Opening the black box of energy throughputs in farm systems: A decomposition analysis between the energy returns to external inputs, internal biomass reuses and total inputs consumed (the Vallès County, Catalonia, c.1860 and 1999)

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1. Introduction: When a single EROI is not enough

In spite the long-lasting research devoted to this important aspect of any sustainability assessment, the energy analysis of agricultural systems remains a site-specific accounting whose results depends on the research question raised, the system boundaries placed and the methodological approaches adopted (Pelletier et al., 2011; Hall et al., 2011; Hall and Klitgaard, 2012). Even if it hampers comparability, this plurality of assessments is not a sign of sloppy science but a reflection of the epistemological challenges faced when dealing with a complex, hierarchical reality (Giampietro and Mayumi, 2000:141). The only workable solution is to make clear from the beginning for what purpose will each energy accounting procedure be used (Jones, 1989), in order to then compile in a transparent way a set of different approaches and protocols that allow researchers to understand each other (Mulder and Hagens, 2008; Murphy et al., 2011b).

Many agricultural energy balances have been accounted by adopting a societal system boundary and an input-output approach addressed to assess to what extent agriculture behaves as a net energy provider or a net consumer, which allows allocating the corresponding polluting emissions among economic sectors. This standpoint only requires computing the energy return obtained from the agricultural system to the inputs invested from outside. Although this makes sense on its own right, such a simple input-output ratio of the energy carriers crossing the agricultural boundary inevitably conceals the internal agroecological functioning of farm systems into a black box.

Any attempt to open the agroecological black box has to deal with the looping character of biophysical flows in agroecosystems where a relevant share of energy carriers driven by farmers cycles again into the underlying funds (Giampietro, 2004;

Giampietro et al., 2012, 2013; Guzmán and González de Molina, 2015). As Ho and Ulanowicz (2005) have pointed out, these internal cycles make thermodynamic sense as long as they provide a dynamic closure in nested space-time domains that enables living systems to minimize entropy. Thanks to this emerging property that increases their internal energy storage capacity, all sorts of living dissipative structures can start a dynamic process to reproduce themselves and evolve far from thermodynamic equilibrium (Prigogine and Stengers, 1984; Morowitz, 2002). This happens in ecosystems, as well as in agroecosystems, by enhancing the complexity of interlinked loops which allow improving energy throughputs within, while entropy dissipation is ejected outside. Although this entropy ejection always involves a relevant energy loss when dissipative structures are seen from outside, the cyclical character of their internal less-dissipative energy loops leads to an integrated spatial heterogeneity able to give rise to biodiversity and keep it along time (Ho, 2013:31; Ulanowicz, 1986:147-161; Tscharntke et al., 2012).

As we shall see, livestock was a key component of many mixed farming systems in the past that kept a tightly integrated spatial diversity of complex agroecosystems, and brought some amount of biomass back into the soil through manure that played a crucial role in keeping up fertility (Krausmann, 2004). The organic matter content of cultivated soils, either reproduced by means of livestock manure or by burying fresh and burnt phytomass, becomes a clear example of how energy carriers driven by farmers were stored within agroecosystems for a while—despite the huge energy loss that this internal loops always entailed throughout the whole chain of bioconversions required before the nutrients caught in reused biomass flows could be released and assimilated again by growing crops. The annual growth of rings of trees, shrubs and woody crops is another example of net energy storage taking place within farmland, once the removals of timber, firewood and pruning have been deducted. They become a part of the unharvested phytomass, which plays a key role in sustaining the associated biodiversity of agroecosystems (Guzmán and González de Molina, 2015).

We are particularly interested in bringing the internal biomass reuses into light because our research project is developing an Energy-Landscape Integrated Analysis addressed to reveal how energy throughputs of agroecosystems relate with the farm-associated biodiversity in landscape mosaics (Altieri, 1999; Margalef 2006), and the ecosystem services that different types of farming may maintain in a land matrix (Marull et al., 2010, forthcoming a, b). This spatial-explicit modelling of farming turnover has to be based on a wider energy profile of agricultural systems than a single linear input-output ratio.

Drawing on these fundamentals, we can assume that the accounting of internal energy cycles becomes an important criterion to understand what sustainability means when looking at the energy carriers flowing in agroecosystems: Entropy can be minimized within a farm system by interconnecting more life cycles so that the by-products from one may become resources for another (Ho, 2013). This is the rationale behind a basic trait stressed by Giampietro et al. (2013:142): «A key feature of agro-ecosystems is that some amount of biomass flows taken from the land is reused within the land system as an investment into the maintenance of its basic funds and services». As we will see in detail, these flows of biomass reuses always entail a relevant cost for farmers in terms of labour and land allocations, which translates in terms of energy as well (Guzmán and González de Molina, 2009). At the same time, they perform vital roles in the fund-flow maintenance of agroecosystems. It is out of question that, from a farm-operator standpoint, they become a significant part of the total amount of inputs invested to maintain a farming system.

But how an Energy Return on Investment (EROI) can be calculated of a cyclical, rather than a linear agroecosystem? Either we give up accounting energy throughputs as a useful tool for a sustainable assessment of farm systems, or we start using several EROIs measured at different parts of the agroecological structure of energy flows so as to interrelate them in a broader energy profile. Taking the second alternative (Tello et al., 2015), we present in this article the core of a proposal of energy analysis of past and present farm systems focused on the role played by the internal biomass reuses as an alternative to resort on external inputs.

Our main point is to highlight that a significant proportion of biomass reused becomes a hallmark of organic farm systems, which have traditionally tended to save external inputs by relying on internal biomass reuses in accordance with a Low External Input Technology (LEIT) strategy (Tripp, 2008). Conversely, industrialized farm systems have tended to proportionally reduce biomass reuses by supplementing them with cheap external inputs mainly coming from fossil fuels—a strategy deeply linked not only with the lower energy returns to these external inputs but with lessening an integrated land-use management of complex landscape mosaics that up to a point may jeopardize the planned and associated biodiversity in agroecosystems (Giampietro, 1997; Gliessman, 1998; Altieri and Nicholls, 2005; Snapp and Pound, 2008).

Section two explains the conceptual framework and accountancy rules of this energy analysis of agroecosystems seen from a farm-operator standpoint at landscape level, the three interlinked EROIs proposed, and a decomposition analysis of *Final EROI* between the energy returns to the external inputs (*External Final EROI*, or *EFEROI*) and to internal biomass reuses (*Internal Final EROI*, or *IFEROI*). This decomposition analysis helps exploring the contrasting energy profiles of organic and industrial farm systems through the equation that relates *FEROI*, *EFEROI* and *IFEROI*; it allows plotting in a three-dimensional space a surface representing all the values that the variables of this equation can take, and using it to perform some optimality assessments; and it opens a way to disentangle the role played by the variations of *Biomass Reuse* and *External Input* flows in any historical change of *Final EROI*. Section three presents the empirical results obtained in our Catalan case study c.1860 and in 1999. Section four discusses the results, and section five concludes by presenting the working hypothesis that organic and industrial farm systems may tend to cluster into two opposite typologies, and the possibilities offered by this analysis to assess certain optimal improvement pathways.

2. Methods of energy accounting of farm systems from a farm-operator standpoint

We account the energy throughputs of agroecosystems by comparing the amount of inputs invested by farm-operators, either coming from inside or outside the agroecosystem, with the final energy outputs obtained to satisfy human needs—and always bearing in mind that the agroecosystem not only enables farmers to obtain these flows of energy carriers to render consumable goods, but involves environmental constraints when it comes to reproduce the underlying fuds that provide those flows and keep up ecosystem services. This conceptual approach is not just energy economics or ecology, but a joint agroecological and socioeconomic accountancy of the energy flows and yields of farm systems that allows comparing the energy profiles in different regions and through time from an environmental history perspective able to take sustainability concerns into consideration (Worster, 1990; González de Molina and Toledo, 2014; Guzmán and González de Molina, 2015).

Fig. 1 represents a simplified flowchart of the energy subsystems and carriers of farm systems taken into account in our modelling. It does not aim at showing all aspects of the agroecological functioning, but only represents the operative concepts used in this energy bookkeeping. The approach is two-sided. On the one hand we adopt the managing point of view of a specific farming community, which entails an economic accountancy of inputs and outputs flowing through a set of funds that remain after a year taken as time frame (Mayumi, 1991). On the other hand, we intend that our energy bookkeeping does not conceal some basic features of the internal agroecological functioning into a black box, but remains open enough to bring to light the renewal of the key components which provide ecosystem services directly or indirectly related with biodiversity: Soil fertility, pest and disease control and pollination, to name but a few.

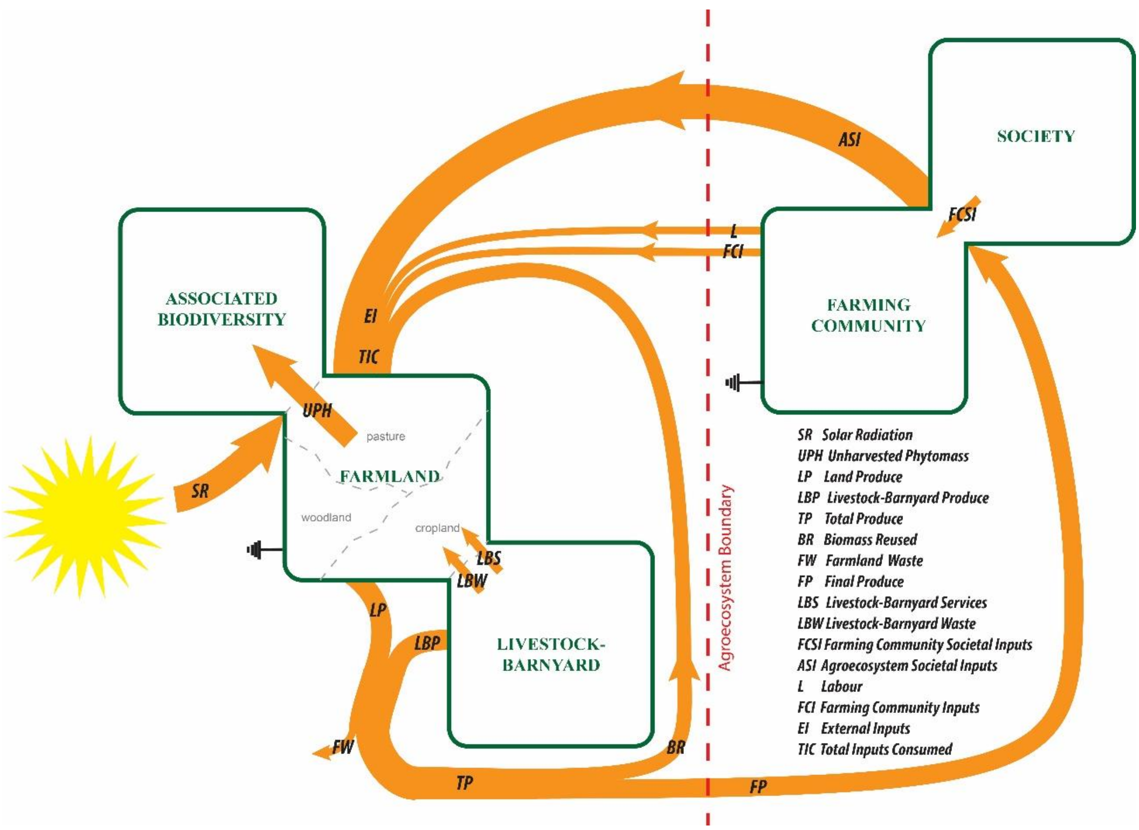

Fig.1.Proposed model of energy flows on farm systems as seen from a farm-operator standpoint with an agroecosystem boundary

Source: Tello et al. 2015.

2.1. Basic funds and flows taken into account in our bookkeeping

The green boxes in the flow diagram represent energy subsystems used by farm activity to convert energy carriers from one form into another, as seen in the way a farm-operator may account for them. According to this approach, on *Farmland* photosynthesis performed by primary producers converts solar radiation into plant phytomass (Smil, 2013). Thanks to the *Unharvested Phytomass* (*UPH*) and habitats that remain available within *Farmland*, an *Associated Biodiversity* remains to provide ecosystem services. The subsystems appear partially merged because they actually overlap one another, meaning that we can conceptually distinguish them in the manner shown in Fig. 1 only when a site-specific management standpoint is adopted (Giampietro, 2004). For instance, the rationale behind splitting the photosynthetic primary production into two different but partially merged subsystems, *Farmland* and *Associated Biodiversity*, can only make sense from this farm-operator viewpoint. In spite of sharing to some extent the same spaces in actual agroecosystems, they define two functional subsystems that must be accounted separately when an energy analysis is locally performed by farmers. Then, after having defined this set of farming subsystems which include many different bioconverters within, we can observe how they are interconnected by different energy flows.

The *Farmland* subsystem encompasses three types of land use: Arable cropland, pasture, and woodland. Many farm systems integrate all three categories at local scale and their relative size distinguishes one from another. Accordingly, farmland products coming from all three types of land use constitute a major energy carrier: *Land Produce* (*LP*) that includes cropland products like cereals, legumes, root crops, vegetables, and fibre, but also firewood and wood, together with straw or brush used for animal bedding in barnyards. This flow is the totality of phytomass harvested from *Farmland* and directed toward human purposes. Adding *Unharvested Phytomass* equals the actual NPP obtained from solar radiation within the system boundaries.

Another important flow is a portion of *Land Produce* called *Biomass Reused* (*BR*). This term describes energy carriers harvested from *Farmland* but then re-directed back to on-farm uses. *Biomass Reused* includes seeds collected for next year's sowing and biomass distributed on cropland soils as fertilizer, such as green manures, stubble or wooden biomass burned or buried underground. In mixed farm systems that combine livestock with cropping a portion of *Biomass Reused* is the feed, forage, fodder, hay, straw or other bedding materials for animal husbandry. The *Livestock-Barnyard* subsystem, after further energy conversions (which take place not only through animal digestion but in manure heaps composted in barnyards), contributes *Livestock-Barnyard Produce* (*LBP*) including meat, milk, eggs, and fibre. It also contributes *Livestock-Barnyard Services* (*LBS*) including manure and physical work in the form of draught power, both of which return energy flows to *Farmland*. When a fraction of *Land Produce* or *Livestock-Barnyard Produce* is not properly reused but is wasted, meaning that the flow does not go to the right place in the right dose to contribute to the renewal of agroecosystem funds, it is designated as *Farmland Waste* (*FW*) or *Livestock-Barnyard Waste* (*LBW*).

The *Total Produce* (*TP*) of the agricultural system includes the gross production of *Farmland* and *Livestock-Barnyard* subsystems, prior to the recycling of *Biomass Reused*. The *Final Produce* (*FP*) of the agricultural system is that portion of *Total Produce* that remains after the re-direction of *Biomass Reused*. That is, *Final Produce* is the share of farm production not needed to sustain agroecosystem functions, and therefore available for human consumption, whether locally or afar. This could include energy consumed by the local *Farming Community* as food, fibre, fuel, and building materials or surplus produce exported to the rest of *Society*.

The two human energy subsystems in the model, the local *Farming Community* and the distant *Society* to which they belong, take in energy carriers from farm produce and convert them once again to support societal subsistence and demographic reproduction, as well as a wide array of cultural endeavours from basic infrastructure (such as shelter and transportation) to high cultural ones (like cathedrals and universities). Both also re-direct energy carriers back to the farm system. Locally such energy contributions take two forms, first the form of *Labour* (*L*), and second the *Farming Community Inputs* (*FCI*) composed by humanure and domestic residues.

Completing the circle, *Agroecosystem Societal Inputs* (*ASI*) bring energy carriers from outside the system boundaries, including organic and inorganic materials such as imported feed, building supplies, farm implements or manufactured machinery and, since the early twentieth century, fossil fuel products (tractors and fuel, fertilizers, pesticides). *Exernal Inputs (EI)* includes *Labour*, *Farming Community Inputs*, and *Agroecosystem Societal Inputs*. *Total Inputs Consumed (TIC)* adds *Biomass Reused* as another input into the farming system.

A subsequent controversial question is how to account for the human population and activity of the *Farming Community* placed outside the agroecosystem (Brown and Herendeen, 1996; Murphy et al., 2011b:1892; Giampietro et al., 2013). In accordance with our approach, we consider human labour as an external input which is accounted for as the fraction of the average diet of the farm operators that corresponds to the work time performed in the agroecosystem—taking physiologically different energy requirements of human activities into account. That is, we use what Fluck (1992) has termed the 'total energy of food metabolized while working' including the basic metabolic rate during work time. In this way our analysis remains open to the choices made by these farm-operators when allocating their own time, and to changes in labour productivity.

Following this energy approach to farm systems, we define inputs as any energy carrier consumed with an opportunity cost for the farm-operators. All energy carriers coming from inside the agroecosystem boundaries, or reinvested inside it, are accounted only for their enthalpy value thus setting aside the photosynthesis performed by solar radiation. All energy carriers coming from outside the system boundaries are accounted for by their direct energy content and their indirect embodied energy (Tello et al., 2015). Drawing on this, we are going to account three different but interrelated EROIs.

2.2.A set of three EROIs seen from a farm-operator standpoint

The first of these EROIs, *EFEROI* $\left(\frac{FP}{EI}\right)$ relates *External Inputs* (*EI*) to the *Final Produce* (*FP*) crossing the agroecosystem boundaries in a way that links the agrarian activity with the rest of the energy system of a society. Hence, it assesses to what extent the agroecosytem analysed becomes a net provider or rather a net consumer of energy at a societal level, an assessment that becomes very important for evaluating the agricultural component of the 'Law of minimum EROI' put forward by Hall et al. (2009) and Hall and Klitgaard (2012). *Final EROI* $\left(\frac{FP}{TIC}\right)$ assesses instead how much external (*EI*) and internal (*BR*) energy carriers have been spent by a farm operator to get a given basket of human consumable *Final Produce* (*FP*) as measured at the exit gate of the agroecosystem studied. It becomes relevant when we want to assess the energy performance as seen from the allocation standpoint of their farm-operators, and ceases to be so when a wider societal perspective is adopted. Yet, even from a farm operator viewpoint, if we take *Final EROI* $\left(\frac{FP}{EI+BR}\right)$ alone an important shortcoming appears from an agroecological perspective, given that *External Inputs* are conflated with *Biomass Reused* in the *Total Inputs Consumed* (*TIC*), disregarding the role *BR* plays in keeping up the underlying funds and ecological functioning of agroecosystems. In order to overcome this limitation, *TIC* must be broken down into both components, *EI* and *BR*. While the ratio $\left(\frac{FP}{EI}\right)$ equals *EFEROI*, the ratio $\left(\frac{FP}{BR}\right)$ gives way to calculate *IFEROI* which assesses the portion of *Land Produce* reinvested in the agroecosystem as *Biomass Reused* in order to get a unit of *Final Produce* that exits the boundaries of the system analysed. Then, *Final EROI* $\left(\frac{FP}{EI+BR}\right)$ can be decomposed into the external (*EFEROI*) and internal (*IFEROI*) returns.

2.3. Interrelation of FEROI, EFEROI, and IFEROI

Final EROI is related with internal (*IFEROI*) and external (*EFEROI*) returns according to equation (1), which can easily be obtained[1] from the previous definitions (Tello et al., 2015):

$$FEROI = \frac{EFEROI \cdot IFEROI}{EFEROI + IFEROI} \tag{1}$$

Expression (1) is the equation of the quadratic surface shown in Fig. 2, which happens to be a cone centred at the origin (right side of Fig. 2) or, to be more precise, a portion of a cone (left side of Fig. 2), as the values of *EFEROI* and *IFEROI* can only be

[1] $\frac{EFEROI \cdot IFEROI}{EFEROI + IFEROI} = \frac{\frac{FP}{EI} \cdot \frac{FP}{BR}}{\frac{FP}{EI} + \frac{FP}{BR}} = \frac{\frac{FP^2}{EI \cdot BR}}{\frac{FP\,(BR+EI)}{EI \cdot BR}} = \frac{FP}{EI+BR} = FEROI.$

positive.[2] We can interpret this figure as the possibility surface that encompasses all the values that *FEROI*, *EFEROI* and *IFEROI* can take in equation (1):

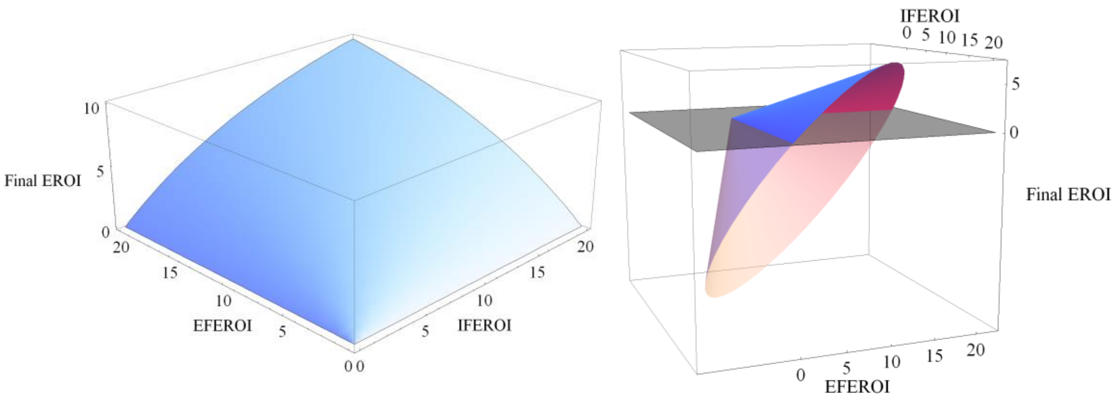

Fig. 2.Graphical representation of *Final EROI* as a function of *EFEROI* and *IFEROI*

Source: our own.

If equation (1) is seen as an expression of *Final EROI* as a function of *EFEROI* and *IFEROI*, the possibility surface shows that this function incurs in decreasing returns at any point: To get any increase in the joint *FEROI* proportionally greater increases in either internal or external returns or both are needed. In fact, at any point (x, y), the directional derivative of the surface in the direction of the gradient is $\frac{\mathrm{x}^4+\mathrm{y}^4}{(\mathrm{x}+\mathrm{y})^4}$, which is strictly smaller than 1 for all points with no null coordinates, and equal to 1 when either coordinate is 0.[3]

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[2] In fact, equation (1) can be rewritten as $z = \frac{xy}{x+y}$ or equivalently $-xy + xz + yz = 0$. In terms of matrices, $(x \quad y \quad z)\begin{pmatrix} 0 & -1/2 & 1/2 \\ -1/2 & 0 & 1/2 \\ 1/2 & 1/2 & 0 \end{pmatrix}\begin{pmatrix} x \\ y \\ z \end{pmatrix} = 0$. The previous symmetric matrix has eigenvalues -1 with multiplicity 1, and $1/2$ with multiplicity 2. Hence the matrix diagonalizes and equation (1) reduces to $x^2 = (y^2 + z^2)/2$, which is the equation of a cone. This cone is trivially centred at point (0,0,0). Vector $(1,1,-1)$ is an eigenvector of eigenvalue -1, therefore the axis of the cone has its direction.

[3] The gradient of the function $f(x,y) = \frac{x\,y}{x+y}$ is $\nabla f(x,y) = \left(\frac{\partial f}{\partial x}(x,y), \frac{\partial f}{\partial y}(x,y)\right) = \left(\frac{y^2}{(x+y)^2}, \frac{x^2}{(x+y)^2}\right)$. Therefore, the directional derivative in the direction v of the gradient is $\nabla f(x,y) \cdot v = \frac{x^4+y^4}{(x+y)^4}$, or

For a given *FEROI*, any increase or decrease of either *IFEROI* or *EFEROI* can be compensated by a decrease or increase of the other, as shown in Fig. 3 where the contour levels, or isoquants, of this function can be seen:

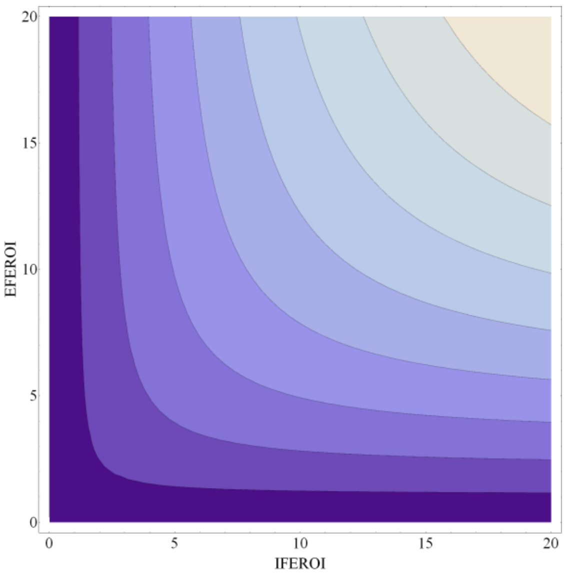

Fig. 3. Isoquants of *Final EROI* as a function of *EFEROI* and *IFEROI*

Source: our own.

It is easy to show that these curves are hyperbolae.[4] Therefore, the relation among the two variations is inversely proportional and the proportional factor depends on the eccentricity of each isoquant.

As we are interested in the role played by external flows and internal biomass reuses in the energy performance of farm systems, we can go deeper into this analysis in order to reveal how variations in *EFEROI* and *IFEROI* affect the value of *FEROI* in terms of the underlying function that relates *Final Produce* (*FP*) with internal (*BR*) and external (*EI*) inputs. For the time being all we can say is that assuming a constant *FP*, the

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$\nabla f(x,y) \cdot \frac{v}{||v||} = \sqrt{\frac{x^4+y^4}{(x+y)^4}}$ if the normalized version is preferred. For our discussion, both are equivalent, as we are interested in comparing their values with 1.

[4] In fact, they are conic sections in the horizontal direction, which forms an angle with the axis of the cone smaller than the one of the generatrix.

variation of *EFEROI* (relative to *IFEROI*) is inversely proportional to that of *EI* (relative to *BR*). Unfortunately, the function –or perhaps ‘functional’ according to Georgescu-Roegen (1971:236)— relating *FP* with *BR* and *EI* is too complex to be determined. In agroecosystems any internal or external biophysical flow interacts with a set of funds which can only bring about a final produce within a limited range of variation in yields and in a discontinuous manner. What really matters are the emerging properties arising out of the whole network of synergistic links of flows established among a myriad of fund components of subsystems working together to attain a joint outcome—and that is the main focus of agroecology as a science (Altieri, 1989; Gliessman, 1998; Snapp and Pound, 2008).

An empirical workable way to deal with such a complex issue is to plot in Figs. 2 and 3 the various combinations of *EFEROI*, *IFEROI* and *FEROI* existing in farm systems, in order to cluster them around characteristic typologies.

2.4. Optimality analysis of Final EROI according to shifts in $\frac{EI}{BR}$ *ratio*

The quadratic surface showing the relationships between *FEROI*, *EFEROI*, and *IFEROI* can also be used to find out optimal improvement pathways for *Final EROI*. Fig. 4 presents the gradient vector at each point that indicates for each pair of values (*EFEROI*, *IFEROI*) the direction to which *FEROI* can be optimally improved. Besides optimal directions, the figure also depicts the improving capacity at each point by means of the length of the gradient vector.

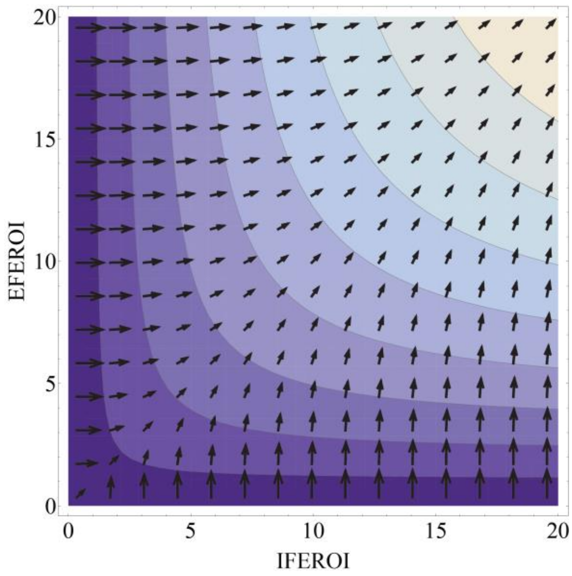

Fig. 4.Directions and comparative lengths of the potential improvement of *Final EROI* by changing the combinations of *IFEROI* and *EFEROI* at any point.

Source: our own.

We can observe that potential improvements are higher if *Final EROI* is lower, or/and when the combination of *EFEROI* and *IFEROI* is unbalanced—that is, when the $\frac{EI}{BR}$ ratio is far from one. All these vectors led towards points of higher *FEROIs* with lower improvement capacities that tend to approach the ones along the diagonal with higher diminishing returns (where *FEROI* = $\frac{EFEROI}{2}$ = $\frac{IFEROI}{2}$, and $\frac{EI}{BR} = 1$).

We have to keep in mind that, according to equation (1), this optimality analysis is restricted to shifts in $\frac{EI}{BR}$ ratios. In spite of its limitations, it allows mapping the improving capacity of *Final EROI* in agroecosystems by looking at the optimal combination of internal and external returns, to then compare the theoretical possibilities with available empirical data and perform counterfactual historical interpretations in the past, or design ways to improve energy yields of farm systems at present. In any case, its actual meaning for a sustainable functioning of agroecosystems requires a wider multi-dimensional analysis by taking into account not only how the variation of this ratio affects *Final EROI*, but also nutrient replenishment of soils and the landscape patterns able to host greater or lower associated biodiversity.

2.5. Assessing the role of EI and BR variations in any shift of Final EROI

Another way to delve into the socioecological changes of farm systems is disentangling the role played by the internal or external energy returns in any historical shift experienced by *Final EROI*. This can be achieved by a decomposition analysis, considering that $FP = h(EI, BR)$, where h is a function we know exists but the expression of which remains unknown. As proved in the Appendix, we can obtain the roles of the corresponding variations of *EI* and *BR* in any shift experienced by *Final EROI* through the following expressions (2):

Effect of variation in $EI = \dfrac{-\frac{FP_1+FP_2}{2}\Delta EI+\frac{EI_1+EI_2+BR_1+BR_2}{4}\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$ and

Effect of variation in $BR = \dfrac{-\frac{FP_1+FP_2}{2}\Delta BR+\frac{EI_1+EI_2+BR_1+BR_2}{4}\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$ (2)

3. Results: Calculating *FEROI*, *EFEROI* and *IFEROI* of the study area

3.1. Location and features of the Catalan study area in the Vallès County

We have applied this energy modelling (Tello et al., 2015; Galán et al., forthcoming) to a case study area located some thirty kilometres away from the city of Barcelona (Catalonia, North-East of Iberia) circa 1860 and in 1999, used as a test bench.[5] The land cover change experienced by this cultural landscape can be seen in Fig. 5:

[5] It is located in the same study area used in Cussó et al. (2006b), but now we have carried out a thoroughly revision using better sources, new accountancy rules and performing a stricter control in order to assess that the energy yields were not attained at the expense of soil fertility, deforestation or livestock malnutrition. Changes are also related to having accounted four instead of five municipalities, due to lack

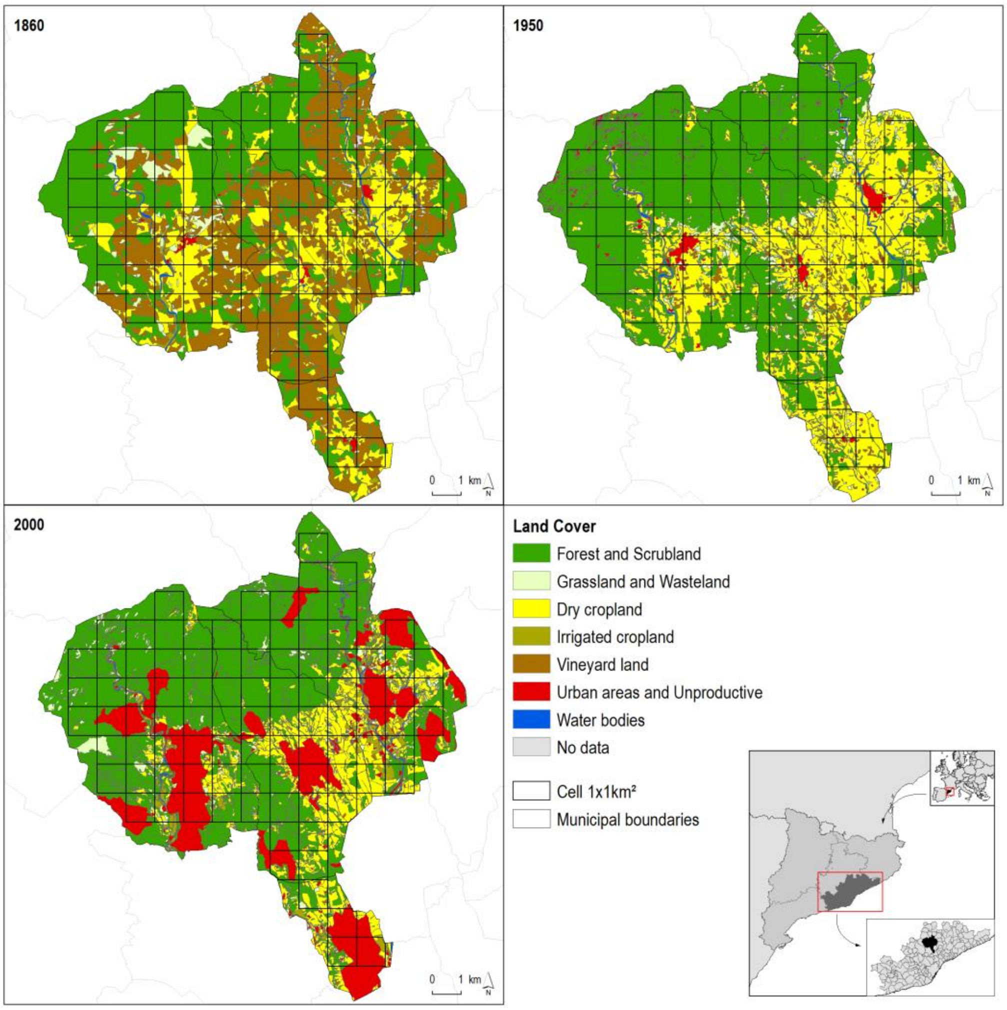

Fig. 5.Location map of the study area in the Barcelona Metropolitan Region (Catalonia, Iberia) and land covers exiting in the 1860s, 1950s and 2000s

Source: Marull et al. 2015.

Many traditional organic farm systems, like the ones existing c.1860 in the study area, had kept complex land-use mosaics as a result of an integrated farming with livestock husbandry. Conversely, these landscape mosaics have tended to vanish from the 1960s onwards when industrial farm management has led to increasingly homogeneous land covers, which became polarized into two main types: Intensive

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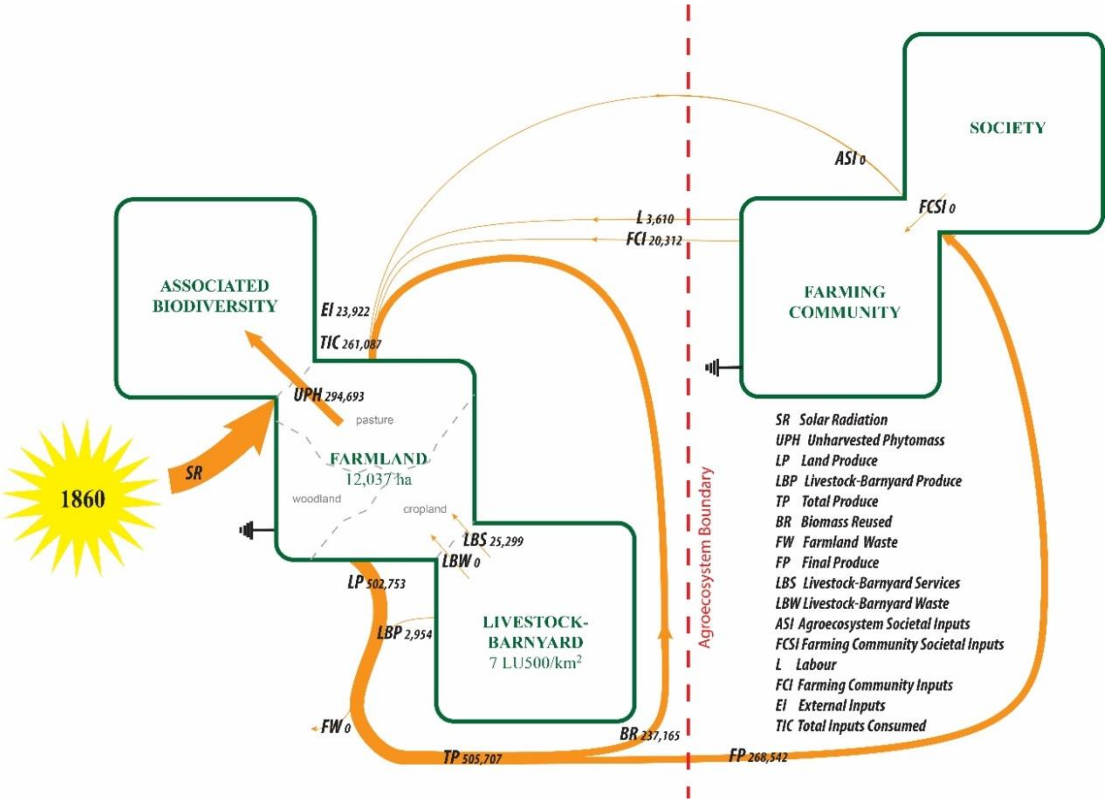
of one cadastral map c.1860, when we discovered some relevant mismatches between the land accounts given in the official statistics and the surfaces accounted by GIS in these maps.

monocultures ever more oriented towards animal breeding in feedlots, and woods left abandoned (Gerard et al., 2010; Parcerisas et al., 2012; Marull et al., 2014)—a process clearly shown in Fig. 5 when urban areas are set aside.

3.2. Energy profiles and EROIs of the Catalan study area c.1860 and in 1999

The historical process of agricultural change summarized in Fig. 5 can be taken as a natural experiment for a comparative analysis of the energy profiles of organic and industrial farm systems seen at landscape level from their farm-operators (Odum, 1984; Gliessman, 1998; Tscharntke et al., 2005). Fig. 6 shows in a simplified flowchart the empirical results obtained by applying our agroecosystem model of energy flows and loops to these four municipalities in the Vallès County c.1860 and in 1999.



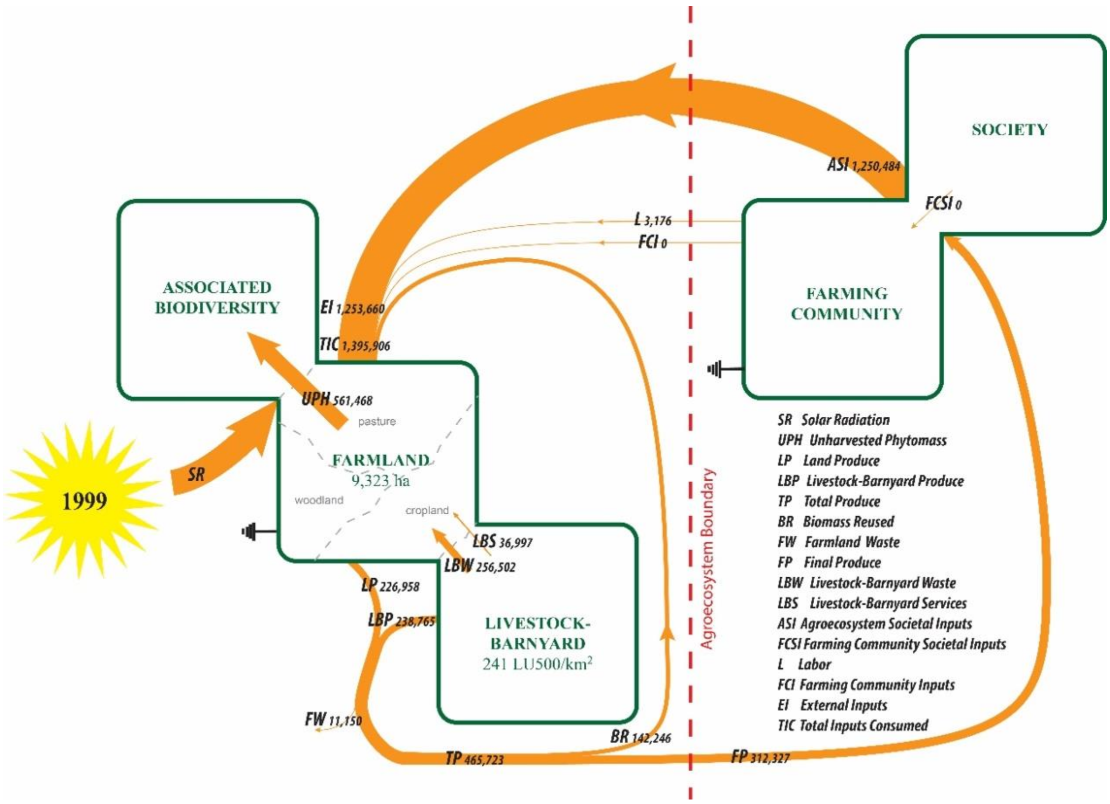


Fig. 6.Main energy flows and loops in the agroecosystems of the Vallès County (Catalonia, Iberia) c.1860 and in 1999.

Source: Tello et al. 2015.

The basic territorial, demographic and biophysical dataset used to calculate the flows of farming energy carriers, and set up the energy balances of Fig. 6, is listed in Table 1:

Agroecosystem Subsystems and Energy Carriers		**c.1860**	**1999**	**units**
Funds				
	Inhabitants in the farming community	7,941	39,189	inhabitants
	Population density	64	327	inhab./km^2
	agricultural active population	2,057	250	AWU*
	Total area	124	120	km^2
	Farmland	12,037	9,323	ha
	Cropland	6,753	2,182	ha
	vegetables & fruit trees in gardens	166	185	ha
	irrigated annual crops	156	104	ha
	rain-fed annual crops	1,620	1,753	ha
	vineyards	4,310	22	ha
	olive groves	500	65	ha
	Pastureland	909	340	ha
	Woodland & scrub	4,376	6,801	ha

	Livestock density per unit of farmland	7	241	LU500/km^2
	Flows of energy carriers			
NPP_{act}	**Actual Net Primary Production estimated**	797,446	788,427	GJ
UPH	**Unharvested Phytomass**	294,693	561,468	GJ
TP	**Total Produce**	505,707	465,723	GJ
LP	**Land Produce**	502,753	226,958	GJ
LP	*LP—Cropland*	309,196	201,912	GJ
LP	*LP—Pastureland*	13,676	993	GJ
LP	*LP—Woodland& scrub*	179,881	24,053	GJ
LBP	**Livestock-Barnyard Produce**	2,954	238,765	GJ
LBP	*LBP— Meat, milk and eggs*	2,754	183,982	
LBP	*LBP— Slaughter residues*	199	54,783	
FP	**Final Produce**	268,542	312,327	GJ
FP	*FP—food*	21,012	198,279	GJ
FP	*FP—grape juice to make wine & olive oil*	18,742	1,093	GJ
FP	*FP—edible forest products*	1,544	0	GJ
FP	*FP—fibre (hemp, wool, hides, slaughter by-products)*	1,399	54,783	GJ
FP	*FP—other industrial crops (rape)*	0	8,451	GJ
FP	*FP—grapevine & olive oil pomaces sold outside*	0	1,123	GJ
FP	*FP—forest timber*	3,741	24,053	GJ
FP	*FP—forest firewood*	162,032		
FP	*FP—pruning & vines or trees removed to firewood*	38,268	1,616	GJ
FP	*FP—other vineyard and olive trees by-products*	21,604	0	GJ
FP	*FP—animal feed sold outside*	0	24,022	GJ
TIC	**Total Inputs Consumed**	261,087	1,395,906	GJ
BR	**Biomass Reused**	237,165	142,246	GJ
FBR	Farmland Biomass Reused	142,154	12,424	GJ
FBR	*FBR—seeds*	3,898	2,148	GJ
FBR	*FBR—buried biomass*	95,689	10,276	GJ
FBR	*FBR—biomass burnt & ploughed* (‘hormigueros’)	42,567	0	GJ
LBBR	Livestock-Barnyard Biomass Reused	95,011	129,822	GJ
LBBR	*LBBR—feed crops*	8,449	35,831	GJ
LBBR	*LBBR—fodder crops*	12,418	32,008	GJ
LBBR	*LBBR—crop by-products to animal feeding*	47,904	25,476	GJ
LBBR	*LBBR—grass*	13,676	993	GJ
LBBR	*LBBR—other animal feeding from woodland*	4,355	0	GJ
LBBR	*LBBR—stall bedding*	8,209	35,514	GJ
EI	**External Inputs**	23,922	1,253,660	GJ
L	**Labour**	3,610	3,176	GJ
FCI	**Farming Community Inputs**	20,312	0	GJ
FCI	*FCI—human garbage and sewage*	17,808	*0*	*GJ*
FCI	*FCI— humanure*	2,505	0	GJ
ASI	**Agroecosystem Societal Inputs**	0	1,250,484	GJ
FSI	**Farmland Societal Inputs**	0	192,562	GJ
FSI	*FSI—machinery*	0	163,043	GJ
FSI	*FSI—herbicides*	0	12,758	GJ
FSI	*FSI—chemical fertilizers*	0	10,971	GJ

FSI	*FSI—seeds bought from outside*	0	*1,982*	GJ
FSI	*FSI—water pumping (electricity)*	0	*3,809*	GJ
LBSI	***Livestock-Barnyard Societal Inputs***	0	1,057,922	GJ
LBSI	*LBSI—animal feed & straw bought from outside*	0	947,109	GJ
LBSI	*LBSI—energy spent in feedlots (fuel & electricity)*	0	110,812	GJ
LBS	***Livestock-Barnyard Services***	25,299	36,997	*GJ*
LBS	*LBS—manure*	22,313	36,997	*GJ*
LBS	*LBS—draft power*	2,986	0	*GJ*
LBW	**Livestock-Barnyard Waste**	0	256,502	GJ
FW	**Farmland Waste**	0	11,150	GJ

Table 1. Biophysiscal Subsystems and Energy flows of farming systems in the Catalan case study c.1860 and in 1999; *AWU: full-time Agricultural Working Units a year

Source: our own, taken from Tello et al. (2015) and Marco et al. (forthcoming).

Finally, Table 2 summarizes three different energy returns on different types of energy inputs invested, *FEROI*, *EFEROI* and *IFEROI*:

EROIs	**definition**	**c.1860**	**1999**
External Final EROI (*EFEROI*)	$\textit{External Final EROI} = \frac{FP}{EI}$	11.23	0.25
Internal Final EROI (*IFEROI*)	$\textit{Internal Final EROI} = \frac{FP}{BR}$	1.13	2.20
Final EROI (*FEROI*)	$\textit{Final EROI} = \frac{FP}{EI+BR}$	1.03	0.22

Table 2. Three different EROIs obtained from Table 2.

Source: our own, taken from Tello et al. (2015) and Marco et al. (forthcoming).

EFEROI (which is similar to the most common indicator used from an input-output approach at societal level) and also *FEROI* (which includes internal biomass reuses as a relevant cost borne by farm-operators) exhibit greater values in the traditional organic farm system c.1860 than in the industrial one of 1999. This is not at all strange given the

5.3-fold increase of *External Inputs* (*EI*) consumed from 1860 to 1999, while the final produce obtained only grew 16% in absolute terms (Table 1).

By far the greatest share of this injection of external energy carriers in this case study was the animal feed imported by industrial feedlots (68% of *EI* in 1999), to which the electricity consumed in these feedlots (8%) has to be added, and the energy embodied in tractors and tilling machinery (12%). Notice that the direct and indirect energy content of this imported animal feed (947,109 GJ in 1999) exceeds the yearly photosynthetic NPP that takes place within the study area (788,427 GJ a year). Conversely, a LEIT strategy explains the higher *EFEROI* c.1860 (11.23) compared with 1999 (0.25).

While the trends found in *EFEROI* and *FEROI* are in line with what is expected (Schroll, 1994; Dalgaard et al., 2001), the picture changes when the biomass reused is taken alone as input in *IFEROI*. In our Catalan example, *IFEROI* increased from 1.13 c.1860 to 2.20 in 1999. What is the meaning of the opposite directionality of change in this case? The comparatively lower *IFEROI* in the former date was a result of the large investment made in *BR*, whose disaggregate composition can be seen in Table 3:

<table>
<tr><td rowspan="9">Biomass Reused (BR): 237,165 GJ (100%)</td><td rowspan="3">Farmland Biomass Reused (FBR): 142,154 GJ (60%)</td><td>Seeds: 3,898 GJ (2%)</td></tr>
<tr><td>Fresh biomass buried into cropland: 95,689 (40%)</td></tr>
<tr><td>Biomass burnt & buried (‘hormigueros’): 42,567 GJ (18%)</td></tr>
<tr><td rowspan="6">Livestock-Barnyard Biomass Reused (LBBR): 95,011 GJ (40%)</td><td>Feed: 8,449 GJ (4%)</td></tr>
<tr><td>Fodder: 12,418 GJ (5%)</td></tr>
<tr><td>Crop by-products used to feed livestock: 47,904 GJ (20%)</td></tr>
<tr><td>Livestock grazing in natural pastures: 13,676 GJ (6%)</td></tr>
<tr><td>Straw used in stall bedding: 8,209 GJ (3%)</td></tr>
<tr><td>Other from woodland & scrub: 4,355 GJ (2%)</td></tr>
</table>

Table 3.Disaggregation of biomass reused (*BR*) flows in the Catalan case study c.1860. Numbers are in GJ, percentages into parentheses are over total *BR* flows.

Source: our own, taken from Tello et al. (2015) and Marco et al. (forthcoming).

Conversely, the greater *IFEROI* of the industrial farming in 1999 was a result not only of the greater *Final Produce* but of the comparatively lower effort in the internal circulation of *BR*. We will go deeper into this question in the next section.

3.3. Plotting the EROIs of the study area c.1860 and in 1999 in the possibility surface

Fig. 7 shows the energy profile of the organic farm system existing in the Vallès County study area c.1860 compared with the industrial one in 1999. It depicts the data as points in the conic surface of all the possible values that the relationship of *Final EROI* with *EFEROI* and *IFEROI* can take:

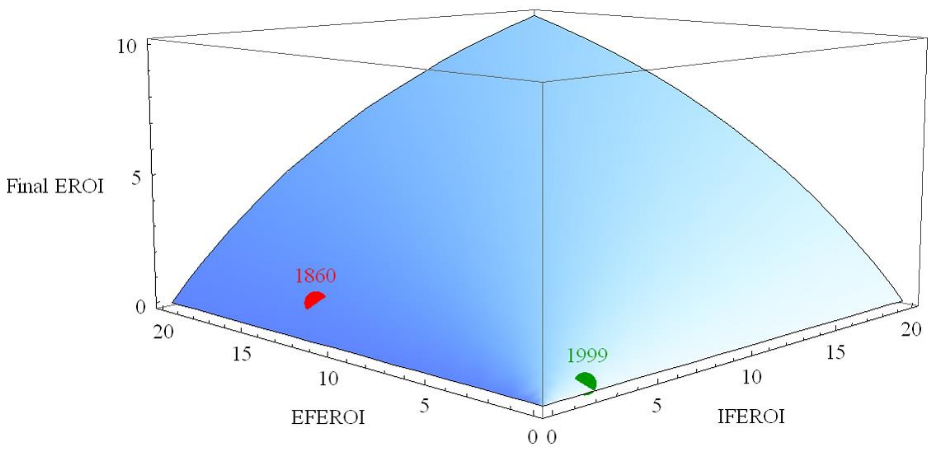


Fig. 7. Plotting *Final EROI*, *EFEROI* and *IFEROI* attained by the farm system of the Catalan study area c.1860 (in red) and in 1999 (in green) in the possibility surface

Source: our own.

The two points express in visual terms the different energy profiles adopted by an organic mixed farming system versus an industrialized agriculture mainly oriented to supply livestock breeding in feedlots. Circa 1860 the internal energy return was low (the red point is close to the *IFEROI*=0 axis) due to the high amounts of *BR* invested (Table

3). However, this low *IFEROI* was compensated up to a point by a much higher external return (the point is located quite some distance away from the *EFEROI*=0 axis) thanks to the strategy of saving external inputs which whenever possible were replaced by biomass reuses. In 1999 *EFEROI* was extremely low and this was compensated only to some (minor) extent by reducing the internal flows of *BR*.

3.4.Assessing improvement pathways of Final EROI c.1860 and in 1999

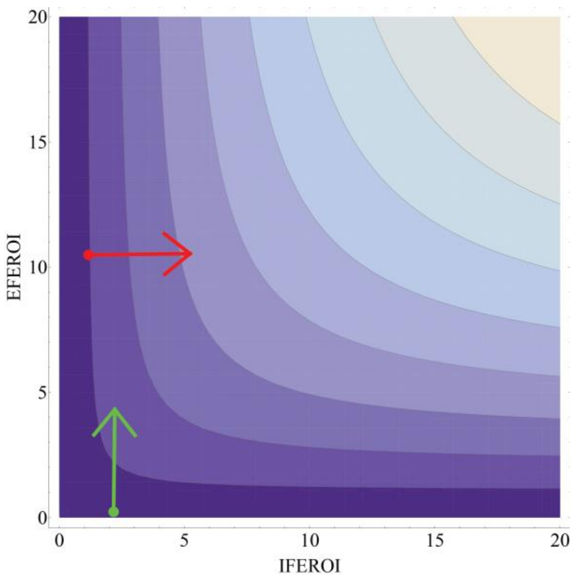


Fig. 8.Gradient vectors for optimal improvements of *Final EROI* in the Catalan study area c.1860 (red) and 1999 (green) according to the possibility surface of $\frac{EI}{BR}$ variation

Source: our own

In the Vallès case study the ratio $\frac{EI}{BR}$ was 0.1 c.1860 and 8.8 in 1999. Hence, internal biomass reuses and external inflows were far from parity in both periods of time, a situation that offered room for improving *Final EROI* by changing the underlying energy fund-flow profiles—as we have seen in section 2.4. The gradient vector c.1860 (red arrow in Fig. 8) indicates that a small increase of *IFEROI* would have resulted in a large increase of *FEROI*, given that the slope of the isoparametric curve representing its

$\frac{FP}{BR}$ return is much higher at this point than the slope of the isoparametric curve representing its $\frac{FP}{EI}$ return, which is close to zero. This means that the internal return had a much higher impact because external inputs were then comparatively small. The opposite is true with the gradient vector of *FEROI* improvement in 1999. The underlying meaning of these results will be discussed in section four.

3.5.The role of EI and BR variations in the shift of Final EROI from1860 to 1999

We have seen that *Final EROI* shifted from 1.03 c.1860 to 0.22 in 1999 in our Catalan case study. Now we want to assess the role played by the variation of *BR* and *EI*, and their corresponding partial energy returns in terms of *FP*, in the following variation experienced in *Final EROI*: $\left(\frac{0.22-1.03}{1.03}\right) \times\ 100 =\ -78.64\%$.

Applying equation (2) we obtain that the variation of −0.80 EROI points (or −78.64%) experienced between $Final\ EROI_{1860}$ and $Final\ EROI_{1999}$ is explained by a sharp increase from EI_{1860} to EI_{1999}, which is equal to −0.93.[6] This represents 115.6% of the total variation. However, the effect driven by the variation of *EI* was counteracted by the decrease from BR_{1860} to BR_{1999}, which is equal to 0.13 and represents −15.6% of the total decomposed variation. The addition of both opposite effects explains the whole variation experienced, which is $-0.93 + 0.13 = -0.80$ *FEROI* points.

The result reveals that the decrease in *Final EROI* between 1860 and 1999 was mainly due to a big increase in *EI*, coming directly from fossil fuels or indirectly through feed imports for livestock breeding in feedlots, which caused *EFEROI* to decline significantly—recall that EI_{1999} was 1.6 times larger than the total NPP in the study area! However, the effect was counteracted to some extent by a parallel reduction

[6] Notice that in this kind of decomposition analysis negative or positive results only mean that the corresponding partial variation has moved in the same direction, thus reinforcing it, when the sign is the same as the variation being decomposed. Inverted signs exert a counterbalancing effect.

in internal flows of *BR* and the ensuing increase of *IFEROI*. Had such a counterbalancing effect not taken place, the drop in *FEROI* would have been even higher. This brings to light an important feature: The grater the change from circularity to linearity in the energy flows going through an agroecosystem, the more important this decomposition analysis becomes, as it will be discussed in the following section.

4. Discussion: Contrasting energy profiles of organic and industrial farm systems

The broader and cyclical energy analysis of farm systems proposed in this article enables us to reveal several underlying agroecological features, and some possibilities for improving sustainable energy throughputs, that are concealed in a simpler linear input-output accountancy with a single EROI. It also helps us to highlight the contrasting energy patterns between organic and industrial farm managements in regard to the renewal of basic funds and services of agroecosystems.

4.1. Why IFEROI grew from c.1860 to 1999, while EFEROI and FEROI decreased?

At the end of section 3.2 we wondered about the meaning of the opposite directionality of the change observed from c.1860 to 1999 in *IFEROI*, compared with the ones registered in *EFEROI* and *FEROI*. The answer requires taking into account the different meaning of *IFEROI* in regard with *EFEROI*, as a result of the looping character of *Biomass Reuse* (*BR*) flows which come from farmland and cycle again back to it, either directly (e.g. green manure) or indirectly through the bio-conversions that take place in the barnyard-livestock subsystem (e.g. manure and animal draught power). Being a flowing loop, the *IFEROI* rate $\left(\frac{FP}{BR}\right)$ inevitably acquires a double meaning. We can interpret it as the partial yield obtained per unit of internal *BR* spent, or the other way round: The internal investment made in keeping up the underlying funds of the agroecosystem per unit of *Final Product* extracted $\left(\frac{BR}{FP}\right)$.

Notice that in a context of self-reliance, where *EI* would be minimal, *IFEROI* would become a straightforward measure of sustainable yield given that the reproduction of the agroecosystem would almost only depend on the proportion of farmland product detracted from farmers' consumption and then invested in the renewal of its basic funds. The role *BR* plays for a sustainable reproduction of the agroecosystem, and the ensuing meaning of *IFEROI*, is kept to a large degree even when *EI* flow increases in farm systems far from a local self-reliance. According to this, the higher *IFEROI* found in 1999 can be interpreted as a result of having given up this investment on the agroecosystem sustainability, while the lower one c.1860 was a result of the high reliance on *BR* flows in a traditional organic farming which tried to sustain the agroecosystem's reproduction by closing at local level as much biophysical cycles as possible.

Therefore, we consider that a high *BR* investment becomes a hallmark of traditional organic farm systems which took over higher sustainability costs currently given up by industrial farm systems (Guzmán and Gonzalez de Molina, 2009; Guzmán et al., 2011; Giampietro et al., 2013). According to this, the energy efficiency as measured by *Final EROI* from a farm-operator viewpoint could be enhanced either by increasing the *Final Produce* per unit of the *Total Inputs Consumed* (*TIC*) or by reducing the inputs spent per unit of output. Given that up to a point *Biomass Reused* (*BR*) and *External Inputs* (*EI*) can be partially substituted one another –although with relevant impacts in the underlying agroecological functioning—, there exist three possible farming strategies to increase *Final EROI* of a farm system: 1) technically searching for a higher complexity and organized information in the agroecosystem, in order to obtain greater output per unit of inputs consumed, whether internal or external, that allows increasing the joint energy efficiency of *FEROI*; 2) relying on internal *BR* and saving as much *EI* as possible, in order to reduce the external inputs consumed per unit of output following a LEIT strategy; and 3) reducing inputs consumed per unit of output through the opposite strategy of relying on *EI* and giving up internal *BR*. It is apparent that there has been a historical trend towards replacing internal biomass reuses by external inputs throughout the socioecological transition from traditional organic to industrialized farm systems.

4.2.On the sustainability role of BR flows and their effect on landscape patterns

We have seen that c.1860 the cultural landscape showed a higher diversity of land covers than at the end of the 20th century (Fig 5). According to the landscape ecology metrics accounted in the same study area and periods by Marull et al. (2010, forthcoming b), the former patchy mosaics might have offered a greater number of habitats and ecotones than the more homogenous land cover existing at present, leading to a lesser associated biodiversity and a decrease in regulatory and supporting ecosystem services. Assuming this as true, could it be related with the abandonment of an integrated management of cropland, woodland and pasture with animal husbandry? If so, the decrease of *BR* in front of *EI* might be used as a proxy to capture these trends in the changing energy profiles of farm systems.

We know that, for the moment, this is only a working hypothesis that requires other models and further evidences to be tested. According to it, higher amounts of biomass reuses would relate with more heterogeneous and complex landscapes as long as this *BR* constitutes a smooth and repeated intermediate disturbance (as opposite to climax community) that helps to maintain ecological functionality into moderate levels of ecological disturbance able to enhance farm-associated biodiversity (Tilman, 1994;

Pierce, 2014; Tscharntke et al., 2005, 2012). On the contrary, relying on *EI* and getting rid of *BR* would have led to monocultures and linear chains of animal breeding in feedlots with more homogeneous land covers, thus reducing landscape complexity and lessening the number of habitats and species richness. Put it bluntly, an increasing dependence on external inputs might have gone hand in hand with biodiversity loss (Giampietro, 1997)—as many fragmentary but widespread evidences are showing, like the collapse of Europe's farmland bird populations throughout the last thirty years (Donald et al., 2001; Inger et al., 2015). What is important here is to make apparent that our energy modelling of farm systems opens a workable way to study whether this hypothesis proves to be true or not, by using it as a starting point for a forthcoming Energy-Landscape Integrated Analysis (Marull et al., 2015 and forthcoming a, b).

4.3.Scanning the composition of Biomass Reused c.1860

As a very preliminary and indirect evidence of the above hypothetical assumptions, we can observe the disaggregate composition of the *BR* flow c.1860. Table 3 reveals that 58% was vegetal organic matter returned to the soil either fresh or burnt, 2% were seeds, and 40% was biomass reused in barnyards as feed, fodder, grass and crop by-products eaten by livestock or straw used in stall bedding. The former was directly used to keep soil biodiversity and fertility, whereas the latter also contributed to soil fertility through manure, leading to high cropland and farmland diversity. The production of fodder and feed involved 14% of cropland area, while livestock was feed in pastures as well (7% of farmland area), or in the grass layers below open forests and other uncultivated land, thus helping to maintain agroforest mosaics—as long as there was neither overgrazing nor deforestation. Besides these direct contributions to belowground associated biodiversity and aboveground diversity of vegetal land cover there were others indirect, such as crop rotations, stubble grazing or fallow weed grazing, which required keeping vegetal hedgerows that in turn enhanced the mosaic pattern in arable land (see Fig. 2).

By comparing Tables 1 and 3 we can observe that c.1860 this *BR* flows entailed a relevant share of the whole biophysical turnover taking place in the agroecosystem: 237,165 GJ a year, equivalent to 30% of the actual NPP photosynthesized in the study area at that time. Driving this loop entailed a great cost for the farm-operators, either in energy or land terms (Guzmán and Gonzalez de Molina, 2009). 40% of this *BR* was devoted to livestock feeding and bedding in barnyards, and in order to minimize somewhat this high cost peasants had to keep a tightly integration of animal husbandry with cropland and uncultivated land management through a mixed farming. The key point here is that it was precisely this integrated land-use management, required to compensate for the high energy and land cost of livestock bioconversion, what led them to organize and maintain complex landscape mosaics (Krausmann, 2004; Cussó et al., 2006a,b; Marull et al., 2010, 2015).

Indeed, a significant amount of energy was lost in this livestock bioconversion: 92,057 GJ a year, resulting of subtracting 2,954 GJ of *Livestock-Barnyard Produce* to the 95,011 GJ spent as animal feed, fodder, pasture and stall bedding. This means a 3% of energy return in the feed-food conversion into the Livestock-Barnyard subsystem. Yet, when the *Livestock-Barnyard Services* obtained as manure and draught power are added, we get a 30% energy return to the entire livestock bioconversion. Put in another way, this means that the overall energy yield of a multiple use of livestock in traditional mixed farming was comparable to the current efficiencies attained by internal combustion engines, and much higher than the actual 8-9% energy efficiency of motor vehicles when the embodied energy required by their manufacturing, maintenance and delivery processes are taken into account (Ayres et al., 2009:124-125).

These are important results that emphasize the multipurpose character of the traditional organic ways of keeping animal husbandry integrated in a mixed farming. Crop by-products reused to feed domestic animals amounted to 47,904 GJ a year, 55% of the whole livestock intake, whereas rough grazing in pastureland and woods covered 21% (18,031 GJ), thus reducing the need to grow feed and fodder in cropland to only 24% (20,867 GJ). So, using pastures and reusing by-products had helped to lessen to some extent the competition between animal feed and human food in cropland allocation. All these features make apparent how important these *BR* flows had been in past organic farm systems, and raises the question about the role that giving up them has entailed not only for the energy profiles and throughputs of industrial agriculture, but of current landscape patterns and agroecological processes as well.

Although accounting for the energy flows that link different land uses one another can only hint that an integrated mixed farming with livestock husbandry translates into more heterogeneous land cover, it helps to raise an important issue which has not yet been studied as it deserves. Farmers transform natural ecosystems into agroecosystems through the biophysical energy flows driven by their labour. Given that these energy flows are spatially distributed following an intended pattern, according to the know-how of farmers, we can understand cultural landscapes as an 'imprint' they carry out in a land matrix. In other words, cultural landscapes can be studied as the spatial imprint of a socio-metabolic profile of energy flows taking place in agroecosystems. This is the rationale behind our forthcoming Energy-Landscape Integrated Analysis (Tello et al., 2006; Marull et al., 2010).

This approach fits with a basic assumption adopted in Landscape Ecology, according to which there is a relationship between spatial patterns and ecological processes where biodiversity is sustained (Turner, 1989; Lindenmayer and Fisher, 2006). Building on this, our socio-metabolic approach to the energy profiles of farm systems opens a bridge between agroecology (Gliessman, 1998; Guzmán and González de Molina, 2015) and landscape ecology (Forman, 1995) that may allow testing these hypothesis in future.

4.4. How could Final EROI have been improved c.1860? A counterfactual discussion

We have seen in the results shown in section 3.3 that, due to the strong effort devoted to increase *BR* so as to minimize *EI* following a LEIT strategy, the optimal direction to increase *FEROI* would have required a drastic increase in *IFEROI*. In turn, this could have been achieved either by increasing *FP* per unit of *BR* through technical improvements, or getting the $\frac{EI}{BR}$ ratio greater than the 0.1 that existed c.1860, or both. The first strategy would have entailed achieving further improvements in the integrated land-use management with animal husbandry, e.g. by increasing livestock breeding and thus having more available manure per unit of land, or by reducing losses in manure heaps and other livestock-barnyard services.

To what extent can this strategy be considered feasible in the Catalan Vallès County c.1860? We know that this highly intensive farm system heavily relied on *BR*. In order to keep up soil fertility, farmers had to feed livestock by growing fodder crops and reusing a large fraction of agricultural by-products, sowing green manures, and burning or burying some amount of forest and scrub biomass on cropland (Cussó et al., 2006a, 2006b; Garrabou et al., 2010; Tello et al., 2012). Land-use intensification, mainly driven by vine-growing specialization (Badia-Miró and Tello, 2014), seems to have increased agroecological stress leading this preindustrial farm system towards lower energy returns—albeit nearly to one (Galán et al., forthcoming; Marco et al., forthcoming). Perhaps a lower population density and land-use intensity would have also helped to get higher *IFEROI* and *Final EROI*, thanks to a reversal of the well-known sequence towards a growing farming activity on the available land that up to a point gives way to diminishing returns (Boserup, 2005; Fischer-Kowalski et al., 2014). However, adopting more extensive land uses would have entailed a more unequal land distribution and forcing the unemployed rural population to emigrate (Badia-Miró and Tello, 2014).

The second strategy consisted in increasing the $\frac{EI}{BR}$ ratio by reducing the amount of *BR* or increasing *EI* per unit of final product obtained, while keeping high land-use intensity. In practice, this would have meant either a greater consumption of industrial fertilizers (that is, increasing *EI*) or a reduction of organic soil fertilization (that is, decreasing *BR*) by mining soils. Whereas the first option considered would rely on improving agroecological management, and the second would entail expelling labourers and smallholders from the land, the latter would led to agroecological unsustainable paths.[7] The dilemma illustrates the difficult choices many past organic farm systems faced just before the onset of agricultural industrialization, when the pressure to increase output arising from local population density and urban markets grew. This issue deserves a comparative analysis about the trade-offs and limits between land-use intensity and sustainability of farm systems (Erb 2012; Krausmann et al. 2012; Tscharntke et al. 2012; Haberl, 2014).

[7] In our first energy balance of the whole Vallès County we get a *Final EROI* of 1.41 c.1870 (Cussó et al, 2006a). Then, in the five municipalities of our study area we obtained 1.67 c.1860 (Cussó et al, 2006b). After a better assessment of the fertilizing methods applied (Olarieta et al., 2011; Tello et al., 2012), it dropped to 1.23 (Tello and Galán, 2013). Now we have obtained a *Final EROI* c.1860 of 1.03. It seems likely that the actual energy yields of this highly intensive organic agriculture led to some degree of soil mining and deforestation (Galán, 2015).

4.5. Plotting the energy profiles of organic and industrial farm systems in the possibility surface

We have seen in the above section 3.5. how getting rid of *BR* had played a role, though smaller than the huge increase of *EI* together with a moderate rise in *FP*, in the shift experienced by the energy profile of the industrial farm system in 1999 towards higher *IFEROI* combined with much lower *EFEROI* and *FEROI*. We have also discussed that the LEIT strategy of the organic farm system c.1860 fits well with an agroecological approach for sustainable agriculture at present (Gliessman 1998; Tripp 2008). This is so because in a low-input agriculture, where the harvested flow of biomass remains not that far from the range of natural turnover, farm activities interfere only to a limited extent with the system of controls regulating matter and energy flows in ecosystems (Giampietro 1997:158).

The opposite strategy adopted by industrialized farm systems of the studied area, based on ever greater external inputs strongly linked to livestock breeding in feedlots, has led to increasingly unsustainable scenarios—e.g., the reduction of organic matter content of soils, over-fertilization and polluting emissions of the intensive cropping performed in flat soils, and the biodiversity loss ensuing the vanishing of complex landscape mosaics as a result of forest encroachment in abandoned steeper lands (Otero et al., 2015).

Gathering more data on *FEROI*, *IFEROI* and *EFEROI* from a broad range of farming systems in different regions and periods of time would allow plotting their energy profiles into three-dimensional graphs like our Fig. 7. Then cross-section and historical analysis can be done, in order to test whether organic and industrialized farm systems tend to appear in similar regions of this possibility surface, which would reveal different energy profiles of agroecosystems. It would also allow identifying the historical paths followed when farm systems evolved from one profile to another. And, finally, it would help to test whether or not organic and industrial farm systems tend to cluster in a specific pair of opposite ‘attractor situations’. By these we mean a set of links established between socioeconomic drivers (e.g. the structure of relative prices of factors and goods in the markets reinforced by the prevailing landownership or institutional settings), and the energy profiles and functioning of agroecosystems, that become more likely than others. Societies can overcome these attractor situations by moving to other energy profiles and performances, but only by changing the underlying set of linkages between agroecological functioning and socioeconomic drivers.

The existence of such attractor situations has been suggested by Giampietro (1997). Once industrial agricultural systems start relying on external inputs coming from fossil fuels in search of greater labour and land productivity, they also tend to engage in monocultures and proportionally reduce internal biomass reuses. This entails a reduction in agroecosystem complexity that undermines the regulatory and supporting services provided by farm-associated biodiversity. This in turn requires replacing them by other artificial controls, such as pesticides and mechanical work that increase again the amount of external inputs. This feedback drives the energy profile of industrialized farm systems towards a high-input combination of lower *EFEROIs* only partially compensated by higher *IFEROIs*, giving way to a big loss in *Final EROIs*—as seen in our Catalan example. All this sounds very familiar to anyone aware of the challenges and opportunities that agriculture now faces worldwide. Through clustering statistics applied to our decomposition analysis of agricultural energy profiles we can test whether this working hypothesis is true or not.

5. Concluding remarks and further research

We presented a method to perform energy analysis of farm systems from a farm-operator standpoint at landscape level that aims to capture how the energy flows driven by farming affect some agroecological funds that provide vital ecosystem services, such as soil fertility and farm-associated biodiversity. This approach does not call into question other forms of accounting for energy balances of agricultural systems addressed from other perspectives and with other system boundaries, but aims to supplement them. Each site-specific entryway gives rise to different energy accounts because of the multidimensional and multi-scalar character of the sociometabolic interaction of human societies with nature. Not only the actors located in different places perceive the energy flowing differently, the system as such actually has different energy performance in each of them (Giampietro, 2004). Far for having to choose a right one and discard the others as wrong, we need to combine all of them in a multi-scalar integrated analysis like the one offered by the MuSIASEM school (Giampietro et al., 2009, 2013).

A main point of our farm-operator energy analysis at landscape level is to highlight the cyclical character and the agroecological role performed by the energy flows of biomass reused, which we consider an investment in keeping up the underlying funds. This assumption leads us to use several EROIs instead of a single one, and also to relate one another in order to draw more complex energy profiles of farm systems. The results will be used in a forthcoming Energy-Landscape Integrated Analysis addressed to observe how energy throughputs affect biodiversity maintenance in agroecosystems (Marull et al., 2015 and forthcoming a, b). In the meantime we adopt as a working hypothesis that a relevant proportion of biomass reused is a hallmark of organic farm systems, which tend to spare external inputs by closing their internal cycles in a way that helps to enhance soil fertility and the associated biodiversity of agroecosystems—together with leaving a relevant share of unharvested phytomass at the mercy of other non-domesticated species (Guzmán and González de Molina, 2015).

The decomposition analysis performed of *Final EROI* (*FEROI*) into internal (*IFEROI*) and external (*EFEROI*) returns allows analysing these energy profiles within a range of possible improvement scenarios, in order to disentangle their respective role in any shift experienced by these energy throughputs. We deem that this approach becomes a very revealing tool in order to conceive better agricultural farm managements, public policies and consumer preferences in a world that faces a worrying crossroads for food security arising from decreasing EROI in oil extraction and climate change (Mulder and Hagens, 2008; Hall et al., 2009; Hall, 2011; Deng and Tynan, 2011; Kessides and Wade, 2011; Pracha and Volk, 2011; Manno, 2011; Arizpe et al., 2011; Murphy et al., 2011; Scheidel and Sorman, 2012; Giampietro et al., 2012, 2013). It can also be used to gain a better understanding of the sociometabolic transition from past traditional organic to industrial farm systems, and to acquire useful knowledge for developing more sustainable agricultures in future (Fischer-Kowalski and Haberl, 2007; Smil, 2010; González de Molina and Toledo, 2014).

Appendix: Assessing the effect of the corresponding variation in *EI* and *BR* on any shift experienced in Final EROI through the partial derivatives at any point of equation (1)

In order to study the effect of variations of *EI* and *BR* in *Final EROI*, we consider the following function:

$$\begin{array}{ccccc} \mathbb{R}^2 & \rightarrow & \mathbb{R}^3 & \rightarrow & \mathbb{R} \\ (EI, BR) & \mapsto & (EI, BR, FP) & \mapsto & Final\ EROI = \dfrac{FP}{EI + BR} \end{array}$$

Using a simpler notation for the variables, the situation is written:

$$\begin{array}{ccccc} \mathbb{R}^2 & \rightarrow & \mathbb{R}^3 & \rightarrow & \mathbb{R} \\ (x, y) & \mapsto & (x, y, z) & \mapsto & w = \dfrac{\mathrm{z}}{x + y} \end{array}$$

where *x* = *External Inputs*, *y* = *Biomass Reused*, *z* = *Final Produce*, and *w* = *Final EROI*.

According to the chain rule, we know that

$$\frac{\partial w}{\partial x} = \frac{\partial w}{\partial x}\frac{\partial x}{\partial x} + \frac{\partial w}{\partial y}\frac{\partial y}{\partial x} + \frac{\partial w}{\partial z}\frac{\partial z}{\partial x} = \frac{\partial w}{\partial x} + 0 + \frac{\partial w}{\partial z}\frac{\partial z}{\partial x} = \frac{-z}{(x+y)^2} + \frac{1}{x+y}\frac{\partial z}{\partial x} = \frac{-z+(x+y)\frac{\partial z}{\partial x}}{(x+y)^2}.$$

Analogously,

$$\frac{\partial w}{\partial y} = \frac{-z+(x+y)\frac{\partial z}{\partial x}}{(x+y)^2}.$$

Consequently, the effects of *x* and *y* on the variation of *w* are:

$$\text{Effect of } x = \frac{-z + (x+y)\dfrac{\partial z}{\partial x}}{(x+y)^2}\Delta x, \qquad \text{Effect of } y = \frac{-z + (x+y)\dfrac{\partial z}{\partial y}}{(x+y)^2}\Delta y.$$

Since the function *FP* = *h*(*EI*, *BR*) is unknown, we need to estimate the value of the partial derivatives of *z* with respect to *x* and *y*. The only approximation possible, from the available data, is trivial:

$$\frac{\partial z}{\partial x} \approx \frac{\Delta z}{\Delta x}, \frac{\partial z}{\partial y} \approx \frac{\Delta z}{\Delta y}.$$

Then, given two situations $s_1 = (x_1, y_1, z_1, w_1)$ and $s_2 = (x_2, y_2, z_2, w_1)$, we get:

$$\Delta w = w_2 - w_1 = \frac{z_2}{x_2 + y_2} - \frac{z_1}{x_1 + y_1} = \frac{z_2(x_1 + y_1) - z_1(x_2 + y_2)}{(x_1 + y_1)(x_2 + y_2)} =$$

$$= \frac{z_2 x_1 + z_2 y_1 - z_1 x_2 - z_1 y_2}{(x_1 + y_1)(x_2 + y_2)} =$$

$$= \begin{cases} \dfrac{z_2x_1 + (-z_2x_2 + z_2x_2) + z_2y_1 + (-z_2y_2 + z_2y_2) - z_1x_2 - z_1y_2}{(x_1 + y_1)(x_2 + y_2)} \\ \dfrac{z_2x_1 + (-z_1x_1 + z_1x_1) + z_2y_1 + (-z_1y_1 + z_1y_1) - z_1x_2 - z_1y_2}{(x_1 + y_1)(x_2 + y_2)} \end{cases}$$

$$= \begin{cases} \dfrac{(z_2x_1 - z_2x_2) + (z_2y_1 - z_2y_2) + (z_2x_2 - z_1x_2) + (z_2y_2 - z_1y_2)}{(x_1 + y_1)(x_2 + y_2)} \\ \dfrac{(z_1x_1 - z_1x_2) + (z_1y_1 - z_1y_2) + (z_2x_1 - z_1x_1) + (z_2y_1 - z_1y_1)}{(x_1 + y_1)(x_2 + y_2)} \end{cases}$$

$$= \begin{cases} \dfrac{-z_2(\Delta x + \Delta y) + (x_2 + y_2)\Delta z}{(x_1 + y_1)(x_2 + y_2)} = A \\ \dfrac{-z_1(\Delta x + \Delta y) + (x_1 + y_1)\Delta z}{(x_1 + y_1)(x_2 + y_2)} = B \end{cases}$$

We can hence write:

$$\Delta w = \frac{1}{2}A + \frac{1}{2}B = \frac{-\dfrac{z_1 + z_2}{2}(\Delta x + \Delta y) + \dfrac{x_1 + x_2 + y_1 + y_2}{2}\,\Delta z}{(x_1 + y_1)(x_2 + y_2)} =$$

$$= \frac{-\dfrac{z_1 + z_2}{2} + \dfrac{x_1 + x_2 + y_1 + y_2}{4}\dfrac{\Delta z}{\Delta x}}{(x_1 + y_1)(x_2 + y_2)}\Delta x + \frac{-\dfrac{z_1 + z_2}{2} + \dfrac{x_1 + x_2 + y_1 + y_2}{4}\dfrac{\Delta z}{\Delta y}}{(x_1 + y_1)(x_2 + y_2)}\Delta y$$

Therefore, the effects of *x* and *y* on the variation of *w* are:

Effect of $x = \frac{-\frac{z_1+z_2}{2}\Delta x + \frac{x_1+x_2+y_1+y_2}{4}\Delta z}{(x_1+y_1)(x_2+y_2)}$ and

Effect of $y = \frac{-\frac{z_1+z_2}{2}\Delta y + \frac{x_1+x_2+y_1+y_2}{4}\Delta z}{(x_1+y_1)(x_2+y_2)}$.

That is,

Effect of variation in $EI = \frac{-\frac{FP_1+FP_2}{2}\Delta EI + \frac{EI_1+EI_2+BR_1+BR_2}{4}\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$ and

Effect of variation in $BR = \frac{-\frac{FP_1+FP_2}{2}\Delta BR + \frac{EI_1+EI_2+BR_1+BR_2}{4}\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$

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