, the capacity provided by organic agroecosystems able to shelter a high farm-associated biodiversity needs to be supplemented by natural protected spaces which offer refuge for the surviving populations of many species that recolonize the land matrix after each farming disturbance, as well as of sanctuaries for some rare highly-specialist species unable to withstand recurring disturbances (Tscharntke et al. 2012). By linking these protected sites one another, the heterogeneous cultural landscapes which host a rich α- and β-biodiversity may also provide suitable ecological connectors to ensure γ-biodiversity at the regional level—as argued by a land-sharing approach (Gabriel et al. 2006). We deem that by combining landscape ecology metrics with a measure of the site-specific energy-information interplay exerted by farming, a useful assessment can be made to capture the underlying dynamics between land-use patterns and species richness.

Confirming or rejecting these provisory hypotheses requires further research applying ELIA to more locations and time periods, and using large biodiversity datasets in order to find out where the abovementioned critical thresholds in energy throughputs and the information-complexity interplay are placed. This research agenda would help to reveal how and why different agroecosystem managements lead to key turning points in the relationship of the pattern of energy flows with landscape ecological functioning and biodiversity. No doubt, the results will be very useful for designing more sustainable farm systems worldwide in the future.

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Figure captions

Figure 1. Graph model of energy carriers into three subsystems of an agroecosystem.

Figure 2. Graph model of interlinked energy carriers flowing in a mixed-farming agroecosystem.

Figure 3. Theoretical relationship between complexity of internal energy loops (*E*) and information held in the network of energy flows (*I*) of an agroecosystem.

Figure 4. Theoretical relationship between complexity of internal energy loops (*E*), information held in the network of energy flows (*I*) and landscape functional structure (*L*), taking three (a) and five (b) agroecosystems typologies (Table 3).

Figure 5. Land-cover maps of the Vallès case study (1860s, 1950s and 2000s).

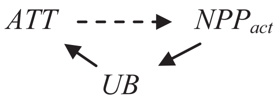
Figure 6. Graph model of energy carriers flowing in the farm systems of the Vallès case study in the 1860s (a) and 2000s (b)

Figure 7. Empirical relationship between the distribution of land-covers in the Vallès case study in the 1860s (a) and 2000s (b), and the following indicators: complexity of internal energy loops (*E*), information held in the network of energy flows (*I*) and landscape functional structure (*L*).

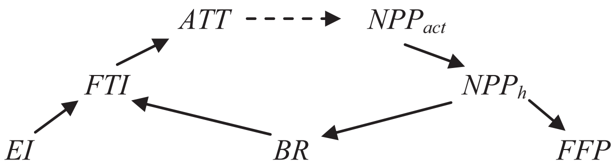
Figure 8. Relationship between complexity of internal energy loops (*E*), information held in the network of energy flows (*I*) and landscape functional structure (*L*). Theoretical values (a), and empirical results (b) in the Vallès case study (1860s and 2000s).

Fig. 1.

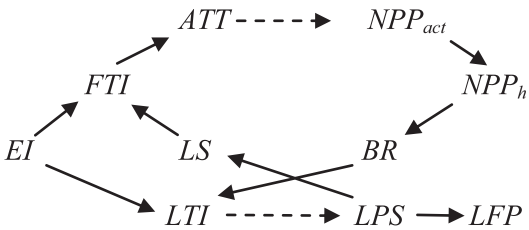
a) ‘Natural’ subsystem



b) ‘Farmland’ subsystem

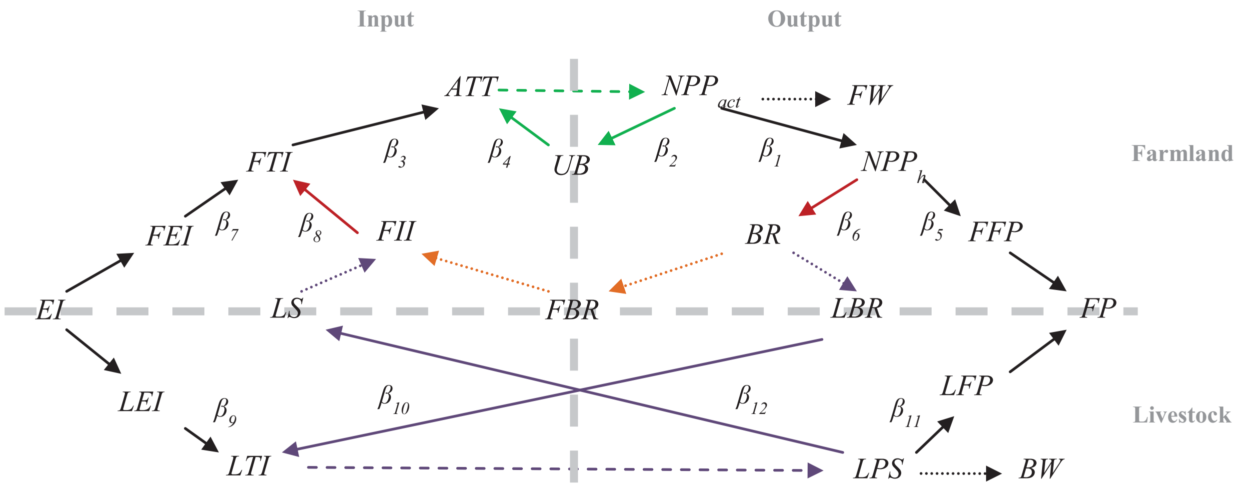


c) ‘Livestock’ subsystem



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*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*).

Fig. 2.

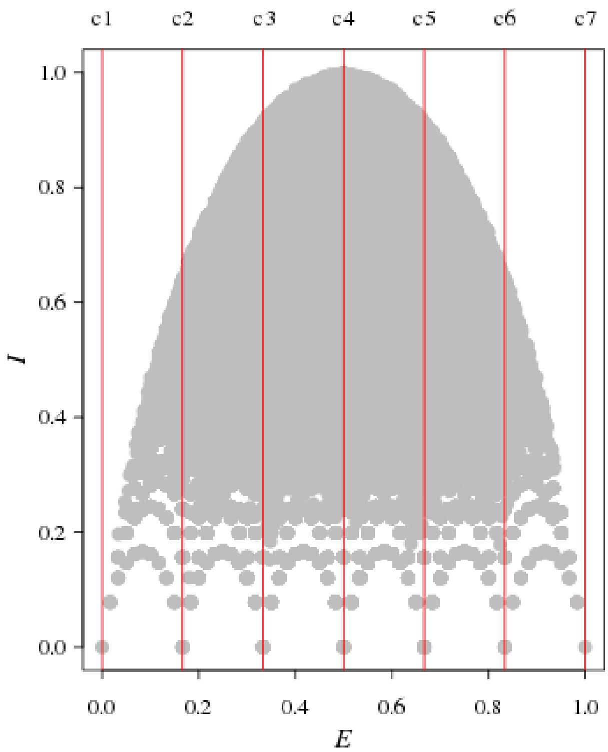


Variables: Actual Net Primary Production (NPP_{act}); Unharvested Biomass (*UB*); Harvested Net Primary Production (NPP_h); Biomass Reused (*BR*); Farmland Biomass Reused (*FBR*); Livestock Biomass Reused (*LBR*); Farmland Final Produce (*FFP*); External Input (*EI*); Farmland External Input (*FEI*); Livestock External Input (*LEI*); Livestock Total Input (*LTI*); Livestock Produce and Services (*LPS*); Livestock Final Produce (*LFP*); Livestock Services (*LS*); Final Produce (*FP*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*). β_i's are the incoming-outgoing coefficients.

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

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

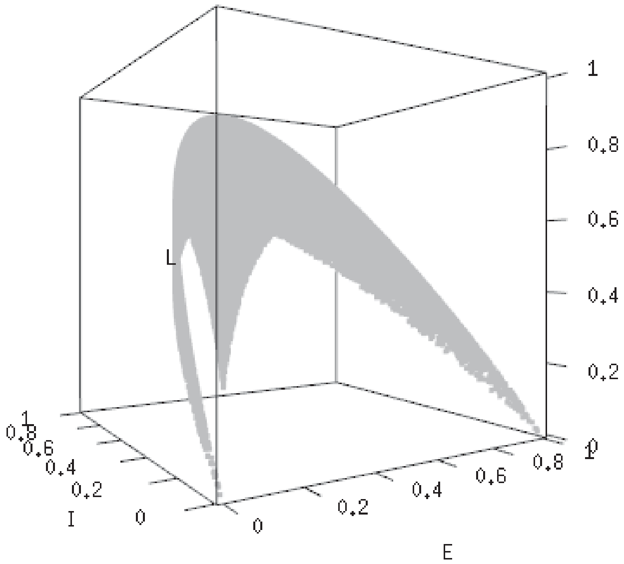
Fig. 3.



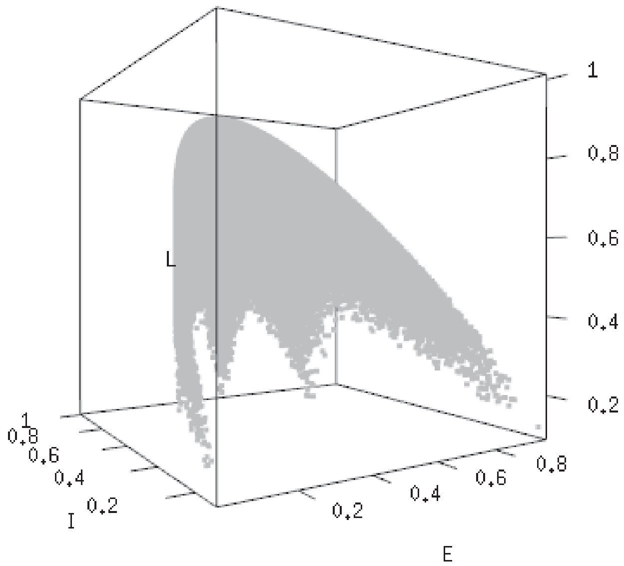
Note: Where $c_i = (i-1)/6$, represent the E values corresponding to the $(\beta_2, \beta_4, \beta_6, \beta_8, \beta_{10}, \beta_{12})$ configurations that make $I = 0$ and all its permutations. We have maximum information (I) for an intermediate level of complexity (E) provided by the storage of energy carriers looping inside.

Fig. 4.

a) 3 Agroecosystem typologies

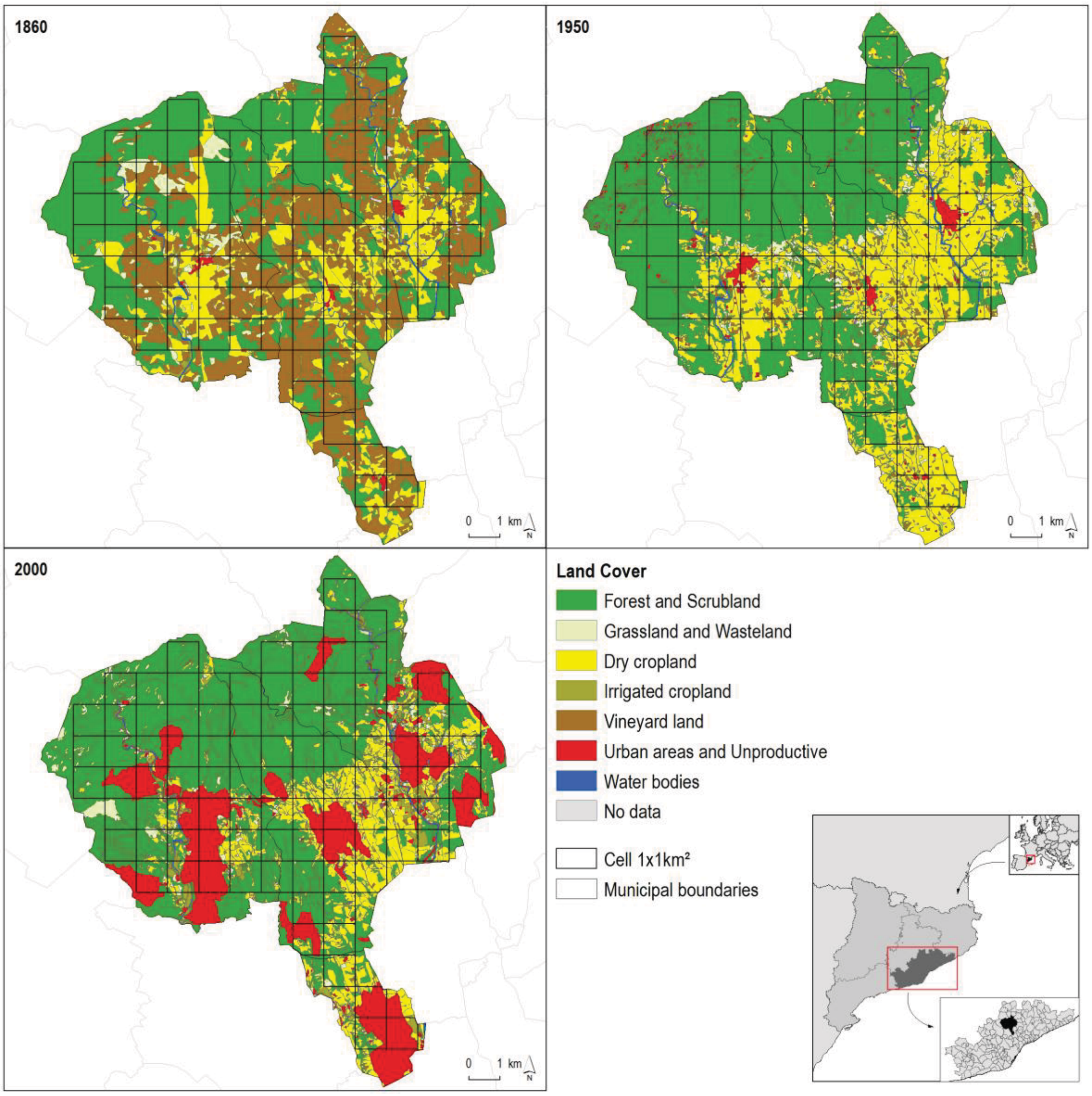


b) 5 Agroecosystem typologies



Note: The lengthening over each weight of the *E* formula corresponds to each agroecosystem typology (T_i) considered in Table 3, from left to right T_1, (T_2 in b), T_3, (T_4 in b) and T_5 are observed.

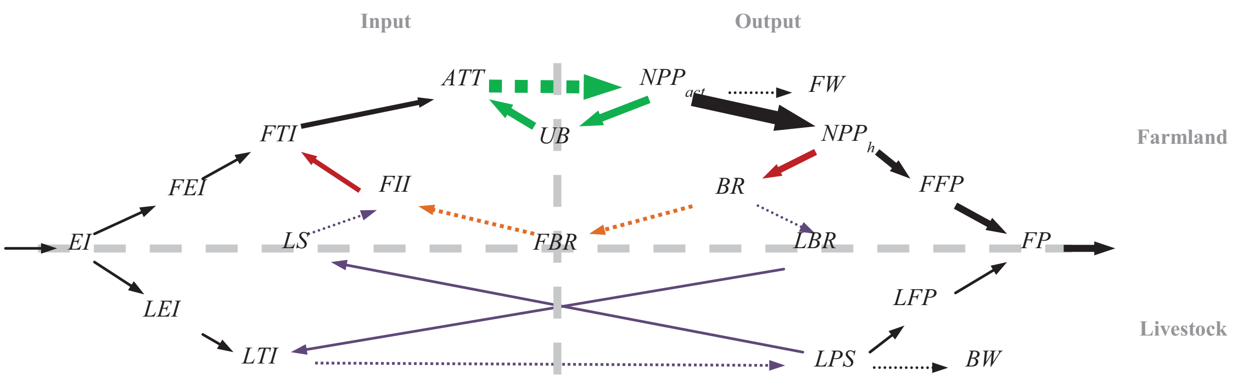
Fig. 5.



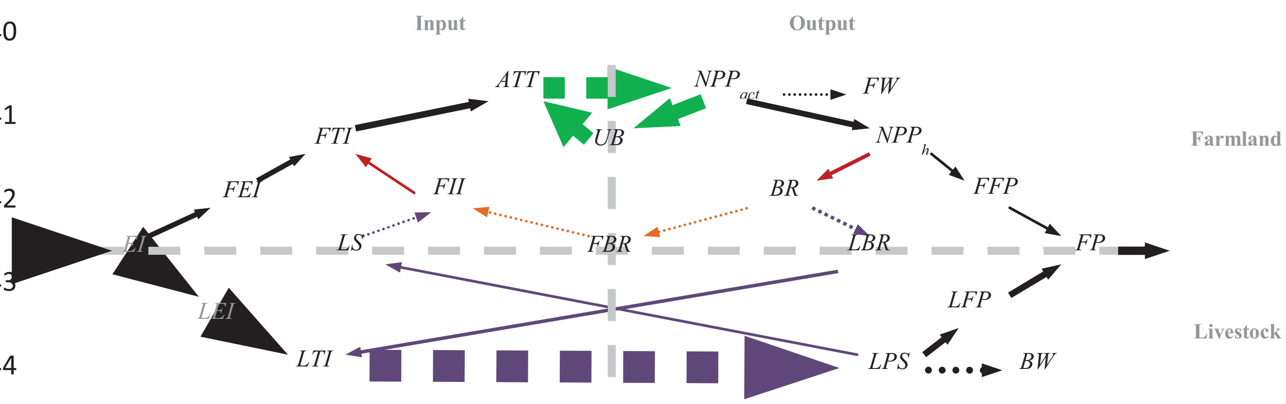
Source: Cadastral maps of mid-19th century from the Old collections of the Map Library at the Institut Cartogràfic i Geològic de Catalunya (ICGC); cadastral maps of mid-20th century from the Regional Office of Catalonia, in Barcelona, of the General Directorate of Cadastral Registry of the Spanish Ministry of Treasure and Public Administration; and for the beginning of the 21st century, the third edition of the Land Cover Map of Catalonia generated by photointerpretation made in the Research Center in Terrestrial Ecology (CREAF) from the colour orthophoto map provided by the ICGC.

Fig. 6.

a) 1860s



b) 2000s



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*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*).

Note: The width of the arrows in both graphs is proportional to the magnitude of energy fluxes in the agro-ecosystem. The colours of the arrows represent the 'natural' (green), 'farmland' (red) or 'livestock' (purple) subsystems.

Fig. 7.

a) 1860s b) 2000s

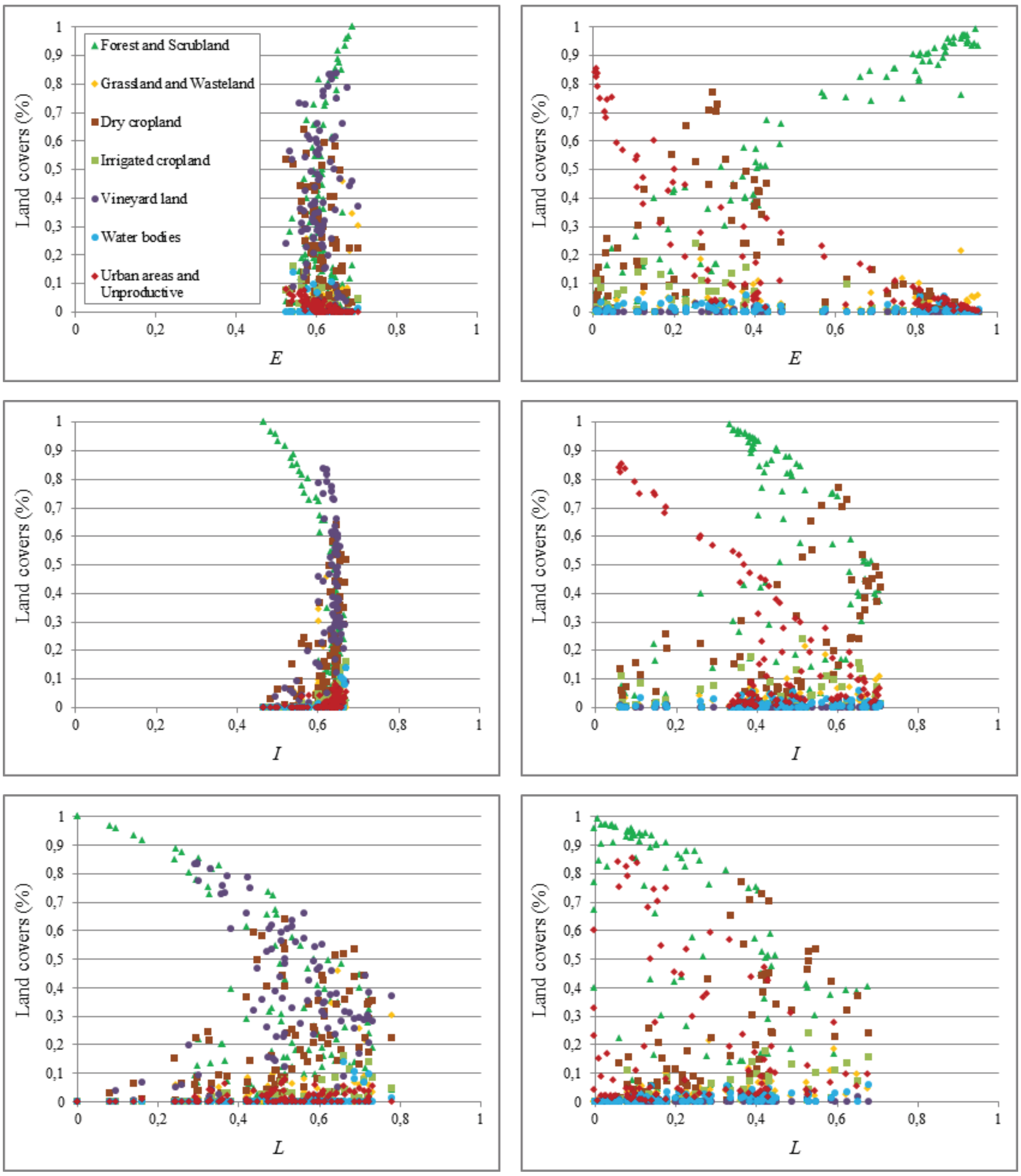
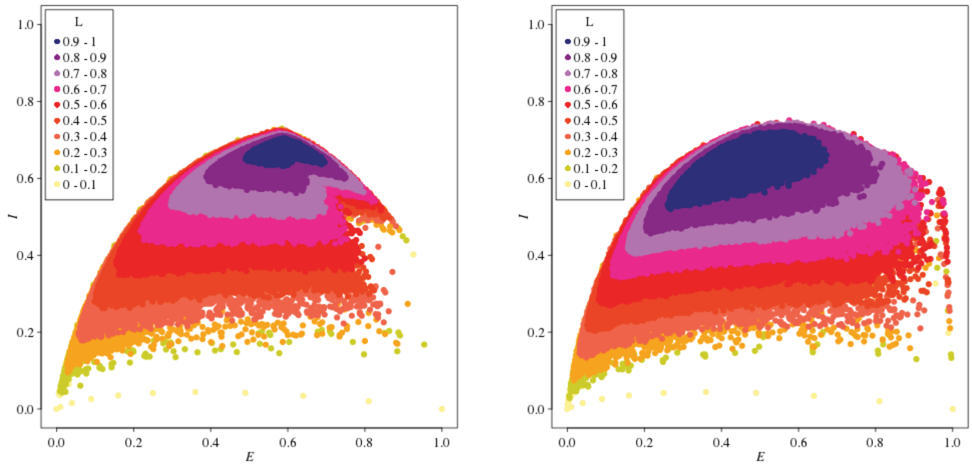
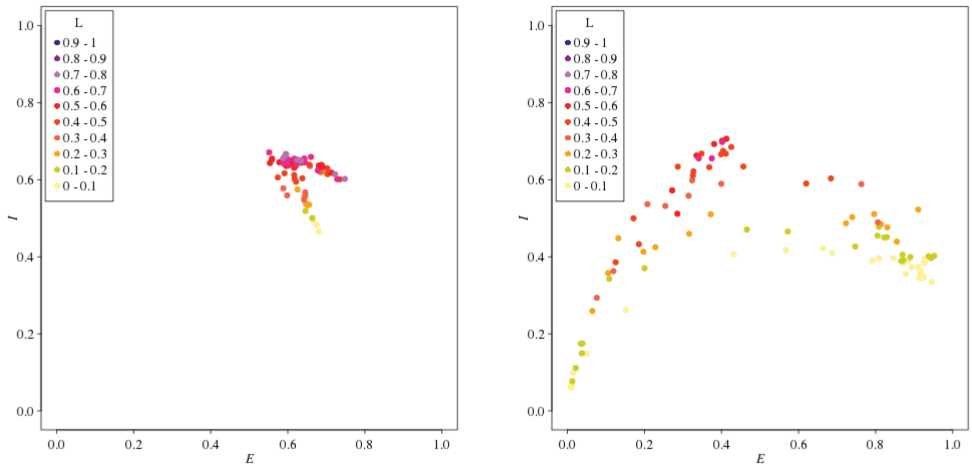


Fig. 8.

a) Theoretical $E - I - L$ values for 1860s (left) and 2000s (right)[1].



b) Empirical $E - I - L$ results for 1860s (left) and 2000s (right).



Note: [1]The figure shows a two dimensional projection of a three dimensional figure (Figure 5). Higher values of L cover lower values of L. Simulated points following uniform distribution are represented.

Tables

Table 1. Agroecosystem energy carriers taken into account and their values in the Valles case study (1860s, 2000s).

	Energy carriers	Formula	GJ a year 1860	GJ a year 2000
Single variables	Farmland External Input *(FEI)*	-	5,553	193,383
	Unharvested Biomass *(UB)*	-	294,693	561,462
	Farmland Waste *(FW)*	-	0	11,150
	Farmland Biomass Reused *(FBR)*	-	146,555	12,424
	Livestock Biomass Reused *(LBR)*	-	96,308	129,822
	Final Farmland Produce *(FFP)*	-	259,890	73,562
	Livestock External Input *(LEI)*	-	6,657	1,060,277
	Livestock Waste *(LW)*	-	0	256,502
	Livestock Services *(LS)*	-	36,980	36,997
	Livestock Final Produce *(LFP)*[1]	-	2,954	238,765
Composed variables	Actually Net Primary Production (NPP_{act})	$NPP_{act}=UB+NPPh+FW$	797,446	788,421
	Harvested Net Primary Production (NPP_h)	$NPP_h=BR+FFP$	502,753	215,808
	Agro-ecosystem Total Turnover *(ATT)*[2]	$ATT=UB+FTI$	483,781	804,267
	Livestock Total Input *(LTI)*	$LTI=LBR+LEI$	102,965	1,190,098
	Livestock Produce and Services *(LPS)*	$LPS=LS+LP+BW$	39,934	532,264
	Farmland Total Input *(FTI)*	$FTI=FII+FEI$	189,088	242,805
	Farmland Internal Input *(FII)*	$FII=FBR+LS$	183,535	49.421
	Biomass Reused *(BR)*	$BR=FBR+LBR$	242,864	142,246
	Final Produce *(FP)*	$FP=FFP+LFP$	262,843	312,327
	External Input *(EI)*	$EI=FEI+LEI$	12,209	1,253,660

Notes: [1] The concept of land produce is the same that Vitousek et al. (1986) used for the Harvested Net Primary Production.[2] We use the ecological term of 'turnover' adapted from Dettmann (2008) meaning all the energy flow-through in an agro-ecosystem; in this specific case it refers to all the incoming energy carriers that go to the farmland. For the terminology used, and the set of EROIs obtained from the energy balances, see Tello et al. (2015a, 2015b) and Galán et al. (2015).

Table 2. Agroecosystem energy coefficients, complexity of internal energy loops (*E*), information held by energy flows (*I*), and their values in the Valles case study (1860s, 2000s).

Energy coefficients		Formula	Case study values 1860	Case study values 2000
Incoming or outgoing flows	β_1	$\beta_1=NPP_h/NPP_{act}$	0.630	0.274
	β_2	$\beta_2=UB/NPP_{act}$	0.370	0.712
	β_3	$\beta_3=FTI/ATT$	0.391	0.302
	β_4	$\beta_4=UB/ATT$	0.609	0.698
	β_5	$\beta_5=FFP/NPP_h$	0.517	0.341
	β_6	$\beta_6=BR/NPP_h$	0.483	0.659
	β_7	$\beta_7=FEI/FTI$	0.029	0.796
	β_8	$\beta_8=FII/FTI$	0.971	0.204
	β_9	$\beta_9=LEI/LTI$	0.065	0.891
	β_{10}	$\beta_{10}=LBR/LTI$	0.935	0.109
	β_{11}	$\beta_{11}=LP/LPS$	0.074	0.449
	β_{12}	$\beta_{12}=LS/LPS$	0.926	0.070
Information – Loss	γ_L	$\gamma_L=(UB+NPP_h)/2NPP_{act}$	0.500	0.493
	γ_B	$\gamma_B=(LS+LP)/2LPS$	0.500	0.259
Subsystem – contribution	k_1	$k_1=UB/(UB+BR+LS)$	0.513	0.758
	k_2	$k_2=BR/(UB+BR+LS)$	0.423	0.192
	k_3	$k_3=LS/(UB+BR+LS)$	0.064	0.050
	k_2'	$k_2'=BR/(BR+LS)$	0.868	0.794
	k_3'	$k_3'=LS/(BR+LS)$	0.132	0.206
Energy Storage	*E*	$E=\frac{\beta_2+\beta_4}{2}k_1+\frac{\beta_6+\beta_8}{2}k_2+\frac{\beta_{10}+\beta_{12}}{2}k_3$	**0.618**	**0.622**
Energy Reinvestment Effort	*Ee*	$E_e=\frac{\beta_6+\beta_8}{2}k_2'+\frac{\beta_{10}+\beta_{12}}{2}k_3'$	**0.754**	**0.361**
Energy Information	*I*	$I=-\frac{1}{6}\left(\sum_{i=1}^{12}\beta_i\log_2\beta_i\right)(\gamma_L+\gamma_B)$	**0.639**	**0.587**

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*); Agro-ecosystem Total Turnover (*ATT*); Farmland Total Input (*FTI*); Farmland Internal Input (*FII*).

Table 3. Theoretical energy coefficients for five agroecosystems typologies (T_i)[1].

Coefficients		T_1	T_2	T_3	T_4	T_5
Incoming or outgoing flows	β_1	0	0.25	0.5	0.75	1
	β_2	1	0.75	0.5	0.25	0
	β_3	0	0.25	0.5	0.75	1
	β_4	1	0.75	0.5	0.25	0
	β_5	0	0.25	0.5	0.75	1
	β_6	1	0.75	0.5	0.25	0
	β_7	0	0.25	0.5	0.75	1
	β_8	1	0.75	0.5	0.25	0
	β_9	0	0.25	0.5	0.75	1
	β_{10}	1	0.75	0.5	0.25	0
	β_{11}	0	0.25	0.5	0.75	1
	β_{12}	1	0.75	0.5	0.25	0
Information – loss	γ_L	0.5	0.5	0.5	0.5	0.5
	γ_B	0.5	0.5	0.5	0.5	0.5
Subsystem – contribution	k_1	1	0.33	0.33	0.33	0
	k_2	0	0.33	0.33	0.33	1
	k_3	0	0.33	0.33	0.33	0

Note: [1] T_1 corresponds to the most 'natural' agro-ecosystem, T_3 refers to a 'balanced' agroecosystem, T_5 refers to an 'industrial-intensive' agro-ecosystem. Then, T_2 and T_4 correspond to intermediate values.

Table 4. Land-cover and landscape functional structure (L) in the Vallès case study (1860s, 1950s and 2000s).

Land-covers[1]	ha			%		
	1860s	1950s	2000s	1860s	1950s	2000s
Forest and Scrubland	3,461.1	5,556.9	5,366.2	36.4%	58.5%	56.5%
Grassland and Pastureland	273.9	282.8	257.3	2.8%	2.9%	2.7%
Dry cropland	1906.2	2,966.8	1,530.7	20.1%	31.2%	16.2%
Irrigated cropland	150.6	0	244.6	1.5%	0.0%	2.5%
Vineyard land	3,452.7	227.6	16.1	36.4%	2.4%	0.1%
Water bodies	151.6	131.4	100.7	1.6%	1.3%	1.1%
Urban areas and Unproductive	55.0	320.0	1,970.0	0.6%	3.3%	20.7%
No data	34.4	0	0	0.4%	0.0%	0.0%
Landscape Structure L $L = \left(-\sum_{i=1}^{k} p_i \log_k p_i\right)(1 - p_u)$	**0.72**	**0.50**	**0.38**	–	–	–

Note: [1] Land-covers into all 1x1 km^2 sample cells (see Fig. 5).

Annex

Table A1. Spatially-explicit values of the energy carriers (GJ/km^2) flowing across the different land-covers in the agro-ecological landscape of the Vallès case study (1860s, 2000s).

1860	Forest and scrubland	Grassland pastureland	Dry cropland	Irrigated cropland	Vineyard land	Water bodies	Urban areas unproductive
fei	61	61	814	5,091	556	0	0
ub	31,740	2,482	26,922	37,605	18,011	16,369	0
fw	0	0	0	0	0	0	0
fbr_1	1,756	0	8,235	8,539	27,418	0	0
fbr_2	0	0	10,257	26,728	27,418	0	0
lbr_1	2,893	15,050	24,618	20,842	4,387	0	0
lbr_2	1,795	9,263	10,593	13,230	13,629	0	0
ffp	35,784	0	14,597	27,184	12,616	0	0
lei	124	640	732	914	942	0	0
lw	0	0	0	0	0	0	0
ls	689	3,555	4,067	5,076	5,234	0	0
lfp	55	284	325	406	418	0	0
npp_{act}	72,174	17,532	74,372	94,170	62,432	16,369	0
npp_h	40,433	15,050	47,450	56,565	44,421	0	0
br	4,649	15,050	32,853	29,381	31,806	0	0
fti	750	3,616	15,137	36,895	33,209	0	0
fii	689	3,555	14,324	31,804	32,652	0	0
ei	185	701	1,546	6,005	1,498	0	0
lps	744	3,839	4,391	5,482	5,652	0	0
lti	1,919	9,903	11,325	14,144	14,570	0	0
att	32,490	6,098	42,059	74,500	51,219	16,369	0

2000	Forest and scrubland	Grassland pastureland	Dry cropland	Irrigated cropland	Vineyard land	Water bodies	Urban areas unproductive
fei	2,448	0	73,698	128,311	80,618	0	0
ub	76,828	14,615	15,465	17,113	4,744	16,369	0
fw	0	0	1,418	23,504	76,109	0	0
fbr_1	0	0	2,469	26,979	0	0	0
fbr_2	0	0	2,469	26,979	0	0	0
lbr_1	139	139	62,307	42,592	0	0	0
lbr_2	255	255	62,744	31,351	71,876	0	0
ffp	3,537	0	18,908	47,181	22,431	0	0
lei	2,085	2,085	512,445	256,046	587,028	0	0
lw	0	0	120,798	102,724	40,655	0	0
ls	73	73	17,881	8,934	20,484	0	0
lfp	470	470	115,398	57,659	132,194	0	0
npp_{act}	80,504	14,754	100,567	157,369	103,284	16,369	0
npp_h	3,676	139	83,684	116,752	22,431	0	0
br	139	139	64,776	69,571	0	0	0
fti	2,521	73	94,048	164,225	101,102	0	0
fii	73	73	20,350	35,914	20,484	0	0
ei	4,534	2,085	586,143	384,357	667,646	0	0
lps	542	542	254,077	169,317	193,332	0	0
lti	2,341	2,341	575,189	287,396	658,905	0	0
att	79,349	14,687	109,513	181,338	105,846	16,369	0

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 Inputs (*ei*); Farmland External Inputs (*fei*); Livestock External Inputs (*lei*); Livestock Total Inputs (*lti*); Livestock Produce and Services (*lps*); Livestock Final Produce (*lfp*); Livestock Services (*ls*); Final Produce (*fp*); Agro-ecosyten Total Turnover (*att*); Farmland Total Inputs (*fti*); Farmland Internal Inputs (*fii*).

Table A2. Spatially-explicit energy coefficients[1] of the graph model of interlinked energy carriers flowing across the different land-covers in the agro-ecological landscape of the Vallès case study (1860s, 2000s).

1860	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}	γ_L	γ_B	k_1	k_2	k_3	E	E_e
Forest and scrubland	0.56	0.44	0.02	0.98	0.89	0.11	0.08	0.92	0.06	0.94	0.07	0.93	0.50	0.50	0.86	0.13	0.02	0.69	0.57
Grassland and pastureland	0.86	0.14	0.59	0.41	0.00	1.00	0.02	0.98	0.06	0.94	0.07	0.93	0.50	0.50	0.12	0.71	0.17	0.90	0.98
Dry cropland	0.64	0.36	0.36	0.64	0.31	0.69	0.05	0.95	0.06	0.94	0.07	0.93	0.50	0.50	0.42	0.51	0.06	0.69	0.83
Irrigated cropland	0.60	0.40	0.50	0.50	0.48	0.52	0.14	0.86	0.06	0.94	0.07	0.93	0.50	0.50	0.52	0.41	0.07	0.58	0.73
Vineyard land	0.71	0.29	0.65	0.35	0.28	0.72	0.02	0.98	0.06	0.94	0.07	0.93	0.50	0.50	0.33	0.58	0.10	0.68	0.86
Water bodies	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	1.00	0.00	0.00	0.00	0.00
Urban and unproductive areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

2000	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}	γ_L	γ_B	k_1	k_2	k_3	E	E_e
Forest and scrubland	0.05	0.95	0.03	0.97	0.96	0.04	0.97	0.03	0.89	0.11	0.87	0.13	0.50	0.50	1.00	0.00	0.00	0.96	0.06
Grassland and pastureland	0.01	0.99	0.00	1.00	0.00	1.00	0.00	1.00	0.89	0.11	0.87	0.13	0.50	0.50	0.99	0.01	0.00	0.99	0.70
Dry cropland	0.83	0.15	0.86	0.14	0.23	0.77	0.78	0.22	0.89	0.11	0.45	0.07	0.49	0.26	0.16	0.66	0.18	0.37	0.41
Irrigated cropland	0.74	0.11	0.91	0.09	0.40	0.60	0.78	0.22	0.89	0.11	0.34	0.05	0.43	0.20	0.18	0.73	0.09	0.32	0.37
Vineyard land	0.22	0.05	0.96	0.04	1.00	0.00	0.80	0.20	0.89	0.11	0.68	0.11	0.13	0.39	0.19	0.00	0.81	0.10	0.11
Water bodies	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	1.00	0.00	0.00	0.00	0.00
Urban and unproductive areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: [1] β_i's are the incoming-outgoing coefficients, γ_i's are the information-loss coefficients, and k_i's the subsystem-contribution coefficients.

Video 1

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