SOCIAL ECOLOGY WORKING PAPER 156

Enric Tello • Elena Galán • Geoff Cunfer • Gloria I. Guzmán-Casado • Manuel González de Molina • Fridolin Krausmann • Simone Gingrich • Vera Sacristán • Inés Marco • Roc Padró • David Moreno-Delgado

A proposal for a workable analysis of Energy Return On Investment (EROI) in agroecosystems. Part I: Analytical approach

ISSN 1726-3816

May 2015

Enric Tello, Elena Galán, Geoff Cunfer, Gloria I. Guzmán-Casado, Manuel González de Molina, Fridolin Krausmann, Simone Gingrich, Vera Sacristán, Inés Marco, Roc Padró and David Moreno-Delgado, 2015:

A proposal for a workable analysis of Energy Return On Investment (EROI) in agroecosystems. Part I: Analytical approach

Social Ecology Working Paper 156
Vienna, May 2015

ISSN 1726-3816

Institute of Social Ecology
IFF - Faculty for Interdisciplinary Studies (Klagenfurt, Graz, Vienna)
Alpen-Adria-Universitaet
Schottenfeldgasse 29
A-1070 Vienna

www.aau.at/socec
workingpaper@aau.at

A proposal for a workable analysis of Energy Return On Investment (EROI) in agroecosystems. Part I: Analytical approach

Authors:
Enric Tello[1], Elena Galán[2], Geoff Cunfer[3], Gloria Guzmán[4], Manuel González de Molina[4], Fridolin Krausmann[5], Simone Gingrich[5], Vera Sacristán[6], Inés Marco[1], Roc Padró[1], David Moreno-Delgado[7]

[1] Department of Economic History and Institutions, University of Barcelona, Spain
[2] Basque Centre for Climate Change, Bilbao, Spain
[3] Department of History, University of Saskatchewan, Canada
[4] Agroecosystems History Laboratory, Pablo de Olavide University, Seville, Spain
[5] Institute of Social Ecology Vienna, Alpen-Adria University, Austria
[6] Department of Applied Mathematics II, Polytechnic University of Catalonia, Spain
[7] Institut de Génomique Fonctionnelle, UMR Montpeiller, France

Table of content

Index of Figures

Index of Tables

Abstract: This paper presents a workable approach to the energy analysis of past and present agroecosystems aimed to contribute to their sustainability assessment. This analysis sees the agroecosystem as a set of energy loops between nature and society, and adopts a farm-operator standpoint at landscape level that involves setting specific system boundaries. This in turn entails a specific form to account for energy outputs as well as inputs. According to this conceptual approach, a clear distinction between *Unharvested Phytomass, Land Produce* and *Final Produce* is established, and also a sharp divide is adopted between the energy content of internal flows of *Biomass Reused* and external *Societal Inputs* when accounting for the amount of *Total Inputs Consumed*. Treating the conversion of solar radiation into local biomass as a gift of nature, enthalpy values of energy carriers are accounted for net *Final Produce* going outside as well as for *Biomass Reused* or *Unharvested Phytomass*, given that all these flows are evaluated from inside the agroecosystem. On the other hand, the external energy carriers are accounted for as embodied values by adding up direct and indirect energy carriers required to produce or deliver these *Societal Inputs* to the agroecosystem. The human *Labour* performed by the farm operators is treated as a special case of external input. It is accounted for the fraction of their energy intake devoted to perform agricultural work, by only using enthalpy or adding transport embodied values depending on the local or external origin of ingredients of the food basket. Following this line of reasoning we propose the definition of two different sets of agroecosystem's Energy Returns On Energy Inputs (EROIs), depending on whether we use as numerator the *Final Produce* or the total phytomass harvested and unharvested included in the actual Net Primary Production. By comparing *Final EROI* with NPP_{act} *EROI* we can obtain a proxy useful to assess whether the different paths taken by the energy throughputs may undermine or not biodiversity and soil fertility in agroecosystems. Then, by alternatively including or excluding *Biomass Reused* and *External Inputs* in the denominator, we split *Final EROI* into their respective energy returns to either internal or external inputs. This leads to a four interrelated EROIs whose meanings, shortcomings or ambiguities are examined respectively, in order to combine them all to draw the sociometabolic energy profiles of different sorts of agroecosystems along the socio-ecological transitions from traditional organic to industrial farm systems. The conceptual and quantitative relationships between the internal and external returns of *Final EROI* provide a method to decompose both dimensions in a way that clarifies their respective roles when comparing different agroecosystems, and reveals their capacity for increasing energy yields. This decomposition analysis also facilitates graphing their changing energy profiles through socio-ecological transitions along history. Finally, we suggest other related or derived indicators that can be useful for different purposes.

With the bookkeeping proposed the energy analysis of farm systems is widened so as to highlight the role played by the biomass unharvested or internally reused in keeping the ecological services that biodiversity and soil fertility provide. This may also allow to test in agro-forest mosaics the Intermediate Disturbance Hypothesis long debated in ecology, by linking our energy analysis with landscape ecology metrics.

Keywords: Energy Return Investment (EROI), agroecosystems, socio-metabolic profiles, integrated land-use management, biodiversity, sustainability

Highlights

- ✓ *Since a relevant share of energy flows driven by the farm-operators cycles again into the agroecosystem as a loop, a single EROI is not enough to give account of the energy profile and functioning of farm systems.*

- ✓ *The internal flows of biomass reused and the integrated land-use management it requires may increase the biophysical complexity of fluxes and the diversity of land-use patterns of an agroecosystem, thus enlarging the number of habitats for the associated biodiversity and the ecological services provided.*

- ✓ *For an agroecosystem to host high species richness, both a large diversity of habitats as well as a sufficient amount of unharvested phytomass are needed, which sets a limit in the environmental pressure exerted by the human appropriation of Net Primary Production.*

- ✓ *The difference between NPP EROI and Final EROI can provide a useful proxy to assess whether a change in the energy throughput undermines or not the biomass available for other non-domesticated species, either aboveground or belowground.*

- ✓ *The dependence on external inputs tends to simplify the biophysical flows of an agroecosystem, increases its linearity and reduces the complexity and diversity of land-use patterns, thus diminishing its capacity to host associated biodiversity even when the human appropriation of NPP decreases.*

- ✓ *The existence of a significant proportion of biomass reused is a hallmark of organic farm systems that tend to save external inputs by relying on these internal biomass reuses. Conversely, industrialized agricultures tend to get rid of reuses replacing them with external inputs coming from fossil fuels.*

- ✓ *Decomposing the energy throughputs into the returns on internal or external inputs brings to light the changing sociometabolic profiles of different agroecosystems and their possible improvement paths from past organic to current industrial farm systems.*

1 An agroecological approach to the energy profiles and EROIs of agroecosystems

The Energy Return on Investment (EROI) is a useful measure of the energy efficiency of a system. Expressed as a ratio, EROI compares a system's energy input to its energy output.

$$EROI = \frac{Energy\ output\ from\ a\ system}{Energy\ input\ into\ a\ system}$$

As an example, one might compare several different electricity generation technologies to assess their relative efficiency. Since the 1970s, when the oil crisis shocked the world and politicians and the public became concerned with energy efficiency, there have been many EROI studies. Most have focused on the EROI of fossil fuels, electricity generation, transportation, and manufacturing (see as recent overviews and analytical proposals, Haberl 2001a and b, Hall *et al.* 2011, Pelletier *et al*. 2011, Hall & Klitgaard 2012, Giampietro 2006, Giampietro *et al.* 2012 and 2013). Only some of them, however, have addressed the energy accounts of agricultural systems (Leach 1976, Pimentel & Pimentel 1979, Naredo and Campos 1980, Bayliss-Smith 1982, Odum 1984, Giampietro 1997 and 2004, Giampietro *et al.* 1992a, 1992b, 1994 and 2013).

Agroecosystems, as hybrid human-natural systems, require a special treatment when assessing energy returns on investment. This working paper explains the agroecological approach to the energy flows and processes of agroecosystems adopted by the international research project *Sustainable Farm Systems: Long-Term Socio-Ecological Metabolism in Western Agriculture*. It presents a workable method to calculate the EROI of historical and current farming systems that aims to be rigorous, systematic, and comparable across case studies and through time. Furthermore, it proposes an assessment of not only some numerical EROI ratios but a broader agroecosystem's energy profile as well.

A first characteristic of agroecosystems is that, thanks to the photosynthesis, from a societal standpoint they *produce* energy as well as consume it. True, current industrialized agricultures use to have EROIs lower than 1— that is, they are net energy consumers instead of functioning as energy providers. But organic agriculture, through most of the past 10,000 years, could not function that way. By definition, farm communities needed to generate more energy carriers for human society than what they invested. Failure to do so literally meant starvation. Thus many agricultural systems typically have had, throughout history, EROIs higher than 1—of course, after having set aside in our calculations solar radiation taken as a gift of nature (Giampietro *et al.* 2013:131). Only in the 20th century did some farm systems adopt an industrial energy profile such that soil fertility and crop productivity have been sustained by external injections of energy, mainly derived from fossil fuels (Stanhill 1984, Gimpietro & Pimentel 1992a, Smil 2001, Krausmann *et al.* 2008). This so-called 'Podolinsky principle', according to which

agriculture should be a sustaining base that provides an energy surplus for the rest of humankind, is now being proclaimed with pride by organic farmers and peasant organizations like Via Campesina (Martínez Alier and Naredo 1982, Martínez Alier 1995 and 2011).

A second unique characteristic of agroecosystems is that they contain complex internal reprocessing loops of material flows and energy carriers. Accordingly, it is too simple to ask how much energy is input and how much is output in order to account for a single output/input ratio. Doing so treats farm landscape as a linear black box and obscures the internal processes that are of crucial importance to understanding the agroecological functioning and environmental relationships of farm communities. For example, a significant amount of the biomass harvested from cropland does not go directly to people; much of it goes instead to feed livestock, to compost that replenishes nutrients in cropland soils or to seeds for next year's sowing. Another amount of it remains unharvested, and eaten by other species before and after harvesting. Far from being a 'loss', this natural leftover can be seen as an essential 'overhead' (Giampietro *et al.* 2013) to sustain the trophic chains of biodiversity that provide key ecological services to the agroecosystem. Here we offer a systematic method to represent, measure, and estimate these internal flows of unharvested phytomass (Smil 2013) and reused biomass that are crucial reinvestments to the energy functioning of agroecosystems.

A third unique characteristic of agroecosystems requires special treatment: human beings are part of the energy pathway. Farmers provide energy inputs through their own physical labour--a relatively small energy flow in comparison with the rest that, nevertheless, carries with a lot of information which drives the whole farm system and organizes the ensuing cultural landscape. The farm community also consumes energy carriers for the subsistence of their members. The more distant society to which this farming community belongs often extracts surplus produce from the local agroecosystem and provides other inputs, implements or services. People may be represented as either being external to the system under evaluation or internal to it. Either way, human components of farm energy paths must be treated with special care.

This working paper addresses in detail these three unique aspects of agroecosystems' energetics. It presents a workable, integrated, and complex energy assessment of the relationship between human societies and nature embodied in farm systems, as seen from their operators at agroecosystem's scale. It aims at a broader multi-criteria assessment of sustainability, and intends to describe the changing energy profiles and performances of past and present agroecosystems along the socio-ecological transitions experienced in history (Fischer-Kowalski & Haberl 2007, Smil 2010). The energy modelling presented can be applied to many agroecosystems around the world and through time, allowing possible comparable energy measures and sustainability assessments of a diverse range of farm systems, including European peasant villages, Caribbean plantations, small family farms on the American frontier, or modern industrial producers, to name just a few of the myriad forms of agriculture in world history. We recognize that important differences distinguish the rich array of agricultural endeavours created by people over millennia and across an astonishing range of terrestrial habitats. Our basic approach has been developed having in mind a typical European and North

American mixed farming of cropland with livestock, and needs to be adjusted to fit other types of farms and environments. Some components of the agroecosystem energy model that we present below are unimportant (or even absent) in some places and times. For example, pre-Colombian Native American agriculture had no livestock component. We are confident that our model is flexible enough to accommodate such variation with some adjustments appropriate to local circumstances.

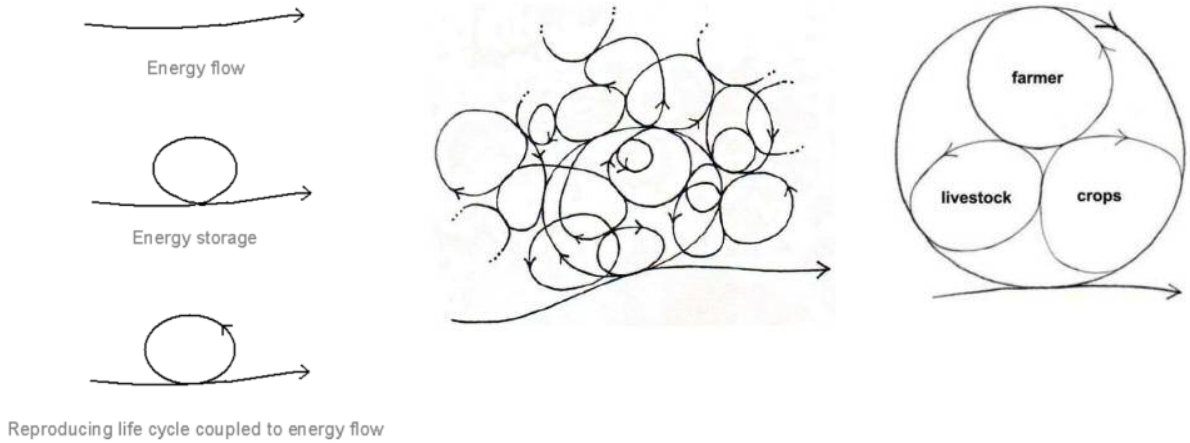
Here we present several nested energy models and two distinct ways to calculate the EROIs of agroecosystems which can be decomposed in their respective internal and external components. Which model and EROI one chooses or combines depends on the research questions of interest, the system boundaries adopted, and the historical sources available. In all cases, our fundamental point of view is that of the farm operator. Depending on the particular case study, the farm operator could be a peasant, a yeoman or a family farmer, a farm manager or a plantation overseer. For our analysis, the individual, family, or small community that makes day-to-day decisions about land use is the farm operator. We assess the energy dynamics and yields at a local community or township scale from the viewpoint of ground-level farm operators.

We have to stress from the onset that by adopting this agroecological approach at the landscape scale entails that our EROIs can only express the energy performance within this specific system boundaries. Being a purpose-oriented and site-specific account, the first step for any energy analysis is to make clear what we are looking to use this accountancy for (Jones 1989). Our approach aims to open a door for further studies linking energy accounting of the agroecosystem functioning with the complexity of landscape patterns and processes, and the biodiversity it may host (Tscharntke *et al*. 2012b). This means placing the system boundaries where the agroecosystem limit is defined, and adopting the standpoint of the people that operate it. This energy analysis is addressed to contribute to a sustainability assessment of farm systems—that is, to what extent the agroecosystem functioning yields a final produce while the underlying funds that maintain soil fertility and provide biodiversity services are kept, enhanced or degraded (Costanza & Patten 1995). We have to bear always in mind, however, the specific scale and standpoint of our energy bookkeeping. A wider sustainability assessment requires an additional multidimensional and multi-scalar analysis to bring into light the connections with other broader ecological dimensions and societal perspectives—e.g. following the way proposed by the MuSIASEM School (Giampietro *et al*. 2012 and 2013).

Our standpoint ultimately draws on some very basic principles of the functioning of any living system able to maintain a dynamic stability far from thermodynamic equilibrium. Their internal cycles always make thermodynamic sense because thanks to them a living system can enhance its own complexity, increase its energy storage capacity, improve the energy throughput and start an ascendancy trend that decreases entropy dissipation thus opening a way to grow and develop (Ho & Ulanowicz 2005, Morowitz 2002, Prigogine & Stengers 1984). In ecosystems these development processes of energy flows translate into an integrated spatial heterogeneity and biodiversity (Ho 2013:31, Ulanowicz 1986:147-161). As Ho (2013) suggests, these principles offer some basic criteria to understand what sustainability means for agroecosystems as well: a dynamic closure in nested space-time domains that enables a farm system to minimize entropy. Sustainable

systems develop by interconnecting more life cycles within them so that the wastes from one cycle become resources for another (Figure 1).

Figure 1: How energy flow and storage characterizes the reproducing life-cycles in any living systems and in an integrated sustainable farm system as well. Source: taken from Ho (2013:33, 35, 43).



Following this cyclical view of the sustainable functioning of farm systems, we present a workable proposal to the energy accountancy of agroecosystems that is exemplified with four Catalan municipalities of The Vallès County circa 1860 and in 1999, after having recalculated all the data previously published by Cussó *et al*. (2006a, 2006b) for this case study, following the criteria and methods proposed in this paper. The accountancy methods, converters, metrics and references used to calculate these energy balances we use as examples in the first analytical part are explained in detail, from an empirical point of view, in the second part of this working paper.

1.1 From ecosystems to agroecosystems

As with any other animal species, human societies live on the net productive capacity of ecosystems. Agroecosystems arise when a community of farm operators within a larger human society invests a certain amount of human labour, animal or mechanical work, seeds, fertilizers and other energy carriers to create a new cultural landscape from the existing ecosystem. Hence, agroecosystems are human-colonized ecosystems. Although they retain their own ecological processes, they cannot maintain and replicate themselves over time in the way natural ecosystems do. The creation and maintenance of agroecosystems requires repeated reinvestment of energy and information by the farm operators, in addition to naturally occurring solar radiation and photosynthesis (Altieri 1989, Gliessman 1998, Altieri & Nicholls 2005, Snapp & Pound 2008, Guzmán & González de Molina 2015). What is more, they always require some additional amount of external land and biomass flows within less-disturbed ecosystems that perform a variety of regulatory services (Odum 1984, Giampietro *et al.* 1992a and 1992b, Guzmán & González de Molina 2009, Guzmán *et al.* 2011). Thus, while providing energy and

ecological services to human society, nature continues functioning in its own right (Farina 2000, Schröter *et al*. 2005, Agnoletti 2006 and 2014, Odum 2007:332-373).

The 'socio-ecological metabolism' of farm systems, that is to say the human appropriation of, transformation of, and use, consumption, and excretion of the Net Primary Production (NPP) of biomass by terrestrial ecosystems, entails an ecological disturbance that may or may not lead to environmental degradation. Whether such appropriation of energy carriers and nutrients contained in NPP damages natural systems depends on the resilience of the original ecosystem transformed, and the density or shape of human-driven energy and material throughputs (Giampietro *et al.* 1992b and 1994, Giampietro, 2004). As long as societal and natural metabolisms are considered as two separate realms, this idea of a joint socio-ecological metabolism may be discussed or even rejected. Nevertheless, the very nature of an agroecosystem is to keep both of them interwoven through a tight self-reinforcing loop. In order to analyse this coupled socio-ecological metabolism we have to start looking at humans as being components of ecosystems (McDonell & Pickett, 1993) as well as agroecosystems as a kind of nature transformed by humans (Gliessman 1998; González de Molina & Toledo, 2014; Guzmán & González de Molina 2015). This agroecosystem approach follows the definition of 'biophysical structures of society' put forward by Weisz *et al.* (2001) and Haberl *et al.* (2004), and applies to it the Flow-Fund model set forth by Georgescu-Roegen (1971) and adopted as a core analytical focus by the MuSIASEM School (Mayumi 1991, Giampietro *et al*. 2009, 2012 and 2013).

Even from this very basic approach, the sustainability of human-managed agroecosystems requires a very complex multidimensional optimization. The basic challenge of farming communities is how to obtain a maximum flow of energy carriers to meet human needs with a minimum energy cost and ecological disturbance, while sustaining the renewable capacity of agroecosystems and their ecological services. The pursuit of this holistic goal created many different agroecosystems and socio-metabolic regimes throughout history by trial and error (González de Molina & Toledo 2014). Any kind of sustainability assessment of human-nature interaction must include an energy socio-metabolic analysis (Giampietro *et al*. 1992a, 2006, 2012, 2013), while it needs to go beyond this energy profile in order to grasp other vital dimensions such as the maintenance of soil fertility and biodiversity.

Howard Odum pointed out that analysing the transformation ratios yielded by agroecosystems capable of providing more energy carriers than the ones spent in producing them may reveal useful ways to improve the energy performance of industrialized agricultural systems which are usually energy sinks at present (Odum 1984:31). This is a relevant task at a time when long-term global food security is at stake, since modern agriculture is now dependent on fossil fuels even as the world faces peak oil, decreasing EROIs for oil extraction and delivery, and climate change (Mulder & Hagens 2008, Hall *et al.* 2009, Hall 2011, Deng & Tynan 2011, Kessides & Wade 2011, Pracha & Volk 2011, Manno 2011, Arizpe *et al.* 2011, Murphy *et al.* 2011a, Scheidel & Sorman 2012, Giampietro *et al*. 2012 and 2013, Costanza 2013). In this scenario of growing environmental pressures, achieving efficient and productive farm systems while conserving biodiversity becomes a global challenge (Sala *et al*. 2000, Tilman 2002,

Schröter et al 2005, Tscharntke *et al*. 2005 and 2012a, Godfray et al 2010, Cardinale et al 2012).

This working paper has three main goals: first to model agroecosystems seen as energetic loops between a farming community and nature by adopting a clear conceptual distinction between external and internal energy carriers, as well as between biomass harvested for human uses and unharvested phytomass left for the associated biodiversity (Altieri 1999; Guzmán & González de Molina 2015); second, to propose two different EROI measurements that can be decomposed in its own internal or external factors to assess agroecosystem energy processes in a way that is both widely applicable and precise; and third to move beyond EROI to consider an agroecosystem's energy profile more broadly.

1.2 Ecological services: Unharvested phytomass, reuses and integrated land-use management in agroecosystems

The sustainability of agricultural systems requires that the human exploitation of natural processes leaves in the ecosystem a flow of energy and matter sufficient to maintain its basic biophysical funds and functions. This means setting aside a part of the land matrix that is sufficiently undisturbed to maintain biological diversity and the stability of biochemical cycles—woodlands, wetlands, grasslands, or brush, for example. Both things entail refraining from exploitation as well as distributing it either in time or across the landscape in various gradients of intensity, in order "not to push exploitation farther than a point of adequate yield," in the words of Ramon Margalef (quoted by Giampietro *et al.* 1992b:235). As Mario Giampietro has pointed out, "agriculture is ecologically unsustainable when the actual density of agricultural throughput exceeds the critical environmental loading, and socioeconomically unsustainable when the actual density of agricultural throughput is too poor to provide food security and/or economic viability for farmers" (1997:155-156; see also González de Molina & Guzmán 2006 and 2015).

Therefore, the boundary of economically necessary land does not coincide with the biological area truly required to continuously obtain a given final agricultural output (Giampietro *et al.* 1992a:452-455). "The fertility of soil, maintenance of natural cycles, pollination, etc. all require the activities of other species that directly and indirectly maintain viable agricultural and natural ecosystems. Nevertheless, the space required for the maintenance of these species is never calculated when assessing agricultural yields" (Giampietro *et al.* 1992b:241). Economic and energy analyses of agricultural systems usually neglect a systematic assessment of these indirect sustainability costs or 'overheads' related to the maintenance of ecological services (Giampietro *et al.* 1994:22, Giampietro 1997, Schröter *et al*. 2005, Guzmán & González de Molina 2009 and 2015, Guzmán *et al.* 2011).

Besides economic yields any sustainable agricultural system has to maintain or increase its biological complexity—sometimes labelled 'natural capital', although we prefer using the Georgescu-Roegen's notion of biophysical 'funds' which unlike other sorts of stocks cannot bring about a flow at any desired rate, or in a continuous manner, as they have to rest from time to time and receive specific caring (Georgescu-Roegen 1971, Mayumi

1991). The most typical way of addressing this ecological constraint in traditional organic agroecosystems was simply not to add to the exploited land some natural-preserved areas (González de Molina & Toledo 2014). Rather it consisted of developing a complex integrated farming system between different land units where various levels of energy throughput per unit area were applied (Margalef 2006). Land-use integration usually interlinked a diversity of cropping, grazing and woodland areas. These mixed agro-forestry-grazing systems evolved into a large variety of agricultural landscape mosaics, adapted to specific bioregions and societal needs, whose main common feature was a combination of diversity and integration that maintained a wise trade-off between exploitation and conservation (Agnoletti 2006 and 2014, Rössler 2006, Marull *et al.* 2008 and 2010).

Since land conservation and land exploitation are not spatially distinct, but rather interwoven in the same place, this entryway reveals the importance of internal agroecological processes that play a key role in maintaining the natural resource base of agriculture, even though they are all too often overshadowed by the external inputs consumed and the final outputs produced. Ecological services run parallel and are interdependent with external socioeconomic flows. According to Edwards *et al.* (1993:103), "it is the understanding of the pattern of parallel flows and the interdependence between the flows that defines an integrated farm or farming system. For a farm to be sustainable, the flows must be coupled." Following the Flow-Fund approach of Georgescu-Roegen (1971), the farming flows are coupled through the agroecological funds.

When they remain coupled within an integrated agroecosystem, these internal flows play a vital role to keep up two basic ecological services: biodiversity and soil fertility (Giampietro 1997). The two are closely connected: "Biodiversity may be spatial, e.g. the soil biota and cropping patterns, or temporal, e.g. rotations, control of pests, weeds, and diseases through mechanisms such as competition, predation, shading, allelopathy, antagonism, and antibiotics. Biological diversity of soil organisms supports nutrient cycling because the decomposition of organic matter is a biotic process. Plants and animals are the sources of organic matter and invertebrate animals, such as earthworms, physically disrupt and mix it, and microbes mineralize nutrients. [...] It is important to recognize that there is a strong link between the availability of organic matter and both biodiversity and nutrient cycling" (Edwards *et al.* 1993:105-107).

Difficulty in maintaining these traditional integrated land uses has arisen when external socioeconomic flows become substitutes for reinvestment of internal flows of organic matter to increase yields per unit of cropland or labour. Therefore, it is worth pointing out the key role that internal flows of biomass reused and their derived livestock services play in organic agroecosystems when we account for their EROIs. In particular, it is crucial to account for crop produce used to feed livestock (biomass reused), which animals then exert energy to perform field work and return energy to cropland soils via their manure (livestock-barnyard services), as well as producing meat, milk, and eggs for human consumption. These kinds of internal energy carriers are essential aspects of agroecosystems that can get lost in a too simple input/output energy efficiency measurement.

Together with the unharvested phytomass left free for other species, the internal flows of biomass reused have a lot to do with the basic ecological services that agroecosystems may or may not provide, depending upon farm management. Organic agricultural systems that aim to be self-sustaining, either by necessity in past times or as a preferable option at present, always require greater internal flows of biomass reused compared with modern conventional ones, which rely on external inputs mainly derived from fossil fuels. For this reason industrialized farm systems can sometimes get greater EROIs than organic ones—particularly if energy balances are only accounted at the field or farm level, instead of at the landscape-agroecosystem scale, where the most important agroecological emerging properties linked to integrated use of land, livestock and other resources arise. In such cases the result obtained can be masking the positive externalities of the latter and the negative externalities of the former.

This problem cannot be fully addressed through EROI accounting alone, it requires a wider, multi-criteria and integrated sustainability assessment. However we can bring this important issue to light by accounting energy balances at a landscape level and by using a set of several, interrelated EROIs of agroecosystems able to capture to some extent the existence of a 'sustainability cost' or 'overhead' mainly dealt with in the past through a wise land-use management. Gloria Guzmán, Manuel González de Molina, and Antonio Alonso (2009, 2011) have put forward the important concept of the 'land cost of sustainability', the extra burden that organic farmers bear compared to conventional ones as they take care of additional land per unit of output in order to maintain the ecological services provided by a well-integrated farm management of agroecosystems.

The sustainability overhead of organic farm systems appears not only as land cost, but in terms of human labour and energy expenditure as well. They can be accounted in our EROIs assessment mainly as a larger internal flow of biomass reused, or phytomass unharvested and left free for the associated biodiversity. To better understand the meaning of the former, we must consider the role of biomass reused and the derived livestock services to replace the purchase of other external inputs. The most relevant example is the Livestock-Barnyard subsystem, which apart from providing some components of final output, such as meat, milk, eggs or wool, may also deliver draught power and manure. The cultivation of green manures, or maintaining weed covers in between the strips of wood crops are other good examples of biophysical reinvestments to keep the basic funds of the agroecosystem. Another example is charcoal, which could be used as a fertilizer or soil conditioner, as well as fuel (Olarieta *et al.* 2011). All these internal loops are not only direct contributions to soil fertility, but also represent other indirect contributions related to the maintenance of a sound land-use integration tightly linked with biodiversity, pest control, prevention of erosion and other vital ecological services (Schröter *et al*. 2005, Drinkwater *et al.* 2008, Guzmán & Alonso 2008, González de Molina *et al*. 2010, García-Ruiz *et al*. 2012, Guzmán & González de Molina 2015). The role played by the latter sustainability cost can be brought to light by considering the difference between the Net Primary Production in the agroecosystem, and the final product extracted from it, as an environmental space left free for other not colonized species to thrive.

Behind these ecological services lies an important emerging property of good integrated management of organic agroecosystems, which Marull *et al.* (2008, 2010) have labelled 'landscape efficiency'. Thanks to tight integration between diverse land uses, with a variety of energy throughputs per unit area (Giampietro *et al.* 1992 and 1994, Giampietro 1997), organic farmers are often able to increase the agroecosystem complexity and, thanks to that, attain final energy outputs greater than total inputs, in spite of all the sustainability overheads they bear (Naredo 2004, Carpintero & Naredo 2006, Guzmán & González de Molina 2006 and 2015, Krausmann 2006, Cussó *et al.* 2006a and 2006b, Tello *et al.* 2008). This landscape efficiency gives way to many additional positive externalities provided by organic farmers to human society, besides their direct produce (Altieri 1989, Gliessman 1998, Giampietro 1997, Altieri & Nicholls 2005, Snapp & Pound 2008). The energy content of internal flows of biomass reused can be seen as a cost farm operators endure and, at the same time, as an investment they make in the renewal and complex integration of its basic funds which, in turn, provide ecological services. Internal flows of biomass reused are like the two sides of a coin: a cost and an investment; both are performed at the same time by the same amount of biomass reused. The same is true of the unharvested phytomass left available for the biodiversity associated to an agroecosystem (Altieri 1999).

Another important issue is establishing a clear-cut distinction between reused by-products and wastes. Mainly in industrialized farm systems there may be some biomass flows that remain within their boundaries but cannot be considered as a proper reuse, because they neither contribute to the renewal of the agroecosystem funds nor the keep up its complexity in the way it has been previously explained. By waste, we are considering here what Eugene Odum (1993:120-124) defines as a natural resource out of place—meaning that this substance no longer fits with the environmental conditions to which the components of an ecosystem are adapted. The fact of being in an excessive quantity, in the wrong place, out of the right time, or all these things altogether, entails damaging the environment. This damage turns out to be actual when the substance becomes a pollutant. But even if it does not, the very fact of throwing away a material that put on the right place and time in the adequate quantity would lead to an environmental improvement involves a damage in terms of an opportunity cost.

A clear example for such waste flows, characterized by being resources out of place, is the excess of dung slurry that springs from intensive livestock breeding in industrial feedlots. If this dung slurry is spread over cropland where chemical fertilizers are also applied, the ensuing over-fertilization cannot be absorbed by the crops grown there and most of its nitrogen compounds end up as water pollutants or greenhouse gas emissions. Notice that in our Catalan case study the energy content of this livestock-barnyard waste was equivalent to 92% of the Final Produce in 1999 (Cussó *et al.* 2006a and 2006b; see also the Part II of this working paper).

Another important caveat is that, sometimes or to some extent, energy efficiency and sustainability can be at odds. It could be possible, for example, for farm operators to increase a system's energy throughput by reducing internal recycling of crop materials so as to redirect them toward the final output—which, in turn, may be at the expense of the renewal of some vital underlying funds like soil fertility or biodiversity. There is a trade-off

between internal energy loops re-invested to stabilize and maintain complex agroecosystems and output energy carriers diverted to meet societal demand. To be sustainable in the long run, energy efficiency should not be achieved simply by reducing the complexity, stability and resilience of agroecosystems (Altieri 1989, Gliessman 1998, Farina 2000, Altieri & Nicholls 2005, Guzmán & González de Molina 2015). Any sustainability assessment of the energy performance of agroecosystems must look not only at the final output obtained per unit of input spent, but also at the long-term environmental constraints involved by its renewability (Pimentel & Pimentel 1979, Giampietro & Pimentel 1991, Giampietro 1997, 2013). Dealing with these ambiguities reminds us that energy analysis provides relevant information about just some aspects of the sustainability assessment we are seeking.

We can conclude that modelling energy flows through the farm's biophysical funds is far from simple. If we only take into account the optimization between the societal energy invested and the energy produced for distant consumption, the agroecosystem itself becomes a black box which conceals its internal processes and ecological functions. In assessing EROIs we must attend to the various roles internal and external energy carriers play, and the tricky issues entailed by substituting one for another. We must also consider whether or not the increase of the final produce is obtained at the expense of the biomass leftover for the associated biodiversity or the renewal of soil fertility. Beyond that, a deeper, multi-criteria integrated analysis of the energy profile and performance of agroecosystems is required to assess their long-term sustainability (Altieri 1999; Giampietro *et al.* 2006; Giampietro & Mayumi 2000:141; see also Odum 2007:333-334, Giampietro 1997:157 and 2004, and Giampietro & Mayumi 1997, Sorman & Giampietro 2011).

1.3 Modelling energy in agroecosystems

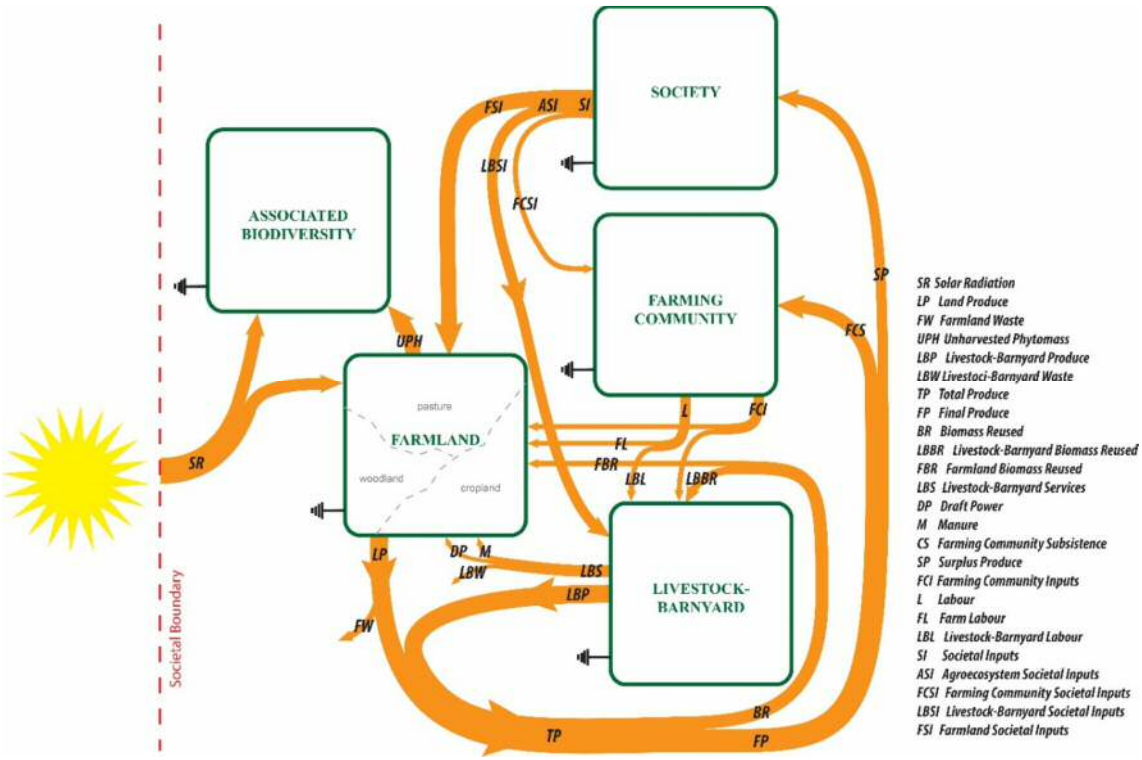
Figure 2 represents a simplified flowchart of the key energy converters and carriers in agroecosystems that our modelling is taking into account. It does not aim at showing all aspects of the ecological functioning of a farm system, but only represent the basic concepts taken into account by our energy bookkeeping of an agroecosystem.[1] The green rectangles in the diagram represent energy subsystems, where basic farm activity uses different converters to turn energy from one form into another. For example, on **Farmland** photosynthesis performed by the Primary Producers converts solar radiation into plant biomass. Thanks to the unharvested phytomass and habitats that remain available within **Farmland**, an **Associated Biodiversity** is kept to provide for a set of ecological services. Within the **Livestock-Barnyard** subsystem, animal digestion converts plant energy into animal energy carriers like meat or draught power, while the decomposing food chains of

[1] There is not a single way widely accepted on how to draw an energy flow diagram of an agroecosystem, and many different ecological flowcharts can be found in the literature. The most ambitious attempt is the set of notations and images used by Howard Odum (1984, 2007). Unfortunately, it has not received a general agreement, and it mainly adopts an ecological vision different from our farm-operator standpoint of an agroecosystem functioning. The flowcharts we are going to use in the paper are only intended to clarify the basic conceptual approach that underlies to our energy accountancy of four different and interrelated EROIs.

small animals and bacteria convert into manure the animal dung mixed with straw or other bedding materials used in barnyards or stalls. The **Farming Community** of the agricultural active population working in the agroecosystem considered includes other energy converters, as it does the more distant **Society** to which they belong.

According to the second law of thermodynamics, energy conversion always results in low-entropy energy loss in a closed system, usually as waste heat, represented here as heat sinks. The orange arrows in the diagram represent energy carriers that flow from one subsystem to another, which are represented as green rectangles that can be seen as funds that play the role of converters. For example, once photosynthesis has converted sunlight into a field of wheat, the harvest extracts a portion of that biomass energy, which flows to the farm livestock, to the local human population, or to distant society. The ideal agroecosystem model presented in Figure 2 tries to capture all of these important energy conversions and transfer processes. Rather than imagining this as a linear sequence, we have to represent the energy dynamics of agroecosystems as a series of intertwined loops and cycles. Much of the energy on farms cycles internally, as this diagram makes it abundantly clear.[2]

Figure 2: Detailed model of energy flows on farms, with a societal system boundary



[2] Note that from now on we will use *italics* every time we write a word in the terminology that we introduce in this working paper to designate each specific flow of an energy carrier, in the particular way they are taken into account in our energy model of a farm system seen from the viewpoint of its operators at the landscape level. We won't to do this whenever we include a term that it is commonly used in the literature in the same or similar way.

The **Farmland** subsystem of the model encompasses three general types of land use: arable cropland, pasture, and woodland. Many farm systems integrate all three categories at local scale. Often, it is the relative size of these three land uses that most distinguishes one region from another. For example, ranches in the U.S. Great Plains devote the majority of their area to pasture for grazing cattle, and only a small amount of space to cropland to raise winter feed for the animals. On the other hand, nineteenth century Austrian farms contained very little pasture, as most land was in crops, and cattle grazed in adjacent woodlands or on stubble fields (Cunfer & Krausmann 2009). In our model, researchers must understand the land use division within their local territory and estimate energy processes on each category, but the **Farmland** subsystem is meant to capture the energy processes of all three types of land use.

Farmland products constitute a major energy carrier in most farm systems and can come from any of the three types of land use. The *Land Produce* (*LP*) from **Farmland** includes cropland products like cereals, legumes, root crops, vegetables, and fibres (such as flax or hemp), but also firewood, and straw or brush used for animal bedding in barnyards. This flow is the totality of phytomass (Smil 2013) harvested from **Farmland** and directed toward human purposes. It is equivalent to 'NPP_h', the harvested portion of *Net Primary Production* (Haberl *et al.* 2007, Guzmán *et al*. 2014). Adding to it the *Unharvested Phytomass* (UPH) we obtain the total phytomass brought about by the NPP_{act} obtained from solar radiation in the system boundaries.

Another important flow in this model is a portion of *Land Produce* that we call *Biomass Reused* (*BR*). This term describes energy harvested from **Farmland** but then re-directed back to on-farm uses. There are two types of *Biomass Reused*. One portion is *Farmland Biomass Reused* (*FBR*), which includes seeds collected for next year's sowing and biomass distributed on cropland soils as fertilizer, such as green manures, stubble or wooden biomass often burned or buried underground. It is worth noting that as *Land Produce (LP)*, and then as *Biomass Reused (BR)*, we are only counting the aerial part of the plants grown so far, setting aside their root systems.[3] Yet, as the development of this root system also depends on manure, fertilizers, tillage, irrigation and crop varieties used in different types of soil, accounting for it would also provide very relevant information. For the moment we are not accounting for root biomass due mainly to lack of data, but we plan to do so in further research.

In many mixed farm systems that combine livestock with cropping a second portion of *Land Produce (LP)*, and then as *Biomass Reused (BR)*, is the *Livestock Biomass Reused* (*LBR*) that provides feed, forage, fodder, hay, straw, or other bedding materials for animal husbandry. The **Livestock-Barnyard** subsystem, in turn, after a further energy conversions, contribute *Livestock-Barnyard Produce* (*LBP*), including meat, milk, eggs, and fibres (such as wool). They also contribute *Livestock-Barnyard Services* (*LBS*) including *Manure* (*M*) and physical labour in the form of *Draught Power* (*DP*), both of which return energy to **Farmland**. When a fraction of *Land Produce* is not properly reused but is wasted, meaning that the flow is not going to the right place in the right dose to actually

[3] We acknowledge that this is an important omission (Smil 2013), and we intend to include belowground biomass in our future research after having recently put forward the methodology and assembled the appropriate data to do it (see Guzmán *et al*. 2014).

contribute to the renewal of the agroecosystems funds, we talk about *Farmland Waste* (*FW*). For example, when livestock slurry is wasted as underground water pollution, instead of restoring soil fertility, we consider this flow as *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 portion of farm production not needed to sustain agroecosystem functions, and therefore available for human consumption, whether locally or afar. One component of *Final Produce* is *Farming Community Subsistence* (*FCS*), consumed by the local **Farming Community** as food, fibre, fuel, and building materials. Finally, a portion of *Final Produce* may be available as *Surplus Produce* (*SP*) for export to the rest of **Society**. Such export may be non-existent in purely subsistence communities, or of major importance for those deeply engaged in trade. It could take the form of regional barter, rents due to a landlord, tithes to the church, or cash exchanges in local, regional, or world markets. Prior to industrialization such exports wholly supported society's urban population and defined the upper limit of the economy.

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 back to the farm system. Locally such energy contributions take two forms, first the form of *Labour* (*L*), including both *Farm Labour* (*FL*) to work the fields and *Livestock-Barnyard Labour* (*LBL*) to tend domestic animals, and second the *Farming Community Inputs* (FCI) composed by humanure and domestic residues.

Completing the circle, *Societal Inputs* (*SI*) bring energy carriers to **Farming Community**, **Farmland** and **Livestock-Barnyard** subsystems, to help sustain the next annual cycle of the agroecosystem. These contributions include organic and inorganic materials such as imported feed, building supplies, farm implements or manufactured machinery and, since the early twentieth century, fossil fuel products (tractor fuel, fertilizers, pesticides). *Societal Inputs* can be subdivided into *Farming Community Societal Inputs (FCSI)* and *Agroecosystem Societal Inputs (ASI)*, with the latter further distinguished between *Livestock-Barnyard Societal Inputs* (*LBSI*) and *Farmland Societal Inputs* (*FSI*).

Energy values may be expressed either in absolute terms, like total Gigajoules (GJ), or as land intensity in GJ per hectare of **Farmland** in order to allow comparison between farming communities with different areas. From a socio-metabolic approach, we thus model agroecosystems as a set of entangled energy loops through which farmers and the society they belong invest a given amount of available energy carriers in order to appropriate, manage and transform a given amount of solar energy converted into biomass through photosynthesis over a given area of **Farmland**.

Yet the basic engineering concept of EROI imagines a linear process, in which economic agents invest energy into a technological system and, after a conversion process, obtain an energy output. Dividing the output by the input calculates the EROI score, which

provides a comparable measure of efficiency. But how can we calculate the EROI of a cyclical, rather than a linear, agroecological system? (Giampietro *et al.* 2013:142). The main answer to this question given in this paper is to go beyond a single EROI assessment by developing a wider and more complex energy profile of agroecosystems, based on an interlinked set of EROIs able to bring to light some key aspects of their internal functioning

Doing so requires us to specify system boundaries, and then measure the energy flows as they cross these boundaries. As Georgescu-Roegen (1971) explained with his Flow-Fund model, it is only after placing the limits of a system that we can identify the flows and distinguish them from the funds that enter and leave the system as agents along the temporal process analysed (Mayumi 1991:50-51). Thus, energy carriers coming in are inputs, and the ones going out are outputs, and from these measures we can calculate EROI. But where should our system boundaries be set?

1.4 System boundaries for agroecosystems

Calculating EROI requires a clear grasp of what boundaries enclose the system under examination. Where, exactly, on a farm system should we measure inputs and outputs? The existing literature is not uniform in this regard. Because agricultural systems are complex and overlapping with tightly integrated loops, different authors measure energy inputs and outputs at different locations in the system. Put in another way, these authors are defining different boundaries around the system. While EROI at first appears as a simple, single numerical indicator of agricultural energy efficiency, in fact many of the EROI results reported in the published literature are not comparable to one another (Bayliss-Smith 1982, Naredo & Campos 1980, Stanhill 1984, Giampietro & Pimentel 1990, Giampietro *et al*. 1993, Giampietro & Mayumi 1997, Giampietro 2004, Naredo 2004, Caprintero & Naredo 2006, Guzmán & González de Molina 2006, Krausmann 2006, Cussó *et al.* 2006a and 2006b, Sorman & Giampietro 2011). Partly this is due to the result of independent researchers approaching their work differently—as we will see later. In the study of historical agroecosystems, the availability of sources can also limit what parts of the agricultural system are 'visible' and therefore measurable. In some cases it is the research questions that lead scholars to choose a particular set of system boundaries. The variation in the literature is understandable, but if we are to develop case studies over time and across space that can be compared, if we are to understand the sustainability of farming, then authors must be systematic and clear about which system boundaries they use and how they calculate EROIs (Giampietro *et al.* 2013). This paper defines three system boundary options available when analysing historical agriculture, and proposes different distinct EROI calculations.

1.4.1 Societal boundary

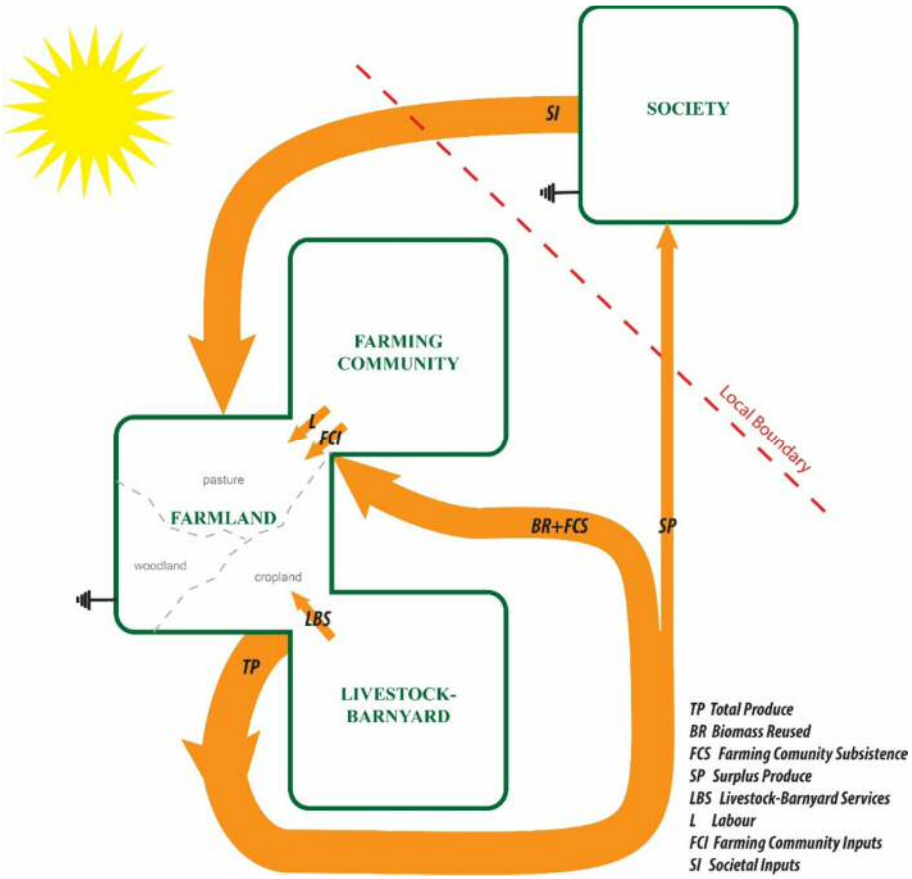
As shown in Figure 2, we can evaluate an entire agricultural society as an energy processing system. The Primary Energy Source is simply solar radiation that rains down on a nation, and which is set aside as a free gift of Nature. Energy carriers are biomass

produce successively bioconverted, and energy loses are the increasing amount of entropy generated through a myriad of conversions. This level of analysis suits regional or national scale studies better than local ones. Some energy analyses of farming communities have employed a broad system boundary, and even translated the energy exchange of surpluses and societal inputs into biophysical terms (Bayliss-Smith 1982).

1.4.2 Local boundary

Another approach is to separate distant **Society** from the Agroecosystem and the local **Farming Community** that works the land (Figure 3). This scale of abstraction recognizes people as an integral part of the energy loop in the **Farmland**. In addition to their broader role as creators, managers, and sustainers of agricultural landscapes in the first instance, local people also function more intimately as contributors of energy to the agroecosystem through labour and also as energy consumers. This system boundary places the broader **Society** outside the system, but includes local people within it. Because the **Farmland**, **Livestock**-**Barnyard**, and **Farming Community** subsystems are partially merged one another, the energy carriers that must be modelled are significantly simplified, which could be an advantage when historical sources are limited. Inputs are only *Societal Inputs* imported from distant **Society**, while outputs are *Surplus Produce* exported to distant or urban markets or to tax and rent collectors. As Figure 3 makes clear, this approach loses much of the complexity of the internal energy flows that are so important in agroecosystems and treats farm systems simply as a 'black box'. Therefore we argue that a more complex model may support better a sustainability analysis from an agroecological perspective (Guzmán & González de Molina 2015).

Figure 3: Simplified model of energy flows on farms, with a local system boundary

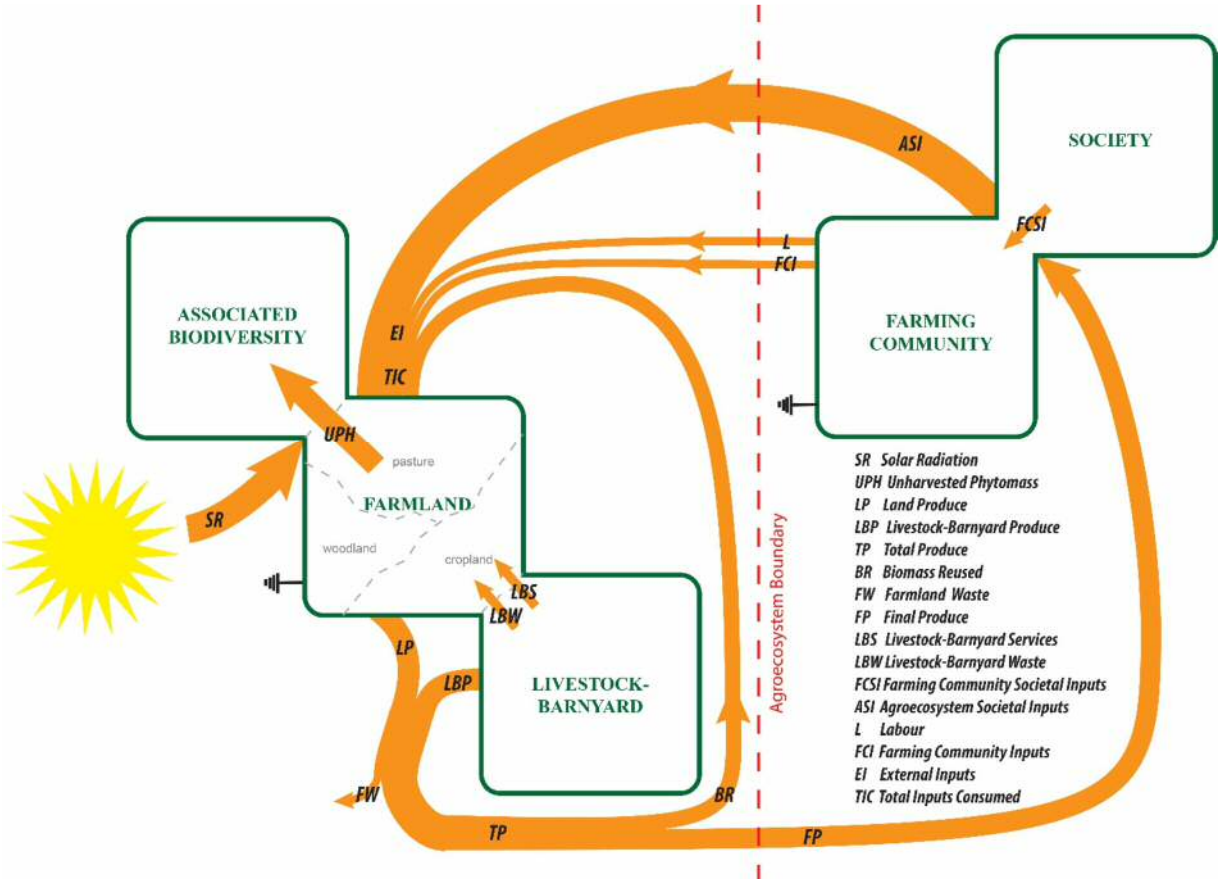


1.4.3 Agroecosystem boundary

A holistic middle ground between the detailed model presented in Figure 2 and the black box approach of Figure 3 is seen in Figure 4. It recognizes that in most agroecosystems productive land cannot function in isolation from livestock as well as the ecological services provided by an associated biodiversity. Accordingly, the **Farmland** rectangle overlaps with **Livestock-Barnyard** and **Associated Biodiversity** boxes, meaning that they are not spatially distinct but only conceptually differentiated subsystems of our energy analysis that interact one another within the farm system. In this approach the **Farming Community** and **Society** components are considered to be outside the agroecosystem they create and reproduce. Hence all human functions, both local and distant, are considered *External Inputs* (*EI*) which includes human *Labour* (*L*) and *Societal Inputs* (*SI*) and *Farming Community Inputs* (*FCI*). Outputs comprises the *Final Produce* (*FP*) of cropland, woodland, and livestock products consumed by people, including subsistence consumption by the local **Farming Community** and any *Surplus Produce* sold or transferred to the broader **Society**. Importantly, *Biomass Reused* cycles within the system, and is not accounted for as an output. Therefore in our agroecological approach *Biomass Reused* (*BR*) is accounted for as an input to **Farmland**, as part of *Total Inputs Consumed* (*TIC*). In the EROI calculations below *TIC* and *EI* become important concepts,

whose use varies with the placement of system boundaries. Another very important distinction arises between *Total Produce* (which comprises *Land Produce*, *Livestock-Barnyard Produce* and *Farmland Waste*) as the harvested share of the actual Net Primary Production (NPP_{act}) and the Unharvested Phytomass (*UPH*) available for the **Associated Biodiversity**.

Figure 4: Proposed model of energy flows on farms, with an agroecosystem boundary



We argue that this agroecosystem boundary provides the most revealing and relevant analysis of energy efficiency in farm systems. The societal boundary is difficult to calculate from historical sources and better suited to regional or national scales of analysis than to local studies. Too local a boundary, on the other hand, obscures important internal energy loops on farms. The agroecosystem boundary presented in Figure 4 nicely balances the limitations of historical information against the need to represent ecological services that are so important to long-term maintenance of farm systems.

To sum up, Figure 4 represents a simplified flowchart of the key energy converters and carriers in agroecosystems that our modelling takes into account. It does not aim at showing all aspects of the ecological functioning of a farm system, but only represent the operative concepts used in our energy bookkeeping. This involves a two-sided approach. On the one hand we adopt the managing point of view of a **Farming Community**, which

entails an economic accountancy of inputs and outputs. On the other hand, we intend that our bookkeeping does not conceal the internal agroecological functioning into a black box, but remains open enough to consider some underlying fund components related to the renewal of basic ecosystem services (and hence, for the agroecosystem sustainability) such as soil fertility, pest and disease control and pollination, to name but a few. This approach is not just economics or ecology, but a joint agroecological accountancy of the energy flows and yields of farm systems that allows comparing the agroecosystem profiles in different regions and through time from an environmental history perspective (Guzmán & González de Molina 2015).

The green boxes in the flow diagram represent energy subsystems used by farm activity to convert energy from one form into another, as seen in the way a farm-operator may account for them. Because they actually overlap one another, they appear partially merged in Figure 4—meaning that they can only be conceptually distinguished in this manner when a farm-operator standpoint is adopted. For example, the rationale behind splitting the Primary Production into two different but partially merged subsystems, named as **Farmland** and **Associated Biodiversity**, can only make sense once a farm-operator viewpoint is adopted. Seen from this perspective, a fraction of the phytomass is extracted by the farm operators in different ways (as harvests, firewood, timber or livestock grazing), and appears recorded in private bookkeeping or official statistics, while the remaining is kept at the mercy of other non-colonized species associated to the agroecosystem functioning. Accordingly, the **Farmland** subsystem describes the site where farmers' labour is purposely addressed to get a *Land Produce* (*LP*). In turn, the **Associated Biodiversity** provides them with a set of ecosystem services either in an intended or unintended manner, thanks to the *Unharvested Phytomass* (*UPH*) and habitats that remain available within **Farmland** in a compatible way with farming. The fraction of *Land Produce* (*LP*) that is reinvested into the agroecosystem as *Biomass Reused* (*BR*) also contributes to its reproduction, its **Associated Biodiversity** and the ecosystem services performed.

The same approach underlies the distinction and partial merging of the green boxes named as **Farmland** and **Livestock-Barnyard**, which are actually linked by the flows of animal feed and the herds that move from one subsystem to the other. Again the conceptual distinction of this overlapping subsystems only makes sense from a farm-operator bookkeeping. The same applies to the accountancy distinction between the local **Farming Community** comprising the agricultural active population working in the farm system studied, and the more distant **Society** they belong. These partially merged societal subsystems include many other energy converters within. Adopting a farm-operator standpoint entails to place them outside the agroecosystem they reproduce by means of the labour and information continuously invested. When using these accounting subsystems where energy flows are interlinked in the manner drawn in Figure 4, we have to remind that they do not intend to describe their agroecological functioning in a realistic manner but simply set the building blocks of the energy bookkeeping here adopted.

Then a subsequent question is how to account for the human population and activity of the Farming Community we have placed outside the agorecosystem they manage (Brown & Herendeen 1996, Murphy *et al*. 2011b:1892, Giampietro *et al*. 2013).

1.5 Accounting for labour from a farm-operator standpoint

How to include human labour in energy analysis of agroecosystems is a much debated topic. Some studies that investigate energy flows in industrial farm systems ignore human labour, mostly on the grounds that it is a comparatively small input compared to other external energy carriers. In other cases labour is considered in units of time rather than as an energy flow. From our long term socioecological perspective, human labour is an essential energy flow which needs to be considered an energy input, both in traditional organic and in industrial agricultural production systems.

In agricultural energy studies there is a range of different approaches available to quantify energy inputs related to human labour. Fluck (1981) and Stanhill (1984) provide a review of the different methods available to measure the energy equivalent of human labour. Fluck (1992) summarizes this discussion and lists nine different accounting principles, basically differing between methods that focus on the direct quantity of energy involved (or enthalpy content of food) and methods that also consider energy sequestered or 'embodied' in labour, that is the gross enthalpy which must be consumed along the whole chain needed to make the labour input available.

The actual values of the direct energy content of human labour that are used in the literature depend very much upon the physical activity, ranging from 0.7 MJ/h (Stanhill 1984), 0.8 MJ/h (Leach 1976) to around 1 (Revelle 1976), resulting in 4 to 12 MJ/day under normal working conditions. If no detailed information on the physical activity and labour hours are available, we suggest using an average of 7-8 MJ/day (which is the most common value to account for this flow that can also be applied when no better information on diets and working time are available). Assuming 6 working days per week and a daily working time of 8 hours, this amounts to 1.7-2 GJ per year or between 30 and 50% of the food energy consumed by a male adult (3.7-5.5 GJ/cap/y, based on Fluck 1992). These values can be applied for production systems where local food supply largely stems from subsistence production and was locally produced.

In accordance with our agroecosystem approach shown in Figure 4, 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 base our accounting method on what Fluck (1992) has termed the 'total energy of food metabolized while working', including the basic metabolic rate during work time[4]. In this way our analysis remains open to the choices made by these farm-operators when allocating their own time. As a consequence, our energy modelling also becomes sensitive to changes in labour productivity, which is a relevant issue when different farm systems are going to be compared historically from a socioecological standpoint.

[4] Some authors argue for excluding the basic metabolic rate here, which means reducing the daily value by 1-2 MJ.

In the case study here used as example, a careful accountancy of all agricultural tasks performed throughout a year was conducted, and a factor of physical intensity has been assessed in relation to the basic metabolic rate, in order to then calculate the proportion devoted to work in the whole energy content of the food intake by the agricultural active people in these Catalan municipalities—as explained in Part II of this working paper. For all components of this food consumption basket coming from the same agroecosystem their energy content (enthalpy) has been valued. Whenever it is imported from other production systems, the energy embodied in transporting these food products has been added. This means taking the energy imprint of transport into account. However, in this very special case we do not extend the embodied accountancy up to the energy spent in producing the food coming from outside, to avoid entering into an incoherent loop when comparing the energy profiles of two or more agroecosystems interlinked by trade. Notice that if full embodied values were here used, we would be double counting the energy cost of producing the food cropped in one agroecosystem that is going to be consumed by people working in another.[5]

Adopting this clear-cut distinction between internal and external energy carriers according to the system boundaries adopted also allows solving the problem whether labouring people are to be considered as internal or external funds of the agroecosystem. As we have seen, farm operators are inside a local community that keeps the agroecosystem functioning, while at the same time they have an external society behind them to which they provide a surplus —via feudal exactions and tithes or market interchanges and tax payment— and from which they receive a set of societal production inputs, consumption goods, services, etc. Accordingly, the energy accounting for labour depends on the system boundaries adopted.

Following this procedure, the energy content of the food basket eaten by the local labouring people is multiplied by a coefficient of their working hours out of their total time. In this way we avoid treating them as livestock or slaves that are fed only to work. Put in another way, the rationale behind this time-budget adjustment is to recognize that these farmers or agricultural labourers eat food to perform many other aims in life besides work. If we account instead the whole consumption basket of this active agricultural population as any other internal flows of *Biomass Reused*, from a farm-operator standpoint we would be treating these people as the slaves in a plantation. They would have been considered '*instrumentum vocale*', just like cattle that are only fed in order to provide draught power, manure, and other contributions to the agroecosystem. Peasants or farmers are something more than any other fund that provides inputs or outputs. They create, manage and improve (or degrade) all sorts of agroecosystems existing on Earth. As long as we are keeping a farm-operator viewpoint at landscape scale, they deserve to be considered as ends in themselves instead of being simple means to society's ends (Naredo 1996).[6]

[5] In the Catalan cases used as examples, we use data from Cussó & Garrabou (2001) for diets circa 1860 and data from Generalitat de Catalunya (1998) for diets in 1999. See the details in Part II of this working paper.

[6] Our approach can also be applied to a colonial or ancient slave plantation. In this case we suggest adding slaves as an additional energy converter within the system boundaries, parallel to the Livestock-Barnyard subsystem, while keeping overseers, guards, landowners and peasants outside the system boundaries.

This is not say that other forms of energy valuation of labour are wrong. To begin with, there are other possible ways to account for human labour as an external input, like using the energy delivered during work time (or the 'muscular energy expended by labour' approach according to Fluck 1992; see e.g. Naredo & Campos 1980, Naredo 2004, Pracha & Volk 2011)—and in fact some of us have used it in our previous work (González de Molina & Guzmán Casado 2006, Cussó *et al*. 2006a and 2006b). An additional important reason to have changed our labour accountancy to the 'total energy of food metabolized while working' was trying to keep using biomass flows as much as we can in our calculations, thus reducing a bit the heterogeneity of energy carriers that are merged in them.[7]

It follows that any shift in system boundaries entails modifying the way labour is energy assessed. For instance, adopting a societal standpoint leads to a wider reproductive approach of human labour accountancy. Then, the energy analysis has to consider not only the entire food basket eaten by the agricultural active population, but include the consumption of the dependent non-working population as well, considering that labouring people also need to be cared and reproduced along time (Norum 1983, Giampietro & Pimentel 1990). This means following the 'farm family support energy' approach according to Fluck (1992), in which it makes good sense to consider peasants or farmers just as any other compartment of the energy system (Giampietro *et al*. 1993 and 2013, Brown & Herendeen 1996, Odum 2007). The entire consumption basket of people, either endosomatic or exosomatic, needs to be considered when the focus is changed from the Food System to the whole Energy System.

All these perspectives are necessary, either the one performed from a farm-operator vantage point at the agroecosystem scale or the other performed from a wider societal standpoint. They cannot be adopted at the same time, but can be combined in a multidimensional and multi-scalar integrated analysis—for example, using the MuSIASEM methods (Giampietro *et al*. 2013, Scheidel *at al*. 2013).

In accordance with the criteria adopted above, that portion of the *Final Produce* consumed by humans is not treated as *Biomass Reused*, whether the consumer population lives in the local **Farming Community** or not. The *Final Produce* allocated to meet the consumption requirements of the local population is taken as equivalent to the part that flows out of the system boundaries for a broader societal use. This means that the subsequent energy expenditure performed in transporting, refrigerating, packaging and delivering that part of the biomass consumed outside the system boundaries has to be allocated to the corresponding points of consumption—in the same way as we do with the *ASI* coming to the agro-ecosystem under analysis (Figure 4).

[7] Notice that, e.g. accounting human labour for the final useful work entails mixing exergy with enthalpy values (see below sections 1.7 and 1.8, and the glossary).

1.6 Stocks, funds and flows: accounting for time at the agroecosystem level

Any energy analysis of societal metabolism with nature does not only depend upon the territorial boundaries adopted, but on a time perspective as well: “every time we choose a particular hierarchical level of analysis for assessing an energy flow we are also selecting a space-time scale at which we will describe the process of energy conversion” (Giampietro *et al.* 2006:70). Within our process-based approach, this time-span is usually defined as one year seen from a quasi-steady-state view (Giampietro & Mayumi 1997). This short-term perspective means that we will consider as funds some key elements, which are linked together by the various energy carriers moving through the agroecosystem every year. This could in turn entail the risk of disregarding their renewal processes over longer periods. Livestock, forests, fertile soils, arboriculture, aquifers and other funds all have a certain capacity to provide annual flows and their corresponding services one year after another without diminishing—provided that people only consume sustainable yields. Treating them as funds that remain indefinitely implies a rate of extraction equal to or below their replenishment rate, meaning that farm management is kept in equilibrium with the renewable capacity of the agroecosystem.

However, we cannot take such sustainability for granted. Indeed, an important aim for reconstructing the energy and nutrient balances of agroecosystems is to gather the basic information needed to assess whether or not exploitation rates are sustainable, by linking the annual flows to the renewable capacity of the underlying funds. As agroecosystems have different sorts of funds, any sustainable assessment requires a multi-criteria (Giampietro *et al.*2006) and multi-level survey (Giampietro & Mayumi 1997, Sorman & Giampietro 2011, Giampietro *et al*. 2013). Therefore, energy analysis and balances need to be complemented with other information and methodologies.

Such an approach reveals the difference in concept between ‘stocks’ and ‘funds’. Farm implements and machinery need to be accounted carefully as capital assets. They are stocks that provide services over many years. However, we can also consider them as flows simply by adding to the direct service they provide an amortization cost per year of use. In this way machine use may be treated like a flow by including its amortized embodied energy spent in producing and repairing it.

While stocks may be diminished by any rate of flow, funds cannot. Following the analytical distinction put forward by Nicholas Georgescu-Roegen (1971:230), funds are ‘the agents of the process’ able to transform the flow of natural resources into a flow of economically valuable products. They enter and leave the process. In contrast, any flow always comes from a fund and ends up being either an input or an output. Hence funds are the biophysical base of the human production process taking place in agroecosystems, while flows represent the transformation achieved with it. By definition, funds cannot be used up if the socio-ecological process taking place in an agroecosystems is to continue.

Moreover, funds cannot be treated as mere stock that can be turned into a flow at any rate per unit of time—like a barrel of oil that can be burnt in a week or a year. Unlike machinery or other farm implements, living funds become tired and need to rest—such as

a horse or a fertile soil. Funds deserve care while machinery only needs repair and maintenance. A fund can bring about a service only at a limited rate—like a woodland area, a vineyard or an aquifer (Georgescu-Roegen 1971:226-236). In other words, we are dealing with a fund resource when its consumption is limited by its availability and with a stock resource when its consumption is just limited by the investment in making it accessible (Giampietro *et al.* 1992:225).The renewal of the basic living and non-living funds of an agroecosystem is a key aspect of its long-term sustainability. To take this into account requires combining EROI data with other biophysical indicators, like nutrient balances or landscape ecology metrics.

1.7 Enthalpy, emergy, and energy modelling of agroecosystems

In order to carry out energy balances we express all relevant biophysical flows in agroecosystems as energy carriers (e.g. different sorts of biomass, chemical fertilizers, diesel fuel, etc.). In our approach to the energy performance of agroecosystems seen from the farm-operators' standpoint, we specify these energy carriers by their energy content, including or not the whole chain of embodied energy depending upon the relationship of each energy carrier to the system boundaries.

In thermodynamically open systems like farms, the **enthalpy** of a substance is the energy stored within it that can be converted into heat under certain commonly-defined conditions. The energy content of substances, accounted in GJ of Gross Calorific Value, can be added to the physical work performed by converters like machinery (e.g. by electric engines, tractors, etc.), also counted in GJ. While such conversion allows calculation in a single common unit, it also supposes adopting some problematic assumptions about different forms and qualities of energy carriers, or about converters that work within very different power ranges. These qualitative differences among diverse energy carriers must always be kept in mind and handled in a transparent manner. Depending on the approach and system boundaries adopted, the necessary conversions among them may lead to different assumptions and procedures—and this explains why there are in the literature different methods of energy accounting (e.g. enthalpy, emergy, exergy, etc.).

Howard T. Odum (1984 and 2007) has proposed using 'emergy' units to account for the energy consumed through the entire chain of energy transformations as a way to solve the problem of non-equivalence among different energy carriers. **Emergy** is "an expression of all the energy used in the work processes that generates a product or service in units of one type of energy" (Brown & Ulgiati 2004). The solar emergy of a product is the equivalent solar energy required to generate it. Sometimes it is convenient to think of emergy as 'energy memory' (Brown & Ulgiati 1999:14).

As explained by Brown & Herendeen (1996) and Herendeen (2004), both 'Energy Analysis' (EA) and 'Emergy Analysis' (EMA) share a common view of the system's dependence on energy in all interactions between its components, meaning that the 'energy embodied' (in EA) or 'emergy value' (in EMA) of any compartment of the system is equal to the sum of direct and indirect flows required to have it. This common assumption enables us to correct the low energy values found at the highest hierarchical

levels of energy chains when only direct energy content is accounted. EMA does so by adding the whole direct and indirect inflow of emergy in every compartment of the energy system, while EA does the same by adding the whole direct and indirect energy embodied in it.

However EMA and EA approaches adopt different accounting procedures to do this aggregation throughout the energy chain, and each one has its strengths and weaknesses. EMA values any energy carrier (EC) by adding the whole inflow needed to have this EC in the specific place it has within the system in terms of the Primary Energy Source (PES) where the energy chain originates. The adjustment between different energy qualities is solved by using transformation ratios attained in any converter that transforms an EC of one type into another of a different type. All energy flows that interlink these compartments are converted into the same emergy unit (i.e. solar units) which allows them to be compared despite the different scales and qualities involved. By taking into account all the increasingly concentrated or degraded forms of energy throughout the whole chain of flows, this procedure also allows us to use emergy as an independent term of value in order to compare the biophysical cost of resources and services regardless of whether they are valued into markets or not (Mulder & Nathan 2008).

From an ecological standpoint EMA offers a coherent framework to describe energy systems, providing a useful way to account in emergy terms the value of all ecological services that support human society. It also allows the formulation of the 'Maximum Emergy Principle', the proposition that systems that reinforce themselves with greater useful work taken from higher emergy inflows, which in turn leads to increased information and system organization, will prevail in competition over others (Brown & Herendeen 1996, Herendeen 2004). However, despite EMA's elegance as a descriptive ecological model, seen from an agency-based standpoint it lacks a prescriptive criterion to enable us to provide practical guidance about what to do (Herendeen 2004:227)—such as agroecological criteria to improve a sustainable energy yield for the farm-operators managing a farm system.

The emergy (EMA) accountancy through transformations of a single energy source would lead to the same results as for the embodied accountancy (EA) through energy intensities, except when dealing with feedback loops and by-products (Brown & Herendeen 1996:230). When an energy conversion process results in two or more outputs (e.g. grain and straw) EMA assigns the total emergy value to each of them, considering that one cannot be created without the other, and that both require the same preceding emergy chain. Then, to avoid double counting, EMA has to select only one product, setting aside the others, in order to follow the emergy chain up to the end—according to Odum's principle of 'nonadditivity of by-product flows' (Odum 1984:27-29). These EMA rules also imply that feedbacks must be truncated because otherwise emergy outputs could exceed emergy inputs, something totally impossible according to the second law of thermodynamics.

On the contrary, EA concentrates only on socio-metabolic energies and does not include the environmental Primary Energy Source coming from solar, geophysical and tidal energies. That is why in EA feedback loops can generate a positive yield, as stated by the so-called 'Podolinsky principle' put forward by Martínez Alier & Naredo (1982). According

to it, the human labour performed in agroecosystems provides a surplus of available energy for the rest of human society in the form of solar energy converted into biomass (Burkett & Foster, 2008; Martínez Alier, 1995 and 2011; Podolinsky [1883]2008).[8] This is so because placing the system boundaries at agroecosystem scale, and putting farmers outside them, means a) excluding solar radiation as an input, and b) including important internal feedback loops in the energy accountancy.

Given that we adopt an agroecological point of view, as seen from the farm operators minds, we are interested in stressing the cyclical character of biophysical energy carriers that flow driven by them and interact with natural processes. Hence, EA provides a better energy methodology for understanding the sociometabolic patterns and functioning of farm systems, and for assessing their sustainability as a co-evolutionary interaction between rural communities and nature.

1.8 Energy carriers in agroecosystems: basic definitions, accountancy rules and equivalences

Following our EA approach to agroecosystems from a farm-operator standpoint, we define inputs as any energy carrier consumed with an economic opportunity cost. An opportunity cost means that in order to acquire an energy carrier, farm operators must a) forego some other goods and b) exclude other users from acquiring them. That explains why, at agroecosystem level, we do not measure the huge amount of solar radiation, despite its essential role in photosynthesis (Odum 1984). Sunlight cannot be directly appropriated or controlled by human beings and hence it has no opportunity cost for them (Georgescu-Roegen 1971:287, Leach 1976, Pracha & Volk 2011; Giampietro *et al.* 2013). Accordingly, 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. Energy carriers coming from **outside** the system boundaries are accounted for instead by both their direct energy content and their indirect 'embodied energy'.

So far this mix of direct energy content and indirect embodied energy values may seem a bit *ad hoc*. Why is an exported cart of wheat valued only by its energy content, while imported chemical fertilizers include the energy used in producing and delivering them as well as their enthalpy? The answer lies in their respective position in relation to the system boundaries adopted. When we are dealing with biomass energy carriers coming from the photosynthesis performed **inside** the agroecosystem considered, or being reinvested in it, no more than its enthalpy has to be counted in this short energy chain up to the primary source of solar radiation, which is nature's gift from the farm operator's standpoint. When

[8] We are not interested in discussing here the Podolinsky principle from a history of economic thought standpoint. It cannot be any doubt that this principle is very relevant either if Paul Burkett and John Bellamy Foster (2006 and 2008) are right or not in pointing out the limitations of the original Podolinsky's proposals, or when they suggest that Martínez Alier & Naredo (1982) went too far when assigned to him the original idea of assessing if the energy relationship between agriculture and the rest of society involves an overall net producing or a net consuming character.

any sort of energy carrier comes from **outside** the agroecosystem we use embodied values following an EA procedure because all the indirect energy spent in producing and delivering these energy carriers is required to put them in this place, beyond their simple enthalpy.

This rule reflects the simple fact that when peasants or farmers buy fertilizer, a *Societal Input* (*SI*), they must pay for all of the embodied energy consumed to produce and deliver it to their specific agroecosystem. But we would engage in double counting if we did the same when these farm operators produce their own manure out of available biomass reused within the agroecosystem by employing their livestock and the composting manure pile as converters. Then we count as costs the land, the agricultural produce reused, and the human labour devoted to care for the livestock that provides draught power and manure. However, adding its own enthalpy value here would miss the difference between *Livestock-Barnyard Services* obtained through internal energy flows of reused biomass (*BR*) instead of buying them as external *SI*. This is why the flow of *Livestock-Barnyard Services* appears inside the partial merging of **Farmland** and **Livestock-Barnyard** subsystems in Figure 4 as a reminder of its importance, but does not enter the EROI calculation.

These rules of energy accountancy create a sharp abstraction that downplays many other relevant characteristics of these biophysical flows. Each may represent different types of energy carriers with different energy qualities. Conversions among them are tricky and must be handled with care. Notice, however, that whether considering *Total Produce*, *Biomass Reused,* or *Final Produce* we are only dealing with a single type of energy carrier: biomass. The main problems of non-equivalence between different forms of energy carriers relates to the *External Inputs*. In many past organic agroecosystems the only relevant external input other than very simple farm implements, or latrines and cesspools, was human labour. As we are evaluating farm labour by the energy content of the proportion of food intake by the labouring people devoted to worktime year round, in this case almost all relevant energy inputs and outputs are going to be different kinds of biomass.

Therefore, the most controversial aggregations of different sorts of energy carriers would arise when dealing with industrialized and fossil-fuelled agricultural systems where *Societal Inputs* (*SI*) represent an overwhelming amount of *External Inputs* and *Total Inputs Consumed*. The energy values of *ASI* involve all the energy consumed in production and delivery up to the point of use by farm operators, together with the enthalpy they contain when it comes to substances. That is to say, we account for their embodied energy. Machinery is treated as an energy stock, whose useful life goes beyond our time-span of a single year, but which can be converted to a yearly flow by adding an amortized cost. The total annual energy value of a tractor, or any other agricultural machine, is the sum of its yearly fuel use, the energy spent in repairs, and also the annual amortization of the amount of energy originally required manufacturing the tractor. To calculate the total amount of energy consumed as fuel by a tractor requires adding to the fuel enthalpy the energy cost of its industrial extraction, refinement, and delivery (Naredo 1996, Carpintero 2005, Carpintero & Naredo 2006).

Certainly, reducing all of these qualitative differences and properties to a handful of energy values involves a drastic abstraction, though a necessary one if we want to aggregate them into an energy balance (Herendeen 2004). In doing so, it should always be kept in mind that we are looking at the agroecosystem as a complex set of energy loops which link farm operators with nature, which is just one among the many relevant analysis of farm systems needed for an integrated sustainability assessment (Giampietro *et al.* 2006, 2013). This kind of energy analysis has to be complemented with other assessments and approaches, such as N-P-K nutrient balances of farmland soils (Garrabou & González de Molina 2010, González de Molina *et al.* 2010, Garcia-Ruiz *et al*., 2012, Tello *et al.* 2012) or landscape ecology assessments of land uses (Marull *et al*. 2008 and 2010). In addition, the social components of agriculture should not remain concealed—including the important question of the distribution of farm produce among different human populations, either inside the rural villages that maintain the agroecosystem or in distant urban marketplaces (Bayliss-Smith 1982).

Energy accounting is a necessary, if difficult, tool for a sustainability assessment of natural resource management. After many decades of energy analyses, there is no single common procedure, but rather a set of different approaches that adopt their own golden rules and specific protocols. Until a future proposal finds a straightforward solution able to encompass and overcome all previous views and reach a general consensus, we have to admit that the same things are be treated in different ways when using different approaches to energy accountancy. Adopting a procedure that is coherent in one context and brings about significant results may at the same time be violating a golden rule or even be illogical from another viewpoint.

True, this hampers comparability of results unless the EROIs have been obtained within an explicit framework that remains constant and congruent (Giampietro & Pimentel 1992a, Giampietro 1997 and Giampietro *et al.* 2006 and 2013). In the words of Mario Giampietro and Kozo Mayumi (2000:141), “different pre-analytic choices will be reflected in different numerical assessments. The existence of a plurality of assessments for the same quantity is not a sign of sloppy science. Rather it is just a reflection of the epistemological predicament faced by science when dealing with a complex, hierarchical reality”. Hence, the fact that a procedure may lead to a nonsensical outcome from a given standpoint does not mean that it has lost its meaning within its own framework. As Murphy *et al*. (2011b) have argued, the only workable way to deal with this state-of-the art in energy analysis is to compile in a transparent way a set of different approaches and protocols, so that at least different researchers could understand each other and benefit from their inherent achievements as much as possible (Jones 1989, Mulder *et al.* 2008).

Inasmuch as we define agroecosystems as a hybrid between nature and culture, and we adopt a farm-operator point of view, our approach may differ from those whose system boundaries are societal (Giampietro *et al*. 2013), or biosphere-centered (Brown & Ugliati 1999), or who use EMA procedures for ecological modelling. At the same time our energy bookkeeping fits many other EROI analyses of agricultural systems (see e.g. Pracha & Volk 2011) and it is in full accord with the most basic concepts and underlying fundamentals of energy analysis (Odum 2007, Giampietro *et al.* 2010 and 2013).

Table 1 specifies the terminology, energy valuation criteria and equivalences used when accounting the energy flows of an agroecosystem according to the system boundaries adopted in Figure 4:

Table 1: Terminology, energy valuation, and equivalences proposed in our bookkeeping of energy carriers of an agroecosystem (see also the Glossary)

Energy Carriers	**Energy Form Accounted**	**Equivalences**
Actual Net Primary Production (NPP_{act})	Enthalpy	$NPP_{act} = UPH+LP$
Unharvested Phytomass (UPH)	Enthalpy	$UPH = NPP_{act} - LP \approx NPP_{eco}$
Total Produce (*TP*)	Enthalpy	*TP = LP+LBP* *LP = BR+FP-LBP+FW* *TP = BR+FP+FW*
Land Produce (*LP*)		
Livestock-Barnyard Produce (*LBP*)		
Final Produce (*FP*)	Enthalpy	*FP = FCS+SP*
Farming Community Subsistence (FCS)		
Surplus Produce (*SP*)		
Total Inputs Consumed (TIC)		*TIC= EI+BR* *TIC = ASI+L+FCI+BR*
Biomass Reused (*BR*)	Enthalpy	*BR = FBR+LBBR*
Farmland Biomass Reused (*FBR*)		
Livestock-Barnyard Biomass Reused (*LBBR*)		
External Inputs (*EI*)	Embodied Energy & Enthalpy (only Embodied Energy in food & feed bought outside)	*EI = SI+FCI+L*
Societal Inputs (*SI*)		*SI = FSCI+ASI* *ASI = FSI+LBSI*
Farming Community Societal Inputs (FSCI)		
Agroecosystem Societal Inputs (*ASI*)		
Farmland Societal Inputs (FSI)		
Livestock-Barnyard Societal Inputs (LBSI)		

	Farming Community Inputs (FCI)		
	Labour (L)	Enthalpy of food intake by labouring people multiplied by the ratio $\frac{working\ time}{total\ time}$ (plus the energy embodied in transport when food comes from outside the system)	*L = FL+LBL*
	Farm Labour (*FL*)		
	Livestock-Barnyard Labour (*LBL*)		
Livestock-Barnyard Services (LBS)		Enthalpy	*LBS = DP+M*
	Draught Power (DP)	Work	
	Manure (M)	Enthalpy	
Waste (W)		Enthalpy	
	Farmland Waste (FW)		*W=FW+LBW*
	Livestock-Barnyard Waste (LBW)		

The aim of assessing the main energy funds and flows in past and present agricultural systems is to draw their specific socio-metabolic profiles, and account for their different energy performances by comparing the amount of inputs invested with the energy outputs delivered to satisfy human needs—bearing in mind that these energy and material flows not only provide consumable goods but involve environmental constraints and ecological services as well. As we have seen, the complexity and emerging properties of an agroecosystem cannot be expressed by a single input/output ratio. In the words of David Pimentel and Mario Giampietro (1991:117), "the existence of different hierarchical levels at which energetic efficiency can be assessed (i.e. individual level, societal level, ecological level) can make an objective definition of efficiency difficult if not impossible." As explained above, one way out of this epistemological difficulty is to start using different but interrelated EROIs accounted following different protocols, while trying to maintain at the same time a common and consistent theoretical framework (Mulder *et al.* 2008, Giampietro *et al.* 2010 and 2013, Murphy *et al.*, 2011b, Costanza 2013).

1.9 Drawing the energy flows and loops of agroecosystems at different disaggregation levels: The Vallès County study area c.1860 and in 1999

From then on we are going to explain this approach (Galán *et al*. forthcoming) by applying it to the agroeocological functioning of a case study area located in Catalonia (North-East of Iberia), near Barcelona, circa 1860 and in 1999 (Figure 5).

Figure 5: Location map of the study area in the Vallès County (Catalonia, Iberia)

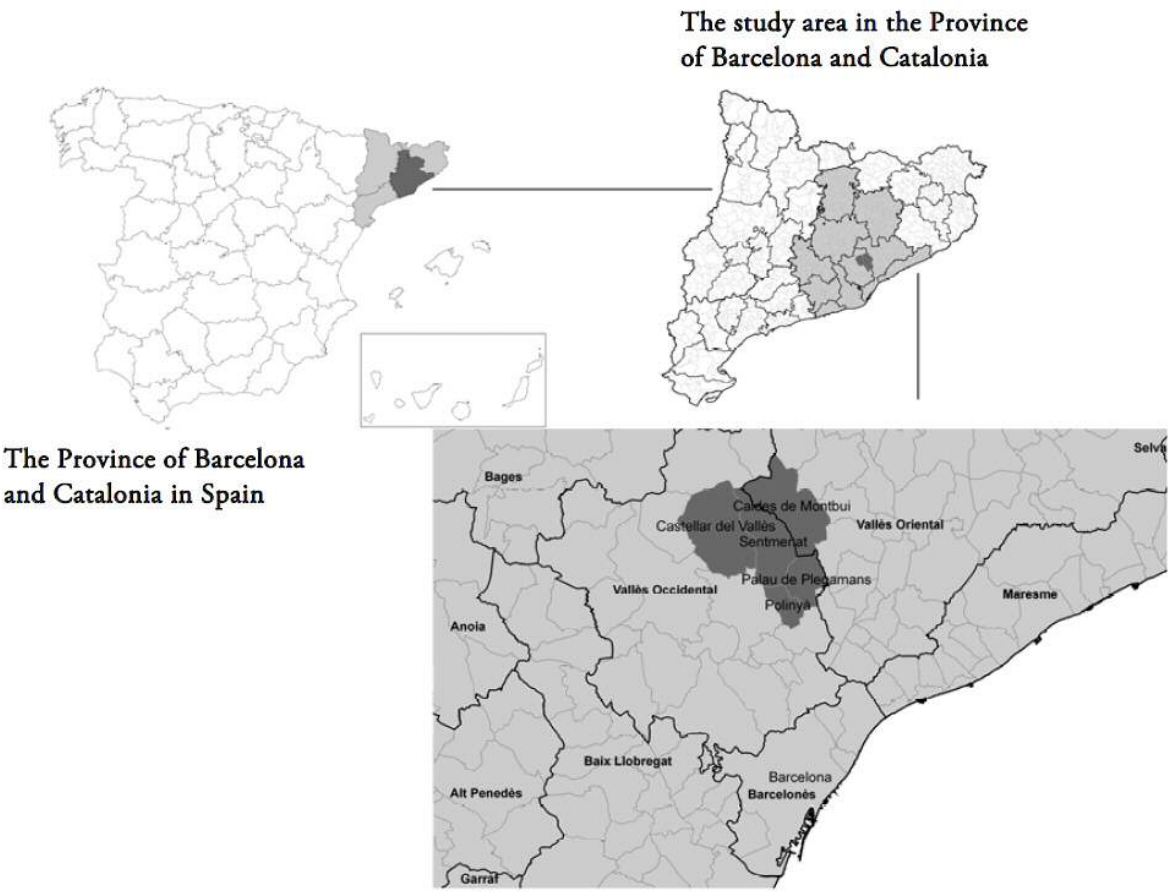
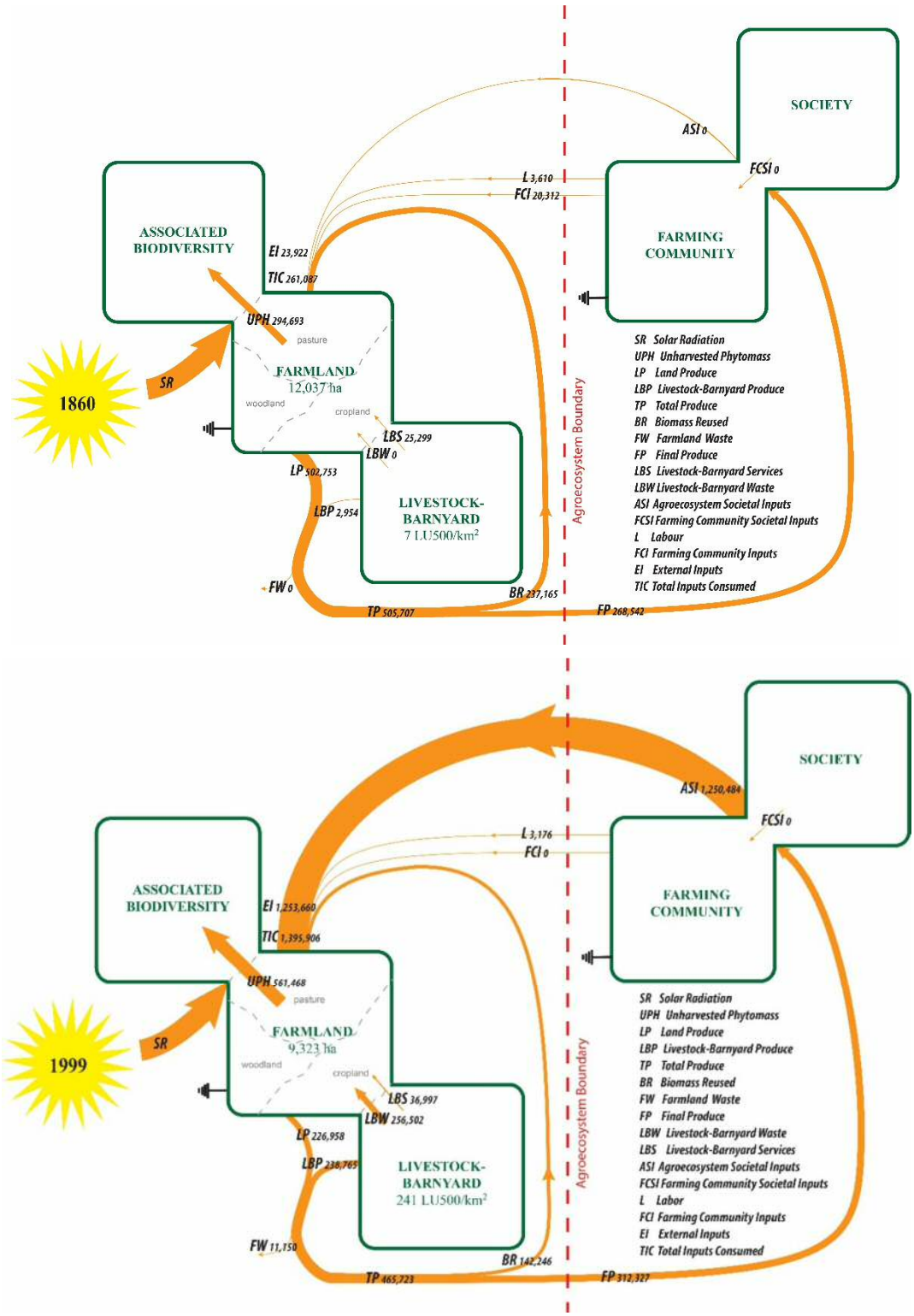


Figure 6 shows the results of our agroecosystem model to the energy flows and loops, as seen from a farm-operators viewpoint at landscape level, when applied to a small rural Catalan community of four municipalities in the Vallès County, first c.1860 and again in 1999. It is the same study area used in Cussó *et al*. (2006b), but here all pieces of the energy balance have been thoroughly recalculated from the onset in order to strictly comply with the approach, methods, accountancy rules and criteria proposed in this working paper. In the first analytical part we are going to use this data only as an example. We postpone a detailed explanation of the methods and converters used to Part II that is focused on empirical grounds, together with the historical interpretation seen from a long-term socioecological perspective.

Figure 6: Two examples of basic energy loops of an agroecosystem: the Vallès County in Catalonia (Iberia) c.1860 and in 1999. Source: our own, conceptually based on Giampetro et al. (2010) and empirically applied to the case study of Cussó et al. (2006b).



Before starting calculating EROIs, by dividing outflows with inflows in different places of the flowcharts that appear in Figure 6, it is worth noting that these flow diagrams can only present some basic data in a highly aggregated manner aimed at allowing readers to grasp the general energy profile and performance of a traditional organic farm system (c.1860), and to compare them with another industrial (in 1999). Behind all these aggregated flows there are a lot of information that has had to be gathered from original sources (or sometimes estimated from them), converted into energy units, and linked one another step by step until reaching the whole transformation chains between *Net Primary Production*, *Land Produce* and *Final Produce*.

When it comes to interpreting these data, it is often useful going down to this disaggregated information that appears listed in Table 2. By looking at them the fitness between all of the funds and components linked by the flowing of aggregate energy carriers shown in Figure 6 can be assessed. This enables us to check the successive steps of the energy balance so that: 1) the total amount of primary energy appropriated and converted through the agroecosystem by human labour and knowledge cannot increase or decrease, but only be changed; and 2) each transformation increases entropy through the corresponding losses in bioconversions or combustions performed. These conversion losses can be calculated by subtracting the energy outflows from the inflows to each converter.

Table 2: Funds and Energy flows of farm systems in the Catalan case study c.1860 and in 1999. Source: Part II of this working paper by Marco et al. *AWU: full-time Agricultural Working Units a year

Agroecosystem Funds 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	km2
	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, fodder & 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

It is a revealing exercise relating the disaggregated flows shown in Table 2 with the more aggregated flowcharts, particularly to bring to light some basic structural features. This is, for instance, the case of the fundamental role the livestock bioconversion played in the two contrasting farm systems, organic and industrial, here presented (Krausmann 2004, Guzmán *et al*. 2011).

Comparing the widths of the fluxes showing the entrance of *Farmland Societal Inputs* (FSI) into the system boundaries that appear in Figure 6 discloses that the sharp reduction in the final energy efficiency obtained by the industrial farm system in 1999 was not only due to the truly significant increase of these kinds of energy flows coming from outside—the direct and indirect energy cost of tractors and other machinery, electricity, chemical fertilizers, etc. It was rather due mainly to the much larger increase in *Livestock-Barnyard Societal Inputs* (*LBSI*) eaten as feed and fodder by livestock in feedlots. The enormous amount of energy biomass moved by this industrial system of livestock feeding also becomes apparent looking at the width of the *Livestock-Barnyard Produce* going to the *Total Produce*—which of course could certainly not be eaten by the local population and was exported to other places. In this Catalan village in 1999, while feed and fodder inputs came from outside, livestock output also went outside the system boundaries. This indicates the extent to which livestock feeding was almost totally decoupled from the rest of the local agroecosystem at the end of the 20th century—except spreading onto cropland the manure slurry produced as a waste by these industrial feedlots (whose energy content was 256,502 GJ, compared with a *NPP* of 788,427 GJ, a *Land Produce* of 226,958 GJ, a *Livestock-Barnyard Produce* of 238,765 GJ and a *Final Produce* of 312,327 GJ).

The energy profile of the traditional organic system that existed in the same place 140 years earlier reveals that livestock feeding was then tightly integrated with other land-uses and farm management of local resources. In fact, the higher energy return then attained was highly dependent on this agroecological land-use efficiency. Indeed, a significant amount of energy was lost in livestock bioconversion: 92,057 GJ, resulting of subtracting 2,954 GJ of *Livestock-Barnyard Produce* to the 95,011 GJ spent as animal feed, fodder, pasture and stall bedding (*Livestock-Barnyard Entries*)—meaning a 3% of energy return

in the feed-food conversion into the **Livestock-Barnyard** subsystem.[9] These numbers emphasize the high cost of livestock dependence, which only through a tight integration between farmland and livestock-barnyard management could be counterbalanced so as to get a nearly positive final return c.1860, as we will see later. The crop by-products reused to feed domestic animals amounted to 47,904 GJ, 55% of the whole livestock feed, whereas rough grazing in pastureland and woods covered 16% (13,676 GJ), thus reducing the need to grow feed and fodder in cropland to only 24% (20,867 GJ).

Table 3: Composition of animal feed systems in the Catalan case study c.1860 Source: Part II of this working paper by Marco et al.

Animal Feeding 86,802 GJ	*Feed*	8,449 GJ	(10%)
	Fodder	12,418 GJ	(14%)
	Crop by-products	47,904 GJ	(55%)
	Grass	13,676 GJ	(16%)
	Other from woodland	4,355 GJ	(5%)

Another interesting feature of this agricultural system c.1860 is the importance of forest and scrubland biomass, plus pruning and cultivated trees removed from cropland and used as firewood: it amounted to 204,041 GJ, 76% of the energy content of the entire *Final Produce* of 268,542 GJ—a feature closely linked with the vineyard specialization that this Catalan study area underwent from the 17th to the 19th centuries (Badia-Miró & Tello 2014) given the high water and low energy content of grapes, compared with the high enthalpy of the vines pruning. On the contrary, in 1999 a great deal of forests had been turned into derelict land where a great deal of biomass was left on the ground in these currently unused woodlands, leading to an accumulation of fallen dead branches and leaves piling up to fuel the next wildfire—a growing environmental problem all over the Mediterranean region (Grove & Rackham 2001, Lloret, *et al*. 2002, Moreira & Russo 2007).

These examples disclose just a few of the interesting aspects of agroecosystem energy profiles, and the functional details that this sort of disaggregated accounting may unravel. From a methodological point of view, what deserves the most emphasis here is the convenience to undertake this detailed energy bookkeeping at scales higher than a single crop or farm level, but rather at a landscape level where positive and negative environmental impacts of biophysical flows moved in agroecosystems can be observed.

[9] Yet if the *Livestock-Barnyard Services* that the peasants obtained as manure and draught power are added to *LBP*, we get a 30% energy return to the livestock bioconversion which emphasizes its multipurpose character when animal husbandry was kept integrated in a mixed farming system.

2 Two distinct EROI assessments, decomposed into external and internal returns

2.1 A single EROI is not enough

As we have already seen, an Energy Return On Investment is the ratio between the energy supplied by a process and the energy used directly and indirectly in this supplying process (Hall *et al.* 2009:26, 2012). The output of the numerator and the inputs of the denominator are measured in the same units, hence the ratio is dimensionless. Given that defining what is considered an input or an output depends on the system boundaries adopted (Giampetro *et al*. 2010, 2013), as well as on the specific point in the flowcharts shown in Figure 6 at which we are measuring them, any EROI becomes a site-specific assessment that cannot be compared one another unless these system boundaries and accountancy rules are clearly established and held constant. Even when comparing EROIs obtained within the same boundaries and rules along different moments of time, we must also consider whether they represent a range of variation between more or less similar agricultural systems, or rather they express a radical systemic shift from one type to another (Giampietro *et al*. 1992:454).

All these puzzling issues, which have been discussed so far, end up leading to the main outstanding question: How can we assess the energy efficiency of a cyclic, rather than linear system? A cyclical and agroecological approach has to go beyond a linear input-output perspective that identifies energy efficiency with a single EROI ratio between the output of consumable agricultural products and the technical inputs that supplement human labour. Since such a linear perspective falls short of capturing the significance of the Unharvested Phytomass, as well as of that part of harvested biomass reused within the agroecosystem (like seeds, green manures or the feed converted into draught power and animal manure), we propose a set of different EROI indicators to adequately capture the bend nature of energy flows in agroecosystems.

Our key proposal that answers this outstanding question is to start using two different EROIs, measured at the entryway and the exit gate of the farm system boundaries, and then decomposing the denominator of the latter into the intermediate flows that cycle again inside the agroecosystem as *Biomass Reuses* and the *External Inputs* coming from outside. This analytical proposal is aimed to make clear the relationship between energy efficiency and agroecological functioning of the underlying funds.

The two sets of EROIs proposed are looking at both sides of a sustainable assessment of the energy performance of farm systems: to what extent human needs are met (***Final EROI***), and checking whether these needs are satisfied in a sustainable way that does not undermine the basic ecological funds and functioning by taking into account the unharvested and reused biomass into the agroecosystem (***NPP_{act} EROI***).

By examining the relationship between NPP_{act} and *Final EROI* we can take into account in our energy analysis the importance of biomass reused and unharvested leftovers for keeping the ecological services related to soil fertility and biodiversity. Then, as we will

see later, we can apply a decomposition analysis of the respective internal or external components of *Final EROI* aimed at exploring the existing paths towards higher or lower energy efficiency by plotting the changing energy profiles of different agricultural systems when they evolved along the socioecological transition that ended the traditional organic agroecosystems and launched the industrialization of agriculture. Charting the evolving energy profiles of this socioecological transition will also help us contemplate more sustainable farm systems in the future.

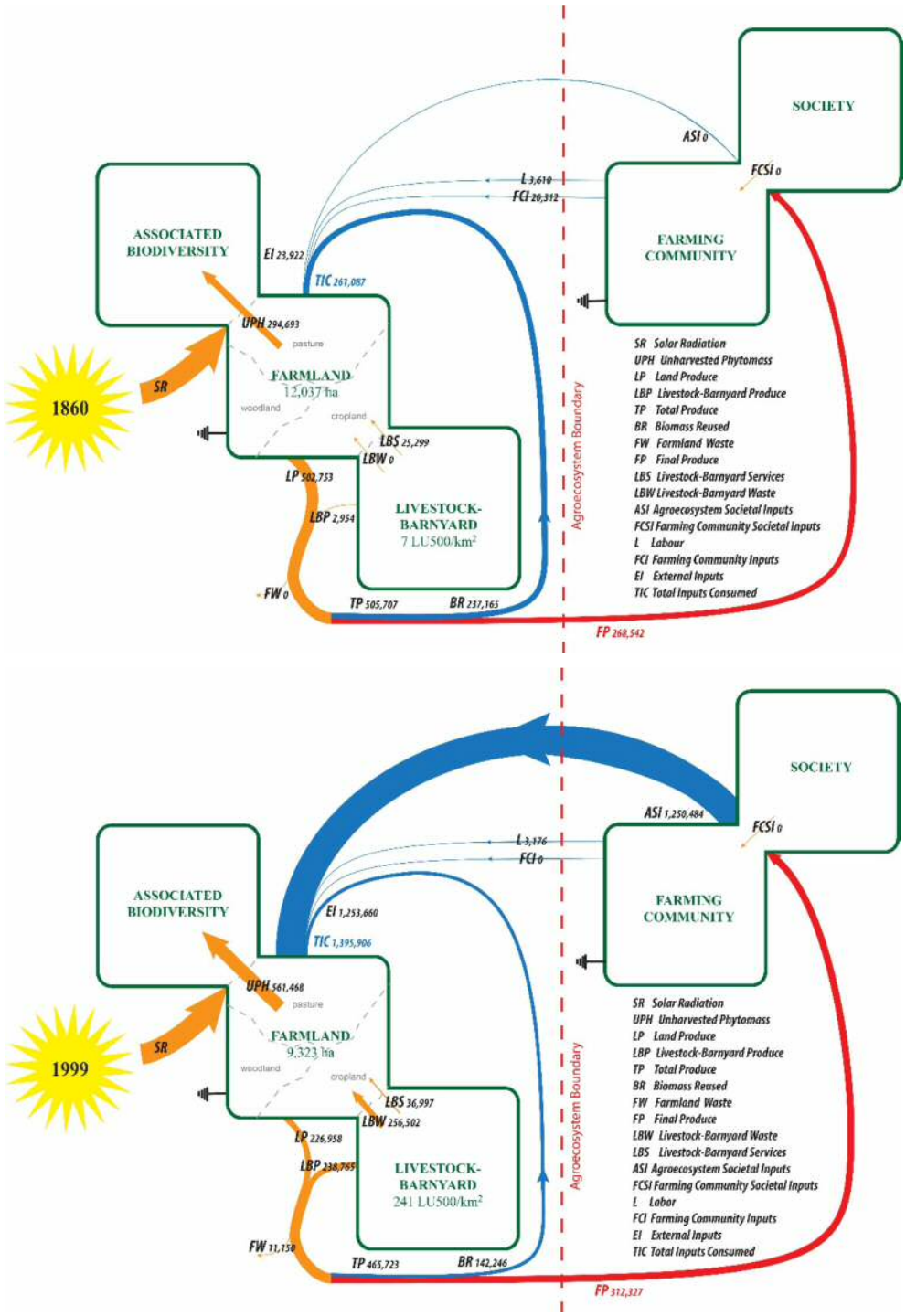
In order to define these EROIs, we have played with including or excluding the flows of *Biomass Reused* (*BR*) or *External Inputs* (*EI*) in the denominator, and *Final Produce* or the *Net Primary Production* of the vegetal biomass photosynthesized (which equals NPP_{act} = *Land Produce* + *Unharvested Phytomass*) in the numerator. The implications of these choices on the interpretation of each EROI are explained in the next sections. In the following Figures 7 to 11 the colour of each flow corresponds with the ones in the definition of each EROI to make apparent the meaning of its accountancy. Thus, the *Inputs Consumed* (either *Total* or only some of them, *BR* or *EI*) appear in the denominator of each EROI coloured in blue. The *Final Produce* included in the numerator is always coloured in red, while the rest of internal flows are kept in orange. The flow of *Livestock-Barnyard Services* is omitted from all final calculations in order to avoid double counting, however it is included in the orange flows as a reminder of its vital role.

2.2 Meeting human needs: the Final EROI (FEROI)

Final Produce (FP) is a net supply of energy carriers able to be consumed by the local population or for use in other parts of the wider socio-economic system (Fluck & Baird, 1980; Pracha & Volk, 2011). This does not mean that the rest of intermediate inputs and by-products included in *Land Produce* but excluded in *FP* are of no use. On the contrary, we have to distinguish the actual energy losses occurring in energy conversions from that part reused as intermediate inputs through internal loops of the agroecosystem, which can be defined as energy and materials needed for the renewal of its funds and processes (Giampietro, 1997:157; Giampietro & Mayumi, 1997). Adding *Biomass Reused* (*BR*) to *External Inputs* (*EI*) we get *Total Inputs Consumed* (*TIC*) in the denominator. That is, *Final EROI* assesses how much external and internal input must be invested by a farm operator to get a given basket of human consumable biomass products as measured at the exit gate of the agroecosystem:

$$\textbf{Final EROI} = \frac{\textit{Final Produce}}{\textit{Total Inputs Consumed}} = \frac{FP}{TIC}$$

Figure 7: Final EROI in the four municipalities of the Valles County (Catalonia, Iberia) c.1860 and in 1999. Source: Part II of this working paper by Marco et al.



Final $EROI_{1860}=\frac{268{,}542GJ}{261{,}087GJ}$= 1.03 Final $EROI_{1999}=\frac{312{,}327GJ}{1{,}395{,}906GJ}$= 0.22

Final EROI becomes the most relevant EROI when we want to assess its energy performance seen from an allocation standpoint aimed at meeting human needs. In the Catalan example it dropped from 1.03 c.1860 to 0.22 in 1999, thus revealing a sharp decrease in overall energy efficiency.[10]

However, taken alone *Final EROI* has an important shortcoming from an agroecological standpoint, as long as the *External Inputs* (*EI*) are mixed with *Biomass Reused* (*BR*) in the *Total Inputs Consumed* (*TIC*) in the denominator, disregarding the role *BR plays* in to keep up the ecological functioning of agroecosystems. In order to overcome this limitation, *TIC* must be broken down into two components, *BR* and *EI*, to give way to the following couple of interrelated EROIs.

2.3 The dependence on Societal Inputs: External Final EROI (EFEROI)

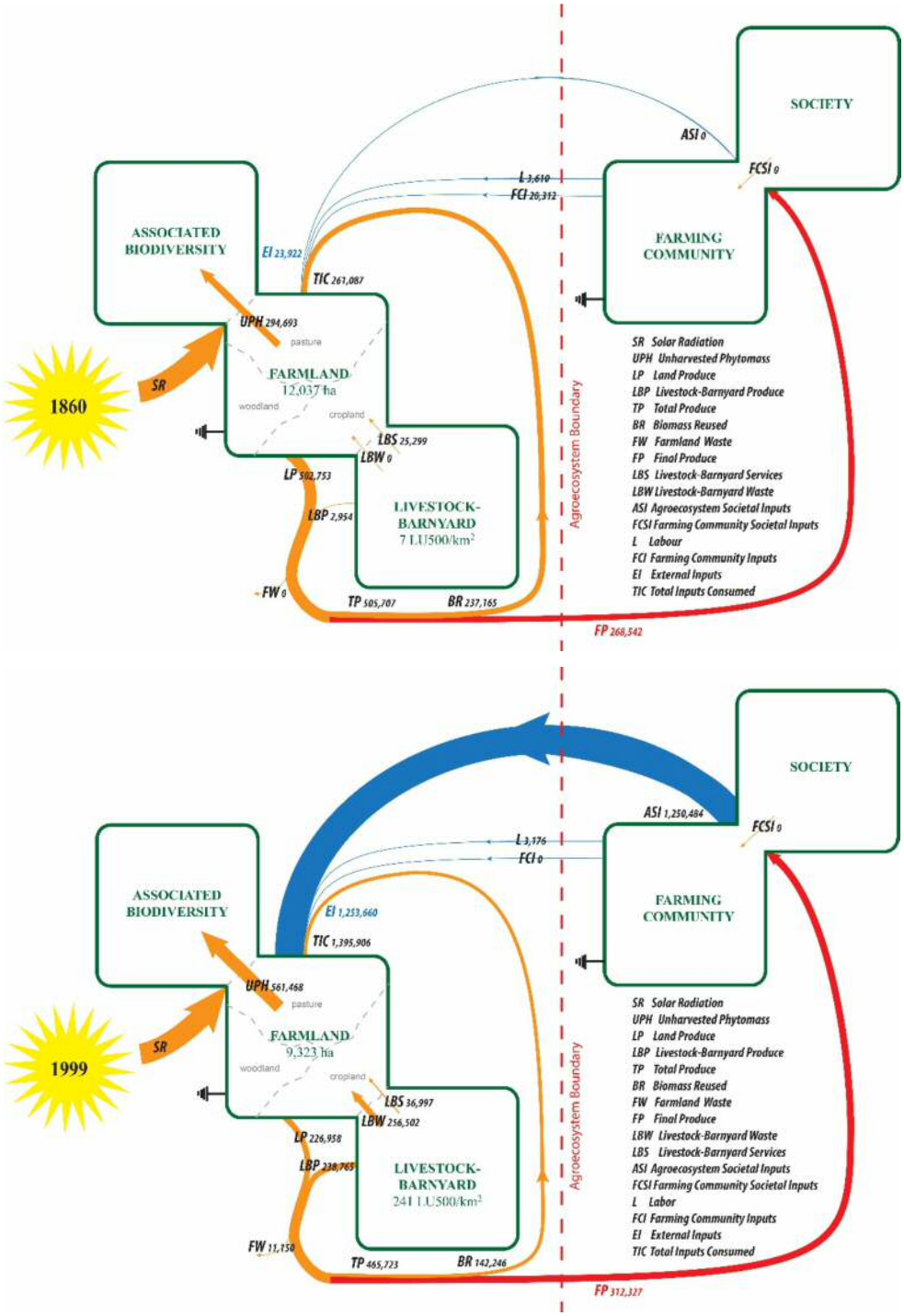
External Final EROI relates external inputs to the final output crossing the agroecosystem boundaries (Carpintero & Naredo, 2006; Pracha & Volk, 2011). This ratio links the agrarian sector with the rest of the energy system of a society—and thus assesses to what extent the agroecosytem analysed becomes a net provider or rather a net consumer of energy in its connection with the broader societal system (Figure 8). Hence it is also the relevant EROI when looking at the so-called Podolinsky principle[11], that is considering whether the human labour and animal or mechanical work performed in agroecosystems provides or not a surplus of available energy for the rest of human society in the form of solar energy converted into biomass energy carriers (Podolinsky [1883]2008, Burkett & Foster 2006, 2008; Martínez Alier 2011):

$$\textbf{External Final EROI} = \frac{\boldsymbol{Final\ Produce}}{\boldsymbol{External\ Inputs}} = \frac{\boldsymbol{FP}}{\boldsymbol{EI}}$$

[10] In Cussó *et al*. (2006b) a *Final EROI* of 1.67 was obtained for the same study area in the Vallès County c.1860, mainly due to these three factors: a) not having solved yet the problem of accounting in a coherent manner the biomass burnt in "*hormigueros*" to be used as fertilizer and soil conditioner, as was done afterwards in Olarieta *et al*. (2011) and Tello *et al*. (2012); b) having accounted human labour for the final useful work applied instead of by the proportion of food intake devoted to agricultural work time; and c) having used Metabolized Energy Values instead of Gross Calorific Values when accounting for the enthalpy of food and feed biomass flows. In a previous study, a Final EROI of 1.41 had been obtained for the whole East Vallès County c.1860 (Cussó *et al*. 2006a) using the same methods not yet improved.

[11] See footnote 6. Sergei Podolinsky (1850-1891) was specifically concerned with the energy return to the energy spent by agricultural labour (Martínez Alier ed. 1995:91-98) at a time when labour was almost the only relevant external input used in the prevailing farm systems still mainly organic. The more general idea of this 'Podolinsky principle' comes from Martínez Alier & Naredo (1982), and then from the study of the genealogy of precursors of current ecological economics undertaken by Joan Martínez Alier who related Podolinsky's 1880 essay with other writings like a book published in 1881 by Eduard Sacher (see chapters two and three of Martínez Alier & Schlüpmann 1990). More recently, Paul Burkett and John B. Foster have published an English version of a later version of Podolinsky essay issued in 1883 after the critical response of Karl Marx (who also died in 1883) and Friedrich Engels (Podolinsky [1883]2008).

Figure 8: External Final EROI in the four municipalities of the Valles County (Catalonia, Iberia) c.1860 and in 1999. Source: Part II of this working paper by Marco et al.



External Final $EROI_{1860} = \frac{268{,}542\text{GJ}}{23{,}922\text{GJ}} = 11.23$ External Final $EROI_{1999} = \frac{312{,}327\text{GJ}}{1{,}253{,}660\text{GJ}} = 0.25$

By assessing how much external energy is needed to produce crop, livestock, and forestry biomass, compared with the endosomatic and exosomatic consumption they supply as measured at agroecosystem level, the *External Final EROI* also offers a proxy of the proportion of agrarian and non-agrarian activities a human society can maintain in the long run. To do so the biomass locally consumed by the local farming community has to be subtracted from *Final Produce* to obtain a surplus flow transferred outside in return to the societal inputs received. However, as explained above, a more precise assessment of this societal link requires adopting a reproductive approach in the human labour accountancy (Giampietro & Pimentel, 1990) by adding up the energy requirement of a Total Time Budget Analysis including non-farm activities and all members of the local community. Being accounted this way, it also becomes very important for evaluating the agricultural component of the 'Law of minimum EROI' recently put forward by Hall *et al*. (2009) and Hall & Klitgaard (2012)—which states that for any social system to survive and grow it must attain a minimum EROI able to support continued economic activity and social functions (Tainter 1988).

Recall that human labour and domestic residues was usually the most relevant *External Input* in past organic agricultural systems, according to our system boundaries and accountancy rules. Consequently these always obtain higher *External Final EROI*s compared with current conventional ones, e.g. in the Catalan example it dropped from 11.23 c.1860 to 0.25 in 1999. While in the first case we are leaving aside the cost of the embodied energy in the rather simple farm implements of that time, the figure obtained c.1860 nearly complies with the 'Podolinsky principle' which points out that *External Final EROI* has to be equal or higher than the efficiency of human body as energy converter—that means a return of some 10 times the inputs spent if only a bare-bones minimum food intake is considered, or greater than 20 taking into account a more adequate level of consumption by people (Martínez Alier ed. 1995:109, Martínez Alier & Schlüpmann 1990).[12]

The main shortcoming of *External Final EROI* is setting aside once more the *Biomass Reused*, as well as the *Unharvested Phytomass*. This omission raises the unsustainability question concerning any farm system that increases *Final Produce* per unit of inputs consumed by means of giving up the reinvestment of biomass and/or reducing the biomass leftovers needed to keep agroecological funds in good order. Omitting this vital side of the agroecosystem functioning leads our energy analysis to fall again into a

[12] The energy cost to produce, repair and replace the simple farm implements of the time has not been included, because of the difficulties to evaluate this rather small part. If in the future we can solve this omission, it would reduce somewhat our *External Final EROI* c.1860 in the Catalan Vallès County. Although the order of magnitude is roughly consistent with the range Podolinsky and Sacher figured out at the end of the 19th century, it also reveals that it was comparatively lower than in other regions which enjoyed either better natural endowment and higher crop yields (like Atlantic or Central Europe), or better land-labour ratios and higher labour productivity (like the Great Plains in the United States and Canada) of the time. According to Sacher, one European agricultural worker could produce in the 1880s on average 20 times more energy in the form of edible biomass than the food consumed by him or her with the rest of the family (Martínez Alier ed. 1995, Martínez Alier & Schlüpmann 1990). By using the data recorded by William Cobbett in 1826, Tim P. Bayliss-Smith estimated that farmers would have produced five times more food than they consumed in the English village of Milton Libourne in South Wiltshire County (Bayliss-Smith 1982:54).

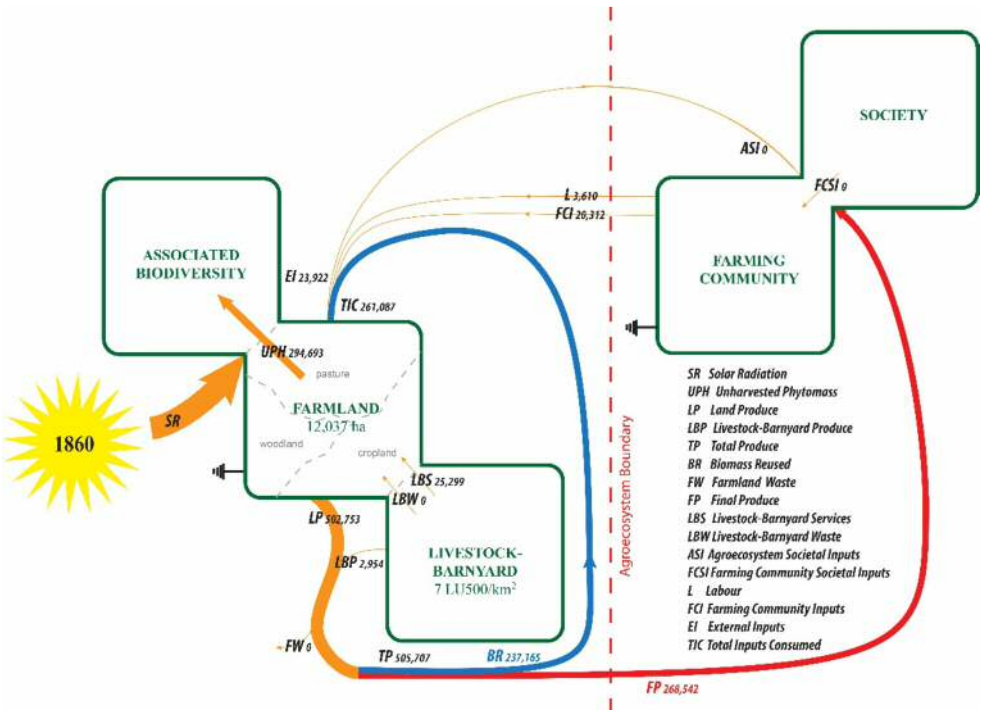
technological black box. Therefore, a sustainable energy assessment cannot rely on the *External Final EROI* taken alone.

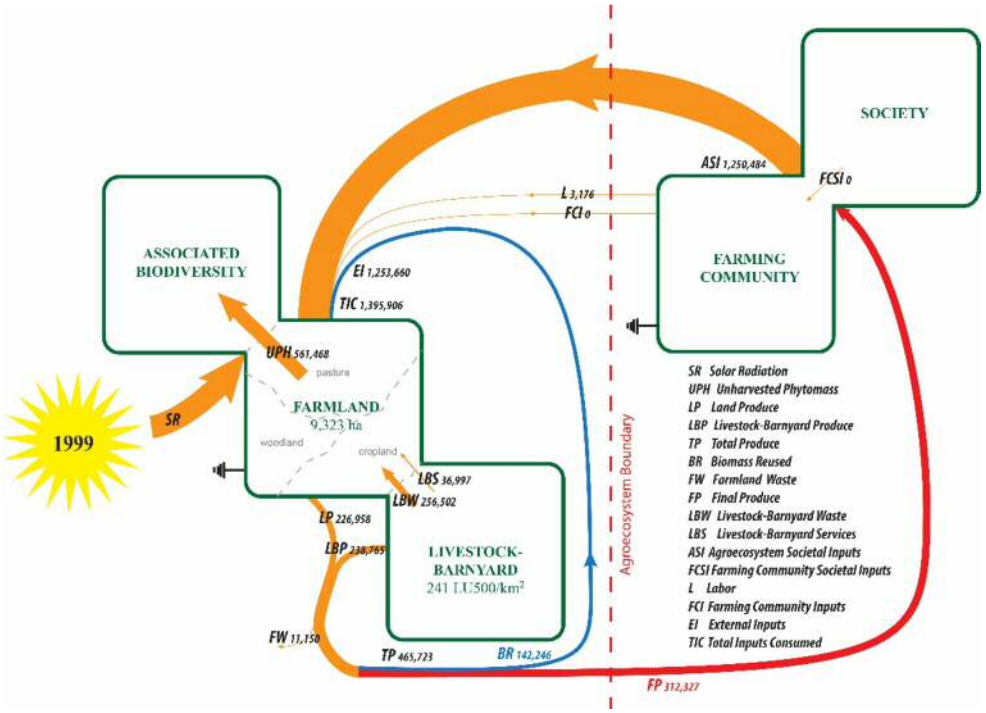
2.4 Reusing to keep up agroecosystem funds: Internal Final EROI (IFEROI)

Internal Final EROI assesses the portion of *Land Produce* reinvested in the agroecosystem as *Biomass Reused* in order to get a unit of consumable *Final Produce*. The relative amount of these internal flows exposes a clear-cut distinction between historic solar-based agricultural systems compared with fossil fuelled industrial ones at present, as organic farm systems nearly always bear greater internal flows per unit of output (Figure 9):

$$\textbf{Internal Final EROI} = \frac{\boldsymbol{Final\ Produce}}{\boldsymbol{Biomass\ Reused}} = \frac{\boldsymbol{FP}}{\boldsymbol{BR}}$$

Figure 9: Internal Final EROI in the four municipalities of the Valles County (Catalonia, Iberia) c.1860 and in 1999. Source: Part II of this working paper by Marco et al.





Internal Final $EROI_{1860} = \frac{268{,}542\text{GJ}}{237{,}165\text{GJ}} = 1.13$ Internal Final $EROI_{1999} = \frac{312{,}327\text{GJ}}{142{,}246\text{GJ}} = 2.20$

In our Catalan example *Internal Final EROI* increased from 1.13 c.1860 to 2.20 in 1999. In this case the opposite directionality of change is the result of a greater investment in keeping up the agroecosystem's funds in the former case compared with the latter one—which means bearing a higher sustainability cost that has been currently given up (Guzmán & Gonzalez de Molina 2009, Guzmán *et al*. 2011). This makes apparent that energy efficiency ratios, as measured by *Final EROI* from a farm-operator viewpoint, can be enhanced either by increasing the *Final Produce* per unit of *TIC* or by reducing the inputs spent per unit of output (that is maximizing the numerator or minimizing the denominator). Given that up to a point *BR* and *EI* can be substituted for one another, three possible strategies to increase agricultural energy yields appear: 1) attain greater output per unit of inputs consumed, whether internal or external, which means increasing the joint energy efficiency—by increasing complexity and organized information in the agroeocosystem; 2) reduce inputs consumed per unit of output by relying on internal inputs and saving external inputs; and 3) reduce inputs consumed per unit of output by relying on external inputs and saving internal inputs. It becomes apparent that there has been a historical substitution trend from internal towards external inputs throughout the socioecological transition from traditional organic agroecosystems to industrialized ones.

According to the above interpretation of the different role played by *BR* and *EI*, we deem that reusing a relevant share of *Land Produce* can be related to a high diversity of land covers in the cultural landscape, which in turn increases the number of ecotones and habitats in the agroforestry mosaics of these types of heterogeneous land matrix, as Marull *et al*. (2010, 2008) pointed out for this same Catalan case and periods, or as been

stated by other authors in different contexts (Murcia 1995, Benton *et al*. 2003, Tscharntke *et al*. 2005, Harper *et al*. 2005, Bianchi *et al*. 2006, Gustavsson *et al*. 2007, Fischer *et al*. 2008b). We presume that this would be true as long as *BR* constitutes a smooth and repeated intermediate disturbance (as opposite to climax community) that helps to maintain ecological functionality into moderate levels of human ecological disturbance, as suggested by Margalef (2006). This assumption fits with the so-called Intermediate Disturbance Hypothesis (IDH), one of the disputed explanations of the maintenance of biodiversity in ecosystems most debated in ecology (Connell 1978; Van der Maarel, 1993; Wilson, 1994; Padisak 1993; Tilman 1994; Reynolds 1995; Chesson and Huntly 1997; Dial and Roughgarden 1998). Several authors have claimed to apply the IDH to the anthropogenic disturbances exerted by agriculture, forestry and pastoral land-uses as well, either from an ecological (Pickett and White 1985; Fahrig and Jonsen 1998), agroecological (Gliessman 1998) or biological conservation (Pierce 2014) viewpoint. Our set of EROIs aims at helping this line of research, by using energy throughputs as a variable to study how different levels of human disturbance affect the associated biodiversity kept in agroecosystems (Altieri 1999).

According to the above hypothesis, an adequate level of internal biomass reusing like the one usually maintained in many traditional organic farm systems, was able to keep up an intermediate level of landscape complexity that maximized biodiversity maintenance (Tscharntke *et al*. 2005 and 2012b), and enhanced the agroecosystem resilience as defined by Holling (1973). On the contrary, relying on *EI* and getting rid of *BR* have led to monocultures with more homogeneous land covers, thus reducing landscape complexity and lessening the number of habitats and species richness. Hence, our EROI analysis assumes that an increasing dependence on external inputs goes hand in hand with biodiversity loss—as has been tested by other observers (Ruiz-Pérez 1990, Matson *et al*. 1997, Myers *et al*. 2000, Sala *et al*. 2000, Alodos *et al*. 2004, Stefanescu *et al*. 2005, Santos *et al*. 2008, Gerard *et al*. 2010, Parcerisas *et al*., 2012, Basnou *et al*. 2013). This is only a working hypothesis that has to be tested or rejected by the forthcoming research, and our EROI analysis intends to make it possible.

As a preliminary empirical evidence of these underlying assumptions, Table 4 disaggregates the flow of *Biomass Reused* c.1860 into their main components. It 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 used to keep soil biodiversity and fertility, whereas the latter also contributed to soil fertility through manure and led to high cropland and farmland diversity. The production of fodder and feed involved 14% of cropland area, while at the same time livestock was feed in pastures **(**7% of farmland area) or in the grass layers below open forests and other uncultivated land, thus helping to maintain agroforestry landscapes mosaics. Besides these direct contributions to belowground associated biodiversity and aboveground diversity of vegetal covers 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, and so on (Table 4).[13]

Table 4: Disaggregation of BR (biomass reused) flow in the Catalan case study c.1860. Numbers are in GJ, percentages into parentheses are weight over total BR flow. Source: Part II of this working paper by Marco et al.

Biomass Reused (*BR*): 237,165 GJ (100%)	*Farmland Biomass Reused* (*FBR*): 142,154 GJ (60%)	Seeds: 3,898 GJ (2%)
		Buried biomass from cropland: 95,689 (40%)
		Hormigueros: 42,567 GJ (18%)
	Livestock-Barnyard Biomass Reused (*LBBR*): 95,011 GJ (40%)	Feed: 8,449 GJ (4%)
		Fodder: 12,418 GJ (5%)
		Crop byproducts eaten by livestock: 47,904 GJ (20%)
		Rough grazing in natural pastures: 13,676 GJ (6%)
		Straw used in stall bedding: 8,209 GJ (3%)
		Other from woodland & scrub: 4,355 GJ (2%)

This hypothesis on the significance of *BR* and the related EROI indicators is a key point of our proposal that requires further research by combining energy analysis with landscape ecology methods (Marull et al, forthcoming a, b and c). As an additional important tool to support this line of research on the funds and functioning that keep up biodiversity in agroecosystems, we propose a further indicator, the *NPP EROI*, in the next section.

2.5 The sustainable role of unharvested phytomass: NPP_{act} EROI

Recall that *Final EROI* expresses the return on energy invested in creating and maintaining agroecosystems only in terms of the final product obtained that is consumable by humans. As this is leaving aside the role played by Unharvested Phytomass in nurturing the rest of non-domesticated species, we cannot assess with *Final EROI* alone whether an increase or decrease in final energy returns is made while undermining or not the agroecosystem capacity to host biodiversity and to maintain the derived ecological services. In order to overcome this shortcoming we need to relate *Final EROI* with NPP_{act} *EROI*, which expresses the return on energy invested in terms of the *Total Phytomass* (Smil 2013) included in the actual *Net Primary Production* (*TPH* of NPP_{act}) obtained from the photosynthesis within the agroecosystem:

[13] The so-called '*hormigueros'* were like small charcoal kilns where pruning as well as branches fallen and removed from forests were burnt covered by topsoil in the cropland, always after harvest times and before seeding the next crop. When the land was ploughed again, the resulting charcoal and ashes were introduced into the soil mixed with the reheated earth of the kiln (Olarieta *et al*. 2011).

$$NPP_{act}\ EROI = \frac{TPH\ of\ NPP_{act}}{TIC}$$

The whole phytomass obtained from NPP_{act} that becomes available for all species, including humans, is equal to the *Land Produce* (*LP*) and *Unharvested Phytomass* (*UPH*) by the farm operators. In turn, *LP* is subdivided into *Biomass Reused* (*BR*) inside the agroecosystem and the *Final Produce* (*FP*) consumable by humans—excluding the *Livestock-Barnyard Produce* (*LBP*) from it in order to avoid incurring in double counting (and setting aside for a while the flow of farmland wastes, if they exist, for the sake of simplicity):

$$NPP_{act} = TPH = UPH + LP = UB + BR + FP - LBP$$

Thus, NPP_{act} *EROI* expresses the energy return in terms of the total phytomass obtained through the photosynthetic conversion of solar radiation in the agroecosystem, which is then available to sustain humans as well as the rest of associated biodiversity:

$$NPP_{act}\ EROI = \frac{Total\ Phytomass\ on\ NPP_{act}}{Total\ Inputs\ Consumed} = \frac{UPH + BR + FP - LBP}{TIC}$$

Notice that having the whole NPP_{act} in the numerator, and the inputs consumed in the denominator, means looking at agroecosystems as human-colonized ecosystems. True, the photosynthetic conversion of solar radiation is a process naturally occurring in ecosystems as well as in agroecosystems. But the rationale behind NPP_{act} *EROI* is recognizing the fact that a natural ecosystem is turned into a human-managed agroecosystem precisely because of the investment of these *TIC* made by the farm-operators. Although nature continues to function in human-colonized agroecosystems, it does so conditioned by the flow of energy and information invested on them by a farming community. Therefore, from a farm-operator standpoint the total phytomass included in NPP_{act} can also be seen as a result of the investment that these farmers make while working with nature.

This approach allows us to link the NPP_{act} *EROI* with *Final EROI*, and becomes a useful way to account for the relationship between the two sides of energy that flows and cycles across agroecosystems: meeting human needs while at the same time looking after the associated biodiversity that agroecosystems require. We can compare the proportions of *Unharvested Phytomass* and *Land Produce* in the *Net Primary Production* (NPP_{act}) taking place in the agroecosystem, and thus control whether an increase in *Final Produce* is obtained at the expense of the biomass left available for the associated biodiversity or not.

Apparently, the historical market-driven technical change towards higher net *Final Produce* per unit of gross *Land Produce* might be considered an efficiency gain. It means

meeting an increasing number of human needs with the same biological NPP_{act} capacity appropriated through agroecosystems. However we must bear in mind that we are looking for a *sustainable* energy efficiency. Diverting a greater proportion of the same NPP_{act} flow of phytomass towards human consumption may also entail a reduction in the internal flows of *Biomass Reused* and of *Unharvested Phytomass.* In fact, most of what uses to be statistically accounted as yield increases from a historical or economic perspective turns out to be the result of a more desired harvest index from a market standpoint (Sinclair 1998; Carpintero & Naredo 2006, González de Molina *et al.* 2014).[14] It has been obtained thanks to greater proportions of grain weight compared with the rest of the plant, rather than a higher amount of total phytomass grown in cropland (Guzmán *et al*. 2014). As a result the consumable parts have grown, in a great share, at the expense of internal *BR* and/or *UPH*. This trend towards lower internal reuses and leftovers becomes unsustainable when it endangers the required energy investment in some key renewable funds of the agroecosystem, such as soil fertility and biodiversity.

2.6 Relating Final EROI and NPP_{act} EROI

We have seen that the energy throughput driven by farm operators entails a disturbance on the ecological patterns and processes that are kept on functioning within an agroecosystem. Like the other side of a coin, NPPact EROI can also be understood as the photosynthetically biomass produced by nature per unit of anthropogenic energy disturbance carried out. If so, by connecting NPPact EROI with Final EROI we can assess to what extent the disturbance exerted by farm-operators through the *Total Inputs Consumed* (*TIC*) gives a room for the rest of non-domesticated species to encounter habitat and be nurtured inside the agroecosystem. Put in another way, by subtracting Final EROI from NPPact EROI we can express a proxy for the environmental space given over to the Associated Biodiversity in a farm system.

By substitution it is easy to get the following equation (1), which is an identity that relates the two energy returns per unit of *TIC* in terms of the total phytomass included in NPPact and the final human consumption, as measured at the entryway or the exit gate of the agroecosystem:

$$NPP_{act}\ EROI = Final\ EROI + \frac{UPH + BR}{TIC} - \frac{LBP}{TIC} \qquad (1)$$

[14] Modern varieties have been bred for higher harvest indices, but this does not always entail the translocation of more nitrogen into the grain because of a genetic dilution effect. As nearly 80-90% of the dry weight is carbohydrate, when breeders select for higher harvest index they are also selecting for less concentration of nutrients in grain (Fan et al. 2008; Davis 2009). Our SFS research project is conducting field experiments in Andalusia (Spain) using traditional and modern seed varieties of cereals and farming methods in order to shed light on these issues.

As explained, the third term in equation (1) is only an accounting adjustment needed to keep this identity complying with the condition that $NPP_{act} = UPH + LP$, thus avoiding double counting the *Livestock-Barnyard Produce* (*LBP*).[15] Beyond this minor adjustment, equation (1) is telling us that NPPact EROI will be greater than Final EROI depending on the proportion kept on the energy content of the Total Inputs Consumed by the *Unharvested Phytomass* (*UPH*) and the *Biomass Reused* (*BR*) inside the agroecosystem. The greater the difference between NPPact EROI and Final EROI the better the capacity to host biodiversity in an agroecosystem is. The equation can be rewritten in this way:

$$NPP_{act}\ EROI - Final\ EROI = \frac{UPH + BR}{TIC} - \frac{LBP}{TIC} \qquad (1)$$

This expression identifies three interrelated components the Associated Biodiversity of an agroecosystem depends on. On the one hand, the food chains available for all other non-domesticated species rely on the *Unharvested Phytomass* (*UPH*). On the other hand, and in a somewhat more complex manner, the Associated Biodiversity also depends on the amount of biomass harvested and then reinvested into the agroecosystem (*BR*). This is so because internal reuses also contribute to the (mainly belowground) agroecological food chains whereas it requires keeping a diverse and integrated land use management—as explained. This, in turn, creates a land cover mosaic which increases up to a certain point the number of habitats and ecotones to host diverse non-domesticated species. Thus, the proportions in the flows of *UPH* and *BR* may capture in energy terms two important sides of the Associated Biodiversity in agroecosystems: habitats and food chains available for all other forms of wildlife.

Recall that the *Total Inputs Consumed* (*TIC*), thanks to which the agroecosystem keeps on operating as such, and not like any other natural ecosystem, are subdivided into *External Inputs* (*EI*) and *Biomass Reused* (*BR*). Therefore, we can express the previous identity in this other way:

$$NPP_{act}\ EROI - Final\ EROI = \frac{UPH+BR}{IE+BR} - \frac{LBP}{TIC} \qquad (2)$$

[15] Recall that *Livestock-Barnyard Produce* (*LBP*) is included in *Final Produce* (*FP*). This does not entail double counting when Final EROI is taken alone, given that in this case *LBP* is only in the numerator and livestock feed included in *Biomass Reused* (*BR*) is only in the denominator—something that makes sense from a farm-operator standpoint. However, when *Final EROI* is linked with *NPP_{act} EROI* through the same flow of biomass bioconverted, then double counting inevitably occurs because we also have *BR* in the numerator. So we need to subtract from *Final EROI* this corresponding amount of *Livestock-Barnyard Produce*. Unlike the second term, the third one in equation (1) is only a small accounting adjustment lacking any other meaning. In a typical mixed farming of cropland and livestock this adjustment will represent a very small amount. However, this reminds us the need to adapt the energy analysis here proposed to other types of agroecosystems.

Given its position in equation (2), any increase in the term $\left(\frac{UPH+BR}{IE+BR}\right)$ will enhance the difference between NPPact EROI and Final EROI that can be used as an indicator of the agroecosystem's capacity to sustain Associated Biodiversity.

Notice that the flow of *Biomass Reused* (*BR*) is both in the numerator and denominator of this term in equation (2). This expresses the basic fact that it forms a loop through which these energy carriers circulate inside the agroecosystem (see Figures 7 to 11). This feature means that the role of *BR* in keeping up the Associated Biodiversity is double-sided. Coming from the harvested biomass, *BR* entails an ecological disturbance that reduces *UPH*. At the same time, *BR* contributes to keep up biodiversity and fertility by being a reinvestment in the maintenance of its basic funds that provide these ecological services in agroecosystems.

We can then see in equation (2) that the value of this second term depends on the proportions that exist in an agroecosystem between the flows of biomass left available for other non-domesticated species (*UPH*), the biomass harvested and reused within (*BR*), and the amount of external inputs (*EI*). The actual meaning of these proportions becomes apparent when we consider, firstly, the existing relationship between the flows of *Biomass Reused* and *External Inputs* $\left(\frac{BR}{EI}\right)$ in the denominator of this term in equation (2). We know that this relationship is largely of a substitution, and replacing *BR* with *EI* characterizes the socioecological transition from traditional organic agricultures to industrialized farm systems reliant on fossil fuels. Conversely, the transition towards new organic agricultures involves implementing once again a strategy of saving external inputs by replacing them with internal biomass reuses.

Furthermore, there is a complementary relationship between the flows of *Unharvested Phytomass* and *Biomass Reused* $\left(\frac{UPH}{BR}\right)$. This means that the Associated Biodiversity depends on having at the same time and in the same place both things at once. It requires enough Unharvested Phytomass left free from human colonization, and viable habitats for different non-domesticated species to live and interact in the landscape. As explained, we deem that beyond its direct contribution to (mainly edaphic) food chains in agroecosystems the importance of *Biomass Reuse* (*BR*) is related to a series of diverse and integrated land uses that generate complex landscape mosaics. These mosaics are able to host different inner species while, at the same time, give rise to a proliferation of transitional ecotones where many other edge species live. The so-called 'edge effect' generated by landscape mosaics leads to a set of microhabitats for a great variety of plants and animals (Peñuelas et al. 2002, Reier et al. 2005; Stefanescu et al. 2005, Cevasco & Moreno 2012). Recent approaches in biological conservation are stressing the role played by the intermediate level of spatial-temporal complexity provided by agroecosystems in determining the landscape-moderated spillover of energy, resources and organism across habitats that are keeping biodiversity at present (mainly *beta*-biodiveristy) [16] and enhancing ecological resilience (Tscharntke et al. 2005 and 2012b).

[16] Agriculture always entails reducing the *alfa*-biodiversity (at plot level) to some extent. However, complex agro-forest mosaics can also enhance *beta*-biodiversity (at landscape level) as well as *gamma*-biodiversity (at regional level) through a sound agroecological integrated management, as explained by Gliessmann

Hence we assume in our energy model that, in general and up to a point, greater flows of *Biomass Reused* (*BR*) are associated with a greater presence of different habitats in agroecosystems.

Taking all this into account, we come to a very relevant conclusion. For an agroecosystem to host a great deal of Associated Biodiversity there must be a balance between *Unharvested Phytomass* and habitats free from human colonization. Habitats may remain empty if there is little food for the non-domesticated species that might occupy them. Conversely, if there is a lot of *Unharvested Phytomass* available to be consumed together with few habitats, the population of a single species will increase to a point where it starts to behave as a plague.

If we now look again at the term $\left(\frac{UPH+BR}{IE+BR}\right)$ in equation (2) considering the partial substitution possibilities existing between *EI* and *BR*, and the complementarity synergies arising between *UPH* and *BR*, we can easily realize the actual meaning of the fact that the flow of *Biomass Reused* may increase the numerator while maintaining constant the denominator as long as any increase in *BR* replaces an equivalent amount of *External Inputs*. This path fits a typical advance of organic farming towards more wildlife-friendly farm systems where human needs are satisfied without reducing and even enhancing the Associated Biodiversity, together with the ecological services it provides (Bengston et al 2003; Perfecto and Vandermeer 2010). Conversely, if the agroecosystem relies on an increasing amount of External Inputs directly or indirectly extracted from fossil fuels which replace internal reuses, the term $\left(\frac{UPH+BR}{IE+BR}\right)$ in equation (2) will decrease even though the phytomass available for other species remains constant. The rapprochement between the values of Final EROI and NPPact EROI will be expressing a loss of Associated Biodiversity. These trends highlight the positive role played by the internal reuses (*BR*) for biodiversity, which can be seen as an intended investment made in the agroecosystem funds in a way that increases its complexity through organized information—an important emerging property that needs to be further studied in future (Marull et al. forthcoming a, b and c).

However, at the same time the value of this second term in equation (2) also depends on whether the biomass left available for other species remains constant, increases or decreases. This, in turn, depends on the proportions kept either by the flows of phytomass unharvested $\left(\frac{UPH}{NPP_{act}}\right)$ or harvested $\left(\frac{LP}{NPP_{act}} = \frac{BR+FP}{NPP_{act}}\right)$ into the Net Primary Production of the agroecosystem.[17] Therefore, a great deal of Associated Biodiversity also requires that

(1998). According to Tscharntke *et al*. (2012b), there is currently a dominance of *beta*-diversity given that a landscape-moderated dissimilarity of local communities determines landscape-wide biodiversity that overrides the negative local effects of habitat fragmentation. This way structurally complex landscapes may enhance local diversity in agroecosystems, which can compensate up to a point the ecological disturbance exerted by farming land-use management (Tscharntke *et al* 2012a).

[17] As explained below, *Unharvested Phytomass* (*UPH*) only approaches roughly to NPP_{eco} in the HANPP accountancy ($\frac{UPH}{NPP_{act}} \sim \frac{NPP_{eco}}{NPP_{act}}$). The main difference comes from the empirical use of available data on used and unused crop residues. In HANPP accountancy they are considered a disturbance and included in $HANPP_{harv}$, whereas from an agroecological standpoint seen at landscape scale the unused leftovers have

the degree of human appropriation of NPP does not exceed a maximum threshold on the proportion of human-colonized phytomass, leaving a sufficient amount of biomass reused and phytomass unharvested in the landscape.

In brief, we can infer from equation (2) that biodiversity in agroecosystems depends on three vital interactions. First, the proportion existing between the amount of *Biomass Reused* and *External Inputs* ($\frac{BR}{EI}$) varies dramatically whether the farming system is based on the replacement of external inputs with the internal recirculation of biomass following a strategy of organic farming, or relies on external energy injections of fossil fuels like in an industrial farm system. Secondly, the Associated Biodiversity also depends on the proportions that exit between the flows of *Phytomass Unharvested* and *Biomass Reused*, which is reminiscent of the fact that non-domesticated species require having habitats and food chains free of human colonization balanced in the landscape. And third, the Associated Biodiversity also depends on the condition that the degree of Human Appropriation of Net Primary Production leaves a sufficient amount of phytomass unharvested and biomass reused in the agroecological landscape.

From this analysis we draw three main conclusions. Firstly, that the path followed by industrialized agricultures which gets rid of internal reuses to rely on increasing external fossil inputs is likely to lead to a loss of habitats and associated biodiversity through the abandonment of an integrated multiple-use of the landscape. Even if the amount of *Unharvested Phytomass* increases as a result of the higher Final Produce per unit of cropland made possible by the injection of external inputs coming from fossil fuels, which in turn would allow to limit cultivation in the best land and set aside farming many others, this will lead to a very unbalanced relationship between habitats and food chains free of human colonization. The most likely outcome will be the typical population imbalances that make certain species become plagues because of the lack of regulation that a high level of associated biodiversity provides.

For example, the large amount of unharvested forest biomass in woodland and shrubs now abandoned in many Mediterranean countries, as a result of the current industrialized agriculture that has given up biomass reusing and keeping the integrated land-uses needed to maintain agroforestry mosaics, generates a typical situation of poor diversity of habitats with a large amount of derelict biomass available for other non-domesticated species. Instead of increasing associated biodiversity, this combination only multiplies the population of a single species such as wild boars (Grove & Rackham 2001, Benton et al. 2003, Parcerisas et al. 2012, Tello et al. 2014, Marull et al. 2014).

Secondly, the opposite strategy of a wildlife-friendly organic farming, which consists of saving external inputs by replacing them with internal reuses, also requires achieving a balance between the Human Appropriation of Net Primary Production and the keeping of high levels of Associated Biodiversity in the landscape. By reinvesting as reuses a substantial portion of the harvested biomass, and keeping an integrated land-use management, organic farmers seek to balance human pressure on the land with the increasing complexity and resilience of agroecosystems. Their strategy will also face an

---

to be included in *UPH* which remains at the mercy of other non-domesticated species. The biomass consumed in human induced vegetation fires is also included in $HANPP_{harv}$, while it is not in our *UPH*.

upper limit though, given that any increase in harvested biomass, either reused or consumed by humans, decreases the *Unharvested Phytomass* available to other non-domesticated species. From a certain point, land-use intensification will cease to be sustainable even in an organic agriculture (Stoate et al. 2001, Krausman et al. 2012, Erb 2012).

This approach may help to understand why traditional low-intensity farm systems had greatly promoted habitat diversity in human-dominated landscapes for centuries, whereas the rapid agricultural intensification and industrialization after the Second World War has reduced the spatial heterogeneity of landscape mosaics through ever more homogeneous monocultures that led to a severe biodiversity loss (Matson et al. 1997; Tilman 2002; Tscharntke et al. 2012a). Knowing where the abovementioned critical thresholds in energy throughputs are placed in different agroecosystems and farm managements, and when they lead to key turning points in relationship with ecological functioning and associated biodiversity, would be very useful for designing more sustainable farm systems and better land-use planning in future. This is one important aim of the sociometabolic energy analysis here proposed.

Besides substituting *BR* for *EI* or the other way round, we have to consider that energy efficiency can also be increased by reducing the whole amount of *TIC* per unit of *Final Produce* as well as per unit of NPPact. This can be achieved thanks to the increase of organized information that counteracts entropy when the reinvestment of BR made by the farm operators enhances the complexity of agroecosystems—mainly because this internal energy storage is tightly linked to the farmers' knowledge that becomes incorporated in the landscape (Ho 1998; Ho & Ulanowicz 2005; Ho 2013). To explore in depth this third possibility also means going beyond the identity drawn in equation (2)—something that will be addressed in another forthcoming article (Marull et al. forthcoming c).

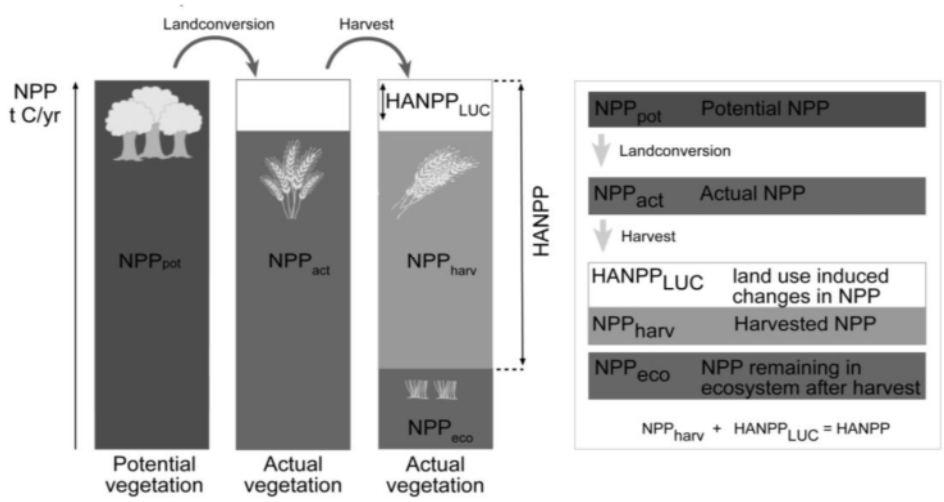
2.7 Accounting for NPP_{act} at landscape level

As we saw in section 1, the boundary of the land considered to be productive from an economic point of view does not coincide with the actual agroecological area required to provide a given final farm produce in a continuous way when the ecological services involved are also taken into account. One consequence of this mismatch is that all available statistics offered in public archives or websites, as well as private data recorded in bookkeeping, do not account for the *Unharvested Phytomass* left to the rest of species not colonized by humans. In order to fill this information gap we start drawing on the methods used to calculate the Human Appropriation of NPP (Haberl *et al*. 2007, Krausmann *et al*. 2008, Krausmann *et al*. 2013). The HANPP methodology has been predominantly used at larger scales (national to global), and it needs to be adapted to the requirements of assessing NPP_{act} at landscape level. Before we start applying this approach to the Catalan case study used as example, it is worth pointing out the similarities and differences of our approach with the standard HANPP procedure, which is as follows:

$$HANPP = NPP_{pot} - NPP_{eco} = HANPP_{luc} + HANPP_{harv}$$

Where NPP_{pot} is defined as the NPP of potential vegetation, i.e. the vegetation assumed to exist without human colonization of the land under current climate. NPP_{eco} is the NPP remaining in ecosystems after harvest, and is calculated by subtracting $HANPP_{harv}$ from the NPP of the currently prevailing vegetation (NPP_{act})—therefore, it roughly approaches what we call *Unharvested Phytomass* (UPH). $HANPP_{luc}$ is the change experienced in NPP as a result of human-induced land use change (Figure 10).

Figure 10: Basic definitions in the HANPP accountancy. Source: our own



The main problem concerning the HANPP calculations is focused on the concept of the *Potential Net Primary Production* as it refers to the supposed climax vegetation. This is a concept criticized by ecologists, paleoecologists and environmental historians, as vegetation not only depends on climate changes but in other disturbances including the subtle, light and persistent human activity along millennia as well. So we are going to use only that important part of the HANPP accounting model which fits with the needs of our own EROI methodology.

Two terms of HANPP accountancy are of particular interest for our EROI analysis of agroecosystems: The NPP of the actual vegetation under prevailing land cover (NPP_{act}) and the NPP remaining in ecosystems after harvest (NPP_{eco}). It has to be noted, though, that in HANPP assessments the harvested NPP ($HANPP_{harv}$) is defined in a broader sense than what is conceived as a socioeconomic harvest and it also includes many unused components of the plant that are not actually extracted but remain in the agroecosystem like the biomass destroyed during harvest. A modified version of NPP_{eco} can be calculated to fit our concept of *Unharvested Phytomass* (UPH) by subtracting only the human appropriated part from NPP_{act} (i.e. harvested biomass for further socioeconomic use and the reused biomass at field or for livestock).

First of all, when looking at NPP we take into account the annual flows of biomass measured either in tonnes (of fresh weight, dry matter or Carbon) or GJ per year. A second

important issue is that a distinction is made between above and belowground components of NPP. The accounting for belowground components is much more difficult than that of aboveground NPP and estimates bear considerable uncertainty. In HANPP studies, belowground NPP is typically extrapolated from aboveground NPP by applying land use specific coefficients for cropland, grassland and woody vegetation. Many available HANPP studies focus on aboveground NPP only.

The main difference of our EROI assessment with the standard method of calculating HANPP consists in leaving aside NPP_{pot}, and hence $HANPP_{luc}$ as well, in order to deal only with NPP_{act} and *UPH*. To assess the NPP remaining in agroecosystems after harvest, the NPP of the actual vegetation has to be figured out. NPP_{act} is not easy to measure. Although a large number of field studies have assessed NPP at site level and provide a rich database from the 1970s onwards, the comparability of these site specific data and their applications to similar ecosystems is often problematic (Esser *et al*. 1997, Scurlock & Olson, 2002, ORNL 2002). More recently, remote sensing data are being used to estimate NPP usually based on measurements of photosynthetically active green biomass and the derived 'normalized difference vegetation index' (NDVI)—e.g. MODIS data (Zhao & Running 2006). Global vegetation models (such as the Lund-Potsdam-Jena Dynamic Global Vegetation Model, or LPJmL used by the SEC-IFF), calibrated with field data measurements also allows calculating NPP on the basis of temperature and precipitation data together with CO_2 concentration, but soil or plant nutrient availability are rarely considered. While global maps of NPP are quite sophisticated and reliable, site-specific information is still bound to large uncertainties, mainly because it is difficult to assess the local impact of land use and soil condition and degradation on NPP.

In current global HANPP assessments, like the ones made by the Institute of Social Ecology in Vienna (SEC-IFF), the NPP on cropland is the only variable which is really site-specific or even plot-specific as it is extrapolated from data on harvested biomass which reflects local productivity taking climate and soil conditions into account. Data of NPP on grassland and forests, or any other land use types, is based on results obtained from global vegetation models (LPJmL) by adopting region-specific assumptions on land management and soil degradation (Sitch *et al*. 2003). But again the main problem of scale on those studies results in still roughly estimations that cannot be used for our Catalan study case.

Actually, in our case study in which flows are assessed at landscape level, we use two different methodologies: the first one regards to cropland while the other one is for pastures and forest. They differ due the challenge that supposes to estimate the real net primary productivity of the non-crop areas as there is less information available.

Crop areas productivity are set based on estimations over the extraction. So we begin calculating the total phytomass harvested (main product, crop residues and woody growth if applicable; NPP_h) in terms of Kg of dry matter. Then several estimations on hervibory and weeds are added to the overall harvested production by using specific ratios taken from Oerke et al. (1994). This study assesses for wheat, barley, corn, potatoes and soybean. As a first attempt we use the lower potential of loses for the 1860's data and the current ones for the 1999's time cut. The other crop losses are estimated mainly from Guzmán et al. (2014) with the exception of the fodder which is calculated based on other

studies (Sheaffer et al., 2014; Bradley et al., 2010). The results of loses due hervibory and weeds allow us to approach the *Unharvested Phytomass* value for crop production.

The methodology used for calculating that part of the NPP_{act} remaining in the agro-ecosystem in pastures and forest is different. It has not been directly estimated from the harvested one, but first calculating NPP_{act} and then subtracting the human-appropriated biomass to obtain *UPH*. The overall dry biomass (NPP_{act}) in pastures is taken from Olea et al. (2010), while in forest it is estimated for the different strata of vegetation. For data on herbs we rely on the same reference used for pastures. The shrub production is estimated from Puy et al. (2007), and for the trees we use the data of NPP_h given that we are considering a stationary state in which the harvested part of timber and firewood was near to a sustainable limit c.1860.

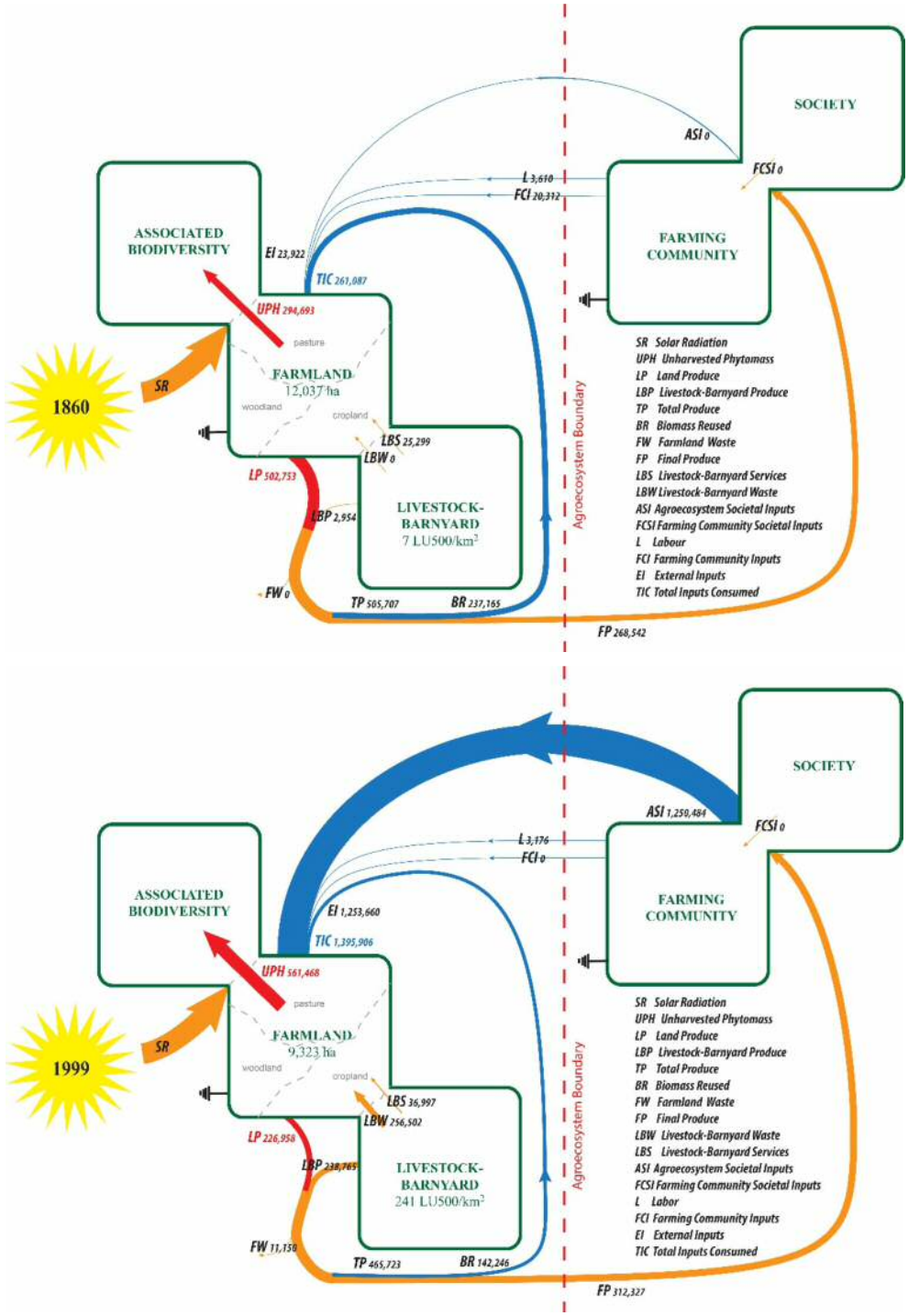
Once we have calculated the NPP_{act} and the NPP_h for both different methodologies, we are finally able to approach the part of the total phytomass left as *Unharvested Phytomass* only by the difference between values. In this first attempt, we do not include yet the belowground biomass calculation as there are still few studies that assess this subject. Nevertheless in further research we want to include them drawing on the database provided by Guzmán et al. (2014).

2.8 NPP_{act} EROI assessed in our Catalan case study c.1860 and in 1999

NPP_{act} EROI expresses the energy return in terms of the whole biomass photosynthesized in agroecosystems which is available to sustain humans as well as the rest of heterotrophic species. These other non-domesticated species, as well as the ecosystem services they provide, continue functioning conditioned by the flow of energy and information that farmers invest. Hence, the total phytomass annually produced by the agroecosystem (*NPP_{act}*) can also be seen from a farm-operator standpoint as a result of their energy investment in spite of the ecological disturbance it entails (Figure 11):

$$\textbf{NPPact EROI} = \frac{NPPact}{Total\ Inputs\ Consumed} = \frac{NPPact}{TIC}$$

Figure 11: NPPact EROI in the four municipalities of the Valles County (Catalonia, Iberia) c.1860 and in 1999. Source: Part II of this working paper by Marco et al.



$$NPP_{act}\ EROI_{1860} = \frac{797{,}446GJ}{261{,}087GJ} = 3.05 \qquad NPP_{act}\ EROI_{1999} = \frac{788{,}427GJ}{1{,}395{,}906GJ} = 0.56$$

Recall that *Final EROI* accounts the return on energy invested in terms of the final product consumable by humans, whereas NPP_{act} *EROI* assesses the return in terms of energy available to sustain humans as well as the rest of heterotrophic species in the associated biodiversity. While the former is to be accounted at the exit gate, the latter is assessed at the entryway of the agroecosystem. From this perspective we are assuming that the energy invested (*TIC*) in an agroecosystem by the farm-operators to get a *Final Produce* (*FP*) is not lineal or single-purpose. They create indeed a set of loops from a specific flow of NPP_{act} whose beneficiaries are not only them but other non-domesticated species as well.

In order to calculate the values of NPP_{act} *EROI* shown in Figure 11 an estimation of the *Unharvested Phytomass* (*UPH*) c.1860 and in 1999 has been required. In cropland we considered the share of aboveground crop NPP consumed during the growing season by other omnivorous and herbivorous species (Oerke *et al*., 1994), and the companion weeds associated to different crops (Bradley *et al*. 2010, Guzmán *et al*. 2014, Sehaffer *et al*. 2014), distinguishing between organic and conventional farming whenever possible. Then the energy content of this *UPH* has been added to the enthalpy of the harvest to obtain NPP_{act}.[18] For other land uses we calculate the NPP_{act} minus the biomass extracted by humans that year (NPP_h) to assess the unharvested NPP, using the data provided by Gobierno de Navarra (2012) and Olea *et al*. (2010) for grassland, by Cañellas (1991) for scrublands, and by Gracia *et al*. (2000-2004) for forests in the bioregion of Iberia. The results are summarized in Table 4:

Table 5: Values of annual aboveground harvested Net Primary Production (NPPh that equals Land Produce) and total Net Primary Production (NPPact) estimated in the land covers recorded in the Catalan study area c.1860 and in 1999. Source: Part II of this working paper by Marco et al.

	c.1860					**1999**				
		NPP_h		***NPP_{act}***			***NPP_h***		***NPP_{act}***	
	ha	***MJ/ha***	***GJ***	***MJ/ha***	***GJ***	*ha*	***MJ/ha***	***GJ***	***MJ/ha***	***GJ***
Cropland	6,753	45,790	309,196	67,344	454,738	2,182	92,535	201,912	108,131	235,887
Pastureland	909	15,045	13,676	17,532	15,931	340	2,921	993	17,532	5,968
Woodland	4,376	41,106	179,881	80,365	326,776	6,801	3,537	24,053	80,365	546,571
Farmland	**12,037**	**--**	**502,753**	**--**	**797,456**	**9,323**	**--**	**226,958**	**--**	**788,427**

As shown in Figure 11 and Table 5, NPP_{act} was greater c.1860 than in 1999 as a result of the significant amount of land given over to urban developments between the two dates, which reduced 22.5% the land covers photosynthetically active. NPP_{act} *EROI* dropped from 3.05 to 0.56, mainly due to the huge increase in *Agroecosystem Societal Inputs* (*ASI*) and *External Inputs* (*EI*), showing again a decrease in energy performance this time assessed at the entry gate of the agroecosystem. Nevertheless, the amount of

[18] Losses as a result of diseases caused by bacteria or fungi have been not taken into account. The missing data of some crops have been filled by the intake values of herbivores and companion weeds in the more similar ones with available information. See Part II of this working paper by Marco *et al*.

Unharvested Phytomass left at the mercy of other non-human species increased 91% from 294,693 GJ c.1860 to 561,468 GJ in 1999 as a result of rural land abandonment.

Does this mean that biodiversity was actually greater in the latter farm industrial system than in the former organic one? We are rather confident that the opposite was true, given that the end of an integrated land use management with livestock husbandry led to a loss of landscape mosaics, a reduction in land cover diversity and ecotones, and a critical decrease of habitats. The greater amount of derelict biomass combined with much lower number of habitats has endangered many species and increased at the same time the populations of very few species well adapted to these homogeneous land covers, which have been increasingly polarized between agricultural intensification in the lower and flatter lands, and spontaneous reforestation of the slopes and hills left abandoned—leaving aside the growing urban, industrial and infrastructural land covers (Peñuelas *et al*. 2002, Marull & Mallarach, 2005, Guirado *et al*. 2006, Serra *et al*. 2008, Parcerisas *et al*. 2012, Otero *et al*. 2013, Tello *et al*. 2014, Marull *et al*. 2014). These trends affect the whole metropolitan region of Barcelona as in many other parts of Europe (MacDonald *et al*. 2000, Schröter *et al*. 2005, EEA, 2006, Weber 2007, Geri *et al*., 2010), and have been specifically studied in depth in the same study area and for the same time periods by using a GIS analysis of the digital land-use maps and matrices of land-use change (Garrabou *et al*. 2008). By applying a set of landscape ecology metrics to these land cover maps, Marull *et al*. (2008 and 2010) have found a significant decrease in the capacity of these agroecosystems to host biodiversity and to offer ecological connectivity from c.1860 to 1999.

According to the meaning of equation (2) that has been examined above, this important question can be assessed in our energy analysis of farm systems by subtracting *Final EROI* to NPP_{act} *EROI*. The difference between the energy returns as measured in the entryway or in the exit gate of the agroecosystem can be taken as an assessment of the environmental space that is being kept within agricultural systems for the rest of non-domesticated species to thrive. Table 6 reassesses that this value was greater in the traditional organic farm system c.1860 than in the industrialized one in 1999, counterbalancing by far the opposite effect exerted by a 91% increase in the *Unharvested Phytomass* left on the ground from the former to the latter date:

Table 6: Values of NPP_{act} EROI-Final EROI and Unharvested Phytomass in the Catalan study area c.1860 and in 1999. Source: Our own, from the previous figures

	A ***NPP_{act} EROI***	***B*** ***Final EROI***	**(A-B) subtraction**	**UPH in GJ**	**% of UPH in *NPP_{act}***
1860	3.05	1.03	2.02	294,693	37.0
1999	0.56	0.22	0.34	561,468	71.2

If we are right when interpreting these changing trends in energy profiles from a landscape ecology standpoint, the best land-use planning to host a great deal of associated biodiversity would then be keeping or recovering the traditional agroforestry mosaics able to provide habitats and ecological connectivity to a well-designed network of natural

protected areas (Pino *et al*. 2000, Pino & Marull 2012, Agnoletti 2014)—a result that has also been assessed in the same study area by using in a prospective manner the landscape ecology model carried out by Marull *et al*. (2010:505-508), complemented with a fieldwork study of the declining populations of some specific species like Mediterranean orchids and butterflies (Tello *et al*. 2014, Marull *et al*. 2014). This interpretation fits very well with the growing scientific and political interest in wildlife-friendly farming combined with land sparing (that is, setting aside of land for biodiversity conservation; see Fischer *et al*. 2008a, Tscharntke *et al*. 2005 and 2012a).

2.9 Adopting a labour or a land cost accountancy of Unharvested Phytomass

We have seen in section 2.6 that *Biomass Reused* (*BR*) is accounted for as an energy cost in the NPP_{act} *EROI* denominator, while at the same time is a component of *Land Produce* in the numerator, thus expressing its looping character within the agroecosystem. In contrast, *Unharversted Phytomass* (*UPH*) only appears in the numerator as a component of NPP_{act}. We may wonder, however, why we do not have accounted *UPH* as a cost together with *BR*. After all, both can be seen as inputs needed to obtain the regulatory services that the associated biodiversity provides in agroecosystems. If both are required for pollination, population control and preventing plagues, should we not put *UPH* as well as *BR* in the denominator?

The real issue behind this doubt is a very interesting question. Should *UPH* be considered a cost from a farm-operator standpoint? The answer is yes or not, depending on which criteria we adopt in full cost accounting. We have followed hitherto a labour cost criteria, and from this perspective leaving some amount of phytomass unharvested available to other species means refraining from doing more human and animal work or even not perform any work at all—unlike what happens when purposely reusing biomass. This explains why, when using a labour cost criterion, *UPH* and *BR* appear in the numerator as a component of NPP_{act} but only *BR* is added to external inputs in the denominator.

At the same time, however, to set aside some amount of less-disturbed land than arable farmland also entails an opportunity cost carried out by the farm operators. Although it does not entail a labour cost, involves a land cost that may be considered as an investment in the complexity, stability and resilience of the agroecosystem—a 'land cost of sustainability' as Guzmán & and González de Molina (2009) have put forward. Accordingly, we found that neither the cropland surface statistically taken into account actually corresponds with the amount of land needed to obtain a given land produce in a sustainable manner, nor incurring in a land cost always entails a labour cost as well. It follows that two distinct full cost accountancies are needed if we want to obtain an encompassing assessment of the agroecosystem functioning. The EROIs of a farm system can be calculated either from a land cost (*EROI-land*) or from a labour (*EROI-lab*) cost accounting.

When a land cost accounting method is adopted, we get this other version (3) of the equation that relates NPP_{act} *EROI* with *Final EROI*:

$$NPP_{act}\ EROI_{land} - Final\ EROI_{land} = \frac{UPH + BR}{UPH + BR + EI} - \frac{LBP}{TIC} \quad (3)$$

Which entails, in turn, that we are considering here that:

$TIC = UPH + BR + EI$, as well as

$NPP_{act}\ EROI_{land} = \frac{NPP_{act}}{UPH+BR+EI}$, and

$$Final\ EROI_{land} = \frac{FP}{UPH + BR + EI}$$

Taking again into consideration that there is a complementary relationship between *UPH* and *BR*, and a partial substitution relationship between *BR* and *EI*,[19] it is easy to infer again from equation (3) that the amount of Associated Biodiversity is inversely proportional to the degree in which an agroecosystem depends upon *External Inputs* (*EI*). Table 7 shows the above EROI results in the same way they have been hitherto accounted from a labour cost approach in the Catalan case study c.1860 and in 1999, and it compares them with the same EROIs calculated by using a land full cost criterion:

Table 7: Comparison of all EROIs values accounted from a labour or land cost criteria in the Catalan study area c.1860 and in 1999. Source: Our own, from the previous figures

	Labour cost criterion *(EROI-lab)*		*Difference 1860-1999*	***Land cost criterion*** *(EROI-land)*		*Difference 1860-1999*
	1860	**1999**		**1860**	**1999**	
Final EROI	1.03	0.22	*0.81*	0.48	0.16	0.32
External Final EROI	11,23	0.25	*10.98*	0.84	0.17	*0.67*
Internal Final EROI	1.13	2.20	*-1.07*	0.50	0.44	*0.06*
NPP_{act} EROI	3.05	0.56	*2.49*	1.43	0.40	*1.03*
NPP_{act} EROI less Final EROI	2,02	0.34	*1,68*	0.95	0.24	*0.72*

In this specific case study it becomes apparent that when a land cost is adopted rather than a labour cost, the differences between the situation c.1860 and 1999 are shortened. However, before concluding that this result confirms that the former organic farm management carried out a much higher land cost of sustainability than the latter industrial

[19] Recall that *EI* can substitute for *BR* only in some aspects, but not in other agroecological functions that will be lost with this change.

one in 1999, we have to realise that this result is mainly due to the significant amount of land given over to urban-industrial developments, which have reduced 29% the land cover photosynthetically active in the study area. Without this effect, the increase in derelict areas where *UPH* has grown significantly would have led to completely different figures. The previous Table 5 shows that the energy content of harvested biomass increased 102% in cropland from 45,790 to 92,535 MJ/ha, whereas in woodland shrunk 91% from 41,106 to 3,537 MJ/ha, and it decreased 81% from 15,045 to 2,921 MJ/ha in pastureland (c.1860 cadastral statistics do not distinguish between pastureland and scrub):

Hence, if the growing amount of *UPH* coming from derelict land would not had been counterbalanced by the contraction of biologically active land covers, the *EROI-land* accounts would have led to different energy profiles in 1999. This raises the question of how to distinguish between a true 'land sustainability cost' carried out by an integrated organic farm management, from the simple abandonment of lands not profitable enough to be exploited from an industrial farming viewpoint.

We know that the world is currently experiencing a worrisome deforestation in many poor or developing countries of the tropics, whereas in developed nations of the northern hemisphere a forest transition towards more extended and homogeneous woodland is underway (Laurance 2001, Achard *et al*. 2002, Lambin & Geist 2006, Feranec *at al*. 2010, Gerard *et al*. 2010). It is a cruel irony that in the latter case there exist set-aside subsidies, and new policies of land sparing for the sake of biodiversity are being proposed, while in the former a strong wave of land grabbing has been unleashed under the guise that these less disturbed agricultural lands are 'underused' or 'unused'—again disregarding the vital agroecological role they play for many rural communities as a true sustainability fund (Borras & Franco 2011, Edelman *et al*. 2013, Schiedel *et al*. 2013, Oya 2013). These two opposite trends are tightly interrelated, particularly in the case of the European Union, which has become the biggest net importer of food and timber in the world (Tscharntke 2012a, Agnoletti 2014).

In order to tackle with this very important issue, analytically strong criteria are required so as to clearly distinguish the market-driven land abandonment from land sparing within a wildlife-friendly organic farming (Bengston et al 2003; Perfecto and Vandermeer 2010). In our agroecosystem energy modelling this means going beyond equation (3) to assess when land allocation entails an increase or decrease of agroecological complexity. This, in turn, involves an analytical step forward addressed to account the site-specific network of fluxes that come across each land unit, thus linking the overall energy flowing with the landscape patterns and processes. We are working in this direction by adopting a closer relationship between energy and landscape ecology analysis (Marull *et al*., forthcoming c).

3 Interrelating different EROIs and plotting energy profiles and improvement paths of agroecosystems

In the previous section we have seen how the energy profiles and yields of agroecosystems can be obtained calculating different EROIs and drawing more or less disaggregated flowcharts and tables. Then we may be interested in knowing which roles the relative amount of either *External Inputs* (*EI*) or *Biomass Reused* (*BR*) played in the *Final EROI* attained in different places, and their evolution over time. Furthermore, we may also be interested in figuring out which margins of improvement of energy efficiency these agricultural systems have, and which would be the optimal pathway to achieve them. Answering these questions requires a deeper analysis relating the external and internal energy returns with the joint energy efficiency attained. This entails decomposing any variation of *Final EROI* into both components (Tello *et al*. forthcoming).

3.1 Relating Final EROI with its internal (IFEROI) and external (EFEROI) returns

While larger reuse flows are related with a greater complexity of agroecosystems, giving up reusing them in order to mainly rely on external inputs entails a linear simplification of industrial farm systems increasingly based in fossil fuels. Therefore, decomposing *Final EROI* into its internal and external returns becomes a very revealing task in order to highlight the different profiles and contrasting trends along the socioecological transitions experienced by agricultural systems.

Let us call *EFEROI* the above explained *External Final EROI*, and *IFEROI* the *Internal Final EROI*. By substitution[20], it is easy to reach the following equation (4):

$$Final\ EROI\ (FEROI) = \frac{EFEROI \cdot IFEROI}{EFEROI + IFEROI} \qquad (4)$$

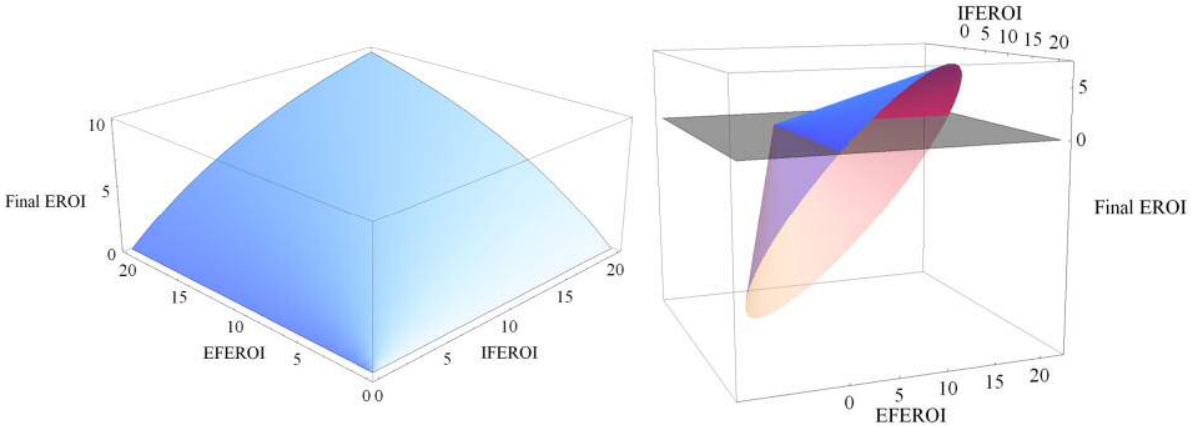
This equation tells us that *Final EROI* equals the product between its internal and external returns divided by their sum. The meaning of this relationship, the possibilities it opens to assess the paths of improving energy efficiency in agroecosystems, or to perform a decomposition analysis in order to discover the role played by internal or external returns in any historical shift from a farm system to another, are explained in depth in this section.

Expression (4) is the equation of the quadratic surface shown in Figure 12, which happens to be a cone centred at the origin (see on left side of Figure 12) or, to be more precise, a

[20] Let us call *a* the *FP*, *b* the *EI*, *c* the *BR*, *p* the *Final EROI*, *q* the *External Final EROI* and *r* the *Internal Final EROI*. Then $q = \frac{a}{b}$, which is the same as $b = \frac{a}{q}$; and $r = \frac{a}{c}$, which is the same as $c = \frac{a}{r}$. Given that $p = \frac{a}{b+c}$, we have $= \frac{a}{\frac{a}{q}+\frac{a}{r}}$, and $p = \frac{a}{\frac{ar+aq}{qr}}$, which leads to $p = \frac{a}{\frac{a\,(r+q)}{qr}}$, and finally to $p = \frac{qr}{r+q}$.

portion of a cone (on right side of Figure 12), as the values of *EFEROI* and *IFEROI* can only be positive.[21]

Figure 12: Graphical representation of Final EROI as a function of EFEROI and IFEROI. Source: our own

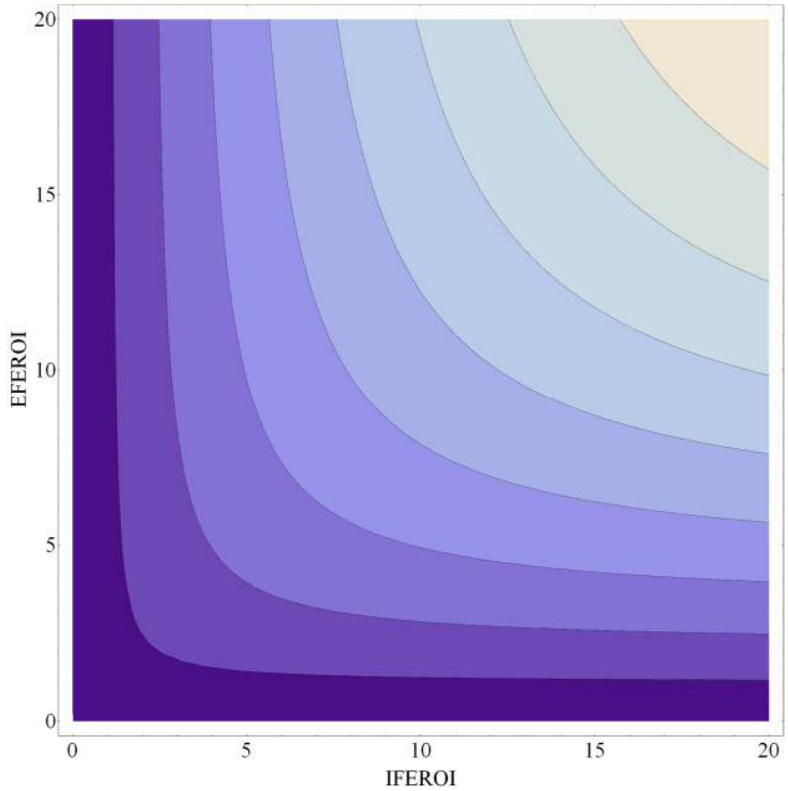


This function incurs in decreasing returns at any point: to get any increase in the joint *Final EROI* proportionally greater increases in either internal or external returns or both are needed. In fact, at any point (x, y) of the surface, the directional derivative in the direction of the gradient is $\frac{\mathrm{x}^4+\mathrm{y}^4}{(\mathrm{x}+\mathrm{y})^4}$ is strictly smaller than 1 for all points with no null coordinates, and equals 1 when either coordinate is 0.

If we consider *Final EROI* as a function of *IFEROI* and *EFEROI* then Figure 13 shows the contour lines, or isoquants, of this function. It is easy to see that these curves are hyperbolae (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). When restricted to one of such curves, any increase or decrease of one of the partial EROIs (internal or external) can be compensated by a decrease or increase of the other, respectively. The isoquants being hyperbolae, the relation among the two variations is inversely proportional. The proportional factor depends on the eccentricity of each isoquant.

[21] In fact, equation (3) 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.

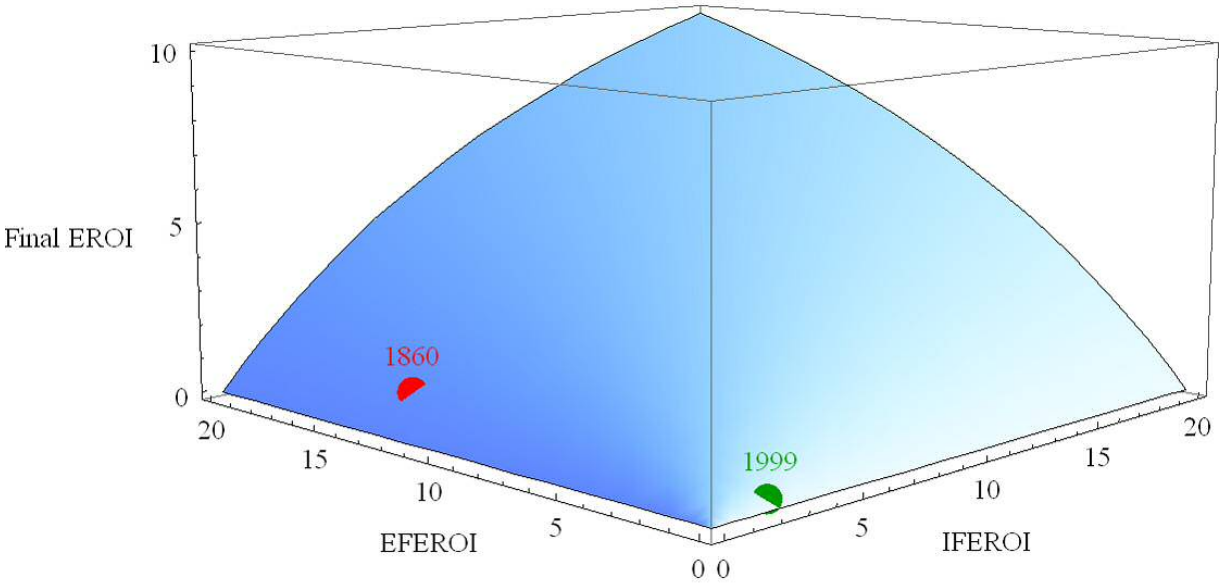
Figure 13: Isoquants of Final EROI as a function of EFEROI and IFEROI. Source: our own



As we are interested in the role played by external flows and internal reuses in the energy performance of agricultural systems, we can delve deeper into this analysis in order to reveal how variations in *EFEROI* and *IFEROI* affect the position adopted by *Final EROI* along the corresponding conic surface 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 *Final Produce*, the 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 funds working together to attain a joint performance and outcome—and that is the main focus of agroecology as a science (Altieri 1989, Gliessman 1998, Snapp & Pound 2008).

An empirical workable way to deal with such a complex issue is to plot the various combinations of *IFEROI* and *EFEROI* existing behind any given *Final EROI* attained by an agricultural system, in order to cluster them around characteristic typologies. Figure 14 shows the organic farm systems existing in the Catalan study area c.1860 compared with the industrial one in 1999. It depicts the data as points in the conic surface, as well as their isoparametric curves.

Figure 14: Plotting the Internal and External final energy returns behind the Final EROI attained by the farm system of the Catalan study area c.1860 (in red) and in 1999 (in green). Source: our own



The two time points express in visual terms the different strategies adopted by organic versus industrialized farm systems to improve final energy returns. Circa 1860 the internal energy return was low (the point is close to the *IFEROI*=0 axis) due to the high amounts of *BR* invested. However, this low *Internal Final EROI* was compensated up to a point by a much higher external return (the point is located some distance above the *EFEROI*=0 axis) thanks to the strategy of saving external inputs which whenever possible were replaced by reuses. In 1999 *External Final EROI* was extremely low and this could be compensated only to some (minor) extent by reducing the internal flows of *BR*.

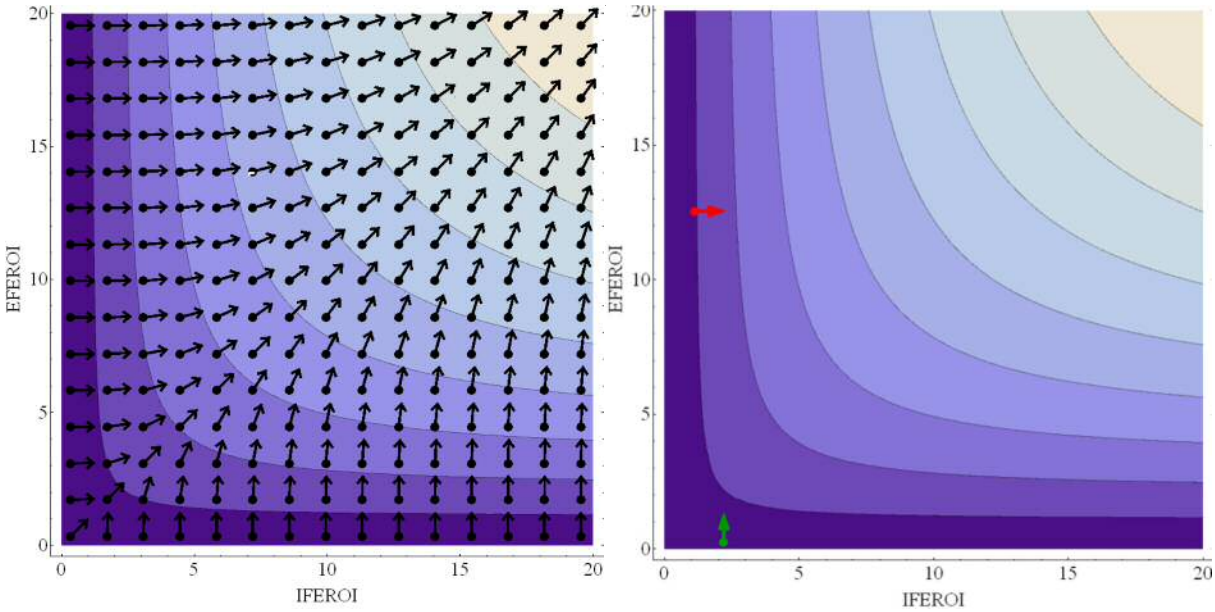
The first of these strategies is currently labelled 'Low External Input Technology' (LEIT) and fits well with an agroecological approach for a wildlife-friendly and sustainable agriculture (Tripp 2008)—given that in low-input agriculture, where the harvested flow of biomass remains within the range of 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 corresponds to the paths taken by industrialized agricultural systems based on ever greater external inputs, mainly fossil fuels that exert a much stronger disturbance over natural processes.

3.2 Looking for improvement pathways of Final EROI

The quadratic surface showing the relationships of *Final EROI* with its external or internal returns can also be used to find out optimal improvement pathways. Figure 15 presents in the left side the gradient vector at each point that indicates for each pair of values

(*EFEROI*, *IFEROI*) the direction to which the function (4) can be optimally improved. The right figure depicts the position adopted by the Catalan case study c.1860 (red point) and in 1999 (green point) and expresses in relative terms the directions and improving capacities that existed at each point by means of the orientation and length of their gradient vectors.

Figure 15: Directions and comparative lengths of the potential improvement (on the left), and (on the right) locations and directions of optimal improvements in the Catalan study area c.1860 (red) and 1999 (green). Source: our own



Potential improvements are higher if *Final EROI* is lower, or/and when the combination of *EFEROI* and *IFEROI* is skewed. All these pathways led towards points of higher Final EROIs with lower improvement capacities that tend to approach the ones along the diagonal with higher diminishing returns (where *Final EROI* = $\frac{EFEROI}{2} = \frac{IFEROI}{2}$, and $\frac{EI}{BR} = 1$). This way, we can plot the improving capacity of *Final EROI* in agroecosystems by following the optimal combination of internal or external returns, and compare the theoretical possibilities with available empirical data (Figure 15).

In the Catalan example c.1860 the gradient vector indicates that a small increase of *Internal Final EROI* would have resulted in a large increase in *Final EROI*, given that the slope of the isoparametric curve representing its $\frac{FP}{BR}$ ratio attains in this point the highest return compared with the other—which means that the internal return had a much higher impact given that external inputs were then comparatively small. One way to improve the $\frac{FP}{BR}$ ratio c.1860 was to further improve the integrated land-use management with increasing livestock breeding and thus available manure per unit of land, or by reducing losses in manure heaps and other barnyard services. To what extent can these improvements be considered feasible in the Catalan Valles County c.1860? We know that

this highly intensive farm system heavily relied on biomass reuse: 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 a large amount of forest and scrub biomass on cropland (Cussó *et al*. 2006a and 2006b; Garrabou *et al*. 2008a and 2010; Tello *et al*. 2012; Galán 2015). Land-use intensification, mainly driven by vine-growing specialization (Badia-Miró & Tello 2014), seems to have increased agroecological stress leading this preindustrial farm system towards lower energy returns—albeit nearly to one (Tello & Galán 2013, Galán *et al*. forthcoming; Tello *et al*. forthcoming). Perhaps a lower population density and land-use intensity would have also led to higher *IFEROI* and *Final EROI*, thanks to a reversal of the well-known sequence towards a growing farming activity on the available land that gives way to diminishing returns (Boserup 2005). However, adopting more extensive land uses would entail forcing the unemployed rural population to emigrate.

There was a third pathway to increase the $\frac{FP}{BR}$ ratio: restraining the labour-intensive effort by reducing the amount of *BR* per unit of final produce obtained while keeping high land-use intensity. Whereas the first option would rely on improving agroecological management, and the second would entail expelling labourers from the land, the latter would led to unsustainable paths—e.g. by mining soils not properly fertilized.[22] 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 growth 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).

[22] 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 a Final EROI of 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 & Galán 2013). Here we have carried out a thoroughly revision not only using better sources and new accountancy rules, but performing a stricter control in order to assess that the energy yields we obtain as a reference were not attained at the expense of soil fertility, deforestation or livestock malnutrition (Marco *et al.*; see Part II of this working paper). Part of the change is also related to having accounted five municipalities at first, and having omitted one due to lack of cadastral map when we discovered some relevant mismatches between the land accounts given in the official statistics and the surfaces accounted by GIS in the cadastral maps. As a result, the *Final EROI* c.1860 dropped again to 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).

3.3 Decomposition analysis of the historical shifts in Final EROI

Another way to delve into the historical changes experienced by agricultural systems is disentangling the role played by the internal or external energy returns in any 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 that exists but the expression of which remains unknown. Using a simpler notation for the variables, the situation is written:

$$\mathbb{R}^2 \rightarrow \mathbb{R}^3 \rightarrow \mathbb{R}$$

$$(x, y) \mapsto (x, y, z) \mapsto w = \frac{z}{x + y}$$

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:

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

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:

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

$$= \frac{z_2x_1 + z_2y_1 - z_1x_2 - z_1y_2}{(x_1 + y_1)(x_2 + y_2)}$$

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

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

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

We can hence write:

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

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

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

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

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

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

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

$$\text{Effect of variation in } BR = \frac{-\frac{FP_1+FP_2}{2}\Delta BR + \frac{EI_1+EI_2+BR_1+BR_2}{4}\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)} \quad (5)$$

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 our Catalan case study *Final EROI* dropped from 1.03 circa 1860 to 0.22 in 1999. Now we want to assess the role played by the variation of internal reuses and external flows, and their corresponding partial energy returns, in the following variation experienced in *Final EROI*: $\left(\frac{0.22-1.03}{1.03}\right) \times 100 = -78.64\%$.

Applying equation (5) we obtain that the variation of –0.80 EROI points (or -78.64%) experienced between *Final EROI*$_{1860}$ and *Final EROI*$_{1999}$ would have been explained by a sharp decrease in the corresponding variation between *EI*$_{1860}$ and *EI*$_{1999}$, which is equal to

$$\frac{-\frac{FP_1+FP_2}{2}\,\Delta EI + \frac{EI_1+EI_2+BR_1+BR_2}{4}\,\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$$

$$= \frac{-\frac{268{,}542+312{,}327}{2}\,1{,}229{,}738 + \frac{23.922+1{,}253{,}660+237{,}165+142{,}246}{4}\,43{,}785}{(23{,}922+237{,}165)(1{,}253{,}660+142{,}246)}$$

$$= -0.93$$

This represents 115.6% of the total variation. However, the effect driven by the variation of *EI* was counteracted by the corresponding variation between *BR*$_{1860}$ and *BR*$_{1999}$, which is equal to

$$\frac{-\frac{FP_1+FP_2}{2}\,\Delta BR + \frac{EI_1+EI_2+BR_1+BR_2}{4}\,\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$$

$$= \frac{-\frac{268{,}542+312{,}327}{2}\,(-94{,}919) + \frac{23.922+1{,}253{,}660+237{,}165+142{,}246}{4}\,43{,}785}{(23{,}922+237{,}165)(1{,}253{,}660+142{,}246)}$$

$$= 0.13$$

This represents -15.6% of the total decomposed variation. Combining both opposite effects we can explain the whole variation experienced, which is $-0.93 + 0.13 = -0.80$ *Final EROI* points. The result reveals that the decrease in *Final EROI* between 1860 and 1999 was mainly due, as expected (Schroll 1994, Dalgaard *et al*. 2001), to a big

increase in *External Inputs*, coming directly from fossil fuels or indirectly through feed imports for livestock breeding in feedlots, which caused *External Final EROI* to decline significantly—notice that EI_{1999} was 1.6 times larger than the total NPP_{act} in the study area! However, the effect was counteracted to some extent by a parallel reduction in internal flows of *Biomass Reused* and the ensuing increase of *Internal Final EROI*. Had such a counterbalancing effect not taken place, the drop in *Final EROI* would have been even higher. The result 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.

3.4 From past socio-ecological transitions to possible future paths

In this section we have presented a method to relate internal and external returns of agricultural systems, by drawing their energy profiles and yields within a range of possible improvement pathways. It also allows disentangling the respective weights of these internal and external returns in any shift of *Final EROI*. 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 peak oil and climate change (Mulder & Hagens 2008, Hall *et al*. 2009, Hall, 2011, Deng & Tynan 2011, Kessides & Wade 2011, Pracha & Volk 2011, Manno 2011, Arizpe *et al*. 2011, Murphy *et al*. 2011a, Scheidel & Sorman 2012, Giampietro *et al*. 2012, 2013). This decomposition analysis can be used to gain a better understanding of the sociometabolic transitions from past traditional organic farm systems to industrial ones, and to gain useful knowledge for developing more sustainable agricultures in future (Fischer-Kowalski & Haberl 2007, Smil 2010, González de Molina & Toledo 2014).

Gathering more information on *Final EROI*, *IFEROI* and *EFEROI* from a broad variety of farming systems in different world regions and from different time periods would allow plotting them into three-dimensional graphs like our Figures 14 and 15, in order to observe how they cluster or not in some regions of the conic surface and the corresponding isoparametric curves. International and historical comparisons can be performed this way in order to test whether organic and industrialized farm systems have tended to a specific pair of opposite 'attractor situations'. By attractor situations we mean here 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 public policies), and the sociometabolic profile and functioning of agroecosystems, that become more likely than others. Societies can overcome these situations by moving to other energy profiles and performances, but only by changing the underlying set of linkages between agroecological functioning and socioeconomic or political drivers.

The existence of such attractor situations has been suggested by Giampietro (1997). Once industrial agricultural systems start relying in external inputs coming from fossil fuels in search of greater labour and land productivity, they also tend to engage in monocultures and reduce internal reuses. This entails a reduction in agroecosystem complexity that

undermines not only the planned biodiversity in cropland harvests and livestock breeding but the regulatory services provided by the associated biodiversity as well (Altieri 1999). 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 agricultural 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. This sounds very familiar to anyone aware of the challenges and opportunities that agriculture now faces worldwide. Through clustering analysis applied to our decomposition analysis of agricultural energy profiles we can test whether this working hypothesis is true or not.

3.5 Other useful EROIs: returns to labour, and to renewable and non-renewable inputs

The above main EROIs proposed are not the only ones researchers may be interested in, depending on the aims and scope of their own research. There may be others that can be accounted from the same information, or by adding further data. Here we present only some examples, like the energy return to labour, or decomposing the former EROIs into renewable and non-renewable inputs:

$$\text{Final Energy Return On Labour} = \frac{Final\ Produce}{Labour}$$

This measure accounts for energy that a society allocates in the agroecosystem through human labour, compared with the energy content of *Final Produce*. Notice that this ratio can be calculated as an EROI, but also using energy values in the numerator and hours of time devoted to agricultural labour in the denominator. The latter may be very useful for some purposes, such as linking the energy balance with a total time budget analysis (Dazhong & Pimentel 1984, Giampietro *et al.* 1993 and 2010, Pastore *et al.* 1999, Grünbühel & Schandl 2005, Garrabou *et al.* 2010). In traditional organic agroecosystems where labour almost equals *Total Inputs Consumed*, this indicator is virtually equivalent to *External Final EROI.*[23]

The value of this *Final Return On Labour*, as well as its meaning, changes radically during the socio-ecological transition from solar-based to fossil-fuel-based agroecosystems (Fischer-Kowalski & Haberl 2007). The main interest of this indicator is precisely to highlight such historical change. The same applies to another pair of derived indicators:

$$\text{Final External Return on Renewable Inputs} = \frac{Final\ Produce}{Renewable\ External\ Inputs}$$

[23] As explained, this corresponds with the original formulation of the 'Podolinsky principle'.

$$\text{Final External Return on Non Renewable Inputs} = \frac{Final\ Produce}{Non\ Renewable\ External\ Inputs}$$

Very relevant information is given when the denominator is split between external inputs coming from renewable and non-renewable energy sources. Aside from being a strategy to reduce *Agroecosystem Societal Inputs* overall, a shift from non-renewable to renewable *ASI* may be an important component of any future socio-ecological transition toward more sustainable farm systems. The same splitting can be also applied to the *NPP EROI*$_{act}$.

4 Concluding remarks

Our approach to characterize and assess the energy profiles of agroecosystems, aimed at comparing them in past or present times and to foresee other more sustainable in future, can be summarized in three main points. First of all, a single EROI is not enough since a relevant share of energy flows driven by the farm-operators cycles again into the agroecosystem as a loop. Therefore we propose calculating four interrelated EROIs, each of which captures different sides of the agroecosystem functioning: *Final EROI*, *External Final EROI*, *Internal Final EROI* and *NPP*$_{act}$ *EROI*. Secondly, we hypothesize that taken together they can bring into light the missing link between energy performance of agroecosystems and the associated biodiversity they are able to maintain.

Finally, either relying on internal reuses or external inputs any farm system always incur in decreasing energy returns that farmers try to compensate up to a point by substituting one for another. Hence, a decomposition analysis of *Final EROI* into the external and internal returns is useful in order to highlight the contrasting energy profiles adopted by organic or industrial farm systems. The results obtained by applying this energy analysis to the Catalan case study in 1860 and 1999 illustrate how useful this approach can be for a further development of this field of study.

Acknowledgements

This work springs from the international research project on *Sustainable Farm Systems: Long-Term Socio-Ecological Metabolism in Western Agriculture* funded by the Social Sciences and Humanities Research Council of Canada as a Partnership Grant between the universities of Saskatchewan (Canada), Barcelona and Pablo de Olavide in Seville (Spain), Alpen-Adria Klagenfurt in Vienna (Austria), Nacional de Colombia in Bogotá, La Habana (Cuba) and Michigan (United States). Some parts have also been supported by the Spanish research project HAR2012-38920-C02-02 included in this Partnership Grant. The participation of Geoff Cunfer has benefited from a six-month stay as a visiting professor in the Institute of Social Ecology at the Alpen-Adria Klagenfurt University in Vienna in 2011, and other six-months term in the Department of Economic History and Institutions at the University of Barcelona in 2012. Enric Tello has benefited from a six-month stay in 2013 as a visiting professor in the Institute of Social Ecology in Vienna. Elena Galán also benefited from a two month stay in the University of Saskatchewan (EEBB-I-13-06025).

The paper has been developed from the very beginning in a collective manner, incorporating the contributions made by all coauthors from their own perspectives and backgrounds. Besides the coauthors, other researchers inside and outside our SFS project have also contributed pointing out dark aspects or mistakes, and suggesting improvements to be made. We thank all the comments, criticism and encouragements received from Stefania Gallini, Olga Lucia Delgadillo and Katherinne Giselle Mora at the Universidad Nacional de Colombia; David Soto and Juan Infante and at the Universidad Pablo de Olavide in Seville; Roberto Garcia-Ruiz at the University of Jaén, Joan Marull , Ramon Garrabou. Alevgul Sorman and Arnim Schiedel at the Universitat Autònoma de Barcelona; Pere Ariza-Montobbio at FLACSO in Ecuador; José Ramon Olarieta at the Universitat de Lleida; Jordi Roca at the University of Barcelona; Gabriel Jover at the Universitat de Girona; Karl-Heinz Erb, Helmut Haberl and all the participants in a research seminar at the Institute of Social Ecology in the IFF of the Alpen-Adria Klagenfurt University in Vienna. And last but not least, to the comments and encouragement received from Fernando Funes-Monzote, Reynaldo Estrada, Alfredo Jam Massó, Alfredo García Jiménez, Angel Bu Wong and all participants in the seminar held at the Cuban Instituto Nacional de Investigaciones Económicas (INIE) in La Havana in 2014. None of them are responsible for our own shortcomings or mistakes.

Glossary

Actual Net Primary Production (NPP_{act}): See Net Primary Production.

Agroecosystem: A model for agroecological systems that accounts for the biophysical flows linking societal metabolism with ecological functioning taking place in a set of relationships between living and non-living components of a given area.

Associated Biodiversity: The associated biodiversity of a farm system is the ensemble of non-domesticated living organisms found in an agroecosystem. This includes all soil flora and fauna, herbivores, carnivores, decomposers and any other species that exist in agroecosystems. These diverse organisms interact aboveground and belowground with each other in a complex web of biological activity that can either harm or help agriculture, such as pests, diseases, and weeds; pollinators and biological control organisms; and the many organisms controlling nutrient cycling. While planned biodiversity includes crops and livestock purposefully introduced and maintained in an agroecosystem, the associated biodiversity can be either planned or unplanned by the farm operators.

Attractor Situation: In the context of this paper, a set of linkages historically established between socio-economic drivers (e.g. the structure of relative prices of factors and goods of agricultural systems reinforced by the prevailing institutional settings and public policies), and the socio-metabolic functioning of agroecosystems, that became more likely than others.

Livestock-Barnyard Produce (LBP): The biomass obtained from the livestock converter that is part-time kept in grazing areas of farmland and part-time in barnyards or stalls, that is able to be consumed by human population (like meat, milk, wool, hides, etc.). As such, it is included in the *Final Produce* (*FP*) of an agroecosystem. Do not confuse this fraction with the *Livestock-Barnyard Services* (*LBS*) obtained from the livestock converter, as well as the composting dung piles fermented in barnyards or stalls, which are reinvested into the agroecosystem (like draught power or manure).

Livestock-Barnyard Services (LBS): All the energy carriers obtained from the bioconversions made by the livestock as well as the manure pile kept in the barnyard or stall, which are reinvested into the agroecosystem (like draught power or manure). After having accounted as input into the *Biomass Reused* (*BR*) all the feed, fodder or natural grass eaten by this livestock, the *Livestock-Barnyard Services* (*LBS*) cannot be added to the produce without incurring in double counting. Therefore, besides showing them in the balance in order to recall its important role, they must be set aside when accounting EROIs.

Biomass Reused (BR): All energy carriers harvested from the Farmland which are reinvested into the agroecosystem, instead of being diverted towards the *Final Produce* (*FP*) consumed by humans. They include the seeds (when they are not bought outside the system) or green manures going to the *Farmland* (*FBR*), together with the feed and fodder harvested in cropland as well as the grass grazed in pastureland that goes to the **Livestock-Barnyard** subsystem. Some fractions of forest biomass removed from woodlands and scrub can also be reused in **Farmland** (like litter or branches plough under cropland, either fresh or burnt, as *FBR*) or in the **Livestock-Barnyard** converters (like some shrubs used as bedding in stalls). Many internal reuses require keeping an integrated management among diverse uses of the land, which in turn gives way to a greater diversity of habitats in cultural landscapes. Hence, the importance of *Biomass Reused* (*BR*) can be taken as a proxy for the complexity in agroecosystems that, in turn, allows increasing energy efficiency.

Embodied Energy: In Energy Analysis is the sum of all direct and indirect energy carriers required to get a product or service along a whole energy chain, considered as if that energy was incorporated or 'embodied' in the product itself. As an accounting method, it aims at finding the sum of the energy carriers necessary to obtain a product along its entire life-cycle, from a Primary Source to a final use and disposal. Different methodologies differ when determining what constitutes the life-cycle considered for a produce, thus leading to different understandings of the scale and scope of application or the type of energy embodied.

Emergy: An account of all energy used in the work processes along the entire chain of transformations that generate a product or service, expressed in units of one type of energy (generally a primary energy source, like solar energy or Tonnes of Oil Equivalent).

Emergy Analysis: By using emergy values of a product, expressed in solar energy units or any other primary source required to generate it along the energy chain, the emergy accountancy solves the problem of non-equivalence among different energy carriers. Unfortunately, this solution entails that Emergy analysis faces a problem when an energy flow becomes split into several flows or it loops back into the system.

Energy Analysis: Energy Analysis uses enthalpy values of substances to value its energy content, which can be then put together with the energy values of work performed by energy converters, adding up the embodied energy needed to get a product or service along the whole energy chain. This offers a workable way to solve bifurcations and loops along this energy chain, at a price of adopting controversial assumptions about the equivalence of different energy forms and qualities.

Energy Carrier: In the field of Energetics, any substance (energy form) or a phenomenon (work performed by living and non-living converters) that can deliver heat and mechanical work or to operate chemical or physical processes. All energy carriers are flows coming directly or indirectly from a Primary Energy Source (or a mix of them), and either come to a converter or to an end use.

Energy Converter: Any living body or human-made device able to transform a flow of energy carriers into another of different form, quality and quantity. In any process of energy conversion Entropy increases.

Enthalpy: In thermodynamic open systems, is the energy stored within a substance that is available for conversion into heat under some conditions commonly settled as a reference.

Entropy: For a closed thermodynamic system, a measure of the amount of thermal energy not available to do work. It can be understood as the tendency for all energy and matter in the universe to evolve toward a state of inert uniformity.

Energy Return on Investment (EROI): In Energy o Emergy Analysis, is the ratio of the energy (or emergy) carriers delivered by a process to the energy (or emergy) carriers used directly or/and indirectly in that process—depending on the system boundaries and analytical approach adopted.

Exergy: In Thermodynamics, Energetics or Engineering, the portion of the total energy of a system that is available for conversion to useful work. The term is used to designate the maximum work a system can perform on moving from a given state to equilibrium with its surroundings. It can be understood as the inverse of Entropy.

Final Produce (FP): Is a net supply of energy carriers under a suitable form to be consumed by the human population, whether locally or afar. At the same time it is the portion of *Total Produce* not needed to sustain agroecological funds and functions, which remains after redirecting *Biomass Reused* into the agroecosystem—either in the **Livestock-Barnyard** converters or the **Farmland**. One component of *Final Produce* is *Community Subsistence* (*CS*), consumed by the local Community as food, fibre, fuel, and building materials. Another portion may be available as *Surplus Produce* (*SP*) for export to the rest of society, in exchange for the *Agroecosystem Societal Inputs* (*ASI*) received.

Gross Calorific Value (GCV): The amount of heat produced when a substance (a material or fuel) is completely burnt at constant volume, and any water produced is entirely

condensed, in an oxygen bomb calorimeter under specified conditions. It is measured in units of energy per mass of material, typically in MJ/kg.

Human Appropriation of Net Primary Production (HANPP): See Net Primary Production.

Low External Input Technology (LEIT): A strategy of Farm Management that intends to reduce the dependence of inputs coming from outside the agroecosystem by substituting them with internal resources, by-products or other forms of biomass reused.

Metabolizable energy (ME): The net energy value available to an heterotroph organism after the utilization of some endosomatic energy carriers in the processes of digestion and absorption, which entail an energy loss through excreta of the partially undigested or indigestible materials (urine, faeces and gas emission). The metabolizable energy is lower than the gross calorific value, and the difference equals the total excreta. The proportions depend on each animal and its feed intake. For of a certain type of biomass it is also species-specific, and for example it differs greatly between monogastrics and ruminants.

Net Primary Production (NPP): The total energy carriers (or dry weight of phytomass, or the nutrients contained) accumulated through the photosynthesis by an ecological unit of interest, excluding the energy used for the process of respiration by the photosynthesizers. Given that all heterotrophic species live from the NPP, the Human Appropriation of Net Primary Production (*HANPP*) reduces the environmental space for the rest of non-colonized species and beyond a threshold it may endanger them with extinction thus undermining the associated biodiversity of an agroecosystem. HANPP disturbance is two-sided. The change in land covers alters the actual NPP (NPP_{act}) in relation to the potential NPP (NPP_{pot}), and to this land-use change effect ($HANPP_{luc}$) the biomass harvested ($HANPP_{harv}$) to provide human consumption is added.

Opportunity Cost: There is an opportunity cost when getting something means not getting something else—a situation that entails a rivalry among different users so that one's use excludes the rest. It is valued by the next second-best alternative forgone when the first option is chosen by the user.

Primary Energy Source: Any primary source used in an energy system, as considered before being appropriated, extracted or transformed into energy carriers by human society. They always come from the natural energy gradients stored in Earth's resources, and include renewable (solar radiation, biomass, water, geothermal, wind, tidal) as well as non-renewable sources (coal, crude oil, natural gas, uranium). They are never human-made, and as such have no opportunity cost for society—unlike their appropriation, extraction or use. It can be accounted in physical terms to assess the Gross Energy

Requirement (or intensity) of an activity or society relying on them. But PES should never be added to energy carriers when accounting for EROIs in an EA procedure.

Total Produce (TP): In a farm system, it is the total gross amount of *Land Produce* (*LP*) plus the *Livestock-Barnyard Produce* (*LBP*) obtained through livestock bioconversion that takes place part-time into the farmland and part-time in barnyards or stalls. Not to be confused with the total phytomass obtained from the actual Net Primary Production taking place within an agroecosystem (NPP_{act}), from which it constitutes only the fraction appropriated by the farm operators. By subtracting *Biomass Reused* (*BR*) from *Total Produce* we obtain the *Final Produce* (*FP*) able to be consumed to meet human needs.

Total Inputs Consumed (TIC): In a farm system, it is the amount of inputs needed to run an agroecosystem, to keep or renew its basic funds and obtain a given *Final Produce* (*FP*). We distinguish between internal *Biomass Reused* (*BR*) and *External Inputs* (*EI*), and among the latter between human *Labour* (*L*), *Farming Community Inputs* (*FCI*) and the rest of *Societal Inputs* (*SI*) coming from outside the system boundaries.

Unharvested Phytomass (UPH): The fraction of the actual Net Primary Production (NPP_{act}) that remains available for the rest of non-colonized species that constitutes the Associated Biodiversity of an agroecosystem. It can be defined as the result of subtracting *Land Produce* from NPP_{act}. In practice, this is a missing data in all available statistics that needs to be indirectly assessed following the procedures explained in this working paper.

References

Achard, F., Eva, H.D., Stibig, H.-J., Mayaux, Ph., Gallego, J., Richards, T., Malingreau, J.-P. (2002). Determination of Deforestation Rates of the World's Humid Tropical Forests. *Science* 297(5583):999-1002.

Agnoletti, M. ed. (2006). *The Conservation of Cultural Landscapes*. Oxfordshire: CABI Pub.

Agnoletti, M. (2014). Rural landscape, nature conservation and culture: Some notes on research trends and management approaches from a (southern) European perspective. *Landscape and Urban Planning* 126:66–73.

Alodos, C.L., Pueyo, Y., Barrantes, O., Escós, J., Giner, L. and Robles, A.B. (2004). Variations in landscape patterns and vegetation cover between 1957 and 1994 in semiarid Mediterranean ecosystem. *Landscape Ecology* 19:543-559.

Altieri, M. ed. (1989). *Agroecology: the Science of Sustainable Agriculture*. Boulder (Colorado): Westview Press.

Altieri, M. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystem and Environment* 74:19-31.

Altieri, M. and Nicholls, C. (2005). *Agroecology and the Search for a Truly Sustainable Agriculture*. Berkeley & Los Angeles: University of California Press.

Arizpe, N., Giampietro, M. and Ramos-Martin, J. (2011). Food Security and Fossil Fuel Dependence: An International Comparison of the Use of Fossil Energy in Agriculture (1991-2003). *Critical Reviews in Plant Sciences* 30:45-63.

Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E., Harris, A.T. (2004). Grazing Systems, Ecosystem Responses, and Global Change. *Annual Review of Environment and Resources* 29 (1):261-299.

Badia-Miró, M.; Tello, E.; Valls, F. and Garrabou, R. (2010). The Grape Phylloxera Plague as a Natural Experiment: The Upkeep of Vineyards in Catalonia (Spain, 1858-1935). *Australian Economic History Review* 50(1):39-61.

Badia-Miró, M. and Tello, E. (2014). Vine-growing in Catalonia: the main agricultural change underlying the earliest industrialization in Mediterranean Europe (1720–1939). *European Review of Economic History* 18:203–226.

Basnou, C., Álvarez, E., Bagaria, G., Guardiola, M., Isern, R., Vicente, P. and Pino, J. (2013). Spatial Patterns and Land Use Changes Across a Mediterranean Metropolitan Landscape: Implications for Biodiversity Management. *Environmental Management* 52:971-980.

Bayliss-Smith, T.P. (1982). *The Ecology of Agricultural Systems*. Cambridge: Cambridge University Press.

Bengston, J., Angelstam, P., Elmqvist, T. et al. (2003). Reserves, Resilience and Dynamic Landscapes. *Ambio* 32(6):389-396.

Benton, T.G., Vickery, J.A., and Wilson, J.D. 2003. Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology and Evolution* 18:182-188.

Bianchi, F.J.J., Booij, C.J. and Tscharntke, T. (2006). Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society B: Biological Sciences* 273(1595):1715–1727.

Borras Jr., S.M. and Franco, J.C. (2012). Global Land Grabbing and Trajectories of Agrarian Change: A Preliminary Analysis. *Journal of Agrarian Change*: 12(1):34-59.

Boserup, E. (2005). *The Conditions of agricultural growth: the economics of agrarian change under population pressure*. New Brunswick (NJ): Aldine Transaction.

Bradley K., Kallenbach R. and Roberts C.A. (2010). Influence of seeding rate and herbicide treatments on weed control, yield, and quality of spring-seeded glyphosate-resistant alfalfa. *Agronomy Journal* 102:751-758.

Brown, M.T. and Herendeen, R.A. (1996). Embodied energy analysis and EMERGY analysis: a comparative view. *Ecological Economics* 19:219-235.

Brown, M.T. and Ulgiati, S. (1999). Emergy evaluation of natural capital and biosphere services. *Ambio* 28(6):486-493.

Brown, M.T. and Ulgiati, S. (2004). Energy Quality, Emergy and Transformity: H. T. Odum's contribution to quantifying and understanding systems. *Ecological Modelling* 178(1-2):201-213.

Burkett, P. and Foster, J.B. (2006). Metabolism, energy, and entropy in Marx's critique of political economy: Beyond the Podolinsky myth. *Theory and Society* 35:109–156.

Burkett, P. and Foster, J.B. (2008). The Podolinsky Myth: An Obituary. *Historical Materialism* 16:115-161.

Campos, P. and Casado, J.M. (2004). *Cuentas ambientales y actividad económica*. Madrid:Colegio de Economistas.

Cannell, M.G.R. (1982). *World Forest Biomass and Primary Production Data*. London: Academic Press.

Cañellas I. (1991). Ecología y manejo de matorrales de coscoja (*Quercus coccifera L.*) en España. In: *International Union of Forest Resaerch Organizations (IUFRO). World Congress #19*, Montreal (Canada).

Cardinale, B.J., Duffy, J.E., Gonzalez, A. et al. (2012.) Biodiversity loss and its impact on humanity. *Nature* 486:59-67.

Carpintero, O. (2005). *El metabolismo de la economía española: recursos naturales y huella ecológica (1955-2000)*. Lanzarote: Fundación César Manrique.

Carpintero, O. and Naredo, J.M. (2006). Sobre la evolución de los balances energéticos de la agricultura española, 1950-2000. *Historia Agraria* 40:531-554.

Chesson, P. and Huntly, N. (1997). The roles of disturbance, mortality, and stress in the dynamics of ecological communities. *American Naturalist* 150:519-553.

Cevasco, R., & Moreno, D. (2012). The historical roots of biodiversity. In M. Agnoletti (ed.), *Historical rural landscapes. Cultural values for the environment and rural development*. Dordrecht: Springer Verlag.

Connell, J.H. (1978). Diversity in Tropical Rain Forest and Coral Reefs. High diversity of trees and corals is maintained only in a nonequilibrium state. *Science* 199:1302-1309.

Costanza, R., (2013). Energy return on investment (EROI). The Enciclopedia of Earth. . Available on-line at: http://www.eoearth.org/view/article/152557 (accessed 17th of August 2014).

Costanza, R. and Patten, B.C., 1995. Defining and predicting sustainability. Ecological Economics 15:193-196.

Cunfer, G. and Krausmann, F. (2009). Sustaining soil fertility: Agricultural practice in the Old and New Worlds. *Global Environment. Journal of History and Natural and Social Sciences* 4:8-47.

Cussó, X. and Garrabou, R. (2001). Alimentació i nutrició al Vallès Oriental en les darreres dècades del segle XIX. *Lauro* 21:26-34.

Cussó, X., Garrabou, R. and Tello, E. (2006a). Social metabolism in an agrarian region of Catalonia (Spain) in 1860-70: flows, energy balance and land use. *Ecological Economics* 58:49-65.

Cussó, X., Garrabou, R., Olarieta, J.R. and Tello, E. (2006b). Balances energéticos y usos del suelo en la agricultura catalana: una comparación entre mediados del siglo XIX y finales del siglo XX. *Historia Agraria* 40:471-500.

Dalgaard, T., Halberg, N. and Porter, J.R., (2001). A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agriculture, Ecosystem & Environment 87:51-65.

Davis, D.R. (2009). Declining fruit and vegetable nutrient composition: What is the evidence?" *HortScience* 3(1):15–19.

Dazhong, W. and Pimentel D. (1984). Energy flow through an organic agroecosystem in China. *Agriculture, Ecosystems & Environment* 11(2):145-160.

Deng, S. and Tynan, G.R. (2011). Implications of Energy Return on Energy Invested on Future Total Energy Demand. *Sustainability* 3:2433-2442.

Dial. R. and Roughgarden, J. (1998). Theory of marine communities: the intermediate disturbance hypothesis. *Ecology* 79:1412-1424.

Drinkwater, L.E., Chipanski, M., Snapp, S. and Jackson, L.E. (2008). Ecologically Based Nutrient Management. In Snapp, S. and Pound, B. (eds.), *Agricultural Systems: Agroecology and Rural Innovation for Development*. Amsterdam: Elsevier, pp. 161-210.

Edelman, M., Oya, C. and Borras Jr, S.M. (2013). Global Land Grabs: historical processes, theoretical and methodological implications and current trajectories. *Third World Quarterly* 34(9):1517-1531.

Edwards, C.A., Grove, R.R., Harwood, C.J. and Colfer, P. (1993). The role of agroecology and integrated farming systems in agricultural sustainability. *Agriculture, Ecosystems & Environment* 46(1-4):99-121.

EEA 2006. *Land accounts for Europe 1990-2000. Towards integrated land and ecosystem accounting*. European Environmental Agency Report Number 11/2006. Luxembourg: Office for Official Publications of the European Communities.

Erb, K.H. (2012). How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity. *Ecological Economics* 76:8-14.

Esser, G.; Lieth, H.; Scurlock, J.M.O. and Olson, R.J. (1997). *Worldwide Estimates And Bibliography of Net Primary Productivity derived from Pre-1982 Publications*. Oak Ridge (TN): ORNL Distributed active Archive Center and Environmental Science Division.

Fahrig, L., and Jonsen, I. (1998). Effect of habitat patch characteristics on abundance and diversity of insects in an agricultural landscape. *Ecosystems* 1(2):197-205.

Fan, M-S., Zhao, F-J., Fairweather-Tait, S.J., Poulton, P.R., Dunham, S.J. and McGrath, S.P. (2008). Evidence of Decreasing Mineral Density in Wheat Grain over the Last 160 Years. *Journal of trace elements in medicine and biology: organ of the Society for Minerals and Trace Elements (GMS)* 22(4):315–324.

Farina, A. (2000). The Cultural Landscape as a Model for the Integration of Ecology and Economics. *BioScience* 50(4):313-320.

Feranec, J., Jaffrain, G., Soukup, T., and Hazeu, G. (2010). Determining changes and flows in European landscapes 1990e2000 using CORINE land cover data. *Applied Geography* 30:19-35.

Fischer, J., Brosi, B., Daily, G. C., Ehrlich, P. R., Goldman, R., Goldstein, J., Lindenmayer, D. B., Manning, A. D., Mooney, H. A., Pejchar, L., Ranganathan, J. and Tallis, H. (2008a). Should agricultural policies encourage land sparing or wildlife-friendly farming? *Frontiers in Ecology and the Environment* 6(7):380–385.

Fischer, M., Rudmann-Maurer, K., Weyand, A. and Stöcklin, J. (2008b). Agricultural Land Use and Biodiversity in the Alps. *Mountain Research and Development* 28(2):148–155.

Fischer-Kowalski, M. and Haberl. H. eds. (2007). *Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use*. Cheltenham: Edward Elgar.

Fluck, R.C. and Baird C.D. (1980). *Agricultural Energetics*. Wesport CT (USA): Avi Pub. Co.

Fluck, R.C. (1981). Net Energy Sequestered in Agricultural Labor. *Transactions of the American Society of Agricultural Engineers* 24(6):1449-1455.

Fluck, R.C. (1992). Energy of Human Labor. In: Fluck, R.C. (eds.), *Energy in Farm Production*. Amsterdam: Elsevier, pp. 31-37.

Galán, E., (2015). *Socio-Ecological Transition of organic agricultures in Catalonia (late 19th-20th century)*. PhD Thesis Dissertation at the Faculty of Economics and Business of the University of Barcelona.

Galán, E., Tello, E., Cunfer, G., Guzmán, G.I., González de Molina, M., Krausmann, F., S. Gingrich, S., Sacristán, V., Moreno-Delgado, D., Marco, I. and Padró, R. (forthcoming). The Energy Return On Investment (EROI) in agroecosystems: An analytical proposal to study socioecological transitions to industrialized farm systems (The Vallès County, Catalonia, in 1860 and 1999).

Garcia-Ruiz, R., González de Molina, M., Guzmán-Casado, G., Soto, D., Infante-Amate, J. 2012. Guidelines for Constructing Nitrogen, Phosphorus, and Potassium Balances in Historical Agricultural Systems. *Journal of Sustainable Agriculture* 36(6): 650–682.

Garrabou, R., Cussó, X. and Tello, E. (2007). La persistència del conreu dels cereals a la província de Barcelona a mitjan segle XIX. *Estudis d'Història Agrària* 20:163-219.

Garrabou, R., Tello, E. and Cussó, X. (2008a). El cambio en los usos del suelo en la comarca catalana del Vallès (1850-2000): fuerzas motoras y agentes rectores en la transformación del territorio. In Garrabou, R. and Naredo, J.M. (eds.), *El paisaje en perspectiva histórica. Formación y transformación del paisaje en el mundo mediterráneo*. Zaragoza, Prensas Universitarias de Zaragoza/SEHA, pp. 233-258.

Garrabou, R., Tello, E. and Cussó, X. (2008b). L'especialització vitícola catalana i la formació del mercat blader espanyol: una nova interpretació apartir del cas de la província de Barcelona. *Recerques. Història, Economia, Cultura* 57:91-136.

Garrabou, R.; Tello, E.; Cussó, X., and Badia-Miró, M. (2009). Explaining agrarian specialization in an advanced organic economy: The province of Barcelona in mid-nineteenth century. In Pinilla, V. (ed.), *Markets and Agricultural Change in Europe from the Thirteenth to the Twentieth Century*. Brepols, Turnhout, pp. 137-171.

Garrabou, R. and González de Molina, M. eds. (2010). *La reposición de la fertilidad en los sistemas agrarios tradicionales*. Barcelona: Icaria.

Garrabou, R.; Tello, E. and Cussó, X. (2010). Ecological and Socio-economic functioning of the Mediterranean agrarian systems in the middle of the nineteenth century. A Catalan case study (the Vallès county, 1850-70). In Landsteiner, E. and Langthaler, E. (eds.), *Agrosystems and Labour Relations in European Rural Societies (Middle Ages-20th Century)*. Turnhout: Brepols Pubishing, pp. 119-152.

Generalitat de Catalunya (1998). Dades bàsiques de l'agricultura, la ramaderia i la pesca a Catalunya. Barcelona, Generalitat de Catalunya.

Georgescu-Roegen, N. (1971). *The Entropy law and the economic process*, Harvard (Mass): Harvard University Press.

Gerard, F., Petit, S., Smith, G., Thomson, A., Brown, N., Manchester, S., *et al*. (2010). Land cover change in Europe between 1950 and 2000 determined employing aerial photography. *Progress in Physical Geography* 34:183-205.

Geri, F., Amici, V., and Rocchini, D. (2010). Human activity impact on the heterogeneity of a Mediterranean landscape. *Applied Geography* 30:370-379.

Giampietro, M. (1997). Socioeconomic constraints to farming with biodiversity. *Agriculture, Ecosystems & Environment* 62(2-3):145-167.

Giampietro, M. (2004). *Multi-Scale Integrated Analysis of Agroecosystems*. Boca Raton: CRC Press.

Giampietro, M. (2006). Comments on 'The Energetic Metabolism of the European Union and the United States' by Haberl and Colleagues: theoretical and practical considerations on the meaning and usefulness of traditional energy analysis. *Journal of Industrial Ecology* 10(4):173-185.

Giampietro, M. and Pimentel, D. (1990). Assessment of energetic of human labour. *Agriculture, Ecosystems & Environment* 32(3-4):257-272.

Giampietro, M. and Pimentel, D. (1991). Energy Efficiency: assessing the interaction between humans and their environment. *Ecological Economics* 4(2):117-144.

Giampietro, M., Cerretelli, G. and Pimentel, D. (1992a). Assessment of Different Agricultural Production Practices. *Ambio* 21(7):451-459.

Giampietro, M., Cerretelli, G. and Pimentel, D. (1992b). Energy analysis of agricultural ecosystem management: human return and sustainability. *Agriculture, Ecosystems & Environment* 38(3):219-244.

Giampietro, M.; Bukkens, S.G.F. and Pimentel, D. (1993). Labour productivity: A Biophisical Definition and Assessment. *Human Ecology* 21(3):229-260.

Giampietro, M., Bukkens, S.G.F. and Pimentel, D. (1994). Models of Energy Analysis to Assess the Performance of Food Systems. *Agricultural Systems* 45(1):19-41.

Giampietro, M. and Mayumi, K. (1997). A dynamic model of socioeconomic systems based on hierarchy theory and its application to sustainability. *Structural Change and Economic Dynamics* 8(4):453-469.

Giampietro, M. and Mayumi, K. (2000). Multi-Scale Integrated Assessments of Societal Metabolism: Introducing the Approach. *Population and Environment* 22(2):109-153.

Giampietro, M., Mayumi, K. and Munda, G. (2006). Integrated assessment and energy analysis: Quality assurance in multi-criteria analysis of sustainability. *Energy* 31(1):59-86.

Giampietro, M., Mayumi, K. and Ramos-Martín, J. (2009). Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. *Energy* 34(3):313-322.

Giampietro, M., Mayumi, K. and Sorman, A.H. (2010). *Assessing the quality of alternative energy sources: Energy Return On the Investment (EROI), the Metabolic Pattern of Societies and Energy Statistics*, Working Paper on Environmental Sciences, ICTA-UAB, Bellaterra (Barcelona). Available on-line at: http://www.recercat.cat//handle/2072/47934 (accessed 17th of August 2014).

Giampietro, M., Mayumi, K. and Sorman, A.H. (2012). *The Metabolic Pattern of Societies: where economists fall short*. London: Routledge.

Giampietro, M., Mayumi, K. and Sorman, A.H. (2013). *Energy Analysis for Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism*. London: Routledge.

Gliessman, S.R. (Ed.) (1998). *Agroecology. Ecological Processes in Sustainable Agriculture*. Boca Raton (FL): Lewis Publishers/CRC Press.

Gobierno de Navarra (2012). *Tipificación, valoración y cartografía 1:25.000 de los recursos pastables de Navarra*. . Available on-line at:: http://www.navarra.es/home_es/Temas/Ambito+rural/Agricultura/Producciones/Pastos/Introduccion/ (accessed 17th of August 2014).

Godfray, H.C.J., Beddington, J.R., Crute, I.R. et al. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science* 327:812-818.

González de Molina, M. and Guzmán Casado, G. (2006). *Tras los pasos de la sustentabilidad. Agricultura y Medio ambiente en perspectiva histórica (siglos XVIII-XX)*. Icaria, Barcelona.

González de Molina, M., García-Ruiz, R., Guzmán-Casado, G., Soto-Fernández, D. and Infante-Amate, J. (2010). *Guideline for constructing nutrient balance in historical agricultural systems. (And Its Application to Three Case-Studies In Southern Spain*), Working Paper of the Spanish Society for Agricultural History DT-SEHA n. 10-08. Available on-line at: http://ideas.repec.org/p/seh/wpaper/1008.html (accessed 17th of August 2014).

González de Molina, M. and Toledo V.M. (2014). *The Social Metabolism. A Socio-Ecological Theory of Historical Change.* Dordrecht: Springer Verlag.

González de Molina, M., Soto, D., Aguilera, E. and Infante, J. (2014). Crecimiento agrario en España y cambios en la oferta alimentaria, 1900-1933. *Historia Social* 80(3): 157-183.

Gracia C., Burriel, J.A., Ibàñez, J.J., Mata, T. and Vayreda, J. (2000-2004). *Inventari Ecològic i Forestal de Catalunya. Obra completa*. Bellaterra: CREAF, Universitat Autònoma de Barcelona.

Grove, A.T. and Rackham, O. (2001). *The Nature of Mediterranean Europe: An ecological history*. New Haven: Yale University Press.

Grünbühel, C.M. and Schandl, H. (2005). Using land-time budgets to analyse farming systems and poverty alleviation policies in the Lao PDR. *International Journal of Global Environmental Issues* 5(3/4):142-180.

Guirado, M., Pino, J., and Rodà, F. (2006). Under storey plant species richness and composition in metropolitan forest archipelagos: effects of forest size, adjacent land use and distance to the edge. *Global Ecology and Biogeography* 15:50-62.

Gustavsson, E., Lennartsson, T. and Emanuelsson, M. (2007). Land use more than 200 years ago explains current grassland plant diversity in a Swedish agricultural landscape. *Biological Conservation* 138(1):47-59.

Guzmán-Casado, G.I. and González de Molina, M. (2006). Sobre las posibilidades del crecimiento agrario en los siglos XVIII, XIX y XX. Un estudio de caso desde la perspectiva energética. *Historia Agraria* 40:437-470.

Guzmán, G.I and, Alonso, A.M. (2008). *Buenas prácticas en producción ecológica. Uso de Abonos verdes*. Madrid: Ministerio de Medio Ambiente y Medio Rural y Marino.

Guzmán-Casado, G.I. and González de Molina, M. (2009). Preindustrial agriculture versus organic agriculture: The land cost of sustainability. *Land Use Policy* 26(2):502-510.

Guzmán, G.I., González de Molina, M. and Alonso, A.M. (2011). The land cost of agrarian sustainability. An assessment. *Land Use Policy* 28(4):825-835.

Guzmán, G.I., Aguilera, E., Soto, D., Cid, A.; Infante, J., García-Ruiz, R., Herrera, A., Villa, I. and González de Molina, M. (2014). Methodology and conversion factors to estimate the Net Primary Productivity of historical and contemporary agroecosystems. *Working Paper of the Spanish Society for Agricultural History* DT-SEHA no. 1407. Available on-line at: http://ideas.repec.org/p/seh/wpaper/1407.html (accessed 17th of August 2014).

Guzmán, G.I. and González de Molina, M. (2015, in press). Energy efficiency in agrarian systems from an agro-ecological perspective. *Agroecology and Sustainable Food Systems*.

Haberl, H. (2001a). The Energetic Metabolism of Societies. I: Accounting Concepts. *Journal of Industrial Ecology* 5:11-33.

Haberl H. (2001b). The Energetic Metabolism of Societies. II: Empirical Examples. *Journal of Industrial Ecology* 5:53-70.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H. and Winiwarter, V. (2004). Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy* 21:199-213.

Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W. and Fischer-Kowalski, M. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* 104(31):12942-12947.

Hall, C.A.S., Cleveland, C. J.and Kaufmann, R. (1986). *Energy and resource quality: the ecology of the economic process.* New York: Wiley.

Hall, C.A.S., Balogh, S. and Murphy, D.J.R. (2009). What is the Minimum EROI that a Sustainable Society Must Have? *Energies* 2:25-47.

Hall, C.A.S. (2011). Synthesis to Special Issue on New Studies in EROI (Energy Return on Investment). *Sustainability* 3:2496-2499.

Hall, C.A.S. and Klitgaard, K. (2012). *Energy and the Wealth of Nations. Understanding the Biophysical Economy*. Dordrecht: Springer Verlag.

Harper, K. A., MacDonald, S. E., Burton, P. J., Chen, J., Brosofsfe, K. D., Saunders, S. C., et al. (2005). Edge influence on Forest structure and composition in fragmented landscapes. *Conservation Biology* 19:768-782.

Herendeen, R.A. (2004). Energy analysis and EMERGY analysis—a comparison, *Ecological Modeling* 178(1-2):227-237.

Ho, M.-W. (1998). *The Rainbow and the Worm. The Physics of Organisms*. Singapore: World Scientific.

Ho, M.-W. (2013). Circular Thermodynamics of Organisms and Sustainable Systems. *Systems* 1:30-49.

Ho, M.-W. and Ulanowicz, R.U. (2005). Sustainable systems as organisms? *BioSystems* 82:39-51.

Holling, C.S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics* 4:1–23.

Infante, J., González de Molina, M., Vanwalleghem, T., Soto, D. and Alfonso, J. (2013). Erosion in the Mediterranean: The Case of Olive Groves in the South of Spain (1752–2000). *Environmental History* 18(2):360-382.

Jones, M.R. (1989). Analysis of the use of energy in agriculture—Approaches and problems*. Agricultural Systems* 29(4): 339–355.

Kessides, I.N. and Wade, D.C. (2011). Deriving an Improved Dynamic EROI to Provide Better Information for Energy Planners. *Sustainability* 3:2339-2357.

Krausmann, F. (2004). Milk, Manure, and Muscle Power. Livestock and the Transformation of Preindustrial Agriculture in Central Europe. *Human Ecology* 32(6):735-772.

Krausmann, F. (2006). Una perspectiva biofísica del cambio agrícola en Austria: dos sistemas agrarios en las décadas de 1830 y 1990, *Historia Agraria* 40:501-530.

Krausmann, F., Schandl, H. and Sieferle, R.P. (2008). Socioecological regime transition in Austria and United Kingdom. *Ecological Economics* 65(1):187-201.

Krausmann, F., Gingrich, S., Haberl, H., Erb, K.H., Musel, A., Kastner, T., Kohleb, N., Niedertscheider, M. and Schwarzlmüller, E. (2012). Long-term trajectories of the human appropriation of net primary production. Lessons from six national case studies. *Ecological Economics* 77:129-138.

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C. and Searchinger, T. (2013). Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences of the United States of America* 110:10324-10329.

Krausmann, F.; Erb, K.-H.; Gingrich, S.; Lauk, C. and Haberl, H. (2008). Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics* 65(3):471-487.

Lambin, E. F., & Geist, H. (2006). *Land-use and land-cover change: Local processes and global impacts*. Dordrecht: Springer Verlag.

Laurance, W.F. (1999). Reflections on the tropical deforestation crisis. *Biological Conservation* 91(2–3):109–117.

Leach, G. (1976). *Energy and Food Production*. Guildford: IPC Science and Technology Press.

Lloret, F., Calvo, E., Pons, X., Díaz-Delgado, R. (2002). Wildfires and landscape patterns in the eastern Iberian Peninsula. *Landscape Ecology* 17:745-759.

Luyssaert, S., Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., Papale, D.,, Piao, S.L., Schulze, E.D., Wingate, L., *et al*. (2007). CO_2 balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology* 13(12):2509-2537.

Mabit, L., Chhem-Kieth, S., Toloza, A., Vanwalleghem, T., Bernard, C., Infante, J., González de Molina, M. and Gómez, J.A. (2012). Radioisotopic and physicochemical background indicators to assess soil degradation affecting olive orchards in southern Spain. *Agriculture, Ecosystems & Environment* 159:70–80

MacDonald, D., Crabtree, J. R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., *et al*. (2000). Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. *Journal of Environmental Management* 59: 47-69.

Manno, J.P. (2011). Looking for Silver Lining: The Possible Positives of Declining Energy Return on Investment (EROI). *Sustainability* 3:2071-2079.

Marco, I., Padró, R., Galán, E., Tello, E., Olarieta, J.R., Garrabou, R, (forthcoming). A proposal for a workable analysis of Energy Return On Investment (EROI) in agroecosystems. Part II: Accounting for an empirical example (The Vallès County, Catalonia, 1860-1999). Social Ecology Working Paper, Social Ecology Institute, Vienna.

Margalef, R. (2006). Ecological Theory and Prediction in the Study of the Interaction between Man and the Rest of Biosphere. In Siolo, H. (ed.), *Ökologie und Lebensschutz in Intrenationaler Sicht*. Freiburg: Rombach, 1973; reprinted in English in *Medi Ambient. Tecnologia i Cultura* 38:114-25. Available on-line at: http://mediambient.gencat.net/cat/el_departament/revista/38/sumario_ingles.jsp (accessed 17th of August 2014).

Martínez Alier, J. and Naredo, J.M. (1982). A Marxist Precursor of Ecological Economics: Podolinsky. *Journal Peasant Stududies* 9(2):207-224.

Martinez-Alier, J. and Schlüpmann, K. (1990). *Ecological economics: energy, environment and society*. Oxford: Basil Blackwell.

Martínez Alier, J. ed. (1995). *Los principios de la economía ecológica. Textos de P. Geddes, S.A. Podolinsky y F. Soddy.* Madrid: Fundación Argentaria/Visor.

Martínez Alier, J. (2011). The EROI of agriculture and its use by the Via Campesina. *The Journal of Peasant Studies* 38(1):145-160.

Marull, J., and Mallarach, J. M. (2005). A new GIS methodology for assessing and predicting landscape and ecological connectivity: applications to the Metropolitan Area of Barcelona (Catalonia, Spain). *Landscape and Urban Planning* 71:243-262.

Marull, J., Pino, J. and Tello, E. (2008). The Loss of Landscape Efficiency: An Ecological Analysis of Land-Use Changes in Western Mediterranean Agriculture (Vallès County, Catalonia, 1853-2004). *Global Environment. Journal of History and Natural and Social Sciences* 2:112-150.

Marull, J., Pino, J., Tello, E. and Cordobilla, M.J. (2010). Social metabolism, landscape change and land-use planning in the Barcelona Metropolitan Region. *Land Use Policy* 27(2):497-510.

Marull, J., Tello, E., Wilcox, P.Th., Coll, F., Warde, P., Valldeperas, N. and Ollés, A. (2014). Recovering the land-use history behind a Mediterranean edge environment: The importance of agroforestry systems in biological conservation. *Applied Geography* 54:1-17.

Marull, J., Font, C., Tello, E., Fullana, N., Domene, E., Pons, M. and Galán, E. (forthcoming a). Towards an Energy–Landscape Integrated Analysis? Exploring the links between socio-metabolic disturbance and landscape ecology performance (Mallorca Island, Spain, 1956-2011). *Landscape Ecology* (under revision).

Marull, J., Tello, E., Fullana, N., Murray, I., Jover, G., Font, C., Coll, F., Domene, E., Decoli, T. and Leoni, V. (forthcoming b). Long-term socio-ecological transition at different spatial scales: Exploring the Intermediate Disturbance Hypothesis in cultural landscapes (Mallorca, 1856-2012). *Biodiversity and Conservation* (submitted).

Marull, J., Font, C., Padró, R., Tello, E., Panazzolo, A. (forthcoming c). Energy-Landscape Integrated Analysis: A proposal for measuring complexity in internal agro-ecosystem processes (Barcelona Metropolitan Area, 1860-2000). *Global Environmental Change* (submitted).

Matson, P.A., Parton, W.J., Power, A.G. and Swift, M.J., (1997). Agricultural Intensification and Ecosystem Properties. *Science* 277(5325):504-509.

Mayumi, K. (1991). Temporary emancipation from land: from the industrial revolution to the present time. *Ecological Economics* 4:35-56.

McDonnell, M.J. and Pickett, S.T.A. (1993). *Human as Components of Ecosystems: The Ecology of Subtle Human Effects and Populated Areas* Dordrecht: Springer Verlag.

Moreira, F., & Russo, D. (2007). Modeling the impact of agricultural abandonment and wildfires on vertebrate diversity in Mediterranean Europe. *Landscape Ecology* 22:1461–1476.

Morowitz, H. J. (2002). *The Emergence of Everything: How the world became complex*. Oxford: Oxford University Press.

Mulder, K. and Hagens, N.J. (2008). Energy Return on Investment: Toward a Consistent Framework. *Ambio* 37(2):74-79.

Murcia, C. (1995). Edge effects in fragmented forests: implications for conservation. *Trends in Ecology and Evolution* 10:58-62.

Murphy, D.J., Hall, C.A.S. and Powers, B. (2011a). New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. *Environment, Development and Sustainability* 13(1):179-202.

Murphy, D.J., Hall, C.A.S., Dale, M. and Cleveland, C. (2011b). Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels. *Sustainabilty* 3:1888-1907.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature* 403:853-858.

Naredo, J.M. (2004). *La evolución de la agricultura en España (1940-2000)*, Universidad de Granada, Granada.

Naredo, J.M. and Campos, P. (1980). Los balances energéticos de la agricultura española. *Agricultura y Sociedad* 15:163-256.

Niedertscheider, M., Gingrich, S. and Erb, K.-H. (2012). Changes in land use in South Africa between 1961 and 2006: an integrated socio-ecological analysis based on the human appropriation of net primary production framework. *Regional Environmental Change* 12(4):715-727.

Norum, L. (1983). Problem Formulation in Energy Analysis. *Energy in Agriculture* 2:1-10.

Odum, E.P. (1993). *Ecology and our Endangered Life-Support Systems*. Sunderland (Massachusetts): Sinauer Associates.

Odum, H.T. (1984). Energy Analysis of the Environmental Role in Agriculture. In Stanhill, E. ed., *Energy and Agriculture*, Dordrecht: Springer Verlag, pp. 24-51.

Odum, H.T. (2007). *Environment, power, and society for the twenty-first century. The Hierarchy of Energy*. New York: Columbia University Press.

Oerke, E.-C. (2006). Crop losses to pests. *The Journal of Agricultural Science* 144(1):31-43.

Oerke E.C., Dehne H.W., Schönbeck F. and Weber A. (1994). *Crop production and crop protection. Estimated losses in major food and cash crops*. Amsterdam: Elsevier.

Olarieta.J., Padrò, R., Masip, G., Rodríguez-Ochoa, R. and Tello, E. (2011). 'Formiguers', a historical system of soil fertilization (and biochar production?). *Agriculture, Ecosystems and Environment* 140(1-2):27-33.

Oldeman, L.R., Hakkeling, R.T.A. and Sombroek, W.G. (1991). World Map of the Status of Human-Induced Soil Degradation (2nd revised edition). Wageningen: ISRIC and Nairobi UNEP.

Olea, L. (2010). Producción y mejora de pastos y cereales forrajeros. In: *Jornada sobre ciencia y empresa de la Dehesa*. Plasencia.

O'Neill, D.W., Tyedmers, P.H. and Beazley, K.F. (2007). Human appropriation of net primary production (HANPP) in Nova Scotia, Canada. *Regional Environmental Change* 7(1):1-14.

ORNL (2002): *NPP Datasets*. Oak Ridge National Laboratory. Available on-line at: http://www.daac.ornl.gov.

Otero, I., Boada, M. and Tàbara, J. D. (2013). Social-ecological heritage and the conservation of Mediterranean landscapes under global change. A case study in Olzinelles (Catalonia). *Land Use Policy* 30:25-37.

Oya, C. (2013). Methodological reflections on 'land grab' databases and the 'land grab' literature 'rush'. *The Journal of Peasant Studies* 40(3):503–520.

Padisak, J. (1993). The influence of different disturbance frequencies on the species richness, diversity and equitability of phytoplankton in shallow lakes. *Hydrobiologia* 249:135-156.

Parcerisas, L., Marull, J., Pino, J., Tello, E., Coll, F. and Basnou, C. (2012). Land use changes, landscape ecology and their socioeconomic driving forces in the Spanish Mediterranean coast (El Maresme County, 1850–2005). *Environmental Science & Policy* 23:120-132.

Pastore, G., Giampetro, M. and Li, J. (1999). Conventional and Land-Time Budget Analysis of Rural Villages in Hubei Province, China. *Critical Reviews in Plant Sciences* 18(3):331-358.

Pelletier, N., Audsley, E., Brodt, S., Garnett,T., Henriksson, P., Kendall, A., Kramer, K., Murphy, D., Nemecek, T. and Troell, M. (2011). Energy Intensity of Agriculture and Food Systems. *Annual Review of Environment and Resources* 36:223-246.

Peñuelas, J., Filella, I. and Comas, P. (2002). Changed plant and animal life cycles from 1952 to 2000 in the Mediterranean region. *Global Change Biology* 8:531-544.

Perfecto, I and Vandermeer, J. (2010). The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proceedings of the Natural Acadademy of Sciences USA* 107(13):5786-5791.

Pickett, S.T.A., and White, P.S. (1985). *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, London.

Pierce, S. (2014). Implications for biodiversity conservation of the lack of consensus regarding the humped-back model of species richness and biomass production. *Functional Ecology* 28:253-257.

Pimentel, D. and Pimentel, M. (1979). *Food, Energy, and Society*, Edward Arnold, London.

Pino, J., Rodà, F., Ribas, J., and Pons, X. (2000). Landscape structure and bird species richness: implications for conservation in rural areas between natural parks. *Landscape and Urban Planning* 49:35-48.

Pino, J., and Marull, J. (2012). Ecological networks: are they enough for connectivity conservation? A case study in the Barcelona Metropolitan Region (NE Spain). *Land Use Policy* 29:684-690.

Planas, J.and Valls-Junyent, F. (2012). Desigualdad, asociacionismo y conflictividad social en un núcleo de la Cataluña rabassaire. *Historia Social* 72:89-111.

Podolinsky, S. ([1883]2008). Human labour and the unity of force. *Historical Materialism* 16:163-183.

Pracha, A.S. and Volk, T.A. (2011). An Edible Energy Return on Investment (EEROI) Analysis of Wheat and Rice in Pakistan. *Sustainability* 3:2358-2391.

Prigogine. I. and Stengers, I. (1984). *Order out of Chaos: Man's New Dialogue with Nature*. New York: Bantam.

Reier, U., Tuvi, E.-L., Meelis, P., Kalamees, R., and Zobel, M. (2005). Threatened herbaceous species dependent on moderate forest disturbances: a neglected target for ecosystem-based silviculture. *Scandinavian Journal of Forest Research* 20:145-152.

Reynolds, C.S. (1995). The intermediate disturbance hypothesis and its applicability to planktonic communities. Comments on the views expressed in Padisak—vs.—Wilson*. New Zealand Journal of Ecology* 19:219–225.

Revelle, R. (1976). Energy use in rural India. *Science* 192(4243):969-975.

Rössler, M. (2006). World heritage cultural landscapes: a UNESCO flagship programme 1992-2006. *Landscape Research* 31:333-353.

Ruiz-Pérez, M. (1990). Development of Mediterranean agriculture: an ecological approach. *Landscape and Urban Planning* 18(3-4):211-219.

Sala, O.E:, Chapin, F.S.III, Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzing, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Wall, D.H. (2000). Global biodiversity scenarios for the year 2100. *Science* 287:1770-1774.

Santos, K., Pino, J., Rodà, F., Guirado, M. and Ribas, J. (2008). Beyond the reserves: the role of non-protected rural areas for avifauna conservation in the area of Barcelona (NE of Spain). *Landscape and Urban Planning* 84:140-151.

Saugier, B., Roy, J. and Mooney, H.A. (2001). Estimations of Global Terrestrial Productivity: Converging toward a Single Number? In Roy, J., Saugier, B. and Mooney, H.A. (eds.), *Terrestrial Global Productivity*. San Diego: Academic Press, pp. 543-557.

Scheidel, A. and Sorman, A.H. (2012). Energy transitions and the global land rush: Ultimate drivers and persistent consequences. *Global Environmental Change* 22(3): 588–595.

Scheidel, A., Giampietro, M. and Ramos-Martin, J. (2013). Self-sufficiency or surplus: Conflicting local and national rural development goals in Cambodia. *Land Use Policy* 34:342-35.

Schroll, H. (1994). Energy-flow and ecological sustainability in Danish agriculture, *Agriculture, Ecosystems &. Environment* 51:301-310.

Schröter, D., Cramer, W., Leemans, R., Prentice, I. C., Araujo, M. B., Arnell, N.W., *et al*. (2005). Ecosystem service supply and vulnerability to global change in Europe. *Science* 310:1333-1337.

Scurlock, J.M.O. and Olson, R.J. (2002). Terrestrial net primary productivity—A brief history and a new worldwide database. *Environmental Review* 10(2):91-109.

Sehaffer, C.C., Martinson, K.M., Wyse, D.L. and Moncada, K.M. (2014). Companion crops for organic alfalfa establishment. *Agronomy journal* 106:309-314.

Serra, P., Pons, X., and Saurí, D. (2008). Land-cover and land-use change in a Mediterranean landscape: a spatial analysis of driving forces integrating biophysical and human factors. *Applied Geography* 28:189-209.

Sinclair, T.R. (1998). Historical changes in harvest index and crop nitrogen accumulation. *Crop Science* 38(3):638–643.

Sitch, S., Smith, B., Prentice, I.C., Arneth A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K. and Venevsky, S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* 9: 161-185.

Skapetas, B., Nitas, D., Karalazos, A. and Hatziminaoglou, I. (2004). A study on the herbage mass production and quality for organic grazing sheep in a mountain pasture of northern Greece. *Livestock Production Science* 87(2–3):277–281.

Smil, V. (2001). *Enriching the Earth: Fritz Haber, Carl Bosch and the transformation of world food production.* Cambridge (Ma): The MIT Press.

Smil, V. (2010). *Energy transitions: history, requirements, prospects*. Santa Barbara (Cal): Praeger.

Smil, V. (2013). *Harvesting the Biosphere: How Much We Have Taken from Nature*. Cambridge (Ma): The MIT Press.

Snapp, S. and Pound, B. eds. (2008). *Agricultural Systems: Agroecology and Rural Innovation for Development*. Amsterdam: Elsevier.

Sorman, A.H. and Giampietro, M. (2011). Generating better energy indicators: Addressing the existence of multiple scales and multiple dimensions. *Ecological Modelling* 223:41-53.

Stanhill, E. (1984). Agricultural Labour: From Energy Source to Sink. In Stanhill, E. (Ed.), *Energy and Agriculture*. Dordrecht: Springer Verlag, pp. 113-130.

Stefanescu, C., Peñuelas, J., and Filella, I. (2005). Butterflies highlight the conservation value of hay meadows highly threatened by land-use changes in a protected Mediterranean area. *Biological Conservation* 126:234-246.

Stoate, C., Boatman, N. D., Borralho, R. J., Rio Carvalho, C., de Snoo, G. R., and Eden, P. (2001). Ecological impacts of arable intensification in Europe. *Journal of Environmental Management* 63:337-365.

Sunyer, P. (1996): *La configuración de la ciencia del suelo en España (1750-1950)*. Madrid: Ministerio de Agricultura Pesca y Alimentación/Ediciones Doce Calles.

Tainter, J.A. (1988). *The Collapse of Complex Societies. New Studies in Archaeology*. Cambridge (UK): Cambridge University Press.

Tello, E., Garrabou, R. and Cussó, X. (2006). Energy Balance and Land Use: The Making of and Agrarian Landscape from the Vantage Point of Social Metabolism (the Catalan Vallès county in 1860/70). In Agnoletti, M., (ed.) *The Conservation of Cultural Landscapes*. Wallingford: CAB International, pp. 42-56.

Tello, E., Garrabou, R., Cussó, X., Olarieta, J.R. and Galán, E. (2012). Fertilizing methods and nutrient balance at the end of traditional organic agriculture in the Mediterranean bioregion: Catalonia (Spain) in the 1860s. *Human Ecology* 40:369–383.

Tello, E. and Galán del Castillo, E. (2013). Sistemas agrarios sustentables y transiciones en el metabolism agrario: desigualdad social, cambios institucionales y transformaciones del paisaje en Catalunya (1850-2010). *Historia Ambiental Latinoamericana y Caribeña. HALAC* 2(2):267-378.

Tello, E., Valldeperas, E., Ollés, N., Marull, J., Coll, F., Warde, P. and Wilcox, P. (2014). Looking backwards into a Mediterranean edge environment: Landscape changes in El Congost Valley (Catalonia), 1850-2005. *Environment & History* 20:347-384.

Tello, E., Galán, E., Sacristán, V., Cunfer, G., Guzmán, G.I., González de Molina, M., Krausmann, F., Gingrich, S., Padró, R., Marco, I., Moreno-Delgado, D. (forthcoming). Opening the black box of energy throughputs in agroecosystems: a decomposition analysis of final EROI into its internal and external returns (the Vallès County, Catalonia, c.1860 and 1999). Submitted to *Ecological Economics.*

Tilman, D. (1994). Competition and Biodiversity in Spatially Structured Habitats. *Ecology* 75(1):2-16.

Tilman, D., Cassman, K.G., Matson, P.A. et al. (2002). Agricultural sustainability and intensive production practices. *Nature* 418:671-677.

Tripp, R. (2008). Agricultural Change and Low-Input Technology. In Snapp, S. and Pound, B. (eds.), *Agricultural Systems: Agroecology and Rural Innovation for Development*. Amsterdam: Elsevier, pp. 129-160.

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., and Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. *Ecology Letters* 8(8):857–874.

Tscharntke, T., Clough, Y., Wanger, T., Jackson, C., Motzke, L., Perfecto, M. *et al*. (2012a). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* 150(1):53–59.

Tscharntke, T.,Tylianakis, J.M., Rand T.A., Didham, R.K., Fahring, L., Batáry, p., Bengtsson, J., Clough, Y., Crist, Th.O., Dormann, C.F., Ewers, R.M., Fründ, J., Holt, R.D., Holzschuh, A., Klein, A.M., Kleijn, D., Kremen, C., Landis, D.A., Laurance, W., Lindemayer, D., Scherber, Ch., Sofhi, N., Steffan-Dewenter, I., Thies, C., van der Putten, W.H. and Westphal, C. (2012b). Landscape moderation of biodiversity patterns and processes—eigth hypotheses. *Biological Reviews* 87:661-685.

Van der Maarel, E. (1993). Some remarks on disturbance and its relations to diversity and stability. *Journal of Vegetation Science* 4:733-736.

Van Tuyl, S., Law, B.E., Turner, D.P. and Gitelman, A.I. (2005). Variability in net primary production and carbon storage in biomass across Oregon forests--an assessment integrating data from forest inventories, intensive sites, and remote sensing. *Forest Ecology and Management* 209(3):273-291.

Vanwalleghem, T., Infante, J., González de Molina, M., Soto, D. and Gómez, J.A. (2011). Quantifying the effect of historical soil management on soil erosion rates in Mediterranean olive orchards. *Agriculture, Ecosystems & Environment* 142(3-4): 341-351.

Weber, J.L. (2007). Implementation of land and ecosystem accounts at the European Environment Agency. *Ecological Economics* 61:695-707.

Weisz, H., Fischer-Kowalski, M., Grünbühel, C.M., Haberl, H., Krausmann, F. and Winiwarter, V. (2001). Global environmental change and historical transitions. *Innovation* 14 (2):117-142.

Wilson, J.B. (1994). The 'intermediate disturbance hypothesis' of species coexistence is based in on patch dynamics. *New Zeal Journal of Ecology* 18:176-181.

Zhao, M. and Running, S.W. (2006). Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. *Journal of Geophysical Research* 111.doi:10.1029/2004JG000004.

Ulanowicz, R. U. (1986). *Growth and Development. Ecosystems Phenomenology*, Dordrecht: Springer Verlag.

WORKING PAPERS SOCIAL ECOLOGY

Band 1
Umweltbelastungen in Österreich als Folge menschlichen Handelns. Forschungsbericht gem. m. dem Österreichischen Ökologie-Institut. Fischer-Kowalski, M., Hg. (1987)

Band 2
Environmental Policy as an Interplay of Professionals and Movements - the Case of Austria. Paper to the ISA Conference on Environmental Constraints and Opportunities in the Social Organisation of Space, Udine 1989. Fischer-Kowalski, M. (1989)

Band 3
Umwelt &Öffentlichkeit. Dokumentation der gleichnamigen Tagung, veranstaltet vom IFF und dem Österreichischen Ökologie-Institut in Wien, (1990)

Band 4
Umweltpolitik auf Gemeindeebene. Politikbezogene Weiterbildung für Umweltgemeinderäte. Lackner, C. (1990)

Band 5
Verursacher von Umweltbelastungen. Grundsätzliche Überlegungen zu einem mit der VGR verknüpfbaren Emittenteninformationssystem. Fischer-Kowalski, M., Kisser, M., Payer, H., Steurer A. (1990)

Band 6
Umweltbildung in Österreich, Teil I: Volkshochschulen. Fischer-Kowalski, M., Fröhlich, U.; Harauer, R., Vymazal R. (1990)

Band 7
Amtliche Umweltberichterstattung in Österreich. Fischer-Kowalski, M., Lackner, C., Steurer, A. (1990)

Band 8
Verursacherbezogene Umweltinformationen. Bausteine für ein Satellitensystem zur österr. VGR. Dokumentation des gleichnamigen Workshop, veranstaltet vom IFF und dem Österreichischen Ökologie-Institut, Wien (1991)

Band 9
A Model for the Linkage between Economy and Environment. Paper to the Special IARIW Conference on Environmental Accounting, Baden 1991. Dell'Mour, R., Fleissner, P. , Hofkirchner, W.,; Steurer A. (1991)

Band 10
Verursacherbezogene Umweltindikatoren - Kurzfassung. Forschungsbericht gem. mit dem Österreichischen Ökologie-Institut. Fischer-Kowalski, M., Haberl, H., Payer, H.; Steurer, A., Zangerl-Weisz, H. (1991)

Band 11
Gezielte Eingriffe in Lebensprozesse. Vorschlag für verursacherbezogene Umweltindikatoren. Forschungsbericht gem. m. dem Österreichischen Ökologie-Institut. Haberl, H. (1991)

Band 12
Gentechnik als gezielter Eingriff in Lebensprozesse. Vorüberlegungen für verursacherbezogene Umweltindikatoren. Forschungsbericht gem. m. dem Österr. Ökologie-Institut. Wenzl, P.; Zangerl-Weisz, H. (1991)

Band 13
Transportintensität und Emissionen. Beschreibung österr. Wirtschaftssektoren mittels Input-Output-Modellierung. Forschungsbericht gem. m. dem Österr. Ökologie-Institut. Dell'Mour, R.; Fleissner, P.; Hofkirchner, W.; Steurer, A. (1991)

Band 14
Indikatoren für die Materialintensität der österreichischen Wirtschaft. Forschungsbericht gem. m. dem Österreichischen Ökologie-Institut. Payer, H. unter Mitarbeit von K. Turetschek (1991)

Band 15
Die Emissionen der österreichischen Wirtschaft. Systematik und Ermittelbarkeit. Forschungsbericht gem. m. dem Österr. Ökologie-Institut. Payer, H.; Zangerl-Weisz, H. unter Mitarbeit von R.Fellinger (1991)

Band 16
Umwelt als Thema der allgemeinen und politischen Erwachsenenbildung in Österreich. Fischer-Kowalski M., Fröhlich, U.; Harauer, R.; Vymazal, R. (1991)

Band 17
Causer related environmental indicators - A contribution to the environmental satellite-system of the Austrian SNA. Paper for the Special IARIW Conference on Environmental Accounting, Baden 1991. Fischer-Kowalski, M., Haberl, H., Payer, H., Steurer, A. (1991)

Band 18
Emissions and Purposive Interventions into Life Processes - Indicators for the Austrian Environmental Accounting System. Paper to the ÖGBPT Workshop on Ecologic Bioprocessing, Graz 1991. Fischer-Kowalski M., Haberl, H., Wenzl, P., Zangerl-Weisz, H. (1991)

Band 19
Defensivkosten zugunsten des Waldes in Österreich. Forschungsbericht gem. m. dem Österreichischen Institut für Wirtschaftsforschung. Fischer-Kowalski et al. (1991)

Band 20*
Basisdaten für ein Input/Output-Modell zur Kopplung ökonomischer Daten mit Emissionsdaten für den Bereich des Straßenverkehrs. Steurer, A. (1991)

Band 22
A Paradise for Paradigms - Outlining an Information System on Physical Exchanges between the Economy and Nature. Fischer-Kowalski, M., Haberl, H., Payer, H. (1992)

Band 23
Purposive Interventions into Life-Processes - An Attempt to Describe the Structural Dimensions of the Man-Animal-Relationship. Paper to the Internat. Conference on "Science and the Human-Animal-Relationship", Amsterdam 1992. Fischer-Kowalski, M., Haberl, H. (1992)

Band 24
Purposive Interventions into Life Processes: A Neglected "Environmental" Dimension of the Society-Nature Relationship. Paper to the 1. Europ. Conference of Sociology, Vienna 1992. Fischer-Kowalski, M., Haberl, H. (1992)

WORKING PAPERS SOCIAL ECOLOGY

Band 25
Informationsgrundlagen struktureller Ökologisierung. Beitrag zur Tagung "Strategien der Kreislaufwirtschaft: Ganzheitl. Umweltschutz/Integrated Environmental Protection", Graz 1992. Steurer, A., Fischer-Kowalski, M. (1992)

Band 26
Stoffstrombilanz Österreich 1988. Steurer, A. (1992)

Band 28
Naturschutzaufwendungen in Österreich. Gutachten für den WWF Österreich. Payer, H. (1992)

Band 29
Indikatoren der Nachhaltigkeit für die Volkswirtschaftliche Gesamtrechnung - angewandt auf die Region. Payer, H. (1992). In: KudlMudl SonderNr. 1992:Tagungsbericht über das Dorfsymposium "Zukunft der Region - Region der Zukunft?"

Band 31
***Leerzeichen.* Neuere Texte zur Anthropologie**. Macho, T. (1993)

Band 32
Metabolism and Colonisation. Modes of Production and the Physical Exchange between Societies and Nature. Fischer-Kowalski, M., Haberl, H. (1993)

Band 33
Theoretische Überlegungen zur ökologischen Bedeutung der menschlichen Aneignung von Nettoprimärproduktion. Haberl, H. (1993)

Band 34
Stoffstrombilanz Österreich 1970-1990 - Inputseite. Steurer, A. (1994)

Band 35
Der Gesamtenergieinput des Sozio-ökonomischen Systems in Österreich 1960-1991. Zur Erweiterung des Begriffes "Energieverbrauch". Haberl, H. (1994)

Band 36
Ökologie und Sozialpolitik. Fischer-Kowalski, M. (1994)

Band 37
Stoffströme der Chemieproduktion 1970-1990. Payer, H., unter Mitarbeit von Zangerl-Weisz, H. und Fellinger, R. (1994)

Band 38
Wasser und Wirtschaftswachstum. Untersuchung von Abhängigkeiten und Entkoppelungen, Wasserbilanz Österreich 1991. Hüttler, W., Payer, H. unter Mitarbeit von H. Schandl (1994)

Band 39
Politische Jahreszeiten. 12 Beiträge zur politischen Wende 1989 in Ostmitteleuropa. Macho, T. (1994)

Band 40
On the Cultural Evolution of Social Metabolism with Nature. Sustainability Problems Quantified. Fischer-Kowalski, M., Haberl, H. (1994)

Band 41
Weiterbildungslehrgänge für das Berufsfeld ökologischer Beratung. Erhebung u. Einschätzung der Angebote in Österreich sowie von ausgewählten Beispielen in Deutschland, der Schweiz, Frankreich, England und europaweiten Lehrgängen. Rauch, F. (1994)

Band 42
Soziale Anforderungen an eine nachhaltige Entwicklung. Fischer-Kowalski, M., Madlener, R., Payer, H., Pfeffer, T., Schandl, H. (1995)

Band 43
Menschliche Eingriffe in den natürlichen Energiefluß von Ökosystemen. Sozio-ökonomische Aneignung von Nettoprimärproduktion in den Bezirken Österreichs. Haberl, H. (1995)

Band 44
Materialfluß Österreich 1990. Hüttler, W., Payer, H.; Schandl, H. (1996)

Band 45
National Material Flow Analysis for Austria 1992. Society's Metabolism and Sustainable Development. Hüttler, W. Payer, H., Schandl, H. (1997)

Band 46
Society's Metabolism. On the Development of Concepts and Methodology of Material Flow Analysis. A Review of the Literature. Fischer-Kowalski, M. (1997)

Band 47
Materialbilanz Chemie-Methodik sektoraler Materialbilanzen. Schandl, H., Weisz, H. Wien (1997)

Band 48
Physical Flows and Moral Positions. An Essay in Memory of Wildavsky. A. Thompson, M. (1997)

Band 49
Stoffwechsel in einem indischen Dorf. Fallstudie Merkar. Mehta, L., Winiwarter, V. (1997)

Band 50+
Materialfluß Österreich- die materielle Basis der Österreichischen Gesellschaft im Zeitraum 1960-1995. Schandl, H. (1998)

Band 51+
Bodenfruchtbarkeit und Schädlinge im Kontext von Agrargesellschaften. Dirlinger, H., Fliegenschnee, M., Krausmann, F., Liska, G., Schmid, M. A. (1997)

Band 52+
Der Naturbegriff und das Gesellschaft-Natur-Verhältnis in der frühen Soziologie. Lutz, J. Wien (1998)

Band 53+
NEMO: Entwicklungsprogramm für ein Nationales Emissionsmonitoring. Bruckner, W., Fischer-Kowalski, M., Jorde, T. (1998)

Band 54+
Was ist Umweltgeschichte? Winiwarter, V. (1998)

Mit + gekennzeichnete Bände sind unter
http://www.uni-klu.ac.at/socec/inhalt/1818.htm
Im PDF-Format und in Farbe downloadbar.

WORKING PAPERS SOCIAL ECOLOGY

Band 55+
Agrarische Produktion als Interaktion von Natur und Gesellschaft: Fallstudie SangSaeng. Grünbühel, C. M., Schandl, H., Winiwarter, V. (1999)

Band 57+
Colonizing Landscapes: Human Appropriation of Net Primary Production and its Influence on Standing Crop and Biomass Turnover in Austria. Haberl, H., Erb, K.H., Krausmann, F., Loibl, W., Schulz, N. B., Weisz, H. (1999)

Band 58+
Die Beeinflussung des oberirdischen Standing Crop und Turnover in Österreich durch die menschliche Gesellschaft. Erb, K. H. (1999)

Band 59+
Das Leitbild "Nachhaltige Stadt". Astleithner, F. (1999)

Band 60+
Materialflüsse im Krankenhaus, Entwicklung einer Input-Output Methodik. Weisz, B. U. (2001)

Band 61+
Metabolismus der Privathaushalte am Beispiel Österreichs. Hutter, D. (2001)

Band 62+
Der ökologische Fußabdruck des österreichischen Außenhandels. Erb, K.H., Krausmann, F., Schulz, N. B. (2002)

Band 63+
Material Flow Accounting in Amazonia: A Tool for Sustainable Development. Amann, C., Bruckner, W., Fischer-Kowalski, M., Grünbühel, C. M. (2002)

Band 64+
Energieflüsse im österreichischen Landwirtschaftssektor 1950-1995, Eine humanökologische Untersuchung. Darge, E. (2002)

Band 65+
Biomasseeinsatz und Landnutzung Österreich 1995-2020. Haberl, H.; Krausmann, F.; Erb, K.H.;Schulz, N. B.; Adensam, H. (2002)

Band 66+
Der Einfluss des Menschen auf die Artenvielfalt. Gesellschaftliche Aneignung von Nettoprimärproduktion als Pressure-Indikator für den Verlust von Biodiversität. Haberl, H., Fischer-Kowalski, M., Schulz, N. B., Plutzar, C., Erb, K.H., Krausmann, F., Loibl, W., Weisz, H.; Sauberer, N., Pollheimer, M. (2002)

Band 67+
Materialflussrechnung London. Bongardt, B. (2002)

Band 68+
Gesellschaftliche Stickstoffflüsse des österreichischen Landwirtschaftssektors 1950-1995, Eine humanökologische Untersuchung. Gaube, V. (2002)

Band 69+
The transformation of society's natural relations: from the agrarian to the industrial system. Research strategy for an empirically informed approach towards a European Environmental History. Fischer-Kowalski, M., Krausmann, F., Schandl, H. (2003)

Band 70+
Long Term Industrial Transformation: A Comparative Study on the Development of Social Metabolism and Land Use in Austria and the United Kingdom 1830-2000. Krausmann, F., Schandl, H., Schulz, N. B. (2003)

Band 72+
Land Use and Socio-economic Metabolism in Pre-industrial Agricultural Systems: Four Nineteenth-century Austrain Villages in Comparison. Krausmann, F. (2008)

Band 73+
Handbook of Physical Accounting Measuring bio-physical dimensions of socio-economic activities MFA – EFA – HANPP. Schandl, H., Grünbühel, C. M., Haberl, H., Weisz, H. (2004)

Band 74+
Materialflüsse in den USA, Saudi Arabien und der Schweiz. Eisenmenger, N.; Kratochvil, R.; Krausmann, F.; Baart, I.; Colard, A.; Ehgartner, Ch.; Eichinger, M.; Hempel, G.; Lehrner, A.; Müllauer, R.; Nourbakhch-Sabet, R.; Paler, M.; Patsch, B.; Rieder, F.; Schembera, E.; Schieder, W.; Schmiedl, C.; Schwarzlmüller, E.; Stadler, W.; Wirl, C.; Zandl, S.; Zika, M. (2005)

Band 75+
Towards a model predicting freight transport from material flows. Fischer-Kowalski, M. (2004)

Band 76+
The physical economy of the European Union: Cross-country comparison and determinants of material consumption. Weisz, H., Krausmann, F., Amann, Ch., Eisenmenger, N., Erb, K.H., Hubacek, K., Fischer-Kowalski, M. (2005)

Band 77+
Arbeitszeit und Nachhaltige Entwicklung in Europa: Ausgleich von Produktivitätsgewinn in Zeit statt Geld? Proinger, J. (2005)

Band 78+
Sozial-Ökologische Charakteristika von Agrarsystemen. Ein globaler Überblick und Vergleich. Lauk, C. (2005)

Band 79+
Verbrauchsorientierte Abrechnung von Wasser als Water-Demand-Management-Strategie. Eine Analyse anhand eines Vergleichs zwischen Wien und Barcelona. Machold, P. (2005)

Band 80+
Ecology, Rituals and System-Dynamics. An attempt to model the Socio-Ecological System of Trinket Island. Wildenberg, M. (2005)

Band 81+
Southeast Asia in Transition. Socio-economic transitions, environmental impact and sustainable development. Fischer-Kowalski, M., Schandl, H., Grünbühel, C., Haas, W., Erb, K-H., Weisz, H., Haberl, H. (2004)

Band 83+
HANPP-relevante Charakteristika von Wanderfeldbau und anderen Langbrachesystemen. Lauk, C. (2006)

Band 84+
Management unternehmerischer Nachhaltigkeit mit Hilfe der Sustainability Balanced Scorecard. Zeitlhofer, M. (2006)

Band 85+
Nicht-nachhaltige Trends in Österreich: Maßnahmenvorschläge zum Ressourceneinsatz. Haberl, H., Jasch, C., Adensam, H., Gaube, V. (2006)

Band 87+
Accounting for raw material equivalents of traded goods. A comparison of input-output approaches in physical, monetary, and mixed units. Weisz, H. (2006)

WORKING PAPERS SOCIAL ECOLOGY

Band 88+
Vom Materialfluss zum Gütertransport. Eine Analyse anhand der EU15 – Länder (1970-2000).
Rainer, G. (2006)

Band 89+
Nutzen der MFA für das Treibhausgas-Monitoring im Rahmen eines Full Carbon Accounting-Ansatzes; Feasibilitystudie; Endbericht zum Projekt BMLFUW-UW.1.4.18/0046-V/10/2005. Erb, K.-H., Kastner, T., Zandl, S., Weisz, H., Haberl, H., Jonas, M., (2006)

Band 90+
Local Material Flow Analysis in Social Context in Tat Hamelt, Northern Mountain Region, Vietnam. Hobbes, M.; Kleijn, R. (2006)

Band 91+
Auswirkungen des thailändischen logging ban auf die Wälder von Laos. Hirsch, H. (2006)

Band 92+
Human appropriation of net primary produktion (HANPP) in the Philippines 1910-2003: a socio-ecological analysis. Kastner, T. (2007)

Band 93+
Landnutzung und landwirtschaftliche Entscheidungsstrukturen. Partizipative Entwicklung von Szenarien für das Traisental mit Hilfe eines agentenbasierten Modells. Adensam, H., V. Gaube, H. Haberl, J. Lutz, H. Reisinger, J. Breinesberger, A. Colard, B. Aigner, R. Maier, Punz, W. (2007)

Band 94+
The Work of Konstantin G. Gofman and colleagues: An early example of Material Flow Analysis from the Soviet Union. Fischer-Kowalski, M.; Wien (2007)

Band 95+
Partizipative Modellbildung, Akteurs- und Ökosystemanalyse in Agrarintensivregionen; Schlußbericht des deutsch-österreichischen Verbundprojektes. Newig, J., Gaube, V., Berkhoff, K., Kaldrack, K., Kastens, B., Lutz, J., Schlußmeier B., Adensam, H., Haberl, H., Pahl-Wostl, C., Colard, A., Aigner, B., Maier, R., Punz, W.; Wien (2007)

Band 96+
Rekonstruktion der Arbeitszeit in der Landwirtschaft im 19. Jahrhundert am Beispiel von Theyern in Niederösterreich. Schaschl, E.; Wien (2007)

Band 98+
Local Material Flow Analysis in Social Context at the forest fringe in the Sierra Madre, the Philippines. Hobbes, M., Kleijn, R. (Hrsg); Wien (2007)

Band 99+
Human Appropriation of Net Primary Production (HANPP) in Spain, 1955-2003: A socio-ecological analysis. Schwarzlmüller, E.; Wien (2008)

Band 100+
Scaling issues in long-term socio-ecological biodiversity research: A review of European cases. Dirnböck, T., Bezák, P., Dullinger S., Haberl, H., Lotze-Campen, H., Mirtl, M., Peterseil, J., Redpath, S., Singh, S., Travis, J., Wijdeven, S.M.J.; Wien (2008)

Band 101+
Human Appropriation of Net Primary Production (HANPP) in the United Kingdom, 1800-2000: A socio-ecological analysis. Musel, A.; Wien (2008)

Band 102 +
Wie kann Wissenschaft gesellschaftliche Veränderung bewirken? Eine Hommage an Alvin Gouldner, und ein Versuch, mit seinen Mitteln heutige Klimapolitik zu verstehen. Fischer-Kowalski, M.; Wien (2008)

Band 103+
Sozialökologische Dimensionen der österreichischen Ernährung – Eine Szenarienanalyse. Lackner, M.; Wien (2008)

Band 104+
Fundamentals of Complex Evolving Systems: A Primer. Weis, E.; Wien (2008)

Band 105+
Umweltpolitische Prozesse aus diskurstheoretischer Perspektive: Eine Analyse des Südtiroler Feinstaubproblems von der Problemkonstruktion bis zur Umsetzung von Regulierungsmaßnahmen. Paler, M.; Wien (2008)

Band 106+
Ein integriertes Modell für Reichraming. Partizipative Entwicklung von Szenarien für die Gemeinde Reichraming (Eisenwurzen) mit Hilfe eines agentenbasierten Landnutzungsmodells. Gaube, V., Kaiser, C., Widenberg, M., Adensam, H., Fleissner, P., Kobler, J., Lutz, J., Smetschka, B., Wolf, A., Richter, A., Haberl, H.; Wien (2008)

Band 107+
Der soziale Metabolismus lokaler Produktionssysteme: Reichraming in der oberösterreichischen Eisenwurzen 1830-2000. Gingrich, S., Krausmann, F.; Wien (2008)

Band 108+
Akteursanalyse zum besseren Verständnis der Entwicklungsoptionen von Bioenergie in Reichraming. Eine sozialökologische Studie. Vrzak, E.; Wien (2008)

Band 109+
Direktvermarktung in Reichraming aus sozialökologischer Perspektive. Zeitlhofer, M.; Wien (2008)

Band 110+
CO_2-Bilanz der Tomatenproduktion: Analyse acht verschiedener Produktionssysteme in Österreich, Spanien und Italien. Theurl, M.; Wien (2008)

Band 111+
Die Rolle von Arbeitszeit und Einkommen bei Rebound-Effekten in Dematerialisierungs- und Dekarbonisierungsstrategien. Eine Literaturstudie. Bruckner, M.; Wien (2008)

Band 112+
Von Kommunikation zu materiellen Effekten - Ansatzpunkte für eine sozial-ökologische Lesart von Luhmanns Theorie Sozialer Systeme. Rieder, F.; Wien (2008)

Band 114+
Across a Moving Threshold: energy, carbon and the efficiency of meeting global human development needs. Steinberger, J. K., Roberts, .J.T.; Wien (2008)

WORKING PAPERS SOCIAL ECOLOGY

Band 115
Towards a low carbon society: Setting targets for a reduction of global resource use. Krausmann, F., Fischer-Kowalski, M., Steinberger, J.K., Ayres, R.U.; Wien (2010)

Band 116+
Eating the Planet: Feeding and fuelling the world sustainably, fairly and humanely - a scoping study. Erb, K-H., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C., Steinberger, J.K., Müller, C., Bondeau, A., Waha, K., Pollack, G.; Wien (2009)

Band 117+
Gesellschaftliche Naturverhältnisse: Energiequellen und die globale Transformation des gesellschaftlichen Stoffwechsels. Krausmann, F., Fischer-Kowalski, M.; Wien (2010)

Band 118+
Zurück zur Fläche? Eine Untersuchung der biophysischen Ökonomie Brasiliens zwischen 1970 und 2005. Mayer, A.; Wien (2010)

Band 119+
Das nachhaltige Krankenhaus: Erprobungsphase. Weisz, U., Haas, W., Pelikan, J.M., Schmied, H., Himpelmann, M., Purzner, K., Hartl, S., David, H.; Wien (2009)

Band 120+
LOCAL STUDIES MANUAL
A researcher's guide for investigating the social metabolism of local rural systems. Singh, S.J., Ringhofer, L., Haas, W., Krausmann, F., Fischer-Kowalski, M.; Wien (2010)

Band 121+
Sociometabolic regimes in indigenous communities and the crucial role of working time: A comparison of case studies. Fischer-Kowalski, M., Singh, S.J., Ringhofer, L., Grünbühel C.M., Lauk, C., Remesch., A.; Wien (2010)

Band 122+
Klimapolitik im Bereich Gebäude und Raumwärme. Entwicklung, Problemfelder und Instrumente der Länder Österreich, Deutschland und Schweiz. Jöbstl, R.; Wien (2012)

Band 123+
Trends and Developments of the Use of Natural Resources in the European Union. Krausmann, F., Fischer-Kowalski, M., Steinberger, J.K., Schaffartzik, A., Eisenmenger, N, Weisz, U.; Wien (2011)

Band 125+
Raw Material Equivalents (RME) of Austria's Trade. Schaffartzik, A., Eisenmenger, N., Krausmann, F., Weisz, H.; Wien (2013)

Band 126+
Masterstudium "Sozial- und Humanökologie": Selbstevaluation 2005-2010. Schmid, M., Mayer A., Miechtner, G.; Wien (2010)

Band 127 +
Bericht des Zentrums für Evaluation und Forschungsberatung (ZEF). Das Masterstudium „Sozial- und Humanökologie". Mayring, P., Fenzl, T.; Wien (2010)

Band 128+
Die langfristigen Trends der Material- und Energieflüsse in den USA in den Jahren 1850 bis 2005. Gierlinger, S.; Wien (2010)

Band 129+
Die Verzehrungssteuer 1829 – 1913 als Grundlage einer umwelthistorischen Untersuchung des Metabolismus der Stadt Wien. Hauer, F.; Wien (2010)

Band 130+
Human Appropriation of Net Primary Production in South Africa, 1961- 2006. A socio-ecological analysis. Niedertscheider, M.; Wien (2011)

Band 131+
The socio-metabolic transition.
Long term historical trends and patterns in global material and energy use. Krausmann, F. (Editor); Wien (2011)

Band 132+
„Urlaub am Bauernhof" oder „Bauernhof ohne Urlaub"? Eine sozial-ökologische Untersuchung der geschlechtsspezifischen Arbeitsteilung und Zeitverwendung auf landwirtschaftlichen Betrieben in der Gemeinde Andelsbuch, Bregenzerwald.
Winder, M.; Wien (2011)

Band 133+
Spatial and Socio-economic Drivers of Direct and Indirect Household Energy Consumption in Australia. Wiedenhofer, D.; Wien (2011)

Band 134+
Die Wiener Verzehrungssteuer. Auswertung nach einzelnen Steuerposten (1830 – 1913). Hauer, F., Gierlinger, S., Nagele, C., Albrecht, J., Uschmann, T., Martsch, M.; Wien (2012)

Band 135+
Zeit für Veränderung? Über die geschlechtsspezifische Arbeitsteilung und Zeitverwendung in landwirtschaftlichen Betrieben und deren Auswirkungen auf Landnutzungsveränderungen in der Region „Westlicher Wienerwald". Eine sozial-ökologische Untersuchung.
Madner, V.; Wien (2013)

Band 136+
The Impact of Industrial Grain Fed Livestock Production on Food Security: an extended literature review. Erb, K-H., Mayer, A., Kastner, T., Sallet, K-E., Haberl, H.; Wien (2012)

Band 137+
Human appropriation of net primary production in Africa: Patterns, trajectories, processes and policy implications. Fetzel, T., Niedertscheider, M., Erb, K-H., Gaube, V., Gingrich, S., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C.; Wien (2012)

Band 138+
VERSCHMUTZT – VERBAUT – VERGESSEN: Eine Umweltgeschichte des Wienflusses von 1780 bis 1910. Pollack, G.; Wien (2013)

Band 139+
Der Fleischverbrauch in Österreich von 1950-2010.Trends und Drivers als Zusammenspiel von Angebot und Nachfrage. Willerstorfer, T.; Wien (2013)

Band 141+
Wie das ERP (European Recovery Program) die Entwicklung des alpinen, ländlichen Raumes in Vorarlberg prägte. Groß, R.; Wien (2013)

Band 142+
Exploring local opportunities and barriers for a sustainability transition on a Greek island. Petridis, P., Hickisch, R., Klimek, M., Fischer, R., Fuchs, N., Kostakiotis, G., Wendland, M., Zipperer, M., Fischer-Kowalski, M.; Wien (2013)

Band 143+
Climate Change Mitigation in Latin America: A Mapping of Current Policies, Plans and Programs. Ringhofer, L., Singh, S.J., Smetschka, B.; Wien (2013)

Band 144+
Arbeitszeit und Energieverbrauch: Grundsatzfragen diskutiert an der historischen Entwicklung in Österreich. Weisz, U., Possanner, N..; Wien (2013)

Band 145+
Barrieren und Chancen für die Realisierung nachhaltiger Mobilität. Eine Analyse der Zeitabhängigkeit von Mobilitätsmustern am Beispiel von Krems/Donau. Gross, A.; Wien (2013)

Band 147+
The rise of the semi-periphery:
A physical perspective on the global division of labour.
Material flow analysis of global trade flows (1970-2005).
Loy, C.; Wien (2013)

Band 148+
Historische Energietransitionen im Ländervergleich. Energienutzung, Bevölkerung, Wirtschaftliche Entwicklung. Pallua, I.; Wien (2013)

Band 149+
Socio-Ecological Impacts of Land Grabbing for Nature Conservation on a Pastoral Community: A HANPP-based Case Study in Ololosokwan Village, Northern Tanzania.
Bartels, L. E.; Wien (2014)

Band 150+
Teilweise waren Frauen auch Traktorist.
Geschlechtliche Arbeitsteilung in landwirtschaftlichen Betrieben Ostdeutschlands heute – Unterschiede in der biologischen und konventionellen Bewirtschaftung.
Fehlinger, J.; Wien (2014)

Band 151+
Economy-wide Material Flow Accounting
Introduction and guide. Krausmann, F., Weisz, H., Schütz, H., Haas, W., Schaffartzik, A.; Wien (2014)

Band 152+
Large scale societal transitions in the past.
The Role of Social Revolutions and the 1970s Syndrome.
Fischer-Kowalski, M., Hausknost, D. (Editors); Wien (2014)

Band 154+
Environmentally Extended Input-Output Analysis
Schaffartzik, A., Sachs, M., Wiedenhofer, D., Eisenmenger, N.; Wien (2014)

Band 155+
Rural Metabolism: Material flows in an Austrian village in 1830 and 2001
Haas, W., Krausmann, F.; Wien (2015)

Band 156+
A proposal for a workable analysis of Energy Return On Investment (EROI) in agroecosystems.
Part I: Analytical approach
Tello, E., Galán, E., Cunfer, G., Guzmán-Casado, G.I.,Gonzales de Molina, M., Krausmann, F., Gingrich, S., Sacristán, V., Marco, I., Padró, R., Moreno-Delgado, D.; Wien (2015)